Predictions for the Rotterdam sheet pile wall field test

Predictions pour l'essai de palplanches à Rotterdam

D.A.Kort – *Geotechnical Laboratory, Delft University of Technology, the Netherlands*
A.F.van Tol – *Geotechnical Laboratory, Delft University of Technology and Rotterdam Public Works, the Netherlands*
A.Jonker – *Centre for Civil Engineering Research and Codes (CUR), the Netherlands*

ABSTRACT: In 1999 a full-scale field test on two steel sheet pile walls in very soft clay and peat with a high groundwater level was carried out in the port area of Rotterdam. Plastic design, oblique bending and short- and long-term behaviour of the sheet pile walls were topics for research. Engineers from different countries have made a type A prediction (before event) for the behaviour of the two test walls. They submitted the soil model and the information used from the soil investigation for parameter assessment. Most predicted wall displacements and bending moments were considerably larger than the measured values. An important reason for the spread may be that the interaction between calculation model, soil model and parameter assessment is insufficiently appreciated.

RÉSUMÉ: En 1999 une expérimentation en vraie grandeur de deux rideaux de palplanches en sol très mou et en haute nappe a été réalisée dans le port de Rotterdam. Sujets de recherche comprenaient des rotules plastiques, de la flexion oblique et du comportement courte durée et longue durée. Plusieurs ingénieurs néerlandais et de l'étranger ont fait une prediction type A (avant de l'événement) pour le comportement des deux rideaux. Ils ont également soumis quel modèle de sol et quelle information des essais de terrain ils ont utilisé pour la determination des paramètres. En général les déformations et les moments fléchissants prédises étaient plus grandes que les valeurs mesurées. Une raison importante pour l'étalement se pourrait bien que l'interaction entre les modèles de calcul, les modèles de sol et l'évaluation des paramètres est reconnue insufficiamment.

1 INTRODUCTION

Recent tests and developments regarding Eurocode 3, Part 5 for design of steel sheet pile walls were inspiration for carrying out a full-scale sheet pile wall field test in very weak clay and peat and with a groundwater level just below groundsurface. In this test the research was focused on:

- the performance of a sheet pile wall with a plastic hinge
- the performance of a sheet pile wall composed of double U-sections (oblique bending)
- 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 by 12 metre was constructed in which two test walls were included, see Figure 1. The rear test wall consisted of AZ13-sections and the front test wall was composed of double U-piles Larssen 607K. Special measures, such as special piles allowing differential displacements between corner and test wall, and slurry screens that prevent the active soil wedge from hanging on the adjacent soil, were taken to obtain a 2-D state as much as possible. For description and background of the test setup, see Kort et al. (1999).

Figure 1. Rotterdam sheet pile wall field test (in Stage III).

The test site was situated near Pernis, a suburb west of Rotterdam. The soil profile consists of a 16.5 m normally consolidated soft clay-peat-clay stratification, overlaying the normally consolidated Pleistocene sand layer. The test period was from April 1999 to January 2000.

The test stages to be predicted were as follows (see Figure 2):

- Stage I: Dry excavation to NAP-4.0 m
- Stage II: Excavation under water to NAP-7.0 m, inside water level at NAP-1.5 m
- Stage III: Lowering the inside water level to NAP-5.0 m
- Stage IV: Stage III after 1 month
- Stage V: Stage III after 3 months
- Stage VI: Stage III after 6 months

The real test procedure has been followed until Stage III for the AZ13-wall and until Stage V for the L607K-wall. For more details about the field test and the results, see Kort (2001).

Sheet piling specialists were invited to make type A predictions (before event) for the behaviour of the two test walls and of two other fictive walls.

This Paper gives a report of the results of 23 predictions in comparison with the measurements. Differentiation will be made between calculation models, soil models and parameter assessment. The influence of each of these three factors on short-term and time-depending calculations will be discussed. Finally the paper will give some conclusions about the general state-of-the-art of steel sheet pile wall design.

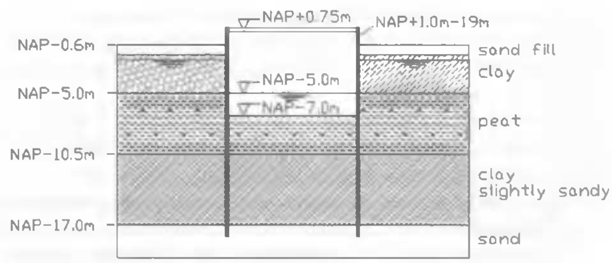

Figure 2. Side view of the Rotterdam sheet pile wall field test.

