Analysis of anchored diaphragm walls displacements in the tunnels of the Warsaw Metro

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ABSTRACT: Due to the influence of engineering activity on buildings in the vicinity of deep excavations, constant monitoring of two large Warsaw underground stations was carried out. The measurement results of the diaphragm wall displacements are presented in the paper. The assessment of the displacements was carried out based on high precision land surveying of fixed points positioned on the diaphragm walls. In the paper the conclusions concerning the maximum horizontal displacement of diaphragm walls as well as evaluation of soil parameters based on the results of the back analysis are presented.

1 INTRODUCTION

The first line of underground in Warsaw has been in construction for many years now. The stations are built using the cut-and-cover method and the route tunnels are bored with a TBM. During the construction of two large stations located in the center of the city: A13 (Centrum) and A14 Świętokrzyska) the displacements of deep excavation and tunnel walls as well as adjacent area were measured. These stations were constructed in difficult geotechnical conditions – Tertiary and Quaternary soils. The measurements were carried out during each phase of excavation deepening and erection of station structure. The goal of this investigation was to:

- determine the actual horizontal displacements of anchored diaphragm walls as a function of excavation depth – the deep excavation of station A13 was the first one with five levels of ground anchors in Poland,
- obtain actual data for performing back analysis, on basis of which the values of elasticity modulus for pliocene clays could be determined (the type of soil in the deep excavation of station A14),
- assess the load capacity of ground anchors in pliocen clays and in sandy clays,
- create database of anchored diaphragm wall displacements that could be used in design of deep excavations in the future.

In the article, the two first of the above-mentioned goals are described.

2 DESCRIPTION OF THE DEEP EXCAVATION OF A13 STATION

2.1 *Geological conditions*

The excavation of station A13 was done in Quaternary soils. Figure 1 shows the agreement of the geotechnical layers differentiated based on the geological-engineering documentation:

– layer I – uncontrolled fills 1–3 m thick, in some places up to 4 m,

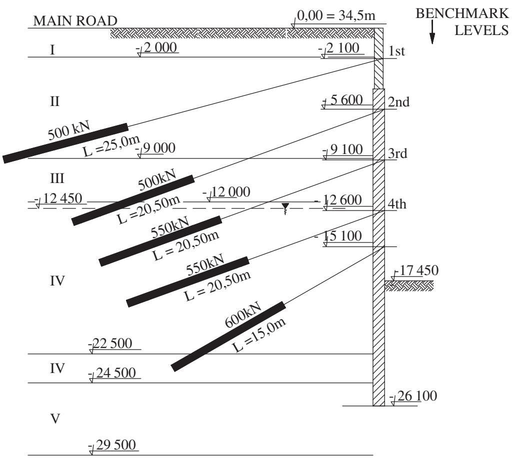

Figure 1. Cross-section of A13 station.

– layer II – moraine deposits reaching a depth of 8–11 m below the ground level, consisting of medium and stiff sandy clays and clayey sands of Warta glaciation and deeper stiff sandy clays of Odra glaciation,
– layer III – continuous layer of sandy deposits 15 m thick represented by fine and medium grained sands,
– layer IV – cohesive soils 1–5 m thick,
– layer V – sandy deposits (fine, medium and coarse sands as well as gravels and sandy gravels of 10–15 m thickness).

Two ground water table levels were observed in the ground of the stations. The first water-carrying level was located in layer III, at 12.45 m below the ground level (bgl), and it was lowered in the excavation area to 19.00 m bgl for the duration of the construction. The second water-carrying level was located in the sands at the depth of over 24 m bgl.

