Combined ground freezing application for the excavation of connection tunnels for Centrum Nauki Kopernik Station - Warsaw Underground Line II

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ABSTRACT
The Station "C13" of Warsaw Underground Line II, with tunnel crown 10m below the water table, required the excavation of three connection tunnels, underpassing a six-lane in service road tunnel, working from two lateral shafts. After the collapse occurred while digging the first tunnel, the use of artificial ground freezing was chosen to ensure the excavation under safe conditions. A complex freezing pipe geometry and excavation sequencing was necessary because of the interferences of the overlying road tunnel diaphragm wall foundations, shaft internal structures and previous grouting activities. A combined freezing method was used: nitrogen for freezing the tunnel arches, brine for freezing the intermediate wall and for maintenance stages. Sandy and silty sandy layers were frozen around the crowns and sides. No treatment was necessary for the inverts, lying in clay. A monitoring system of ground temperatures and structure movements allowed for successful completion of work in 8 months.

INTRODUCTION
The C13 Station of the Warsaw Underground-Line II is located on the West bank of the Vistula River. It consists of two shafts and three connecting tunnels, passing under the Wislostrada (WS) Road tunnel.

According to the initial geotechnical investigation, tunnels should have been excavated in high-plasticity clay, but during the first borings non cohesive soil was encountered. Additional investigations were performed on both shafts and a more detailed stratigraphy was reconstructed (Lombardi et al. 2015). Layers of fine sand, sandy silt and sandy silty clay were present along the tunnels crown arches and in the North East tunnel they extended down to the centre line (-13.735m above the Vistula River medium level).

Based on the new stratigraphy, it was decided to stabilize the crown and control the groundwater inflow from the face with jet-grouting columns extending the treatment down to the clayey soil, but a collapse occurred in the North West tunnel with soil and water inflow inside the shaft.

The empty cavities under WS were filled with lean mix concrete. At a later stage, grouting with cement and silica mixtures was carried out (again from WS) down to the tunnel invert, in order to recompact the soil so as to enable the restart of the excavation. Beside a partial compaction effect, grouting also caused soil fracturing, thus inducing a sensible uplift of WS up to 8cm, which settled the ground loss event, but producing differential heaves of the structures without obtaining the water tightness of the ground. The grouting had to be stopped and it was impossible to restart the excavation.

To ensure the safe excavation of the tunnels, the only possible solution was to create a watertight and resistant frozen shell around the tunnel excavation line, above the clayey layers (Balossi Restelli 1995).

THE FREEZING DESIGN

Design stratigraphy and groundwater conditions

The design stratigraphy derived from the pre-tender and additional geotechnical investigation consisted of CPT and CPTU tests, boreholes, seismic tomography and Drilling Parametric Recording (DPR) tests.

Subsequently silty sand or fine sand was found at the crown of the tunnels, with silty sand, silty clay or clay on the sides and clay at the invert. The sandy soil extended at least 1.8 m beneath the crown.

This was found in correspondence of the North West (NW) tunnel where the collapse occurred.

According to the pre-tender boreholes (2010), the high-plasticity clay layer had a minimum thickness of 15.0m, therefore it should have ensured an adequate cover of impermeable soil. Figure 1 shows the actual soil stratigraphy and DPR parameters at the NW tunnel. The figure shows how DPR test confirms borehole stratigraphy; for example specific energy increases in correspondence of the lean mix layer (orange) and fluid pressure (blue) increases in the high-plasticity clay layer.

The water table varies from elevation -1.50m to 0.00m, which means from 10.5m to 12.0m above the crown of the tunnels.

Site geology and geotechnical parameters of the natural soils are described by Lombardi et al. 2015.

Structure's geometry and interference between tunnels and Wislostrada structures

The two shafts (West shaft and East shaft) are connected by two lateral tunnels, 9.68m in diameter, and a narrower central one, 8.10m high. The elevation of the crown of the side tunnels is -9.595m, the inverted arch lower level is -18.275m (see Fig. 1 and 2). Depth are referred to Vistula water level.

The tunnels pass under the WS road tunnel, whose structure is a double reinforced concrete U-shaped section. The top structure is a concrete slab, supported on the sides and in the middle by diaphragm wall, *barrettes*, spaced in order to ensure water table flow below the structure. The U-shaped structures are free to move vertically in case of uplifts due to water table fluctuation; at the ends they are constrained by the top slab.

The central *barrettes* interfered with the new tunnels because their bottom level was just below the tunnels spring line. During excavation of the tunnels, therefore, the *barrettes* were demolished at their bottom end, up to a maximum height of 5.0m.

Freezing geometry

The layout of the freezing pipes in the ground is critical for the success of the treatment, and it has been carefully designed.

