Line II of Warsaw Underground: the excavation of tunnel connector (Centrum Nauki Kopernik station) under existing Wislostrada tunnel

Ligne II du Métro de Varsovie: l'excavation du tunnel de connexion (station Centrum Nauki Kopernik) sous le tunnel existant Wislostrada

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ABSTRACT The Centrum Nauki Kopernik station of the Line II of the Warsaw Underground is located along and close the Vistula river. The station consist of three parts: the east and west shaft and one connecting tunnel of large cross section (170 m^2), which includes the rails along the sides and the platform along the center. The reason for the underground connection of two shafts with a tunnel is due to the presence of a road tunnel, which must be underpassed by the new metro line. The existing tunnel (Wislostrada) was built between diaphragms walls by top-down method and some foundation parts of its structures interfere with the underground tunnel. The challenging target was to build the connectors without stopping the traffic of vehicles along the above highway. All works have occurred in very difficult geological and hydraulic conditions due to the presence of Vistula alluvial deposits of poor mechanical characteristics. In particular the soil profile consists of upper relatively loose sands and silts overlying the Pliocene high plasticity clays strongly disturbed by the effects of repeated over sliding of the glacial moraine deposits. In order to carry out the work in high safety conditions, it was decided to improve the poor soils by cement-chemical injections and freezing method using liquid nitrogen and brine. An extensive monitoring system was installed in order to control in continuous mode stress-strain state of each structural part of the highway and of the station. In this paper are shown finally the comparison between the expected results from design and the observed behavior of the structures.

RÉSUMÉ La station de la Ligne II du Métro de Varsovie (Centrum Nauki Kopernik) est placée le long et proche de la Vistule. La station se compose par trois parties: les puits est et ouest et un tunnel de grande section (170 m^2), qui comprend les voies sur les côtés et le quai dans la partie centrale. La raison de la connexion de deux puits avec un tunnel est due à la présence d'un tunnel routier, qui doit être sous traversée par la nouvelle ligne du métro. Le tunnel existant (Wislostrada) a été construit entre parois moulées par la méthode top-down et certaines parties de ses structures de fondation interférent avec le tunnel de connexion. Le but ambitieux c'était celui de construire les connecteurs sans arrêter la circulation des véhicules le long de l'autoroute ci-dessus. Tous les travaux ont eu lieu dans des conditions géologiques et hydrauliques très difficiles en raison de la présence de dépôts alluviaux de la Vistule de faibles caractéristiques mécaniques. En particulier, le profil du sol se compose de sable et de limons peu compactes recouvrant les argiles du Pliocène de forte plasticité à structure fortement perturbée par les glissements répétés des dépôts morainiques glaciaires. Afin de réaliser les travaux dans des conditions de sécurité élevées, il a été décidé d'améliorer les sols avec faibles propriétés mécaniques par des injections de ciment et de mélanges chimiques et en utilisant la méthode de congélation du sol à l'azote liquide et saumure. Un système de surveillance étendu a été installé afin de contrôler en continu l'état d'éffort et de déformation de chaque partie de la structure de l'autoroute et du tunnel en construction. Dans cet article est présentée en fin la comparaison entre les résultats attendus de la conception et le comportement observé des structures.

1 INTRODUCTION

The Warsaw II subway line cross the city from the west to the east and connect Wola District on the left bank of the Vistula River throughout the centre of the city with Praga Północ District on the right bank of the river. The central part of the line covers a distance of 6.3 kilometers with 7 stations between the two terminals of Rondo Daszynskiego and Dworzec Wilenski.

Near Vistula River is located the subway station Centrum Nauki Kopernik (hereinafter referred to as C13 station). This is one of the most complicated construction of the project, performed within the flooding area of Vistula River and perhaps one of the most daring works ongoing in EU if is taken into account its hydrogeological context.

The station is located entirely on the left bank of the Vistula River: the eastern boundary of the station shaft is less than 10 m from the river bank. The station has been constructed in top-down technology with diaphragm wall (1.40 m thick). The maximum excavation depth reach the value of 24 meters. The entire structure is divided into two parts due to the presence of existing Wislostrada Motorway tunnel (WS), passing at middle of the station layout. The two parts of the station are joined with a connector of large section (total area about 170 m^2) which has to be constructed using traditional methods. The connector consists of three tunnels which include the rails along the sides and the platform along the center for a length equal to approximately 40 m (Figure 1). The side tunnels have an internal diameter of about 7 meters and their shape is perfectly circular as it originally had to allow, after their completion, the TBM passage.