2.2 *Excavation wall structure*

The lining of station A 13 excavation consisted of an anchored diaphragm wall joined in the upper part to a soldier pile wall. The depth of excavation in its deepest place was 17.45 m. The soldier pile wall 4.1 m high was made of I-sections HEB500 spaced at 1.5 m to 2.5 m, cast in the diaphragm wall and steel or timber lining. The diaphragm wall 0.80 m thick and 22 m high was cast using B 30 grade concrete without special requirements concerning water tightness. The stability of the excavation walls was ensured by four to five levels of ground anchors with load-carrying capacity of: 500 kN, 550 kN and 600 kN. The total length of each anchor varied from 25 m to 15 m, while the length of grouted body was the same for every level – 8.5 m. The pre-stressing of ground anchors was made to 80% of their load-carrying capacity. The displacements of anchors, i.e. elastic extension (Δs) of the anchor tendons during the acceptance test was within the limits recommanded by EN 1537 norm. The values of Δs, depending on the tendon free length and the proof load, were from 30 to 45 mm. The total number of the anchors built in station A 13 was 1241. The width of the excavation was variable and its value varied from 40,8 m in the southern part to up to 44,7 m in the northern part. A schematic drawing of the structure protecting the excavation together with the geotechnical conditions and the location of the benchmarks is shown in Figure 1.

2.3 *Order of construction activities*

Stage – excavation to the depth of 3.1 m, construction of the soldier pile wall, drilling and stressing of the first level of anchors with anchors head at 2.2 m bgl;
Stage 2 – excavation to the depth of 6.6 m, construction and stressing of anchors of the second level with anchors head at 5.6 m bgl;
Stage 3 – excavation to the depth of 10.1 m, construction and stressing of anchors of the third level with anchors head at 9.1 m bgl, starting the dewatering of the area with the depression wells installed outside of the excavation, maintained until the waterproofing was completed;
Stage 4 – excavation to the depth of 13.6 m, construction and stressing of the fourth level of anchors with anchors head at 12.6 m bgl;
Stage 5 – excavation to the depth of 16.1 m, construction and stressing of the fifth level of anchors with anchors head at 15.1 m bgl;
Stage 6 – excavation to the depth of 17.5 m, meaning the bottom level of the ground slab;

3 DESCRIPTION OF THE DEEP EXCAVATION OF A14 STATION

3.1 *Geotechnical conditions*

In the vicinity of the station, the Tertiary – Pliocene deposits occur disturbed by glacial tectonics. They are mainly cohesive deposits (clays, silty clays) including layers of saturated silty and fine-grained sands.

These layers have not a horizontal position. The diaphragm walls are located in the clays. There are two ground water levels: the first one – the free water table – is 4 m bgl, the second one – the artesian water table – below the bottom of the station and it stabilizes about 7 m higher. Taking into consideration the technology of the excavation (ground anchors) and its bottom stability, the ground water was lowered during the station construction by pumping. Its level was maintained at about 0.50 m below the bottom of the excavation.

The ground strength parameters for diaphragm wall design were determined based on the laboratory tests. Their values for the geotechnical layers differentiated for stations A13 and A14 are provided in table 1. The values of elasticity modulus were determined in laboratory environment for moderate strain levels.

3.2 *Excavation wall structure*

The underground station A14 is located in the vicinity of an important street crossing with an intensive car and tram traffic. As a protection of the excavation, diaphragm walls 0.80 m thick and 20.7 m deep were designed. Two levels of ground anchors and one row of steel, tubular struts ensured the stability of the walls. The total depth of the excavation was 14.6 m. The capacity of the anchors was 500 kN and 600 kN and the total length was 20.0 m or 21.0 m, with the grouted body of 6.0 m and 8.0 m. The tubular struts of the diameter of 0.508 m were spaced at 2.0 m. The total width of the excavation was 20 m. The cross-section of the excavation wall together with the geotechnical conditions is presented in Figure 2.

3.3 *Order of construction activities*

The excavation was executed in the following stages:

Stage 1 – excavation to the depth of 4.55 m, construction and stressing of the first level of the ground anchors;
Stage 2 – excavation to the depth of 8.65 m, construction and stressing of the second level of the ground anchors;
Stage 3 – excavation to the depth of 11.85 m, mounting of strut φ 0.508 m;
Stage 4 – excavation to the final depth of 14.60 m;
Stage 5 – casting of 20 cm deep layer of lean concrete and then casting of the ground slab.

Table 1. The values of the ground parameters assumed in analysis of wall for excavation of stations A13 and A14.

