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The effect of deep excavation on surrounding ground and nearby structures

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ABSTRACT: In the paper problems related with the execution of 29 m deep excavation of Nowy Swiat Station (S11) of 2nd metro line in Warsaw are discussed. In the central section, Warsaw 2nd metro line runs below the center of the city (office and housing buildings and high traffic roads) as well as below Vistula river. This central section consists of 7 stations and 6 running tunnels – 6 km length in total. Running tunnels will be constructed using TBM, stations – cut and cover method. Deep excavation will be executed within diaphragm walls. The stability of the walls will be provided by several levels of slabs and struts. The analysis of settlements of ground surface, surrounding foundations and displacements of walls of the excavation have been made. Additionally, settlements of the surface were calculated above the TBM (running tunnels). Resulting values of settlements in both cases were compared and discussed.

1 INTRODUCTION

Construction of 2nd Metro line in Warsaw is scheduled to begin in January 2008, announcement of design and build tender has been already published. In the central section, Warsaw 2nd Metro line crosses below the center of the city (office and housing buildings and high traffic roads) as well as below Vistula river. This central section consists of 7 stations and 6 running tunnels – 6 km length in total.

Running tunnels will be constructed using TBM, stations – cut and cover method. In the paper problems related with the execution of 29 m deep excavation in Quarternary soils (silty sands, sands, clayey sands and Pliocene clays) are discussed. Within the excavation Nowy Swiat Station (S11) of the 2nd metro line will be built. The S11 station will be founded at the depth of 29 m below ground surface (b.g.s.) in the vicinity of so called "Warsaw Slope", where the denivelation (difference in ground surface levels) reaches 30 m (Figure 1).

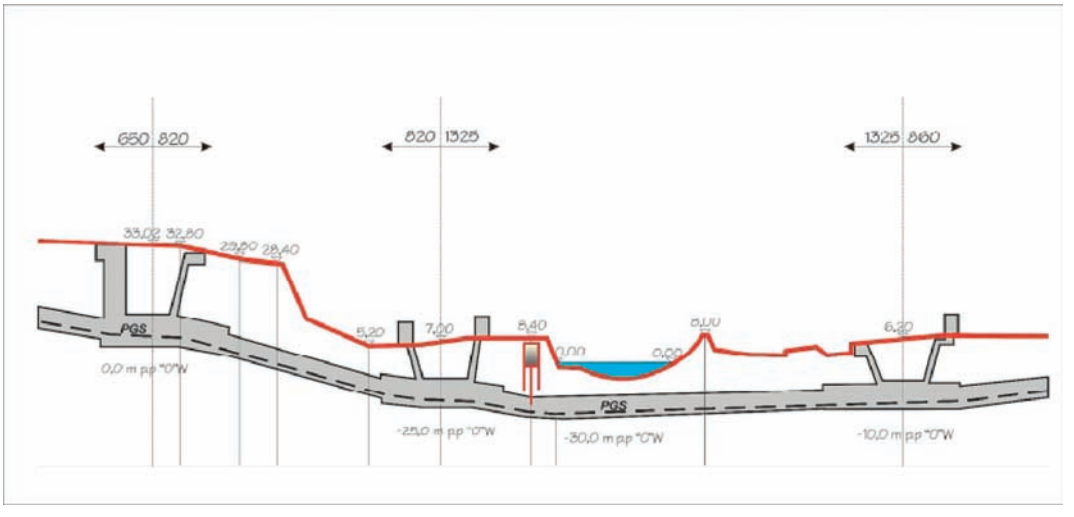

Figure 1. Longitudinal section of the central part of the 2nd Metro line in Warsaw.

