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The Rotterdam sheet pile wall field test: Test setup

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ABSTRACT: The recent development of Eurocodes in the design practice for steel sheet piling has led to the initiative for a full scale field test on two steel sheet pile walls in soft soil. The main goal of this field test is to examine the performance of two facing single strutted steel sheet pile walls with a length of 19 metres and a width of 8 metres. In one wall a plastic hinge will be developed to obtain a redistribution of bending moments; the other wall is composed of double U-piles to examine the phenomenon of "oblique bending". For this field test a question for type A predictions was distributed to 50 geotechnical engineers worldwide. This Paper describes the setup of the field test. This test may contribute to a better understanding of both plastic design and sheet pile design with double U-sections and may therefore lead to a safer and more economic design of steel sheet pile walls.

1 INTRODUCTION

The introduction of Eurocodes in the design practice for steel sheet piling may lead to a gradual replacement of national building codes by one European standard. ENV 1993-5 (CEN 1997) treats, together with ENV 1997-1 (CEN 1994), the design of steel sheet piling. ENV 1993-5 offers the possibility to introduce plastic hinges in the design of steel sheet pile walls and gives guidance by means of a stepwise procedure.

If the excavation in front of a sheet pile wall is continued after yielding in the ultimate fibre, a plastic hinge is developed, which involves a moment redistribution in the wall and therefore a rotation in the first plastic hinge upto collapse as a second plastic hinge is formed, see Figure 1. In 1953 Brinch Hansen (1953) proposed a design method for steel sheet pile walls with plastic hinges. This method is still the basis of the Danish design code and until now almost solely applied in the Danish design practice of steel sheet piling. The possibility of plastic design may lead to an interesting saving of material compared to elastic design (Steenfelt 1988, Hartmann-Linden 1997 and Van Tol & Kort 1997).

In ENV 1993-5 the design of sheet pile walls composed of single and double U-piles is also treated. In case a lack of friction in the driving interlocks exists, the sheet piles will not fully work

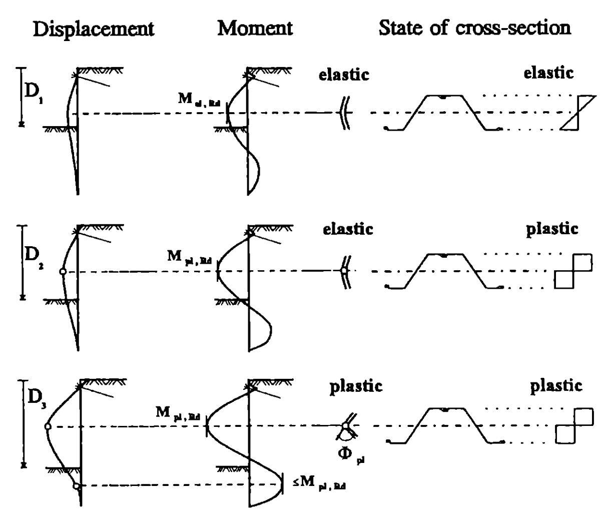

Figure 1: States of stresses in a sheet pile wall during an excavation (Hartmann-Linden 1997)

together in bending, which may be clear for the single piled wall. However, due to the rotated neutral axis, the wall composed of double U-piles might not only bend out of plane but also in plane of the wall. This phenomenon is called oblique bending and can cause a considerable loss of strength and stiffness of the sheet pile wall. The Netherlands is probably the only country which has severe design rules for oblique bending of steel sheet pile walls. In most other countries the problem of missing interlock friction for double U-piles is denied, because oblique

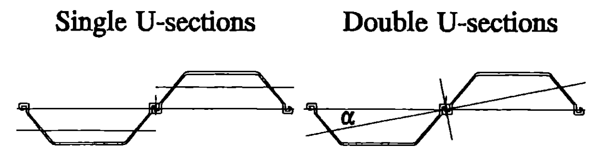

Figure 2: Bending of single and double U-sections

bending has hardly ever been observed in practice. In some countries even single U-piles are treated as fully cooperating. At this moment it is not clear whether steel sheet pile wall design is too expensive in the Netherlands or unsafe in the other countries.

Large scale field tests on sheet pile walls composed of single U-piles in Le Havre (Hebert et al. 1978) and in Paris (Gigan 1984) proved to be an effective tool to investigate the loss of bending stiffness due to missing interlock friction. However, during the formation of Eurocode 3 part 5 sufficient evidence was missing for the development of appropriate application rules for U-sections.

