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The study of displacements of diaphragm walls built in Warsaw Quaternary soils

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ABSTRACT: In the paper 18 cases of deep excavations executed in Quarternary soils (silty sands, silty clays, clayey sands and Pliocene clays) in Warsaw are presented. All of the cases were executed in urban areas that is why excavation walls were protected by means of diaphragm walls and measurements of displacements of these walls were performed. The results of measurements and geotechnical conditions, support systems (anchors, struts, slabs) as well as methods of construction (open excavation or top and down method) are presented. Final conclusions concerning the displacements of diaphragm walls executed in Warsaw Quaternary soils are given.

1 INTRODUCTION

Over the last few years, in Poland a lot of deep excavations are being built especially in big cities. Road and metro tunnels as well as deep underground car parks (2–5 levels) under office and housing buildings are a common issue nowadays. Theses excavations are typically protected by means of soldier pile walls, sheet pile walls, continuous bored piling or most often by diaphragm walls. In order to ensure the safety of surrounding structures displacements of excavation walls, ground surface and building settlements as well as the heave of the bottom of excavation are measured during excavation. In Warsaw, 10 to 20 m deep excavations are built mostly in soft soils—Tertiary and Quaternary deposits—with very high water level behind the wall. Difficulties with proper assessment of design parameters of these soils cause problems with precise theoretical assessment of deep excavation walls displacements values. The estimation of theses displacements is necessary for proper risk evaluation of excavation walling and surrounding structures. From the other hand wide database of real displacements values gives opportunity to asses mechanical parameters of surrounding soil body using the method of back analysis.

18 cases of deep excavations executed in Warsaw were analysed. In all cases the excavations were protected by means of diaphragm walls, but different wall support methods were used. In the paper, 3 chosen cases, representing typical construction stages when using anchors, struts or top and down method of construction, were described. Geotechnical conditions below the bottom of excavation and measurements results (maximum and minimum wall displacements) were presented and discussed, Tomczak (2010).

2 GEOTECHNICAL CONDITIONS

In Warsaw region, in general, differential Quaternary overburden (1–100 m thickness)—mostly glacial deposits—covers a layer of Tertiary clays. The processes of soil erosion connected with forming the river net as well as a glacitectonic deformation effects in this region appeared in geological past. The decompression, erosion and weathering processes followed. As a result of these processes the soil body, especially Tertiary soils in Warsaw are non-homogenous with discontinuities and contain lots of lenses of different lithology often with water under high pressure. Therefore it is difficult to properly asses design parameters of theses soils.

In order to determine mechanical parameters of soils, especially the deformation modulus, in-situ and laboratory tests are usually carried out. In situ tests such as e.g.: Dynamic Probing Light (DPL), Cone Penetration Tests (CPTU), pressuremeter tests and geophysical technique—vertical electrical sounding VET or laboratory tests, e.g.: triaxial shear test CIU, consolidometer tests CRL, bender elements test (undrained, isotropic loads), etc. All these methods of determination of soil parameters give a very wide range of its values. The ranges of values of typical Warsaw soil parameters, specified basing on 18 excavation cases, are given in Table 1.

Proper evaluation of mechanical soil parameters is a main issue in the displacements approach to the static analysis of diaphragm walls. Siemińska-Lewandowska (2001, 2006) states that calculation values of soil parameters are frequently underestimated, especially values of modulus of elasticity E_0. It is estimated that over half of deep excavation walls in Poland are designed and constructed using geological and engineering documentation drawn up based on results of simple drilling and dynamic probing, Wysokiński et al. (1999). Only macroscopic assessment of type of soil and its state is performed during surveys. Results are then used to determine values of geotechnical parameters of soil (e.g. c, φ, M, E) based on a number of simplified charts and tables included in applicable standards and in literature, Wiłun (2001). E_0 modulus value, however, is not constant for a soil and it changes with variation of axial deformation ε_1 and effective average stress p'. Physical non-linearity is very strong for small deformations, Burland (1989), Gryczmański (1995). Deformations of diaphragm walls calculated using the finite element method under the assumption of linear soil elasticity are much larger than observed in reality and measured with inclinometers or using precise geodesic leveling methods. The best method of the E_0 modulus value assessment is to derive it from back analysis based on in-situ displacements measurements, Mitew-Czajewska (2005). Back analysis may be performed if a large number of measurement data is available. The data base created basing on the in-situ measurements in Warsaw, described below, will be used in the back analysis for the estimation of soil parameters, especially the E_0 modulus value. Future analysis of diaphragm walls using finite elements method (and Mohr-Coulomb or other constitutive soil models) may be based on these parameters.

Table 1. Geotechnical parameters of typical soil layers.