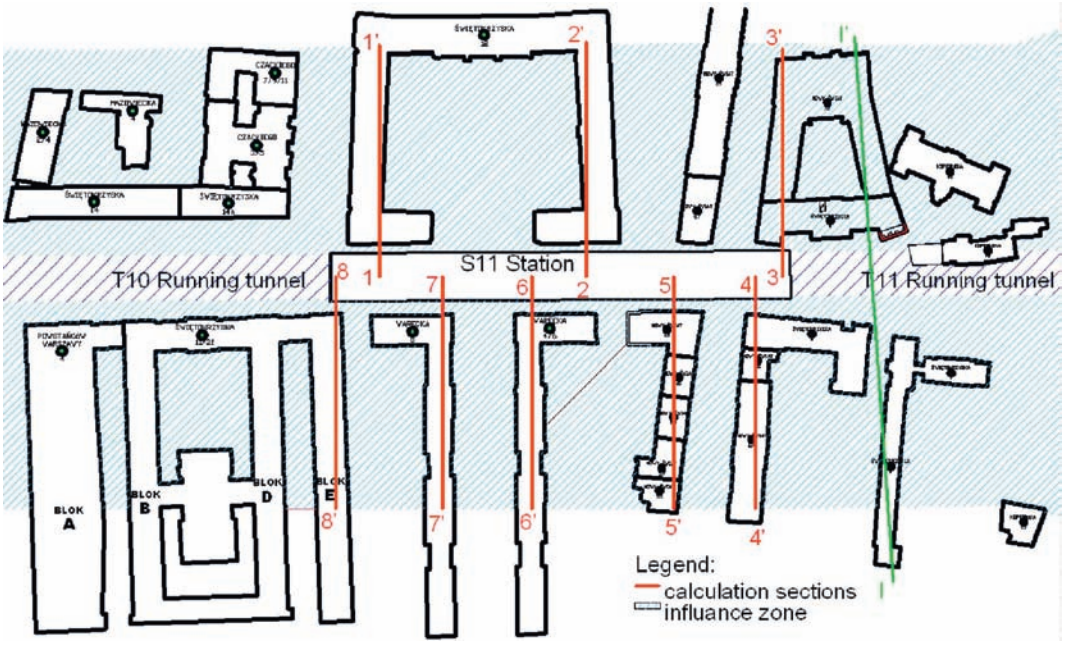

Figure 2. Longitudinal section of the central part of the 2nd Metro line in Warsaw.

The depth of the station is a consequence of sudden lowering of the tunnel from the upper slope level to the level below the bottom of the river with the consideration of appropriate soil cover resulting from TBM technology. Deep excavation will be executed within 100 cm thick diaphragm walls. The stability of the walls will be provided by several levels of slabs and struts. In the close vicinity of the excavation and above the tunnel there are many old buildings, such as:

- historic buildings built in XIXth century, partially destroyed during the 2nd World War and rebuilt after the war. Polish Academy of Sciences, Warsaw University and a Hospital are located there. These buildings are founded on spread foundations at a depth of 4,80 m b.g.s. Shortest distance between the excavation wall and foundation of the building amounts to 3 m;
- residential buildings constructed in 30. of XXth century, probably founded on piles. These buildings are located above the tunnel drilled using TBM;
- residential and office buildings constructed in 50. and 60. of XXth century on old pre-war foundations. These buildings are founded on spread foundations at a depth of 4,00 m b.g.s., 6 m apart from the excavation wall;
- masonry and concrete residential and office buildings constructed in 60. of XXth century, founded at a depth of 6,00 m b.g.s., 5 m apart from the excavation wall.
- Polish Central State Bank and the Ministry of Finance are located there.

Theses buildings are mostly masonry or reinforced concrete structures in good technical state. The majority of them is protected by the heritage conservator law. The location of the excavation of S11 Station, running tunnels and surrounding buildings is shown on Figure 2.

The analysis of settlements of ground surface, surrounding foundations and displacements of excavation walls have been made. Additionally, settlements of the surface were calculated above the TBM, T11 running tunnel (cross-section marked by green line). Figure 2 shows the location of all calculation cross-sections in the vicinity of S11 Station and T11 running tunnel.