The tunnel will be excavated, according to traditional methods, only partially in clayey soil: about half of the size section, instead, results in sandy materials below groundwater. Substantially, it is as if the tunnels were excavated in sub bed of the river in the presence of flowing water. A further great complication was due to the presence of the of WS tunnel foundations which would have been dismantled during tunnel excavation and in presence of normal vehicular traffic.

This paper focuses on the geotechnical and structural aspects of construction and design of tunnel as well as the difficulties encountered.

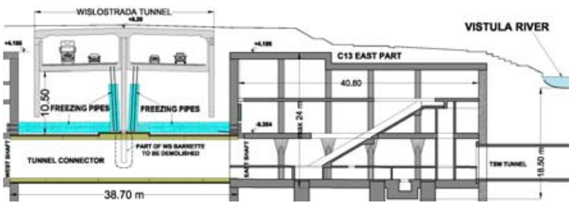

Figure 1. Longitudinal section of the connector tunnel

2 GEOLOGICAL AND GROUNDWATER CONDITIONS

2.1 General

Warsaw is located on two main geomorphologic forms: the plain post-glacial moraine plateau and the Vistula Valley with its asymmetrical pattern of different terraces. The Vistula River divides the city into two parts: the left one is situated both on the moraine plateau and on the Vistula terraces.

The subsoil consists of upper Cretaceous deposits overlain by Tertiary (Oligocene, Miocene and Pliocene) and Quaternary soils. The top of the Tertiary deposits is mainly caused by processes of erosion and glacitectonic origin. The Pliocene deposits consists of high plasticity clays and stiff silty clays (Figure 2).

Figure 2. Sample of Pliocene clay

In soil mechanics context the mass of Pliocene clays must be classified as a non-homogeneous, anisotropic and discontinuous medium, characterized by discontinuity surfaces-cracks (brittle fracture combined with displacements (Kaczynski 2002). The clayey layer may contain zones of more permeable material (silts, clayey silts, sandy silts and fine sands). The Pliocene clays are covered with Quaternary deposits, including anthropogenic ones, of variable thickness. The first meters of depth are constituted by uncontrolled fill (up to 10 m of thickness) and by a layer of dense sands, gravelly sands and silty sands. From hydrogeological point of view, the groundwater levels vary between -1.50 and 0.00 m above Vistula level.

2.2 Geotechnical characteristics of soils

The geotechnical characterization of soils of C13 tunnel arises from a series of tests (laboratory and in situ) carried out from 2007 to 2013. The soil profile consists, of:

- medium and coarse sands;
- medium or fine sands and silty sands;
- clays, silty clays and silts;

- high plasticity clays and high plasticity silty clays up to 25m below Vistula river.

The geotechnical parameters which results by tests are summarized in Table 1 (as average values). The undrained resistance of clayey soils increases with depth (c_u=100-250 kPa) and in some CPTU tests were measured negative values of pore pressure excess. The same behavior, observed by Szymanski et al. (2006), is probably due to the presence of macro cracks. The results of triaxial tests (in terms of t and s' stress invariants) are shown in Figure 3.

Table 1. Geotechnical parameters for soil involved by the excavation of Wislostrada Tunnel Underpass

Layer	γ	c'	c_u	φ'	E	k
(-)	(kN/m^3)	(kPa)	(kPa)	(°)	(MPa)	(m/s)
artificial fill	19	0	-	23	10	-
sand	20,4	0	-	34	70	3E-5
silt	20,6	5	250	18	60	10^{-7}
h.plast. clay	20,9	11	130	18	32,5	$<10^{-9}$
hard clay	21,5	11	190	18	52,5	10^{-8}