Table 1. Comprehensive set of soil parameters supplied for prediction level 1.

		Triaxial compression		ε =1%		ε =2%		ε =3%		failure		extension failure		Field vane
Level (m NAP)	Soil type	γ_{sat} (kN/m^3)	E_{50} (MPa)	c' (kPa)	φ' (°)	c' (kPa)	φ' (°)	c' (kPa)	φ' (°)	c' (kPa)	φ' (°)	c' (kPa)	φ' (°)	$f_{u,peak}$ (kPa)
+0.50	sand fill													
-1.50	clay, silty slightly sandy	16.8	3.5	6.1	22.5	6.3	29.1	6.3	32.5	5.8	41.6			67.6
-5.75	peat	10.2	2.7	7.7	11.2	9.4	18.8	10.3	24.8	8.4	56.8	2.0	44.0	65.7
-9.00	peat, very clayey	11.4	3.2	10.0	12.0	11.8	20.1	12.5	26.5	8.0	73.3			64.3
-10.50	clay, humous	13.9	5.2	6.3	14.9	7.1	20.3	7.8	23.6	8.7	27.2			37.6
-12.50	clay, slightly sandy	16.3	6.2	6.4	21.6	7.4	27.1	8.0	30.0	7.3	37.4	1.0	30.0	32.8
-16.10	clay, highly silty	12.3												30.7
-17.00	clay, slightly sandy	16.7												
-17.50	sand, silty, medium coarse	20.0	10.0	4.6	34.0	9.8	37.2	11.6	38.0	11.5	38.3			
-18.50	sand, coarse													

NAP: Dutch reference level.

2 PREDICTION QUESTION

The aims of the prediction question were:

- Determination of the state-of-the-art of calculation models for steel sheet pile walls in soft soil, including short-term and long-term behaviour
- Introduction of the new phenomena of plastic design and oblique bending according to Eurocode 3, part 5

The prediction question was subdivided in two prediction levels.

Prediction level 1 was focused on the practising geotechnical design engineers. The aim of prediction level 1 was to make these group of 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 more economic sheet pile walls.

Using a comprehensive set of results of the field and laboratory tests, see Table 1, predictions were asked to be made for deflections, bending moments, earth and water pressures in Stage I, II and III for four different types of sheet piles:

- AZ13 with M_u=426 kNm/m (used in field test)
- L607K-Double (used in field test)
- L607K-Single (imaginary)
- Z20 (imaginary and not existing)

The imaginary walls were introduced to emphasize the phenomena of plastic hinges and oblique bending. The L607K-Single can be compared with the L607K-Double and the Z20 would have been used if a plastic hinge would not be permitted.

Prediction level 2 was focused on the scientific aspects of the test and on the short-term and long-term behaviour of the sheet pile walls. The aim of prediction level 2 was to provide a benchmark for engineers who are specialised in design of complex retaining structures using calculation tools with advanced soil models.

The participants were requested to assess the soil parameters using the complete report of the soil investigation and to make predictions of Stage I to VI for the same wall types as were asked for level 1. In addition the predictors were requested to submit the soil models and soil parameters they used, and which information they have used to determine the necessary soil parameters.

The complete documentation of the prediction question is given by CUR (1999) and by Kort & Kelleners (2000), and a comprehensive version is given by Kort et al. (1999).

Twenty predictors made a total of twenty-three predictions for the behaviour of the two test walls: 12 of level 1 and 11 of level 2. Geographically, 19 predictions came from the Netherlands, 2 from Germany, 1 from France and 1 from the UK.

3 SUBMITTED PREDICTIONS

An overview of the submitted predictions for Stage III, categorised in level 1 and level 2 is presented for the AZ13 wall in Figure 3 and for the L607K-wall in Figure 4.

An overview of the calculation models used for the level 1 predictions is given in Table 2. Most of the level 1 predictions were carried out with the subgrade reaction model (SRM) MSHEET (2000); two predictions were made with the finite element model (FEM) PLAXIS (1998). In almost every prediction with a SRM a bi-linear spring relation was used, although most predictors had a multi-linear spring at their disposal. For the earth pressure coefficients the curved slip plane theory of Kötter was used more frequently than the straight slip plane theory of Müller-Breslau (MSHEET, 2000). For the wall friction angle most predictors used δ=2/3φ in sand and clay, and δ=0° in peat. In about half of all predictions a reduction factor R_I was applied to account for the loss of stiffness of the double U-pile. The Dutch directives (CUR 1995) give a value of R_I=0.7 for the field test.