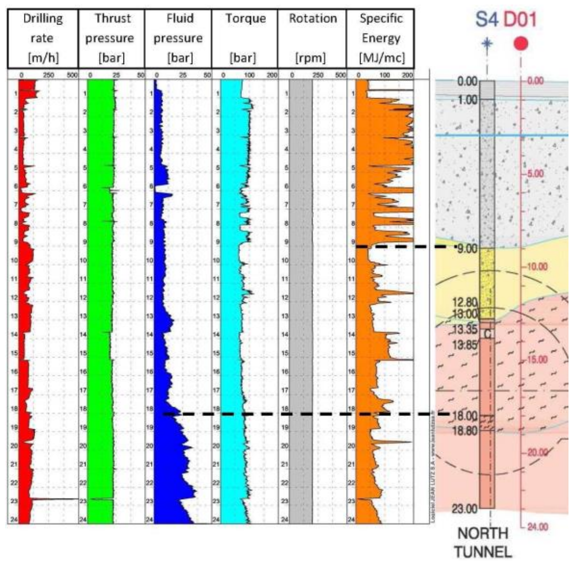


Figure 1. Soil stratigraphy obtained from borehole S4 compared with drilling parameters of DPR test D01 after the filling with lean mix concrete and grouting operations.

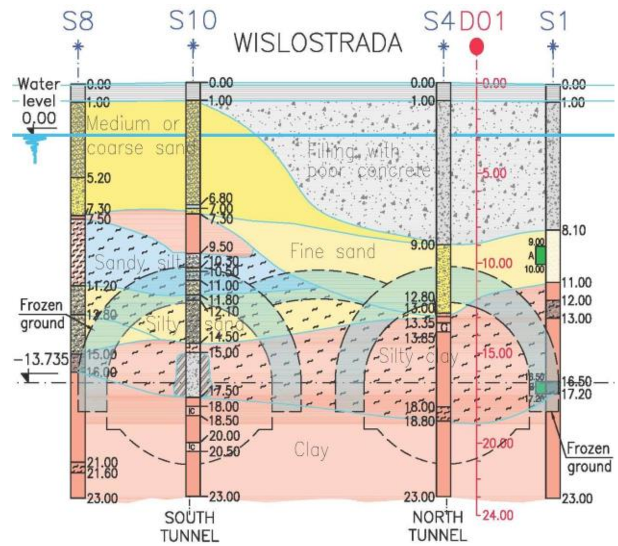


Figure 2. Soil stratigraphy at the West shaft with frozen ground arches around the tunnels.

After the collapse, the WS tunnel was closed to traffic for more than eight months. As a consequence it was not possible to close the WS again for an extended period. Moreover, the presence of central *barrettes* required the drilling of the freeze pipes to be done in two parts in order to ensure a more regular geometry.

The final scheme consisted of two double lines of vertical freezing pipes drilled from the two central lanes of WS alongside of the central *barrettes*, two sub-horizontal lines of freezing pipes drilled from the two shafts, connected with the vertical ones drilled from WS. The freezing pipes followed the crown and the lateral side of tunnels as well as the crown of the central one (see Fig. 2). Longer drillings through the *barrettes* may have deflected significantly, compromising the design geometry and jeopardizing the WS structures.

The drillings executed from the two shafts had to be performed with a very complex layout because of the presence of the slabs which interfered with the ideal layout of the frozen arch.

Moreover the presence of jet-grouting standpipes and steel forepoling from the previous work created a very difficult situation. Such a complex geometry required a 3D study of the pipes layout, involving, in many cases, the execution of drillings with compound angles (see Fig. 3).

Thermometric pipes were placed at a distance of about 3m from each other and at 0.6m and 1.0m from the external freezing pipes line to check the temperature at different distances.

Drilling parameter recording and deviation control

Due to the complexity of the stratigraphy, especially in the NW tunnel, drilling parameters were recorded to verify the presence of residual voids and to identify the high-plasticity clay layer which ensured the impermeability of the inverted arch, and adequate depth of the freeze. All drill holes were checked and all of them confirmed the presence of high-plasticity clay at the level of the inverted arch or at a higher elevation. No significant voids were detected.

Because of the complex geometry and the soil heterogeneity, drilling deviations were expected; as a consequence the alignment of all the drilled pipes was verified. Deviation was measured with different methods: vertical holes from WS were checked with an inclinometer, while measurements in the horizontal holes, drilled from the two shafts, were performed with a Reflex Maxibor II system. In general a good correspondence between theoretical and actual layout was found.

All borehole deviation was plotted in a 3D drawing; if spacing greater than 1m between adjacent pipes was detected, the formation of frozen ground in that zone may slow down, or even fail, so that an integrative pipe was installed. Pipes interfering with the excavation profile were disconnected from the freezing circuit when the excavation face was at a distance of about 2m from the interference zone (see Fig. 4).

Some drillings had to be stopped earlier than expected because of the presence of granite boulders, other holes due to the presence of the *barrettes* of the WS tunnel.