2 GEOLOGY

There are Quaternary and Tertiary soils in the area of the deep excavation of the station and running tunnels. According to the geotechnical investigations report, following geotechnical layers are distinguished:

- layer I – uncontrolled fills 1,5–2 m thick, in some places up to 3 m;
- layer II – moraine deposits reaching depth of 4 m b.g.s., consisting of medium and stiff sandy clays and clayey sands of Warta glaciation;

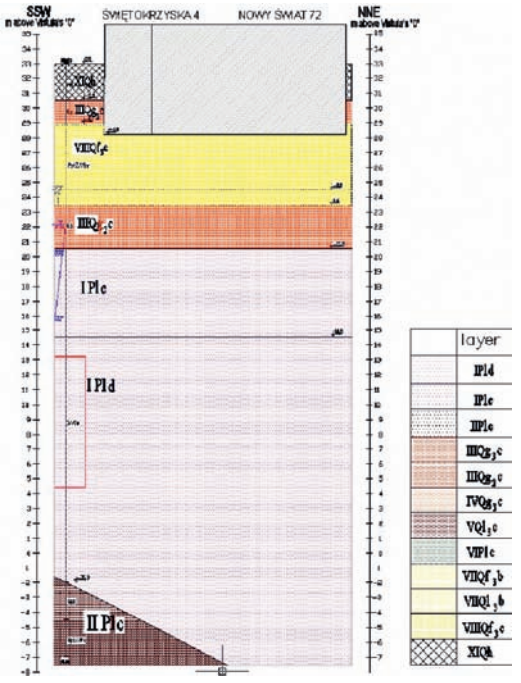

Figure 3. Calculation section N° 3.

– layer III – medium sands and silty sands of Odra glaciation, to the depth of 10 m b.g.s.;
– layer IV – moraine deposits reaching depth of 13 m b.g.s. consisting of medium and stiff sandy clays of Odra glaciation;
– layer V – pliocen clays till the depth of 50 m b.g.s.

There are three levels of ground water table. Considering temporary stability of the bottom of the excavation, it was assumed that the water table would be lowered during construction of the station. Geotechnical conditions, distribution of soil layers and location of foundations are shown on Figure 3 and Figure 4. S11 station and T11 running tunnel are both located within the layer of stiff and very stiff Pliocene clays.

3 DESCRIPTION OF THE DEEP EXCAVATION OF THE S11 STATION

It was designed that the deep excavation of S11 Station will be executed within 100 cm thick diaphragm walls, founded 10 m below the bottom of the excavation (that means the height of walls is 39 m). Due to the great depth of the excavation, amounting to 29 m, slab method of the execution of the excavation was chosen in order to provide maximum safety of the construction works. The stability of diaphragm walls will be provided by 8 levels of 35 cm thick underground slabs. Vertical spacing of slabs is 3 m, which gives an opportunity to adopt underground surface for car parks and retail. Construction stages are considered as follows:

– execution of guide-walls, 1 m thick diaphragm walls and 1 m high reinforced conrete girt on the entire perimeter of the excavation,
– excavation till the depth of 2 m b.g.s., i.e. below the slab at level −1, execution of barrettes and temporary slab supports,
– construction of the slab at level −1, backfilling the excavation and allow traffic back,
– excavation till the depth of 5 m b.g.s., i.e. below the slab at level −2,
– construction of the slab at level −2,
– excavation till the depth of 8 m b.g.s., i.e. below the slab at level −3,
– construction of the slab at level −3,
– excavation till the depth of 11 m b.g.s., i.e. below the slab at level −4,
– construction of the slab at level −4,
– excavation till the depth of 14 m b.g.s., i.e. below the slab at level −5,
– construction of the slab at level −5,
– excavation till the depth of 17 m b.g.s., i.e. below the slab at level −6,
– construction of the slab at level −6,
– excavation till the depth of 20 m b.g.s., i.e. below the slab at level −7,
– construction of the slab at level −7,
– excavation till the depth of 23 m b.g.s., i.e. below the slab at level −8,
– construction of the slab at level −8,
– excavation till the depth of 26,5 m b.g.s.,
– installation of temporary struts at the depth of 26 m b.g.s.,
– final excavation till the depth of 29 m b.g.s.,
– construction of 1,5 m thick foundation slab,
– deinstallation of the temporary struts.

Calculations were made in 3 sections, chosen because of the vicinity of significant buildings.