These developments gave rise for the Geotechnical Laboratory of Delft University of Technology and the Dutch Centre for Civil Engineering Research and Codes (CUR) to initiate a full scale field test in Dutch soft soil with a high groundwater level. In this test the research is focused on:

- the performance of a sheet pile wall with a plastic hinge;
- the performance a sheet pile wall constructed of double U-sections;
- the short-term and the long-term performance of both sheet pile walls in soft soil.

For this field test a square building pit of approximately 12 to12 metre is constructed in which two test walls are included. In order to obtain a benchmark for calculation tools special measurements are foreseen for a 2-dimensional performance of both test walls.

This Paper presents necessary information to perform a prediction for this field test. The Paper describes the layout of the test site, the soil data, the construction details, the test sequence and a possible hazard when during the test the plastic hinge is developed. Finally the Paper motivates the question for predictions, which has been distributed to more than 50 specialists in sheet pile wall design.

2 LAYOUT OF THE TEST SITE

Figure 3 shows the layout of the sheet pile walls. The four walls are installed in an almost square form, which sides of about 12 metre. The top of the sheet piles is at NAP +1.0 m (NAP is Dutch reference level) and the greenfield is at NAP -0.6 m. The north and the south walls are test walls. In order to minimise the corner effects on the test walls, four bentonite screens have been installed and four special interface piles have been developed which are cut over a length of 16 metre.

2.1 North wall

The north wall consists of 10 double piles Arbed AZ13. Of them, 6 form the test wall, 2 the interfacing piles AZ13S (see below) and 2 the corner piles. The interconnecting interlocks of the double piles have been welded over the full length but for the driving interlocks no special measures have been

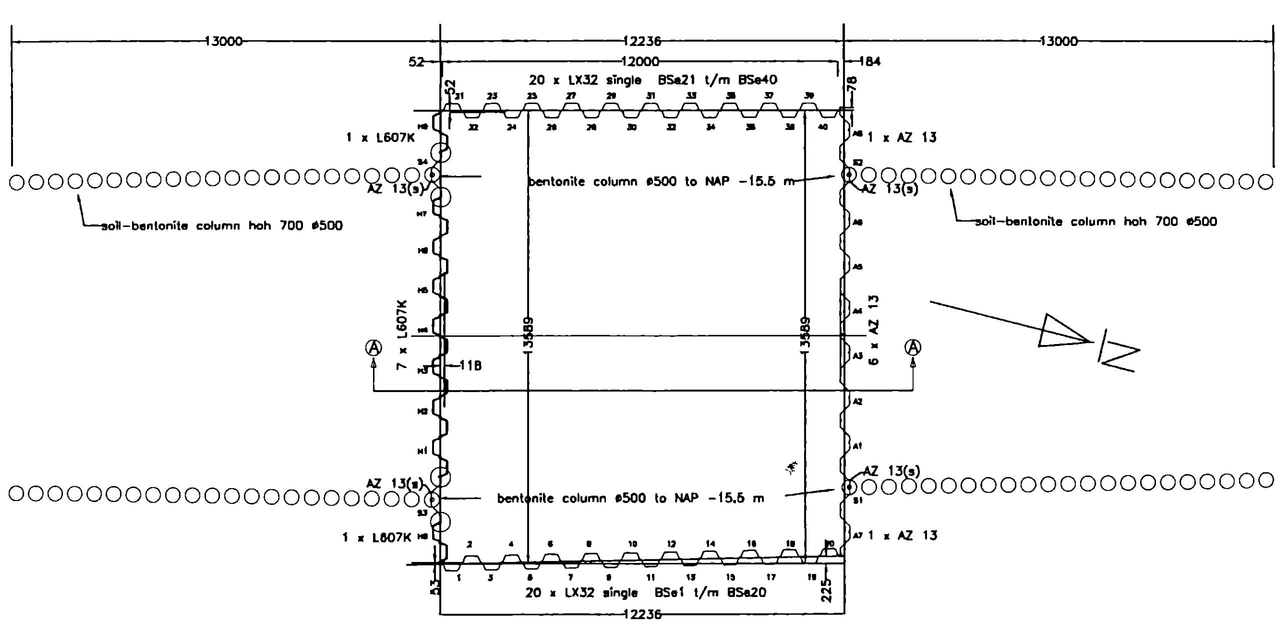

Figure 3: Layout of the sheet pile walls

taken. The sheet piles have been vibrated to NAP -18 m. On test piles A2, A4 and A5 inclinometer tubes have been welded. Test pile A3 is equipped with 12 earth pressure cells, 4 on the excavated side and 8 on the retaining side, and test pile A4 with 40 vibrating wire (VW) strain gauges.