Table 2. Models used for the level 1 predictions

Pred.	Method	Soil model	Slip plane	Wall friction angle sand	clay	peat	Reduction EI U-piles
1	SRM	bi-linear	straight	5/9φ	5/12φ	0°	calculated
3	SRM	bi-linear	curved	2/3φ	2/3φ	2/3φ	-
5	SRM	bi-linear	-	25°	10°	0°	-
6	SRM	bi-linear	curved	27.5°	17.8°	0°	-
9	FEM	MC dr./HS undr.		-	-	-	0.7
10	SRM	bi-linear	straight	2/3φ	2/3φ	2/3φ	-
13	FEM	HS/SS	-	-	-	-	0.97
14	SRM	bi-linear	straight	2/3φ	2/3φ	0°	1.0
15	semi-FEM	bi-linear	curved	φ	φ	φ	1.0
17	SRM	bi-linear	curved	2/3φ	2/3φ	0°	0.7
18	SRM	bi-linear	curved	φ-2.5°	1/2φ	0°	0.7
21	SRM	multi-linear	-	2/3φ	0°	0°	0.8

MC Mohr-Coulomb model; HS PLAXIS Hardening Soil model
SSC PLAXIS Soft Soil Creep model; SS PLAXIS Soft Soil model

In Table 3 an overview of the results of the level 2 predictions is presented. Prediction 7 & 8 and Prediction 19 & 20 were submitted by one person/team. Prediction 4 was made with MSHEET, the other predictions were all made with PLAXIS.

Most predictors used the HS model for the sand layers and the clay and peat layers were modeled both with the HS-model, the SS-model and the SSC-model. In contrast to the level 1 predictions, in almost every level 2 prediction the bending stiffness of the L607K-wall was reduced to account for oblique bending.

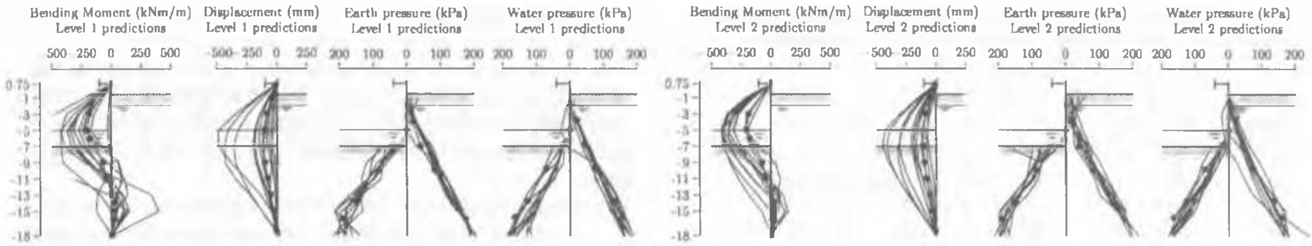

Figure 3. Level 1 and level 2 predictions for the AZ13-wall in construction stage III. The bullets indicate the measured results.

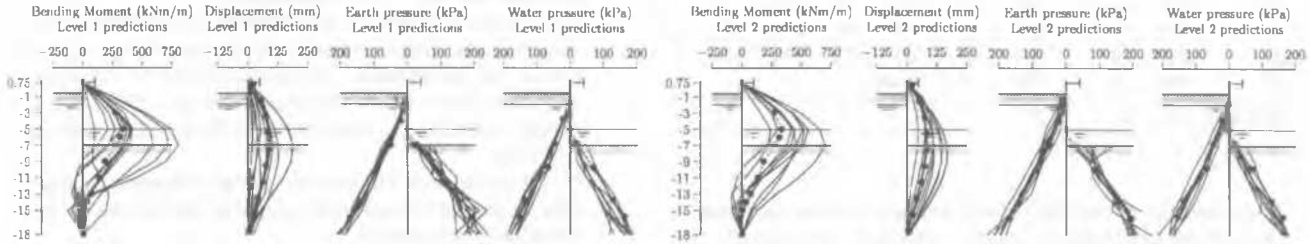

Figure 4. Level 1 and level 2 predictions for the Larssen 607K-wall in construction stage III. The bullets indicate the measured results.

Table 3. Soil models and material parameters used for predictions level 2.

