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Deep excavation in Bulgaria—comparison of measured and computed performance

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ABSTRACT: This paper presents a comparison between the results of field monitoring during the construction of a bored pile wall anchored at level 4 with results computed by the finite element analysis (FEM) using the Mohr-Coulomb model and Hardening Soil model (PLAXIS Software). Field monitoring was carried out to measure wall displacement and anchor forces by using inclinometer measurement, geodetic surveying and resistance strain gauge measurement.

1 INTRODUCTION

A 14 m deep excavation for underground garages was planned during the construction of a new office-and-apartment centre in the town of Stara Zagora, Bulgaria. The southern and eastern sides of the excavation are situated next to a 9- and 5-storey building, respectively. The northern and eastern borders are the main streets in the city. Instruments for monitoring activities were concentrated in the northern side, next to Tsar Kaloyan St., where the excavation depth was 14.3 m (Fig. 2). There were no buildings or machines during the excavation works in that area. As a results, the interpretation of the experimental data was not affected by uncertainties associated to the presence of buildings.

Inclinometer measurement in the pile construction, geodetic surveying and resistance strain gauge measurement in the anchors and piles were made during all excavation stages. The results present the variation in the anchor forces, bending forces in the pile, lateral movements and elastic line of the wall. These data are used for comparison with the calculation results by applying different constitutive models.

2 SUPPORT CONSTRUCTION

The excavation was protected by bored pile walls supported by four levels of anchors (Fig. 1). The exact depth of the excavation is 14.30 m. The wall is made of drilled piles with a diameter of 0.40 m (Fig. 1). The piles are 13.00 m long with a 3.00 m embedded length. The pile spacing is 1.50 m. The anchors are 15 m long with force at installation zero. The diameter is 0.15 m. The anchor inclination is 15°–20°. A wooden plank is placed between the piles and in front of the soil. Above the pile head 4.30 m of the excavation is supported with soil nails, a steel net and shotcrete (Fig. 1). The reinforcing mesh is held in place with 2.0 m–2.5 m long soil nails. Shotcrete with a 3–5 cm thickness is designed to “close” the system. The construction of the retaining wall can be divided into the following separate phases (Fig. 2):

- Stage I: Excavation up to 2.00 m. Shotcrete with soil nails and reinforcing net;
- Stage II: Excavation up to 4.30 m. Shotcrete with soil nails and reinforcing net; Drilling and concreting the piles;
- Stage III: Excavation up to 5.30 m. Drilling and concreting the anchors—Level 1;
- Stage IV: Excavation up to 7.30 m. Drilling and concreting the anchors—Level 2;
- Stage V: Excavation up to 10.30 m. Drilling and concreting the anchors—Level 3;
- Stage VI: Excavation up to 12.30 m. Drilling and concreting the anchors—Level 4;
- Stage VII: Excavation up to 14.30 m.

3 FIELD MONITORING

The measurements made during excavation are used to describe the construction behaviour and consist of: 1. Anchor force measurement; 2. Lateral wall displacement measurement; 3. Pile elastic line determination; 4. Pile force measurement. Two different approaches based on the resistance strain gauge measurement are used for anchor force determination. An inclinometer was installed within a pile allowing for measurements

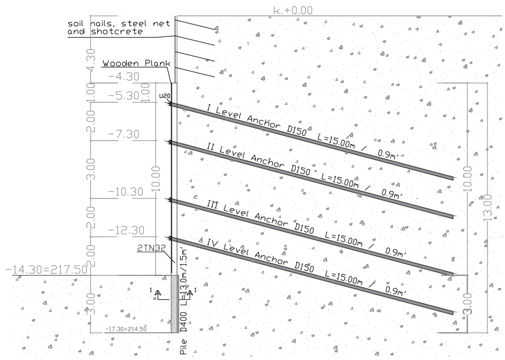

Figure 1. Cross section of excavation. Construction stage.

Figure 2. Northern part of the excavation.