2.2 South wall

The test section is formed by 7 double U-piles Larssen 607K from Hoesch, H1 to H7. The interlocks of the double piles have been welded but for the driving interlocks no special measures have been taken. The toe of the sheet piles has been installed at NAP -18 metre. On test piles H2, H4 and H6 inclinometer tubes have been welded. Test pile H3 is equipped with 12 earth pressure cells, 4 on the excavated side and 8 on the retaining side and test pile H5 with 40 vibrating wire strain gauges. The south wall is completed by 2 interface piles AZ13S and two corner piles H8 and H9.

2.3 East and west walls

The east and the west walls are each formed by 20 single piles LX32 from British Steel. These piles have been installed to NAP -20 metre in order to minimise disturbance of the passive zones of both test walls. The piles BS6, BS14, BS26 and BS34 are equipped with inclinometer tubes.

2.4 Special interface piles AZ13S

As the corners of the building pit would have a strong influence on the test walls, 4 special interface piles have been developed, see Figure 4. These piles, consisting of AZ13 sections are cut over a length of 16 metre. In order to prevent water leakage into the building pit the gap has been covered with a 2 mm thick VLDPE foil. For a better drivability of these piles 2 metre at the pile toe and 1 metre at the top of the pile are remained intact and for the protection of the foil the special piles are placed in a bentonite column which reaches to NAP -15.5 m. After driving the pile is also cut at the top.

2.5 Bentonite screens

Behind each test wall two bentonite screens have been installed. The bentonite screens are composed of bentonite-soil columns ø500-700 which are mixed-in-place with a hollow auger rig. The toe of the columns varies from NAP -13.5 m close to the test wall to NAP -3.5 m at 13 metres behind the test walls. Inside the building pit the bentonite screens

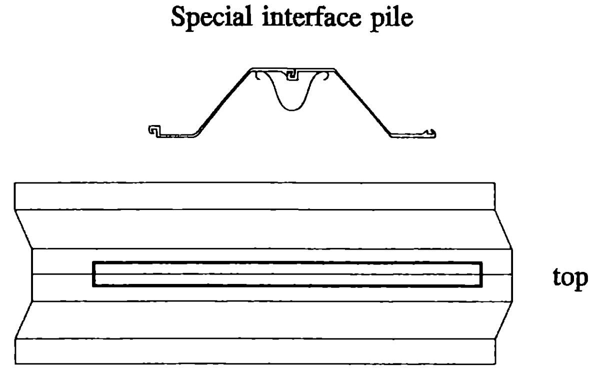

Figure 4: Special interface piles

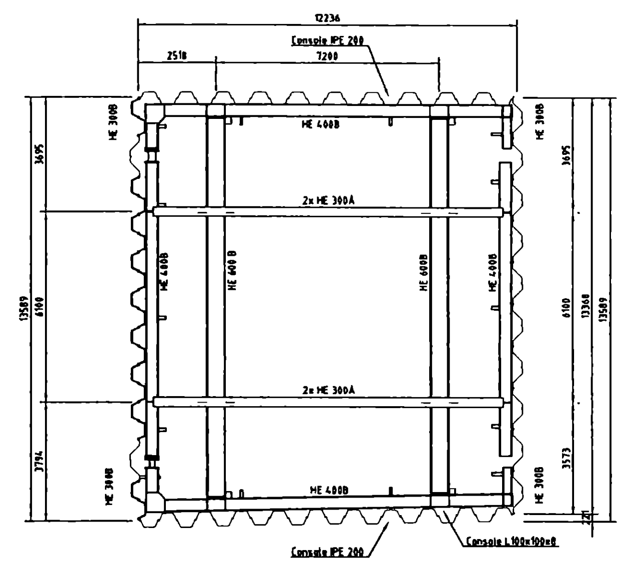

Figure 5: Plan of the struts

have been left out because of possible seepage during excavation.

2.6 Struts and walings

The plan of the struts and walings is given in Figure 5. The centre line of the frame work is at NAP +0.75 m. The struts for the test walls north and south are designed in a way that both test walls act independently and are not influenced by the other sheet piles. The difference between the strut forces is led to the stiff HE600B struts between the east and the west walls. The struts and the walings are constructed as hinged connections with sufficient rotation capacity between the sheet pile walls and the