No	Name	IL/ID (°)	ϕ (°)	c (kPa)	E_o (MPa)
1.	Clay (I)	0	11–13	55–60	16–22
2.	Sandy clay (Gp)	0.3–0.2	16–18	28–31	22–28
3.	Sandy clay (Gp)	0.1–0.0	20–25	35–50	36–67
4.	Fine sand (Pd)	0.5–0.6	30–31	0	46–55
5.	Fine sand (Pd)	0.7–0.8	31–33	0	65–66
6.	Medium sand (Ps)	0.45	33	0	73
7.	Medium sand (Ps)	0.7–0.8	34–35	0	80–111
8.	Gravel (Po)	0.45–0.5	38	0	129–154

3 CASE STUDIES

In the paper, 3 typical methods of construction of deep excavations protected by diaphragm walls are presented—anchored walls, strutted walls and top and down method.

3.1 *Anchored diaphragm wall*

The method of anchored diaphragm wall is described basing on an example case—the construction of underground car park of "Canal+" building in Warsaw (Fig. 1). Typical cross section is shown on Figure 2.

In that case the stability of the diaphragm wall has been provided by one level of ground anchors at −3,0 m below ground level (b.g.l.). There were two designed capacities of anchors—560 kN and 750 kN. Anchors were made of high tensile strength steel wires (Rv = 1260 MPa). Total anchor length was 17 m, in which 9 m was the anchor grouted body.

Designed construction stages were as follows:

1. Soil levelling, forming of the working platform;
2. Execution of guide walls;
3. Execution of diaphragm walls;
4. Execution of the reinforced concrete capping beam;
5. Excavation—3,5 m b.g.l.;
6. Forming and stressing of ground anchors at −3,0 b.g.l.;
7. Final excavation, max. −11,70 m b.g.l.;
8. Execution of foundation slab;
9. Execution of all underground slabs;

Figure 1. Construction site "Canal+".

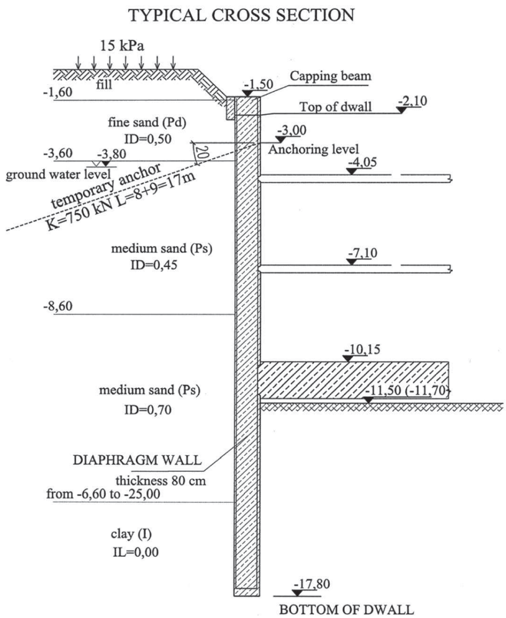

Figure 2. Typical cross-section of anchored diaphragm wall.

10. Cutting off anchors after the foundation slab and slabs reached 100% of its designed strength;
11. Execution of the remaining structure.

Geotechnical conditions:
1–2 m thick layer of uncontrolled fills covers 6–18 m thick layer of Pleistocene non-cohesive soils (fine, medium sands and gravel) under-lied by Tertiary clays.
Ground water level occurs at 2,7–3,5 m b.g.l.

3.2 *Strutted diaphragm wall*

The method of strutted diaphragm walls is one of the most commonly used methods of excavation support. This method is described basing on an example case—the construction of underground car park of "Equator 2" office building in Warsaw. Typical cross section is shown on Figure 3.

Designed construction stages were as follows:

1. Soil levelling, forming of the working platform;
2. Execution of guide walls;
3. Execution of diaphragm walls;
4. Execution of the reinforced concrete capping beam;
5. Excavation—5,65 m b.g.l.;
6. Installation of struts—5,15 b.g.l.;
7. Final excavation, max. –11,00 m b.g.l.;
8. Execution of foundation slab;
9. Execution of "–1" slab at –6,675 m m b.g.l.;

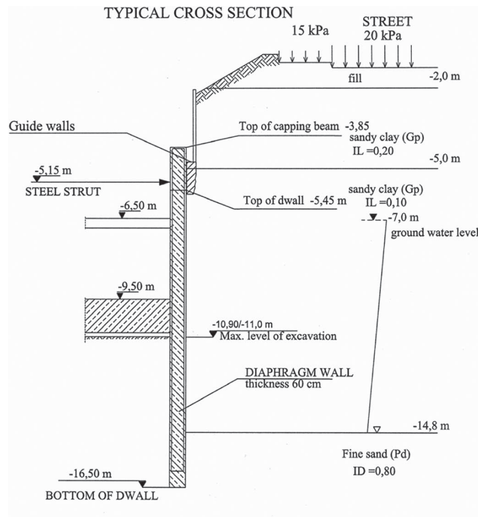

Figure 3. Typical cross-section of strutted diaphragm wall.