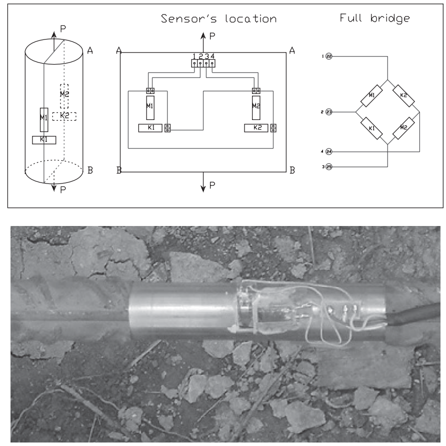

Figure 3. Anchor force measurement: design and arrangement.

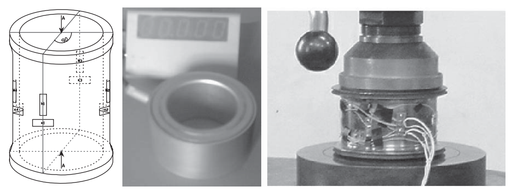

Figure 4. Dynamometer: design and arrangement.

of wall deflections. Additionally, the lateral wall displacement is determined by using geodetically gauging points.

3.1 *Anchor force measurement*

3.1.1 *Sensor bar*

Four strain gauges, two measuring and two compensating, connected in a full Wheatstone bridge were placed on the anchor bar (Fig. 3). The measurement technique used for the resistance strain implementation is Hottinger Baldwin Messtechnik-vd 73002. Two anchors on both sides of the inclinometer pile were investigated. The quality of the measuring system was laboratory tested before the field test realization. The results yielded a less than 2% error.

3.1.2 *Dynamometer*

A dynamometer was designed along with the sensor bar for the anchor force measurement. The same idea was implemented in manufacturing the dynamometer. Eight strain gauges (4 measuring and 4 compensating) connected in a full Wheatstone bridge were placed on the four main axes of a 5.5 cm high steel ring. The external and internal diameters of the ring are 10.5 cm and 7 cm (Fig. 4). Before using the dynamometer it was laboratory tested on 20t and 30t presses and the resultant deflections were less than 0.5% of the range (30t).

3.1.3 *Anchor forces*

The final values for the anchor forces determined after estimation of the available results are presented in Table. 1. The results for the different construction stages are summarised in Fig. 6.

3.2 *Bending moment measurement*

Foil strain gauges were also placed along the reinforcement length (2T-profile) to determine the pile forces using the same arrangement as that for the anchors (Fig. 5)

In view of protecting the individual gauging points from external effects, they were coated with strain gauge varnish, mastic, silicon and protective foil.

The measurement of the relative linear deformations was performed by resistance strain gauges based on the tensoeffect (the property of some materials to change proportionally their electric resistance under the action of the element deformation). The final values for the bending moments in the pile are presented in Table. 2. The results for the different construction stages are summarised in Fig. 6.

Table 1. Anchor forces [kNm].

	Anchor			
Stage	No1	No2	No3	No4
No1	–	–	–	–
No2	–	–	–	–
No3	–	–	–	–
No4	43.17	–	–	–
No5	80.22	94.21	–	–
No6	75.77	82.24	112.46	–
No7	80.44	95.64	138.22	124.70

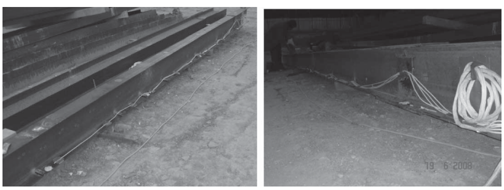

Figure 5. Bending moment measurement.

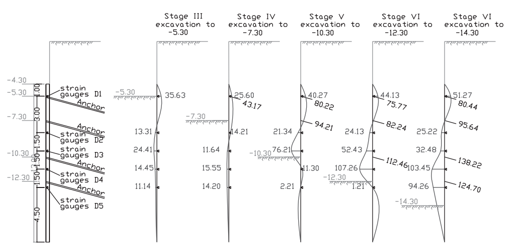

Figure 6. Anchor forces and bending moments in the pile measured at different stages.

Table 2. Bending moments [kNm].