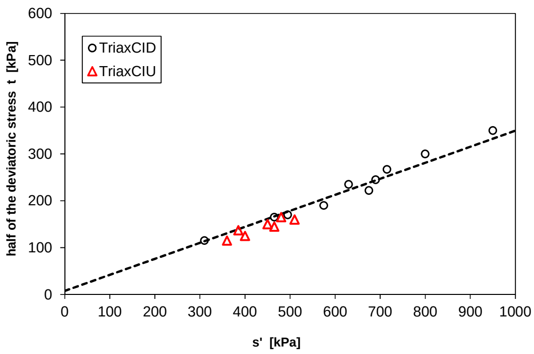

Figure 3. Triaxial tests on undisturbed samples of Pliocene clays-results in terms of stress invariants

3 TUNNEL EXCAVATION

This tunnel project despite its conceptual and executive complexity was based on a reasonable certainty that the excavation of the tunnels would affect entirely clayey soils of good consistency, poorly deformable and impervious. As well the presence of overlying WS tunnel moreover had hindered any further prior investigation able to highlight significant stratigraphic variations along of the tunnel.

During the execution of first drilling for steel forepoling installation an important water and sand ingress occurred: the works has been immediately suspended. Hence has failed the certainty that it was always in the presence of clay (Figure 4). The availability of the east and west station's shafts has enabled a geotechnical investigation in sub-horizontal direction to investigate the soil below the WS tunnel. After the geological boreholes, executed in March 2012, a new soils conditions were found (more thick sandy layer shown in Figure 5).

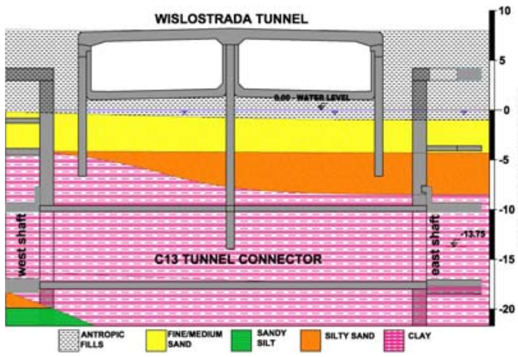

Figure 4. Building Permit geotechnical profile (tunnel entirely embedded in clayey soil)

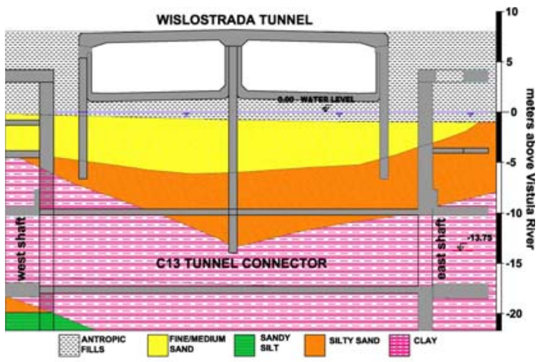

Figure 5. New geotechnical profile (tunnel partially embedded in sandy soils below water)

At first to taking into account this stratigraphic variability to protect the top half of the tunnel (in sand) was considered to apply jet grouting system, but collapse of north west tunnel occurred (Figure 6) during execution before reaching the sandy layer.

After filling the void under the WS tunnel with weak concrete, there were made boreholes, on the basis of which there were determined the soil conditions under bottom slab of the WS tunnel. Basing on the tests, it was stated that under the concrete filling there are layers of watered non-cohesive soil (Figure 8).

Figure 6. Collapse of north tunnel

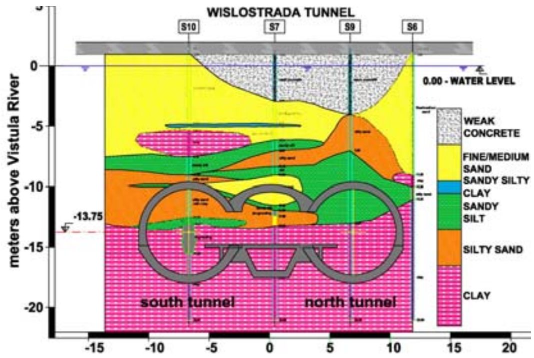

Figure 7. Final transverse geotechnical section (east shaft side)

On the basis of the benefit reached by the injection works (substantially for the filtration factor), the freezing methodology has been let to be considered applicable. Having considered all the boundary conditions, not as last the stability and working of the WS tunnel, the only possible solution is the implementation of the freezing system to ice, and then maintained frozen, the soil during the excavation of the tunnel. Additional investigation have been carried out with the aim to finalizing this type of intervention. Due to soil improvement by grouting these risks have been excluded. No direct communication of the water present in the sandy strata with the level of Vistula river is now possible.