Ground layer	γ kN/m^3	Φu °	Cu kPa	E0 MPa
I (fill)	17,0	25,0	0,0	10,0
II (sandy clays – Warta glaciation)	21,5	19,0	25,0	30,0
II (sandy clays – Odra glaciation)	22,0	23,0	35,0	42,0
III (fine and medium sand)	19,5	34,0	0,0	55,0
IV (silty clays)	20,5	18,0	15,0	22,0
V (sandy deposits)	19,5	34,0	0,0	60,0
Clay	20,7	13,0	37,0	24,0

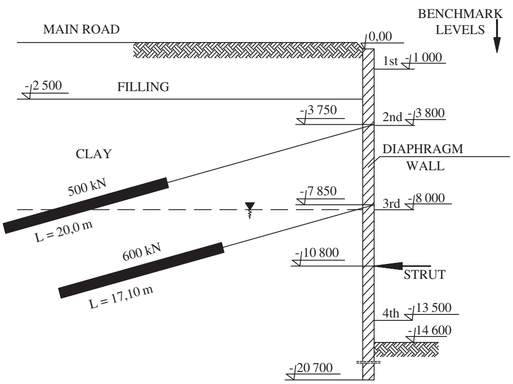

Figure 2. Cross-section of A14 station.

4 MEASUREMENTS

4.1 *Measurements of the horizontal displacements of the excavation wall in station A13*

Monitoring of the diaphragm wall was carried out at all levels of the anchoring in 25 vertical lines spaced at about 20 m along the excavation. The measurement points, identified by special benchmarks, were located on special supports, made of angle sections and fixed near the anchors heads. Figure 3a shows the location of the vertical measurement lines in a plan view of the station while Figure 1 shows the location of the measurement points in a cross-section of the excavation. The earth works were carried out from the center of the station towards south and north. A time schedule of the monitoring matched with the assumed order of the construction activities, i.e.:

- measurements after excavation to the depth of: 3.1 m, 6.6 m, 10.1 m, 13.6 m, 16.1 m;
- measurements before and after stressing of each level of anchors;
- measurements after achieving the final depth of the excavation of 17.5 m;
- until casting of the ground slab – once per month.

The method for measurements was designed so as to obtain a full picture of the displacements of the excavation walls in the entire period of observations (9 months). The significant depth of the excavation (in the deepest zone reaching 17.45 m) implied considerable horizontal displacements of the diaphragm wall. Monitoring and ongoing analysis of the results of the measurements allowed the investor and the contractor

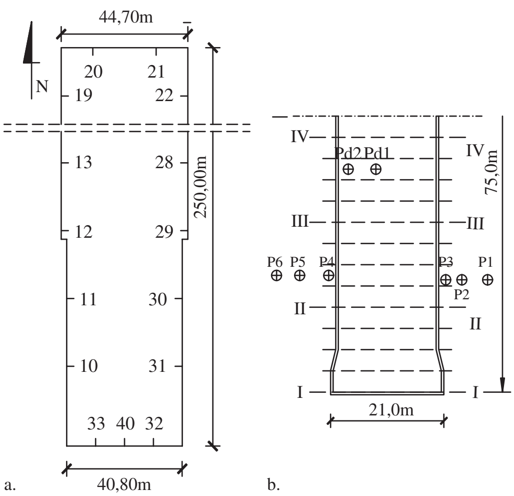

Figure 3. Sketch of vertical lines and measurements points of A13 (3a) and A14 (3b) station.

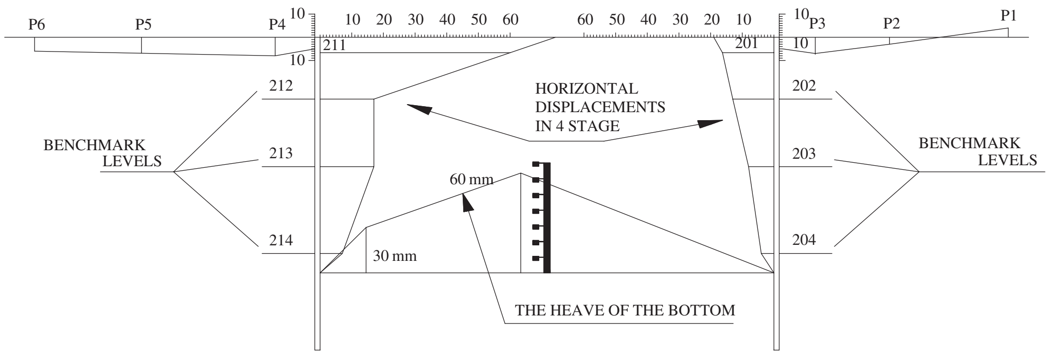

Figure 4. The results of measurements os A14 station.

for continuous control of the wall stability as well as supervision of stressing and reliability tests of the ground anchors in use, ensuring their capacity to be according to the design.