Figure 3 presents example cross-section N° 3, located close to the beginning of the running tunnel (for the location of the section refer to Figure 2), showing geotechnical conditions and surcharges.

4 DESCRIPTION OF THE T11 TUNNEL

Two versions of the tunnel structure has been considered: 1 tube including 2 tracks and 2 tubes, single track each.

The lining of the tunnel was assumed to be constructed of 40 cm thick segments. Following stages of the execution of the tunnel were modeled:

– initial stress including overburden and surcharges (buildings and traffic),

– excavation of the tunnel and construction of the lining of the tunnel.

Figure 4 shows calculation cross-section N° I-I (for the location of the section refer to Figure 2) including geotechnical conditions, tunnels (2 tubes) and location of existing buildings.

5 CALCULATIONS

5.1 *Calculations of the excavation of S11 station*

Finite element plain strain analysis were carried out using PLAXIS v. 8 software, Coulomb-Mohr constitutive soil model was chosen for modeling the soil body, diaphragm walls as well as slabs were modeled as 3-nodes, linear beam elements. Non-associated plastic flow law was considered. For modeling wall frictions Coulomb-Mohr low was used. Model dimensions are: 65 m (vertical), 100 m (horizontal), they were estimated taking into account polish regulations according to the range of influence zone of the excavation.

FEM model mesh, generated automatically, was built of 807 15-nodes triangle elements and 9773 nodes. For the purpose of the paper 3rd cross-section was chosen to be presented and discussed because of it's vicinity to the T11 running tunnel. Geotechnical conditions and location of existing buildings has been presented on Figure 3, FEM model is shown on Figure 5. Figure 6 presents maximum deformations of the model in the final construction stage. Maximum calculated lateral displacement of the diaphragm wall in section 3 amounts to 49,3 mm; maximum foundation displacement −30,6 mm.

Table 1 presents maximum calculated values of horizontal and vertical displacements of the wall as well as settlements of the surrounding buildings in 3 cross-sections chosen for calculation.

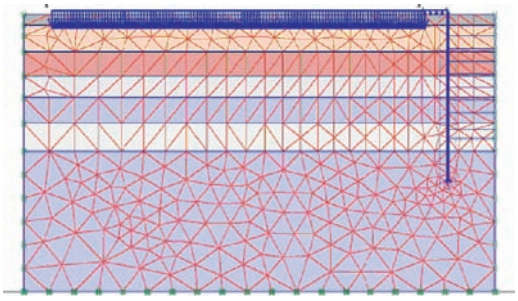

Figure 5. Numerical model – section 3 (PLAXIS).