Table 1: Structural data of the sheet piles

Section	A cm^2/m	Ix cm^4/m	Wx cm^3/m
AZ 13	137	19700	1300
L 607K	244	70030	3220

Table 2: Summary of soil parameters

			Triaxial tests (ε=2%)		Stiffness parameters		Vane tests
Top level (m-NAP)	Soil Type	γ_{avg} (kN/m³)	c' (kN/m²)	φ' (°)	E_{50} (MPa)	k (kN/m³)	f_u (peak value) (kN/m²)
0.5	sand	18	0	30.0	2.0	7000	
1.50	clay, silty slightly sandy	16.6	6.3	29.4	3.5	2000	67.6
5.75	peat	10.0	9.3	18.9	2.7	800	65.7
9.00	peat very clayey	10.6	11.8	20.1	3.2	2000	64.3
10.50	clay, humous	13.9	7.0	20.0	5.2		37.6
12.50	clay, slightly sandy	16.2	7.4	27.1	6.2	1400	32.8
16.10	clay, highly silty	12.3	5.0	25.0	10.3	1200	30.7
17.00	clay, slightly sandy	16.2	7.4	27.1	6.2	1000	
17.50	sand, silty, medium coarse	20	9.8	37.9	10.0	10000	
18.50	sand, coarse	20	0	38.0	10.0	10000	

frame work. The strut frame includes 6 pressure cells, 4 cells to measure the lateral strut force of the north and south test walls and two to measure the axial force in the waling of the double U test wall.

3 MATERIAL PARAMETERS

3.1 Structural data

The most relevant structural data of the sheet pile is presented in Table 1. Since one of the aims for this field test is to investigate a wall with a plastic hinge, it is important for the design that the failure chance of the north wall is as high as possible, which is of course in contrast with common designs. Therefore the AZ13 test piles have an unusual low yield stress of about f_y=280 N/mm², which results for elastic-plastic structural models in M_{pl}=426 kNm/m'. For the struts and walings the stiffness and the ultimate stress may be considered as sufficient high.

3.2 Soil data

The soil data is obtained from an extensive soil investigation programme consisting of common-used in situ tests, such as CPT's, vane tests, and pressuremeter tests and laboratory tests, such as oedometer tests, triaxial compression and extension tests (CUR 1998).

In Figure 6 a representative CPT is presented as well as the initial water pressures. The soil consists of a 16.5 metre normally consolidated soft clay-peat-clay stratification. Underneath, the normally consolidated Pleistocene sand layer is found, which is connected to the river Maas 2km farther. The initial water pressures in the different soil layers is determined with 9 piezometers and 3 open stand pipes. A summary of the most relevant soil data is presented in Table 2.

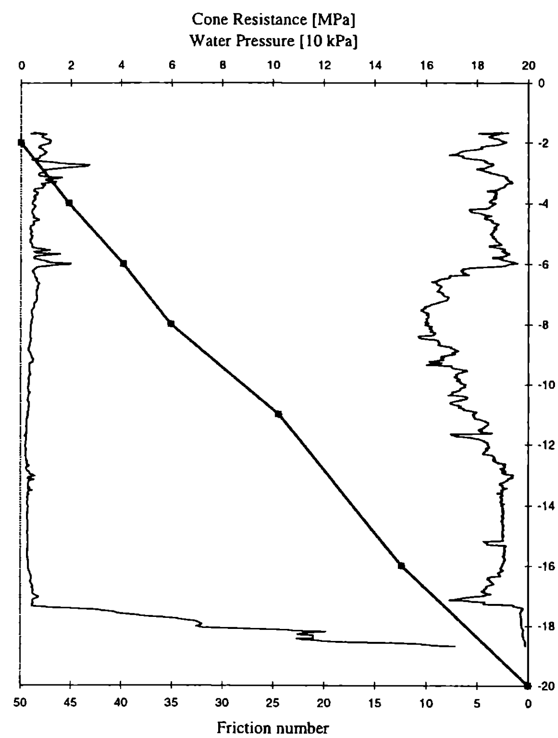

Figure 6: CPT and piezometric heads

4 TEST SEQUENCE

Before the start of the test, the greenfield level was at a level of NAP -1.6 m. In order to make the test site accessible for the CPT and bpre rigs, cranes and other construction equipment, the test site was filled first with 0.4 metre dry sand and later filled upto 1 metre sand in total. The test is performed in 4 stages.

Stage 1

After construction of the sheet pile walls, the bentonite screens and the strut frame, a dry excavation is executed to NAP -4 m; both soil and water are removed to this level. The excavation equipment is situated as much as possible behind the east wall.

Stage 2

The water in the excavation is raised to NAP -1.5 m and the excavation is subsequently increased to a level of NAP -7 m. During the excavation the water level is kept at NAP -1.5 m.