The geometry of the perforations for freezing pipes was very articulate as can be observed in the figure 8. The freezing occurred on both sides of the tunnel: the east and west. Even the WS was subject to vertical pipes in order to achieve a vertical screen.

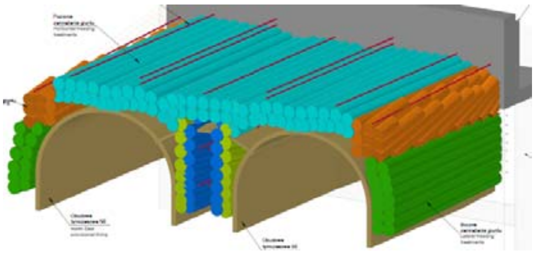

Figure 8. Three-dimensional view of the arrangement of freezing pipes (east shaft side)

The freezing phase began in November 2013. The tunnel excavation start in January 2014, maintaining the reached temperature with brine until the end of the excavation. The consumption of liquid nitrogen during freezing and maintenance stages is summarized below.

Table 2. Consumption of liquid nitrogen

	NW TUNNEL	SW TUNNEL	NE TUNNEL	SE TUNNEL
m^3 of ground	970	1085	1085	970
FREEZING STAGE				
total days freezing	18	14	10	10
consumption LN	1700 m^3	1560 m^3	2100 m^3	1720 m^3
MAINTENANCE STAGE				
total days	28	28	40	30
consumption LN	350 m^3	350 m^3	600 m^3	370 m^3

The final solution adopted has provided excavation of laterals tunnel by following steps:

- Excavation (full face excavation method) by step 0.75 m long and installation and positioning of steel ribs (HEB240).
- Stabilization of excavation perimeter with shotcrete and steel mesh.
- Waterproofing membrane installation.
- Reinforcing and concreting of invert part.
- Reinforcing and concreting of shoulders and crown parts.

The central tunnel was excavated using omega section steel ribs (TH360) realizing the crown and then the invert part.

4 FRONT FACE BEHAVIOR

During several visits on the site it was possible to observe the excellent behavior of the face as a result of soil freezing. Due to the strength and hardness of the iced soil was necessary to use the point cutter in order to proceed with tunnel excavation. The excavation proceeded without particular problems and never results in instability phenomena. Even cutting of central barrettes of the WS tunnel was completed quite quickly.

Figure 9. demolition of station diaphragm walls and start of tunnel excavation

Figure 10. WS barrettes demolition

5 MONITORING SYSTEM

The monitoring system for has provided essentially:

- measures of deformation on WS Motorway structures (using: optical targets and/or miniprisms; crackmeters; levelling staffs);
- convergences measures on temporary linings of C13 tunnel;
- strain measures on temporary and final linings of C13 tunnel;
- monitoring of groundwater levels
- monitoring of temperatures in the soil.

5.1 *Deformations induced by tunnel excavation*

From the beginning of freezing intervention (December 2013), the trend of the vertical displacements shows an initial rise of all points resulting from frost heaving. Higher displacements were measured on mini prisms "B" (see Figure 11) installed on the internal structures of the WS tunnel (inner vertical walls connected to bottom slab and resting on the soil). Maximum values of raising (52 mm) was reached on central alignment of WS tunnel. Generally the soil freezing has raised the west span of WS tunnel more than the eastern one, probably due to the presence, below the bottom slab of the WS tunnel, of a thicker layer of weak concrete, stiffer than soil in place. The settlements have started after 10-15 days from the start of the excavation of NW tunnel. The global trend of the curves indicates a phase with higher gradient for the period between February 15th, and June 1th, 2014. After this date, the slope of the curves appears to be significantly reduced. At the end of the excavation settlements have stopped over a period of about a month and then have shown a new increase, due to soil thawing, after July 1th, 2014, (about 0.3 mm/day) until complete stabilization (Figure 12). At the end of tunnel construction the maximum settlement was equal to 70 mm. Measurements of the thermocouples have shown a lowering of the temperature ranging from 0.1 and 0.5 °C/day.

