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Soil Displacement Induced Laterally Loaded Piles Test Embankments Bloemendalerpolder – Geo-Impuls Program

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Abstract. In the Bloemendalerpolder two test embankments were constructed in 2010 to study the long term behaviour of embankments on very soft soils with respect to settlement and lateral pile loading resulting from horizontal soil deformations. A detailed description of the test embankments, performed soil investigation, laboratory tests and instrumentation is given in an accompanying paper. This paper provides a brief description of both test embankments consisting of sandfill with a height of 3.0 m and a ground area 26 x 36 m^2 with slopes 1:2. At one embankment – overlying 5.7 m of peat/clay – wick drains are installed at a triangular spacing of 1.0 m. The second embankment – overlying 4.0 m of peat/clay – is not provided with any additional drainage accelerating measures. In each embankment two steel H-beam piles have been installed, one located at the crest of the slope and one 4 m from the crest. Both piles have been installed 3 weeks after completion of the final fill increment. The pile bending stiffness represents a prefabricated concrete pile square 0.26 m. The piles were equipped with a steel square guiding tube to perform inclinometer measurements. Inclinometer readings were performed at regular time intervals, each reading at depth intervals of 0.1 m. The small interval was selected to improve interpretation with respect to pile curvature and therefore the derivation of pile bending moments. Although horizontal soil deformations after pile installation are significant the resulting bending moments remain limited.

Keywords. Soft Soils, Clay, Peat, Lateral Soil Displacements, Laterally Loaded Piles, Bloemendalerpolder, Geo-Impuls program, Inclinometer Measurements, Bending Moments

1. Introduction

Settlement of embankments for urban development or road construction on soft soils is a well-known issue resulting in both vertical and lateral deformations. Existing design guidelines and case studies show a need for datasets of continuous long term soil deformation measurement, e.g. CUR 228. Especially long term behaviour in very soft clays and peats is not adequately documented. It results in conservative estimates of lateral soil deformation, mainly based on elastic soil behaviour, e.g. the theory of Van IJsseldijk en Loof (De Leeuw (1963)), or empirical data, e.g. Bourges and Mieussens (1979). Better understanding and predictions of long term soil deformation will decrease risks and cost during the life time and construction of structures.

For an urban development in the Bloemdalerpolder in the Netherlands field tests were designed to study the settlement behaviour for one year. The Geo-Impuls program took the opportunity to extend the field tests to a five year monitoring period as well as to include inclinometers and test piles for monitoring their behaviour with respect to horizontal soil deformations.

The existing grasslands at the Bloemendalerpolder are underlain by a 4.0 m to 5.7 m thick very soft peat/clay layer with a groundwater table at 0.2 m below ground level. Below the soft soil layers a loose to medium dense sand layer is present down to the maximum explored depth, approx. NAP[*] -11 m. Urban development requires 0.5 to 1.0 m clearance of the ground level above the groundwater table. Two test embankments consisting of sand fill were designed with a construction height of 3.0 m and a ground area 26 x 36 m^2 with slopes 1:2. The test piles were installed in the crest of the slope and 4 m out of the crest in both embankments. The Geo-Impuls

[*] New Amsterdam Level (commonly used reference level in the Netherlands)

program aimed to provide a well described and documented field test with long time monitoring results.

2. Test Embankments

This paper elaborates on the installed inclinometers and test piles. Hoefsloot (2015) presents the full monitoring program and results of the test embankments in the Bloemendalerpolder.

The embankments are constructed in stages, starting with a 1.0 m fill and 0.5 m fill in the consecutive stages every 3 weeks up to a height of 3.0 m. After the first 1.0 m fill wick drains were installed in a triangular grid with 1.0 m spacing at Embankment 2, with the thickest peat layer, to study the application of consolidation with acceleration measures. A detailed schedule of the staged construction is given in Table 1.