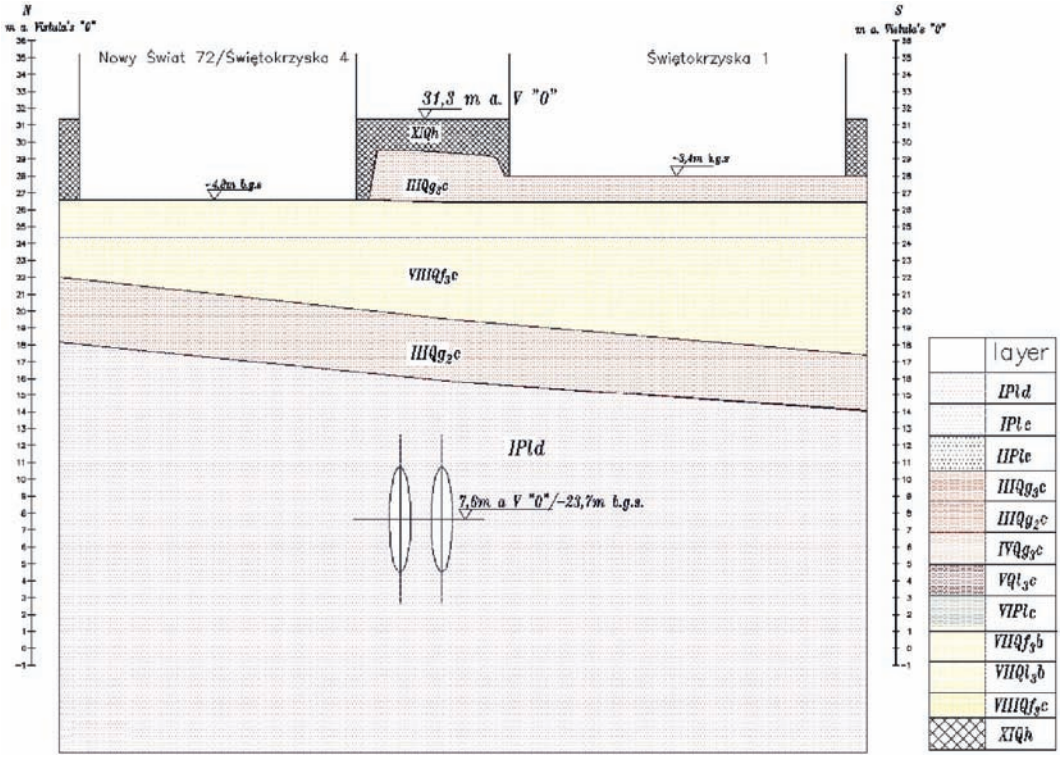

Figure 4. Calculation section No I-I (T11).

5.2 *Calculations of the T11 running tunnel*

Place Finite element plain strain analysis were carried out using GEO4 TUNNEL software, Coulomb-Mohr constitutive soil model was chosen for modeling the soil body, tunnel lining was modeled using 3-nodes, linear beam elements. Non-associated plastic flow law was considered. For modeling wall frictions Coulomb-Mohr low was used.

Section I-I, 1 tube, 2 tracks:

– model dimensions: 60 m (vertical) and 240 m (horizontal);
– FEM model mesh, generated automatically, was built of 7060 6-nodes triangle elements and 15011 nodes.

Section I-I, 2 tubes, single track each:

– model dimensions: 60 m (vertical) and 240 m (horizontal);
– FEM model mesh, generated automatically, was built of 8178 6-nodes triangle elements and 17284 nodes.

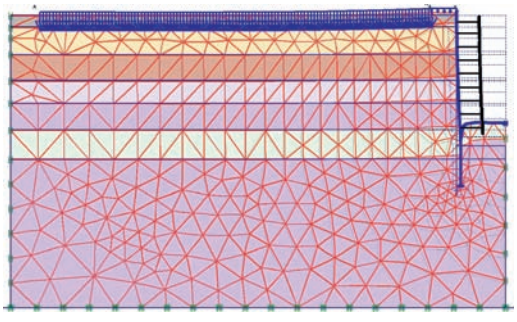

Figure 6. Final displacements – section 3 (PLAXIS).

Table 1. Results of calculations of deep excavation S11.

	Maximum displacements of diaphragm wall		Maximum settlements of buildings
Section	Ux [mm]	Uy [mm]	U [mm]
1-1	46,1	−32,8	24,5
2-2	61,0	−52,8	35,2
3-3	49,3	−53,3	30,6

Geotechnical conditions, tunnels location (2 tubes, single track each case) and location of existing buildings has been presented on Figure 4, corresponding FEM model is shown on Figure 7. Figure 8 presents maximum deformations of that model.

Table 2 presents maximum calculated values of bending moments, and displacements of the lining as well as settlements of the surface and surrounding buildings.

6 CONCLUSIONS

Taking into consideration results of analysis of the excavation of S11 Station as well as the results of T11 running tunnel calculations following conclusions are formed:

1. In the vicinity of the 29 m deep excavation, which will be executed during the construction of S11 Metro Station estimated settlements of the surface and surrounding buildings amount to 24,5–35 mm.
2. Calculated settlements of the ground surface and surrounding buildings above the T11 running tunnel constructed by the means of TBM, taking into consideration both cases 1 two track tunnel and 2 single track tunnels are similar and amount to 37,5–37,8 mm.
3. Theoretical values of settlements as well as displacements and forces in the structures were