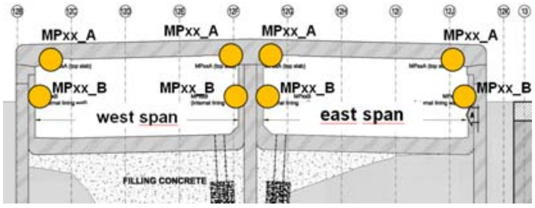

Figure 11. Monitoring system used for WS tunnel structures (cross section)

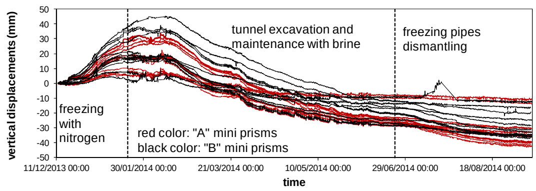

Figure 12. Vertical displacements measured on central alignment of WS tunnel

5.2 *Stress-strain state on linings*

The values of normal force measured at steel ribs foots were rather low (around to 30 kN). In some cases the value of the normal force is different on the two pads of steel rib. The measured values of stress in the steel were equal on average to 42 MPa (compression values).

The average values of steel ribs convergences are equal to about 10 mm.

The stress state of final lining was checked by strain gauges placed on reinforcing bars in the most stressed points. The maximum values measured in reinforcing bars are equal to 126 MPa.

5.3 *Water table monitoring*

The values of the groundwater level outside of the tunnel showed no significant changes: values fall in the range -1.00 and +1.50 m a.V.l. during construction and confirm the absence of a direct communication of the water present in the sandy layers with the Vistula river.

6 FINITE ELEMENTS ANALYSIS

The analysis to predict soil-structures behavior has been performed using finite elements code PLAXIS 2D. The stress-strain state of the whole tunnel connector was checked using 3D model with code SAP2000: this model was used in order to simulate the interaction with WS tunnel barrettes and to design the reinforcement. The soil behavior has been represented in PLAXIS 2D by Hardening Soil Model. In SAP2000 model the soil was modeled by Winkler's springs. The model has taken into account also the soil improved by injections and the void filled with weak concrete. The frozen soils parameters were chosen using Literature values properly reduced, because it was rather difficult to characterize the behavior of soils, not always improved homogeneously and probably affected by claquage phenomena. For sandy soils following parameters were considered: c'= 250 kPa and φ'= 32°, E_{50}^{ref}= 250 MPa, E_{ur}^{ref}= 750 MPa.

The results obtained from PLAXIS shown a maximum vertical displacement equal to 63 mm near excavation boundary and 52 mm below WS slab. These differences with respect to the measured values (slightly larger) are acceptable if we consider the complexity of the boundary conditions.

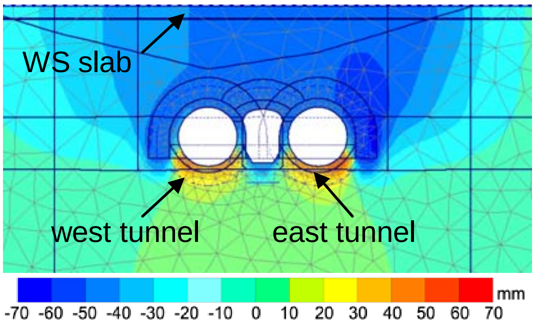

Figure 14. Vertical displacements at the end of construction

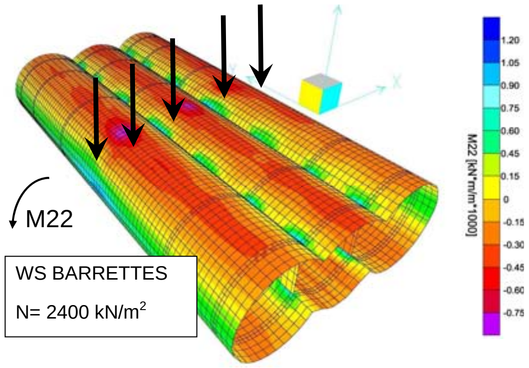

Figure 15. SAP2000 3D model: transversal bending moments

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