10. Dismantling of struts after the foundation slab and the "-1" slab reached 100% of its designed strength;
11. Execution of the remaining structure.

Geotechnical conditions:
2 m thick layer of fills covers Quaternary deposits: 3–12 m thick layer of sandy clays under-lied by fine and medium dense sands.
Ground water level stabilises at –7 m b.g.l.

3.3 *Top and down method*

The top and down method, using basement slabs to successively prop diaphragm walls, is used to restrict horizontal wall displacements and vertical settlements behind the wall, Puller (1996). The minimisation of soil movement is obtained due to regular propping of the diaphragm wall by all underground slabs, considerable elastic stiffness of slabs and the avoidance of displacements occurring during re-propping. The top and down method is therefore used in urban areas, close to existing structures and buildings. This method is described basing on an example case—the construction of 5 storey, underground car park of an office high-rise building at Prosta street in Warsaw (Fig. 4). Typical cross section is shown on Figure 5.

Designed construction stages were as follows:

1. Soil levelling, forming of the working platform;
2. Execution of guide walls at –2,0 m b.g.l. and –2,5 m b.g.l. (for barrettes);
3. Execution of diaphragm walls and barrettes;
4. Execution of the reinforced concrete capping beam;

Figure 4. Construction site at Prosta St.

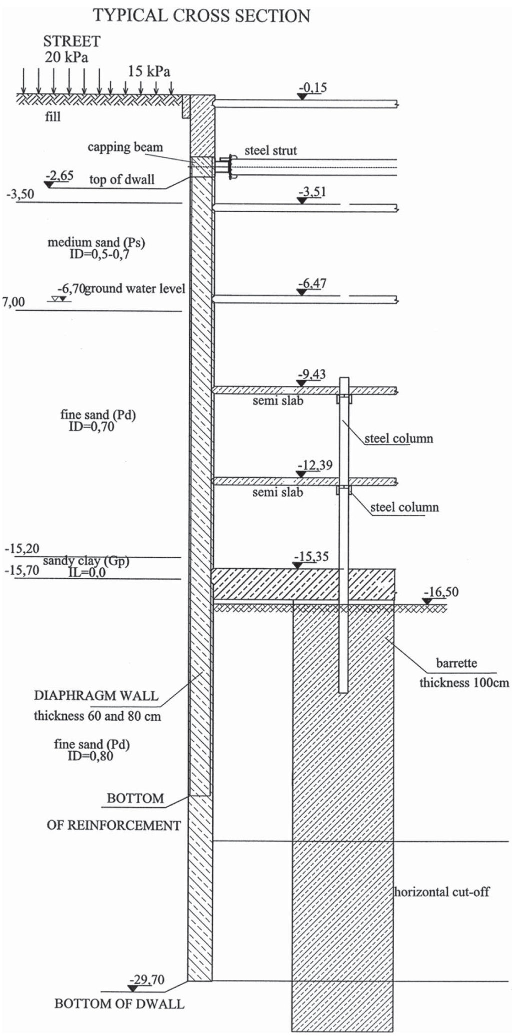

Figure 5. Typical cross-section in top and down method.

5. Excavation—3,0 m b.g.l.;
6. Execution of water cut-off barrier and installation of dewatering systems;
7. Installation of struts—2,40 b.g.l.;
8. Excavation –9,70 m b.g.l. (below the bottom of "–4" slab);
9. Execution of "–4" slab (top level of the slab –9,43 m b.g.l.);
10. Excavation –12,65 m b.g.l. (below the bottom of "–5" slab);
11. Execution of "–5" slab (top level of the slab –12,39 m b.g.l.)
12. Final excavation, max. –16,50 m b.g.l.;
13. Execution of foundation slab;
14. Execution of local excavations below lift shafts execution of the foundation slab in theses areas;
15. Execution of the remaining structure.

Geotechnical conditions:
A 3–5 m thick layer of fills covers Quaternary fluvio-glacial deposits—medium and fine, mostly dense sands, in which cohesive, 0,5 to 5 m thick, interbedding of sandy clays could be found. Ground water level occurs at –6,7 m b.g.l.