Table 1. Construction phases

Phase			**1**	**2**
Ground area [m^2]			36 x 26	36 x 26
Construction height [m]			3.0	3.0
Slope			1:2	1:2
Wick drains [triangular grid]			No	Yes
Phase	Wk	Day		
1st stage	1	0	1.0 m	1.0 m
Installing drains	2	5	n.a.	1 m c.t.c.
2nd stage	4	25	0.5 m	0.5 m
3th stage	7	47	0.5 m	0.5 m
4th stage	13	92	0.5 m	0.5 m
5th stage	16	112	0.5 m	0.5 m
Pile installation	19	133	2 pcs	2 pcs
Baseline measurement piles	21	145	Done	Done

Four soil inclinometers and two H-beams (HEA300) are installed in each embankment to study the behavior of horizontal soil deformations and the resulting pile loading. The soil inclinometers are installed in a line parallel to the piles; one inclinometer next to each pile and two at the toe and 4 m out of the toe of the embankment as shown in Figure 1. The latter two inclinometers were installed prior to construction.

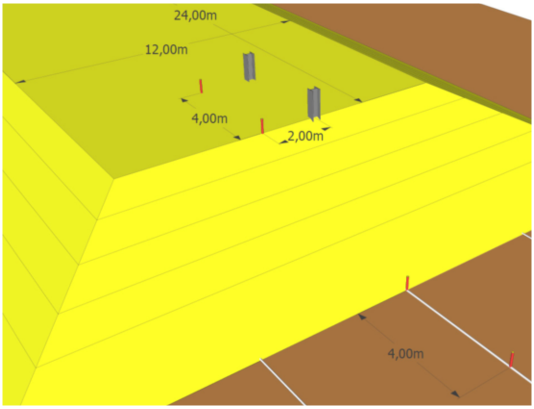

Figure 1. Pile and Inclinometer configuration.

The pile heads have no fixation. A steel casing is welded on the piles for inclinometer measurements. Lateral soil displacement load the pile in its weakest axis, x-axis of Figure 2, which has a comparable stiffness to a precast concrete square pile of 0.26 x 0.26 m^2. Table 2 presents the pile properties of the installed piles and the comparable pile type.

Table 2. Mechanical properties of the piles

Pile Type	**HEA300**	**Prefab Concrete**	**Unit**
Length	13.00		m
Pile tip level	-11.45		m+NAP
Dimensions	0.29 x 0.30	0.26 x 0.26	m
Young's Mod. [E]	210,000	35,000	MPa
Weakest bending stiffness [EI$_x$]	$1.33 \cdot 10^4$	$1.33 \cdot 10^4$	kNm^2

3. Monitoring

Lateral soil displacements are measured by lowering an inclinometer in the installed (inclinometer) tubes. The inclinometer measures its tilting over 0.5 m depth, in one direction as shown in Figure 2. The inclination was measured in two direction, A_0 and B_0, where the device is also flipped by 180º for negative tilt readings as calibration.

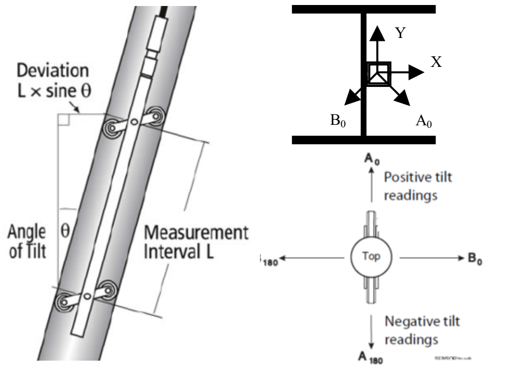

Figure 2. Schematic view of inclinometer mechanism from DGSI (2001)

Lateral soil displacements are measured with an interval of 0.5 m. The 0.5 m measurement interval is recommended to measure the lateral displacements of a tube.

A smaller interval is used for the pile inclinometers as the results are also used to determine the curvature of the piles due to deformation caused by soil displacement induced lateral pile loads. For the piles a measurement interval of 0.1 m was used. As shown in Figure 2 the measurements, A_0 and B_0, are not exactly in the X and Y direction of the pile, where X is the general direction of lateral soil displacements. Inclinometer results of the piles in this article are presented in the X direction of the pile, as shown in Figure 2, which were derived from the A_0 and B_0 readings.

4. Data Processing

4.1. Inclinometer Measurements

From the inclinometer measurements; the lateral deflection, the curvature, and the bending moments are derived. The curvature and bending moments are only derived for the pile inclinometer measurements.