Pred.	Soil model			c' (kPa)			φ'°			κ^* (-) or E_{50} (kPa)			λ^* (-) or E_{ur} (kPa)			k (10^{-10} m/s)			Reduction EI U-piles
	sand	clay	peat	c^1	p^2	c^3	c^1	p^2	c^3	c^1	p^2	c^3	c^1	p^2	c^3	c^1	p^2	c^3	
2	HS	HS	HS	6.3	9.4	7.5	29.1	19	27.5				18000	2600	4000	55	70	20	0.8
4				4	2	9	35	44	30										0.8
7	MC	MC	MC	3	3	4	28	37	26	4050	2430	5360				10	13	2.5	0.8
8	HS	SSC	SSC	3	3	4	28	37	26	0.008	0.03	0.034	0.022	0.12	0.073	10	13	2.5	0.8
11	HS	HS	SS	6.3	10.3	7.5	32.5	24.8	30.6	7200	0.045	2500	35000	0.19	14000	5.7	9.3	2.3	1
12	HS	SS	SS	7	10	7.4	28	19	27	0.001	0.033	0.047	0.011	0.14	0.072	3.7	9.99	4.66	0.8
16	HS	SS	SS	6.3	10.3	8	32.3	24.8	30	0.003	0.009	0.007	0.017	0.044	0.033	5.8	8.8	2.7	
19	HS	SSC	SSC	10	10	10	30	30	30	0.005	0.023	0.016	0.03	0.19	0.098	6	10	2.2	
20	HS	HS	HS	10	10	10	30	30	30	10970	1350	2860	52660	6490	13740	6	10	2.2	
22	MC	SSC	SSC	6.3	10.3	8	32.5	24.8	30	0.003	0.033	0.01	0.012	0.13	0.05	6000	1000	1000	0.8
23	HS	SS	SS	7.8	7.7	7.3	38.3	57.1	38.8	0.008	0.039	0.011	0.031	0.19	0.081	9000	8000	4500	0.68

c^1: clay NAP-3.0m p^2: peat NAP-7.0m c^3: clay NAP-15.0m

Table 3 gives also an overview of the most important soil parameters assessed for the level 2 predictions for three important soil layers:

- Clay layer at NAP-3.0m
- Peat layer at NAP-7.0m
- Clay layer at NAP-15.0m

The wide difference between the values of the various strength and stiffness parameters is striking and may be the result of a missing clear stepwise procedure for parameter assessment in excavation problems:

- Predictor 4 and 7/8 chose for the cohesion in the peat layer c' = 2-3 kPa, which corresponds to the value from the triaxial extension test, Predictor 23 used c' = 7.7 kPa, corresponding to the 1% strain value from the triaxial compression test, Predictor 2 used c' = 9.4 kPa, the 2% strain value and the Predictors 11, 12, 16, 19 and 20 used c' = 10 kPa, the 3% strain value (see also Table 1).
- Predictor 2 and 12 used for the peat layer φ' = 19° (2% strain value), Predictor 11, 16 and 22 φ' = 24.8° (3% strain value) and Predictor 4, 7/8 and 23 φ' > 35°, the failure value either for compression or for extension.
- Compare the λ^*-values between Prediction 12 and 22 with those from Prediction 19 and 23. Predictor 12 and 22 used λ^*-values which can be recalculated from the e-log p curves, whereas the Predictors 19 and 23 used λ^*-values which can be recalculated from the ε-log p curves.

It can not be concluded that the large differences in parameter choice can be explained by the fact that the parameters given in Table 3 have been considered as *model parameters*. Model parameters depend not only on physical soil properties but also on other factors accounting for a specific soil model. On the other hand, it can be concluded from the submitted parameters that the state-of-the-art of parameter assessment for advanced calculations of sheet pile walls is not consistent.

Parameters should be assessed with respect to the calculation model and soil model, especially when more advanced models are used. This requires great expertise on finite elements, advanced soil models and parameter assessment in order to make an accurate prediction.

4 COMPARISON WITH MEASURED RESULTS

4.1 *General*

The predicted bending moments with respect to the measurements are given in Table 4, and can be related to the submitted parameters given in Table 3.

A general tendency that can be derived from Figure 3 and 4 and from Table 3 and 4 is that in Stage III the maximum displacement and maximum moment are significantly larger than measured, and that the time-depending behaviour is considerably underestimated.

4.2 *Short-term behaviour*

A good prediction (no.4) was obtained with the relatively simple subgrade reaction model, maybe because the predictor was very experienced with this model in similar Dutch soil.