4.2 *Measurements of the displacements of the excavation wall in station A14*

The program of the monitoring of the wall and the surface of the ground included:

– measurements of the horizontal displacements of the diaphragm walls at 9 (I–IX) vertical cross-sections on depths of: 1.0 m, 3.8 m, 8.0 m and 13.5 m bgl – similar as for station A13, the benchmarks were installed on angle sections mounted to the wall;
– measurements of the diaphragm walls;
– measurements of the displacements of the ground surface – benchmarks (P1–P6) installed on the eastern and western sides of the excavation in two investigated cross-sections at the distance of 1 m, 7 m and 14 m from the excavation wall;
– measurements of the excavation bottom heaving based on measurements taken for the deep benchmarks (P_{d1}, P_{d2}).

A sketch of the vertical line locations in a plan of the station is presented in Figure 3b and the location of the measurement points in the cross-section of the excavation is shown in Figure 2. The time schedule of the measurements was made to match the respective stages of the excavation.

5 RESULTS OF MEASUREMENTS

- For station A13 (Centrum), the maximum values of the horizontal displacements occurred for the first level measured and they were +0.014 m for the excavation depth of 13.6 m and +0.015 m for the depth of 17.5 m, being 0.103% and 0.09% of its length.
- For station A14 (Świętokrzyska), the maximum vertical displacements of the anchored diaphragm wall occurred for the first measurement level, reaching value of +0.016 m, being 0.164% of the excavation depth of 14.6 m.
- Across the height of the diaphragm wall, during the excavation, the horizontal displacements decrease along its depth (cantilever-like character of the displacements).
- The total value of the vertical displacements of the excavation bottom measured in the middle of its width and caused by the relaxation is +0.060 m (Fig. 4).
- Under the geotechnical conditions of station A14 (Pliocene clays), the maximum observed value of the relaxation of the ground surface was +0.0075 mm, at the distance of 14 m from the edge of the excavation (Fig. 4)

The range of the appearance zone of the vertical displacements of the ground surface around the excavation in the Pliocene clays is greater than its depth, which is 14.6 m. The actual values of displacements were significantly smaller from the ones assumed in the design, calculated with the use of the Finite Element Method.

6 BACK ANALYSIS

The calculations using the back analysis method were performed on the data from the II measurement cross-section of station A14 (Figure 3b) shown in Figure 4, which corresponds to Stage 4 of excavation for station A14. In addition to measured values of horizontal wall displacements, it also shows the path of the excavation bottom relaxation. The initial prediction of the displacements during the design phase of the station was performed by means of Finite Element Method using

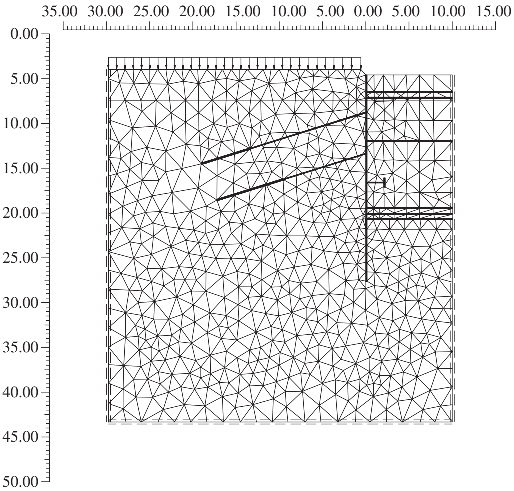

Figure 5. FEM mesh of A14 excavation.

Mohr-Coulomb model, characterized by parameter values provided in Table 1. Therefore, the elastic-plastic Mohr-Coulomb model was also chosen for the calculations using the back analysis method.