Lateral displacements (u) are derived as shown in Figure 2 using the measured inclination θ and measurement interval L according Eq. (1).

$$\Delta u = L \times \sin\theta \tag{1}$$

The measurement interval at the pile is smaller than the height of the used device, therefore the lateral deflection is a series of 5 measurements. Figure 3 shows the lateral displacement of one series on the left. The right figure shows to 5 series of measurement (u1 to u5). A small bandwidth can be observed, which is within the inaccuracy of the inclinometer.

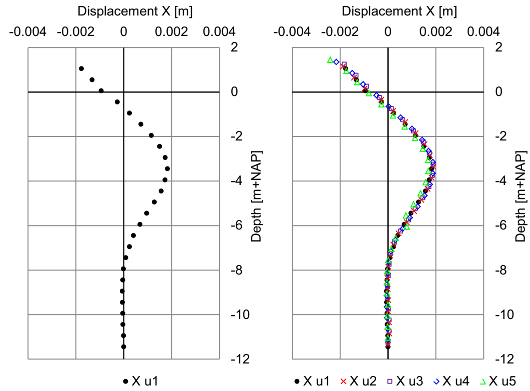

Figure 3. Data points from higher resolution inclinometer measurement.

4.2. Bending Moments from Inclinometer Measurements

The product of the pile curvature and the bending stiffness (EI) is the bending moment in the pile as shown in Eq. (2).

$$M = -EI\frac{d\varphi}{dx} = -EI\frac{d^2u}{dx^2} \tag{2}$$

The curvature is mathematically defined as the first derivative of the inclination (φ) or second derivative of the displacement (u). The curvature and bending moment are determined per set of measurements.

One measurement series results in a spread of data points of the bending moment in the pile, as presented on the left graph of Figure 4. By averaging the 5 measurement series the bending moments over pile length are derived. This is shown in the right graph of Figure 4.

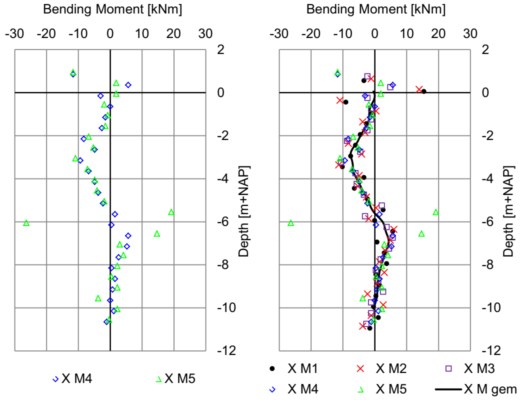

Figure 4. Bending moments in pile derived from inclinometer measurements.

5. Measurements

Inclinometer measurements, taken at regular intervals, are available up to 4 years after construction of the embankments. Results of the field test are presented in Hoefsloot (2015) and accessible in Dutch via www.geoimpuls.org and www.geonet.nl/684. The total settlements of Embankment 1 is 1.3 m to 1.55 m. Settlement of Embankment 2 are 2.0 m to 2.25 m. Typical lateral soil displacement profiles, lateral pile displacement and forces in the pile are shown in Figure 5 to Figure 7. The general soil profile at the location is plotted next to the figures as indication. Displacements away from the embankment are defined as positive.

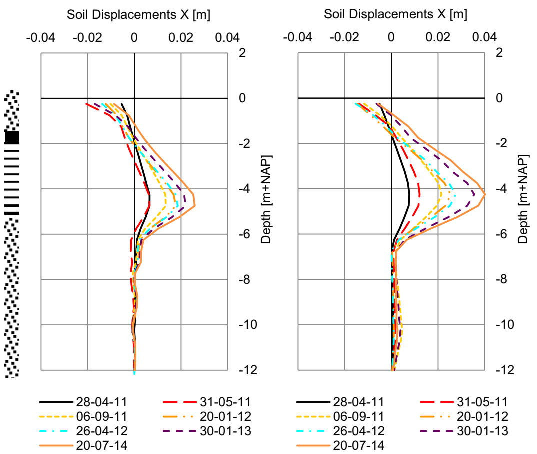

Figure 5. General soil profile and lateral soil displacements next to the pile, 4 m from the crest (HT1-1, left) and at the crest of the embankment (HT1-2, right).