	Level				
Stage	D1	D2	D3	D4	D5
No1	–	–	–	–	–
No2	–	–	–	–	–
No3	–35.63	13.31	24.41	14.45	11.14
No4	–25.60	+14.21	11.64	15.55	14.20
No5	–40.27	21.34	76.21	–11.30	2.21
No6	–44.13	24.13	52.43	107.26	1.21
No7	–51.27	25.22	32.48	103.45	94.26

3.3 *Wall displacement measurement*

The lateral displacements at the pile and anchor heads were measured by using geodetically gauging points and measurement devices SOKKIA-330R-Fine AVG with expected accuracy of 5/10 mm and by building an inclinometer tube in a pile. The most interesting points are at the pile and anchor heads. Detailed measurements describe the exact deformation (move) of the wall during the construction period. The results for five stages (Stage III—Stage VII) are summarized in Table. 3 and Fig. 7.

4 SOIL PARAMETERS

The soil properties used in the analysis were taken from a site investigation carried out in September 2007 together with additional in-situ testing performed in April 2008. The soil consists of five soil layers. Clay formations with organic substances and gravel mixed with ceramic debris and artificial embankments outcrop on the surface. That first layer is 3.00 m thick. Immediately under the embankment opens up a layer of gravel-interspersed compact clay loam, light brown in color. Its thickness varies within 3.30–4.10 m (Layer 2). Layer 3 is granite gneiss, broken, highly weathered, argillized, friable and yellowish-brown. That layer occurs under Layer 2 to the end of the investigated depth. Layer 4 consists of loams, friable and in some places calcareous, light gray and yellow, which occurs at depths of approx. 9.70–10.40 m.

In certain places Layer 3 is interrupted by interlayers of yellow, plastic loam—Layer 5. These clayey interlayers of 0.60–1.00 m thickness alternate with granite gneisses. The excavation design was performed taking into account the continuous water pumping and a dry foundation pit.

The strength parameters used in Mohr-Coulomb and Hardening Soil model analyses for the different soil layers are summarized in Table 4.

Table 3. Wall displacement [mm].

	Level				
Stage	GGP 1	GGP 2	GGP 3	GGP 4	GGP 5
No1	–	–	–	–	–
No2	0	–	–	–	–
No3	1.4	0	–	–	–
No4	3.9	1.9	0	–	–
No5	7.7	4.1	2.8	0	–
No6	9.1	5.7	7.6	2.7	0
No7	11.4	7.2	8.4	4.1	2.9

Table 4. Soil parameters used in FE analysis.

Soil layer	Soil parameters			
	γ, *[kN/m³]*	E, *[kN/m²]*	c, *[kN/m²]*	φ, *[°]*
No1 (0–3.0 m)	21.0	5500	10	20
No2 (3.0–6.8 m)	20.8	7000	25	25.3
No3 (6.8–30.0 m)	24.1	19000	16	25
No4 (9.7–10.4 m)	20.7	19000	8	20
No5 (16.7–17.1 m) (18.9–19.5 m) (19.9–20.5 m)	21.1	16000	18	21

5 NUMERICAL ANALYSIS

5.1 *Basic assumptions*

The analysis using the FEM is further presented for the different construction stages and compared with the final measurement data. Several parameters enter the analysis of a sheet pile wall. The issue of determining the soil parameters as a function of field measurement and numerical analysis comparison will not be discussed. The example will be calculated by means of a FEM analysis using one of the most widely used software in design practice, PLAXIS with two possibilities for soil model idealization: the Mohr-Coulomb model and the Hardening Soil model The idea in this analysis is based on the following prerequisites:

I. Calculation of the different construction stages with PLAXIS using the Mohr-Coulomb model and modeling anchors as "fixed-end anchor" elements or an inclined pile using beam elements;
II. Calculation of the different construction stages with PLAXIS using the Hardening Soil model and modeling anchors as "fixed-end anchor" elements or an inclined pile using beam elements;
III. Comparison and discussion of the results