4 RESULTS OF MEASUREMENTS AND DISCUSSION

In all cases, measurements of horizontal displacements of diaphragm walls were performed in all

Table 2. Horizontal displacements of diaphragm wall.

Retaining system	Horizontal displacements min. (mm)	max. (mm)	min. (%H)	max. (%H)	average (%H)
Anchors					
Case 1	1.9	15.8	0.02	0.14	0.08
Case 2	1.6	7.7	0.02	0.07	0.04
Case 3	0.6	7.9	0.01	0.10	0.05
Case 4	7.9	23.0	0.09	0.26	0.18
Case 5	0.3	3.0	0.00	0.03	0.01
Case 6	1.3	5.3	0.01	0.05	0.03
Case 7	0.0	2.6	0.00	0.02	0.01
Case 8	0.7	5.8	0.01	0.05	0.03
Struts					
Case 1	1.8	11.6	0.02	0.14	0.08
Case 2	3.6	10.1	0.05	0.14	0.10
Case 3	0.1	8.3	0.00	0.11	0.05
Case 4	2.9	12.0	0.02	0.10	0.06
Case 5	2.0	11.7	0.02	0.09	0.06
Top and down method					
Case 1	0.5	1.7	0.00	0.02	0.01
Case 2	8.0	24.0	0.07	0.20	0.13
Case 3	3.0	16.5	0.02	0.10	0.06
Case 4	4.0	14.8	0.03	0.12	0.08
Case 5	0.4	11.7	0.00	0.14	0.07

Table 3. Summary of structure details and geotechnical conditions below the excavation.

Retaining system	D. Wall thickness (m)	Depth of exc. (H) (m)	DW Depth below excavation level (m)	Geotechnical conditions below excavation (m)
Anchors				
Case 1	0.8	11.50	6.05	Clay I*
Case 2	0.6	10.55	5.80	Sandy clay Gp*
Case 3	0.6	8.05	4.00	Sandy clay Gp*
Case 4	0.6	8.70	3.80–4.80	Clay I*
Case 5	0.6	11.03	4.00	Sandy clay Gp*
Case 6	0.6	10.71	3.00–3.50	Sandy clay Gp*
Case 7	0.6	10.65	3.10–3.60	Sandy clay Gp*
Case 8	0.6	11.00	4.20	Sandy clay Gp*
Struts				
Case 1	0.6	8.15	3.55–4.05	Fine sand Pd
Case 2	0.6	7.15	3.55	Sandy clay Gp*
Case 3	0.6	7.85	3.45	Sandy clay Gp*
Case 4	0.6	11.70	4.00–4.90	Sandy clay Gp*
Case 5	0.8	12.40	5.50–6.10	Fine sand Pd
Top and down method				
Case 1	0.6	10.68	5.00	Fine sand Pd
Case 2	0.6	12.20	4.35–4.85	Sandy clay Gp*
Case 3	0.8	16.50	12.20	Fine sand Pd
Case 4	0.8	12.30	5.10–6.30	Sandy clay Gp*
Case 5	0.6	8.60	4.0	Sandy clay Gp*

*cohesive soil.

construction stages. Benchmarks were located on capping beams, at the top of diaphragm walls. The measurements were made using precise geodesic leveling method (angle-linear method) by means of Leica TPS1200+ appliance.

Maximum and minimum horizontal displacements of diaphragm walls measured during excavation in all cases are presented in Table 2. Column 4 of Table 2 shows displacements in relation with excavation depth.

Additionally—the thickness of diaphragm wall, the depth of the excavation, the depth of the wall below the final excavation level, method of excavation support as well as geotechnical conditions below the excavation are given in the Table 3.

There were: 8 anchored, 5 strutted and 5 top and down cases analysed. In all cases excavations and diaphragm walls were executed in Quaternary soils.

In all cases, there was constant quality of work control performed during construction in accordance with International Standards (ISO).

5 CONCLUSIONS

Taking into account all analyzed cases the general conclusion may be derived that in case of 7–12 m deep excavations executed in Warsaw the horizontal displacements do not exceed 0,2% of the excavation depth (H).

It was observed that when cohesive soils occur below the bottom of excavation the displacements range from 0,01 to 0,26% of excavation depth. In case of non-cohesive soils the range is 0,0 to 0,14% of the excavation depth.

When analyzing the horizontal displacements of the diaphragm wall in relation to the method of excavation support it may be stated that:

- in case of anchored excavations average horizontal displacement is up to 0,18% of excavation depth (H),
- for strutted (propped) excavations average horizontal displacement is from 0,05 to 0,10% of excavation depth (H),
- when using top & down method the average horizontal displacements is up to 0,08% of the excavation depth (H).

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