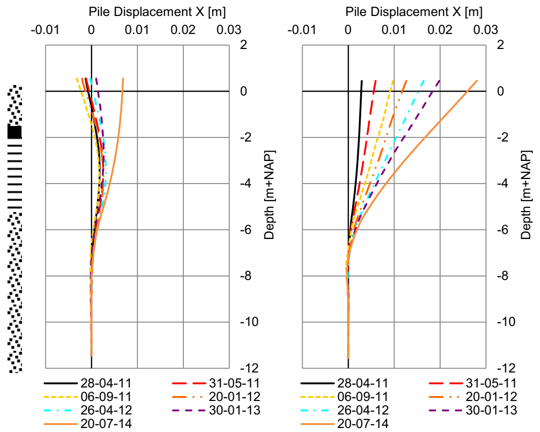

Figure 6. Soil profile, lateral pile displacements Pile PT1-1 (left), 4 m from the crest, and PT1-2 (right) in the crest of Embankment 1.

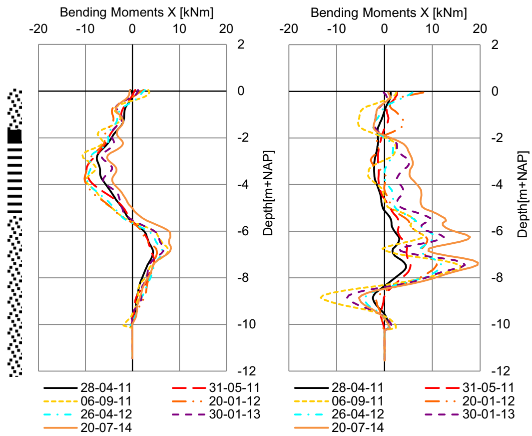

Figure 7. Soil profile, bending moments in Pile PT1-1 (left), 4 m from the crest, and PT1-2 (right) in the crest in Embankment 1.

6. Discussion and Evaluation

The previous sections presented the data processing and results of measurements taken from the two test embankments in the Bloemendalerpolder. The results apply to the situation after installation of the inclinometer casings and therefore after completion of the embankments

Compared to the total settlement after completion of the embankments, ranging from 0.30 m to 0.35 m, the lateral soil displacements are much smaller, ranging from 0.016 m to 0.040 m. The maximum lateral soil deformations occur in the soft soil layer, which is squeezed and deforms in lateral direction due to the load of the embankments after construction. Lateral displacements of the embankment itself, e.g. from NAP 0 m to -2 m in Figure 5, is much smaller. The centre of the embankment settles more and faster causing the embankments to tilt towards the centre if a 2D cross section is considered. These differential settlements between the centre and the slope of the embankments cause a negative lateral soil displacement at the top of the embankments.

Initially the maximum lateral pile deformations occur at the elevation of the soft soil layers. In the soft layers the lateral pile deformations are much smaller compared to the measured lateral soil deformations. The negative lateral soil displacement at the top of the embankment is not observed in the lateral pile behaviour. However the lateral displacement of the pile head increases, as observed in the lateral soil displacement measurements next to the pile. Eventually the maximum lateral pile displacements occur at the pile head.

Smaller intervals of pile inclinometer measurements enable the derivation of the curvature and bending moments in the pile due to lateral loads caused by soil deformations. Derived bending moments in the pile show small variations as lateral soil deformations develop further. As the upper part of the pile continuously deforms, bending moments in the pile decrease or even change sign (negative to positive). This is a result of the smaller curvature of the pile. The maximum bending moments occur near the layer transition of the firm sand layer at the pile tip to the soft soil layers.

The soil displacement induced laterally loaded piles installed in the Bloemendalerpolder test embankments are less influenced by the soil displacement than expected. The lateral pile displacement in the soft soil layer is less compared to the lateral soil displacement. The maximum pile displacement occurs at the pile head. In this case 5 data series are derived of the lateral pile deformations by decreasing the measurement interval to 0.1 m. By comparing the series, errors in the measurements are checked and the bending moments in the piles are derived. The smaller inclinometer measurement interval of 0.1 m increases the confidence in the derived moment distribution significantly as more information becomes available.

7. Acknowledgements

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