5.2 *FE-Modeling*

The excavation was modelled by the FEM programme PLAXIS. The analysis took into account all the stages of the excavation. The finite element mesh used in the plane strain calculation is shown in Fig. 8. The bored pile wall was schematized as a beam element. The anchors were simulated by PLAXIS "fixed-end anchor" elements (Fig. 8a). That means elastic springs of a given axial stiffness with one fixed (no displacement) end and the other movable end connected to the pile wall by a given longitudinal distance from the wall. The anchors were also simulated as an inclined pile using beam elements (Fig. 8b). The soil behaviour was simulated

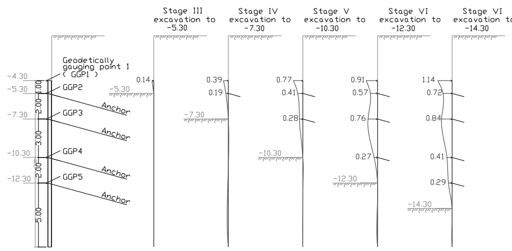

Figure 7. Wall displacement results.

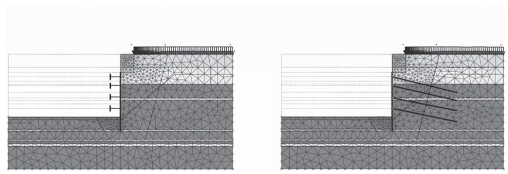

Figure 8. FE Model: a) "fixed-end anchor"; b) plate elements.

Table 5. Calculation and field monitoring results—M, Q, δ.

Combination	parameters		
	M_{max}, *[kNm]*	δ_{ph}, *[mm]*	δ_{max}, *[mm]*
MC.FA.CS3	24.57	0.799	2.60
MC.PE.CS3	24.57	0.799	2.60
HS.FA.CS3	34.46	0.717	2.41
HS.PE.CS3	34.46	0.717	2.41
FMR.CS3	*40.20*	*1.40*	*1.40*
MC.FA.CS4	33.23	1.010	4.450
MC.PE.CS4	27.13	14.88	14.88
HS.FA.CS4	29.59	0.980	4.500
HS.PE.CS4	20.47	9.170	9.170
FMR.CS4	*35.30*	*3.900*	*3.900*
MC.FA.CS5	86.46	0.980	12.39
MC.PE.CS5	96.97	29.73	33.18
HS.FA.CS5	80.66	1.070	9.460
HS.PE.CS5	96.60	21.65	24.92
FMR.CS5	*76.70*	*7.700*	*7.700*
MC.FA.CS6	84.53	1.200	16.92
MC.PE.CS6	118.68	52.97	62.68
HS.FA.CS6	66.33	1.18	12.70
HS.PE.CS6	109.88	48.37	57.66
FMR.CS6	*107.30*	*9.100*	*9.100*
MC.FA.CS7	88.07	1.470	21.11
MC.PE.CS7	154.95	101.3	109.5
HS.FA.CS7	70.50	1.61	16.4
HS.PE.CS7	141.43	99.50	110.61
FMR.CS7	*109.40*	*11.4*	*11.4*

*HS – Hardening Soil Model; MC – Mohr-Coulomb model; FA – fixed-end anchor; PE – anchor as a plate element; CS – construction stage; FMR – field monitoring results; δ_{ph} – horizontal displacement in pile head.

using the Mohr-Coulomb model and the Hardening Soil model of the PLAXIS code. The selection of the soil properties used in the calculation was based on the results of the geotechnical investigation performed at the site.

6 COMPARISON AND ANALYSIS OF THE RESULTS

In this study of the performance of an anchored pile wall founded in Stara Zagora an interesting correlation was obtained between the field measurements and final element analysis based on the Mohr-Coulomb model and Hardening soil model. Although no soil characteristics were changed, the comparison with the results of monitoring activities lead to the following conclusions:

- The most accurate solution as compared with the experimentally determined values is obtained for the bending moments in the beam.