An other good prediction is number 22, who used the SSC model for the clay and peat layers. This prediction is better for the AZ13 wall than for the L607K wall, because the can-

Table 4. Predicted ultimate field moment (M_f) and ultimate cantilever moment (M_c), and measured moments for level 2 (in kNm/m).

	AZ13		Larssen 607K					
Stage	III		III		IV		V	
Pred.	M_f	M_c	M_f	M_c	M_f	M_c	M_f	M_c
2	-361	48	701	0	748	0	778	0
4	-225	76	300	-75	not predicted			
7	-399	50	513	0	528	0	550	0
8	-419	0	596	0	646	0	failure	
11	-315	14	524	0	543	0	546	0
12	-421	45	590	0	596	0	601	0
16	-363	114	419	-58	441	-50	449	-51
19	-420	140	559	-87	632	-40	failure	
20	-319	65	445	-32	445	-40	448	-46
22	-200	76	240	-91	337	-95	370	-80
23	-406	0	454	0	failure			
Measured	-206	30	337	-11	413	-4	460	0

tilever moment of the L607K wall seems to be overestimated. The strength parameters c' and φ', however, are identical to those of prediction 11 and 16 which gave much larger bending moments.

On the other hand predictions 8 and 12, made with different soil models and different soil parameters, give the same moment for Stage III of the L607K-wall. And although the predicted moment was much too high, these two predictions indicate that large differences in stiffness parameters can be compensated by large differences in strength parameters.

Consequently a proper choice of strength parameters only is not sufficient for an accurate prediction. Other parameters, such as soil model, stiffness parameters and even the permeability are of equal importance. These influences can also cancel each other out.

It can be concluded from the predictions that good predictions can be obtained with subgrade reaction models (Prediction 4) and with the soft soil creep model (Prediction 22), but a satisfactory prediction was also obtained with the hardening soil model (level 1 Prediction 13). However, it can not be concluded which soil model and what soil parameters should be used to obtain an accurate prediction.

4.3 *Time-depending behaviour*

Table 4 gives also an overview of the predictions for the long-term behaviour of the L607K-wall. The measurements show that the maximum field moment M_f increased 76 kNm/m (23%) after 1 month and 123 kNm/m (37%) after 3 months. The maximum cantilever moment M_c decreased during the long-term period. Few predictors predicted an increase of more than 10% after 3 months. Only Predictor 22 predicted an increase of more than 100 kNm/m after 3 months.

In Table 3 the permeabilities used in the different predictions are summarised. Prediction 22 (and Prediction 23) were the only predictions in which the SS(C)-model was used in combination with a permeability of $k \approx 10^{-7}$ m/s, the other predictors used $k \approx 10^{-9}$ to 10^{-10} m/s which was found from the oedometer tests, interpreted with Taylor's method. Leroueil et al. (1990) remark that an evaluation of the coefficient of consolidation using the methods of Taylor and Casagrande leads to an underestimation of the permeability. They determined consolidation coefficients using observations from settlements of embankments, which are 3 to 200 times larger, with an average of a factor 20.

It is suspected but not yet investigated that a considerable part of the underestimated deformations of the test walls during the long-term test can be explained by the underestimation of the permeability.

5 CONCLUSIONS

The two aims of the prediction question were to determine the state-of-the-art of the models for the calculation of steel sheet pile walls in soft soil, and to introduce the new phenomena of plastic design and oblique bending to practising design engineers.

Concerning the first aim the following conclusions are drawn:

- In almost every prediction the maximum displacement and bending moment are significantly larger than measured. On the other hand the time-dependent behaviour of the sheet pile walls is underestimated.
- The spread in predicted displacement and bending moment is large, which suggests that the reliability of predicted wall performance is quite insufficient. The same conclusion was drawn by Kudella et al. (1997) for a similar research of a sheet pile wall field test in sand in Karlsruhe.
- In the predictions the mutual relation between calculation model, soil model and parameter assessment is not sufficiently appreciated.
- It is possible to make accurate predictions both with simple models and with advanced models, provided that calculation model and input parameters are satisfactorily adjusted. Otherwise the quality of the prediction may be extremely poor, see also Lambe's Figure 5 & 6 (1973).

Concerning the second aim, the positive discussions that arose among predictors, researchers and other design engineers suggest that a prediction question is a nice tool to introduce new development to practising engineers.

Sound recommendations for steel sheet pile wall design in soft soil subdivided in calculation models, soil models and parameter assessment can only be drawn up after extensive analyses of type C1 predictions (recalculations).

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