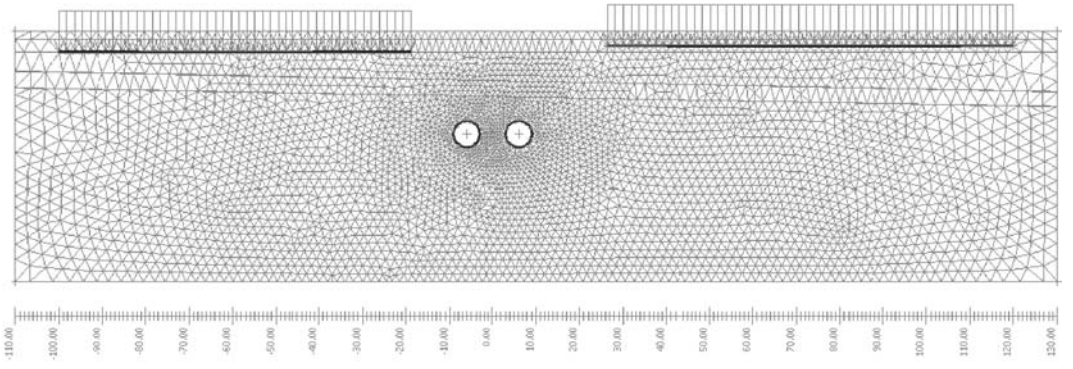

Figure 7. FEM model, T11 tunnel – 2 tubes, (GEO4 TUNNEL).

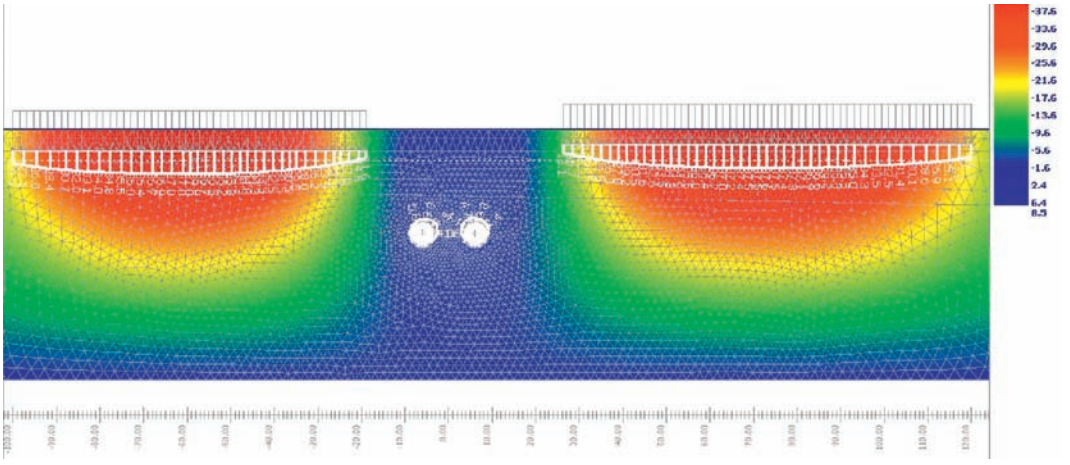

Figure 8. Maximum deformations of the model, T11 tunnel.

Table 2. Results of calculations of running tunnel T11.

	Finite elements method			
	Maximum bending moments, displacements of tunnel lining		Maximum surface settlements	Maximum settlements of buildings
Type of tunnel	Mmax [kNm/m]	Umax [mm]	Umax [mm]	Umax [mm]
1-1 (1 tunnel)	306,6	24,2	37,7	37,8
1-1 (2 tunnels)	290,2	8,1	37,5	37,6

calculated considering that the value of the modulus of deformation of Pliocene clays, within which the structures are located, is E = 50 MPa. This value must be verified by means of in-situ tests and then the calculations will be adjusted.

4. Due to the expected differences in the values of settlements of the ground surface close to the deep excavation and above the tunnel further analysis of the case including 3D modeling of the contact of 2 types of tunnel structure (running tunnel and station) will be performed.
5. During the construction, the results of analysis described in the paper will be carefully verified and discussed.

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