The method of simplified back analysis was applied using formula (1):

$$J_\varepsilon = \sum_{i=1}^{N} \left| y_i - \hat{y}_i(E, \nu, \phi, c) \right| = \varepsilon = \min \qquad (1)$$

For the back analysis it was assumed that the determination of a minimal value $J\varepsilon$ would be carried out for the increasing values of clay elasticity modulus E (from 24 MPa) and given φ and c combinations. The value of E = 24 MPa was evaluated on the basis of the geotechnical report and was also recommanded by the Polish Norm. For every combination of φ and c, y_i was calculated at the points 201, 202 and 203 in stage IV of the structure execution when the clay elasticity modulus had the values: 24, 50, 65, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 140, 150, 160, 170, 180, 200, 220, 240, 260, 280 MPa. The analysis considered only the horizontal wall displacements.

The calculations were performed with FEM using Plaxis v.7 software, taking into consideration elastic-plastic analysis of bi-phases medium and assuming plane strain. An unassociated rule of flow was assumed. For the reinforced concrete structure, a model of isotropic linear-elastic medium was assumed. The mesh (Fig. 5) was made of izoparametric six-node triangle elements. The soil, the diaphragm wall and the reinforced concrete structure of the station were modeled as 2D massive elements. The anchors and the struts were modeled as 2D linear elements assuming their proper stiffness. For the contact of the structure and the soil, use of contact elements (interfaces) of zero thickness was foreseen. For the combinations of E, φ and c given above, more than 1000 calculations were performed. The results of these calculations are given in Figure 6. The acceptable value of elasticity modulus determined from the back analysis, for which the condition $\varepsilon \leq 0{,}01$ is met, varies from 85 to up to 110 MPa. The values of the elasticity modulus of Pliocene clay determined from the back analysis are almost four times greater than the Polish Norm recommendation, determined in laboratory for moderate strains level.

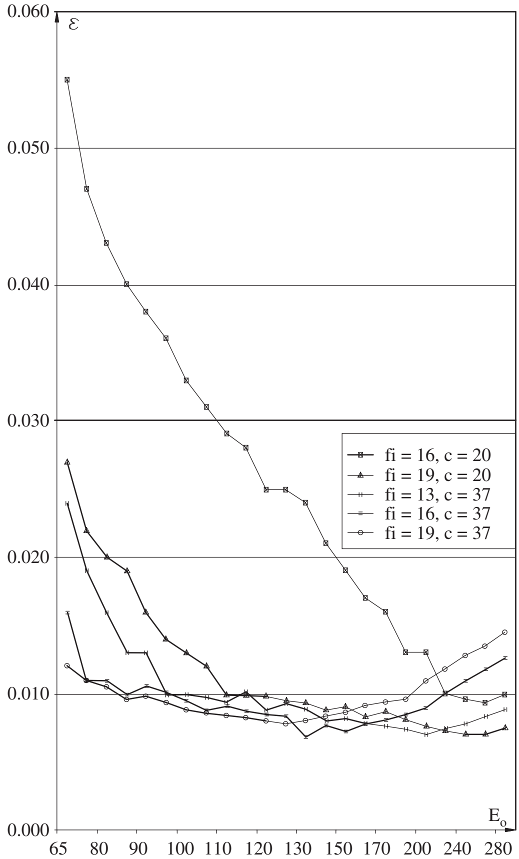

Figure 6. The results of calculations.

7 CONCLUSIONS

The maximum actual horizontal displacements of an anchored diaphragm wall occur at the top of the wall in the deepest section of the excavation and their value does not exceed 0.2% H_W (greatest depth of the excavation). The shape of the displacements has a cantilever-like character, which means that they decrease with depth. This conclusion was based on the analysis of the measurement results of the horizontal displacements of the anchored diaphragm walls. The measurements were executed in 34 vertical lines for four measurement levels during 19 months. These walls were properly designed and the anchors ensured their stability achieving the required capacity.

In the engineering practice, the values of elasticity modulus for the evaluation of displacements of deep excavation walls and adjacent terrain using Finite Element Method should be assessed with the consideration of small deformation (of 1%) range or with the use of comparable experiences. The use of the values provided by the Polish Norm is not recommended because the results of such calculations will not reflect the measured values of displacements.

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