Stage 3

Lowering the water level to NAP -5 m in 5 steps. The intermediate steps are NAP -2.5 m, NAP -3.5 m, NAP -4.0 m, NAP -4.5 m and NAP -5.0 m. After the third step to NAP -4 an evaluation step is introduced, in order to assess the critical failure load of the north wall.

Stage 4

Maintaining the final water level of stage 3 for a period of 6 months.

During all stages measurements are carried out from which the action effects can be derived, such as lateral and transverse wall displacements, strut forces, bending moments and earth pressures. A summary of the activities with a cumulative time table is given in Table 3.

Table 3: Test sequence

no.	activity	time (days)
1.1	sand fill to NAP -1.25 m	0
1.2	sand sill to NAP -0.65 m	125
2	sheet pile driving	296
3.1	dry excavation to NAP -4.0 m	331
3.2	fill with water to NAP -1.5 m	335
4	excavation under water to NAP -7.0 m	340
5.1	lowering water level to NAP -2.5 m	342
5.2	lowering water level to NAP -3.5 m	345
5.3	lowering water level to NAP -4.0 m	346
5.4	evaluation of test data	
5.5	lowering water level to NAP -4.5 m	355
5.6	lowering water level to NAP -5.0 m	359
6	long-term performance	

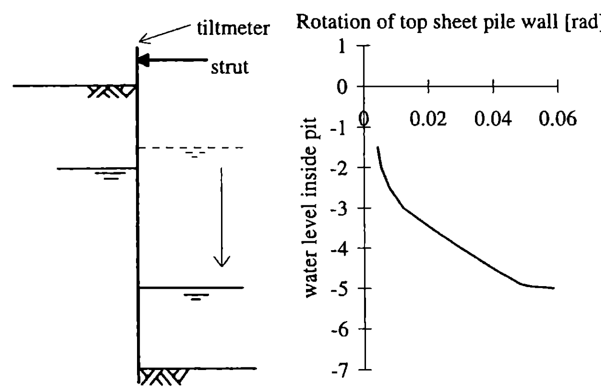

Figure 7: Rotation of the sheet pile around the strut due to the lowering of the water level

5 EXECUTION OF THE TEST

One of the difficulties of the design is that the test on the wall with a plastic hinge is a destructive test and therefore not free from danger. Moreover, the lowering of the water level is a load controlled testing procedure, whereas the plastic hinge has a softening behaviour due to the combination of yielding and local buckling (Van Tol and Kort 1997). Consequently, if the lowering of the water level in front of the sheet pile wall is continued after yielding in the ultimate fibre occurs (see Figure 1), not only the plastic hinge is developed, but also the resistance of this plastic hinge decreases, which may cause a sudden and unpredictable development of the second plastic hinge.

In order to control the execution of the test, the water level is lowered with a speed of 10 cm per hour. The formation of the plastic hinge will be observed in real time with a tiltmeter, which measures the tilt of the sheet pile close to the struts, and a piezometer which measures the water level inside the building pit: a sudden tilt of the sheet pile in comparison with the water head inside the building pit indicates the formation of the plastic hinge, see Figure 7.

6 PREDICTION QUESTION

The interest of predictions in geotechnical engineering is extensively discussed by Lambe (1973). Von Wolffersdorff (1997) organized (also in cooperation with the CUR) a full-scale field test and included a prediction question. More than 40 type A predictions had been submitted, but more valueable was the broad discussion that arose among the engineers about the test results and the consequences for their design practice.

For the Rotterdam sheet pile wall field test a prediction question in two levels has been organized (CUR 1999). In the first level the aim of the organisers is to make geotechnical design engineers aware of plastic hinges and oblique bending in steel sheet piling, especially because these phenomena have a large influence on design and construction of safer and cheaper sheet pile walls. These people received approximately the information presented in this Paper. The second prediction level was focused on geotechnical engineers who work in a more scientific environment. The organisers expect that valuable discussions among a large group of engineers may help to improve the knowledge about steel sheet pile walls in soft soil in general.

7 CONCLUSIONS

New developments in the Eurocode gave rise to initiate a full scale field test in soft soil with a high groundwater level. This test is focused on:

- the performance of a sheet pile wall with a plastic hinge;
- the performance a sheet pile wall constructed of double U-sections;
- the short-term and the long-term performance of both sheet pile walls in soft soil.

For this field test a square building pit of approximately 12 to 12 metres is constructed in which two test walls are included.

A prediction question was organised with a focus on making the design practice aware of the new developments in steel sheet piling as well as on learning from the observations. This Paper presents necessary information to perform a prediction.

This test may contribute to a better understanding of both plastic design and oblique bending and may therefore lead to more economical and safer designing of steel sheet pile walls.

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