Table 6. Calculation and field monitoring results—anchor forces.

	parameters			
Combination	A_1,*[kN]*	A_2,*[kN]*	A_3,*[kN]*	A_4,*[kN]*
MC.FA.CS3	–	–	–	–
MC.PE.CS3	–	–	–	–
HS.FA.CS3	–	–	–	–
HS.PE.CS3	–	–	–	–
FMR.CS3	–	–	–	–
MC.FA.CS4	89.87	–	–	–
MC.PE.CS4	81.71	–	–	–
HS.FA.CS4	91.28	–	–	–
HS.PE.CS4	77.80	–	–	–
FMR.CS4	*43.17*	–	–	–
MC.FA.CS5	69.86	226.8	–	–
MC.PE.CS5	97.78	84.25	–	–
HS.FA.CS5	93.45	235.50	–	–
HS.PE.CS5	96.02	105.03	–	–
FMR.CS5	*80.22*	*94.21*	–	–
MC.FA.CS6	73.78	208.0	244.2	–
MC.PE.CS6	90.94	97.39	118.37	–
HS.FA.CS6	103.7	254.4	314.7	–
HS.PE.CS6	107.9	131.7	143.4	–
FMR.CS6	*75.77*	*82.24*	*112.46*	–
MC.FA.CS7	83.12	219.1	227.1	304.3
MC.PE.CS7	100.2	105.8	140.96	168.38
HS.FA.CS7	115.8	279.96	373.4	358.4
HS.PE.CS7	139.5	156.5	220.9	198.95
FMR.CS7	*80.44*	*95.64*	*138.22*	*124.70*

*HS – Hardening Soil Model; MC – Mohr-Coulomb model; FA – fixed-end anchor; PE – anchor as a plate element; CS – construction stage; FMR – field monitoring results.

The difference in the maximum values for the different computational schemes varies within ± (26–28)%. The method of modeling the anchorage bearing has a basic effect on the value of the bending moments.

- Regarding the displacements in the pile head, the selected soil model and to a higher degree, the method of supporting (anchor modeling) is of particular significance. The results concerning the maximum displacements in modeling the anchor as a "fixed-end anchor" approximate considerably the experimentally determined displacements. The differences are negligible within several mm and not exceeding 60%. In modeling the anchors as plate elements the differences reach and exceed 600%.
- It should be noted that the experimentally obtained deformed line for the pile differs considerably from that obtained by computational methods. The latter is mostly valid for the final construction stage CS7.
- When comparing the experimentally obtained values for the anchor forces with the computational ones it can be seen that the differences reach and exceed 200% depending on the computational schemes adopted. In the anchored bored pile wall the forces, regardless of the computational scheme used, have similar values whereas with increasing the number of anchor series, the adopted computational model influences highly the forces obtained. Results closest to the experimentally ones are obtained when using the Mohr-Coulomb model and modeling anchors as plate elements. The differences in that case (with some exceptions) are about 9–12%. Unfortunately, it is this computational combination that yields the most inaccurate results with respect to the wall displacements and maximum bending moment redimensioned by 42%.

The difference between the measured and calculated wall displacement can be explained by the assumed increase in the stiffness modulus (about 2–2.5 times). Some authors recommend such a reduction [Ilov] taking into account the three-dimensional soil behavior.

7 CONCLUSION

The requirements for accuracy in designing excavation projects in city areas call for comprehensive analytical models like the Finite Element Method to be put into practice. Another analytical model widely used in Bulgarian practice is the Subgrade Reaction Method. A basic conclusion drawn from the investigation carried out is that there is no computational model or scheme, even in the most recent software products, which can reflect accurately the actual behavior of the structure. From a designer's point of view, avoiding accidents means building up excess reserves and raising the degree of safety. A literature survey [von Wolffersdorff] confirms the dispersion of the results using different calculation models even for relatively simple excavation cases. As demonstrated in the example above, the estimation of the results complies with the full numerical analysis, soil parameters interpretation and the most important field monitoring. Numerical back analysis can be performed for reducing the input soil parameters as a result of detailed measurement of the construction behavior during the different construction stages [Totsev, Vogt&Totsev]. Similar timely exercised control can prevent accidents or reduce the construction price by specifying the primary project.

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