All drillings from the two shafts were carried out using a blow-out preventer device and with cement mud in order to fill any residual voids and to embed the steel pipes.

SET UP OF FREEZING AND THERMOMETRIC PIPES

The WS freezing pipes were equipped with an external lost drill rod made of steel suitable for low temperatures with an external diameter of 90mm, an inner copper pipe and a coaxial PVC pipe.

Pipes drilled from the two shafts were equipped with the same external lost drill rod, and two coaxial copper pipes. The inner pipes were suitable both for the LN ground freezing method (Direct Method) and for the brine method (Indirect Method). The Direct Method was used for freezing the ground around the tunnel, operating from the shafts. The brine method was used for the maintenance stages, and for freezing the vertical wall from WS, where, for safety reasons, LN was not allowed.

The monitoring of ground temperatures occurred through a chain of thermocouples installed at different positions inside the thermometric steel pipes. Each thermocouple was connected by a cable to the monitoring system which recorded the sensor temperatures at one-hour intervals. All recorded data were transmitted to a central read out unit.

Freezing pipes circuits were designed in order to connect two pipes in sequence in primary/ secondary fashion and following a similar pattern for the adjacent row, so as to equally distribute the primary and secondary pipes. Figure 5 illustrates the circuit layout of the East shaft.

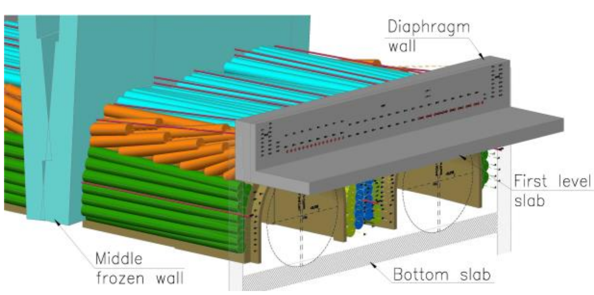


Figure 3. Freezing pipes geometry. In the background the vertical frozen walls installed from Wislostrada and in foreground the pipes installed from the West shaft.

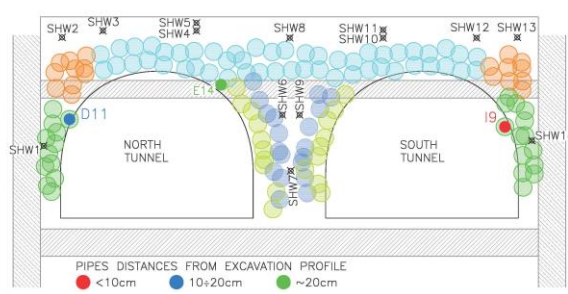


Figure 4. The effective position of freezing and thermometric pipes surveyed with the Reflex Maxibor II system at a distance of 10m from the front wall of the West shaft.

Figure 6 shows the freezing plants installed for direct and indirect freezing methods.

The LN plant of the West shaft fed 172 freezing pipes for a total amount of 2,500m of pipes while the East shaft plant fed 172 freezing pipes for a total amount of 3,090m of pipes.

Outlet pipes were connected to the automatic temperature registration system which regulated the nitrogen inlet.

The indirect or brine freezing system was powered by a 380 kW plant with a second auxiliary plant available in case of failure of the first one. Initially the brine plant supplied the 63 WS circuits, both for the freezing and for the maintenance stages; later it also supplied the pipes of Western and Eastern tunnels for the maintenance stage.

Wislostrada freezing pipes uplift

Freezing pipes executed from Western and Eastern sides joined with the vertical pipes drilled from WS, so that the excavation of Eastern and Western tunnel sides were independent; the vertical pipes produced a frozen curtain end wall inside the tunnels profiles as well (see Fig. 3).

When the tunnel excavations reached a distance of about 2m from the vertical pipes, the circuits interfering with the excavation were temporarily closed and the internal freezing lances were dismantled. An expansion packer was inserted inside the steel pipes at a distance of 0.5m from the excavation profile. Finally, the internal lances were inserted again and the circuits switched on so that the soil external to the excavation, at the *barrettes*, still remained frozen.

When the tunnel excavation reached the vertical steel pipes, they were cut.

FREEZING AND EXCAVATION STEPS

Freezing from WS was activated at first by using the brine method while the complex drillings from the shafts were still running so that, when pipes installed from the two shafts were completed, the vertical end-wall was frozen. The Direct Method was used to accelerate tunnel shells freezing, saving time to start the excavation stages.

The standard work sequence for each tunnel was the following (see also the table in Fig. 7): freezing of the central vertical barrier (1a - 1b); freezing the soil on the West side (2 - 3); excavation of the tunnel on the West side during the freezing operations on the East side (4 - 5); reinforced concrete (RC) lining cast of the West side during the excavation of the East part; cutting the freezing pipes firstly in the vertical central barrier from West and then the East side; demolition of the WS barrettes

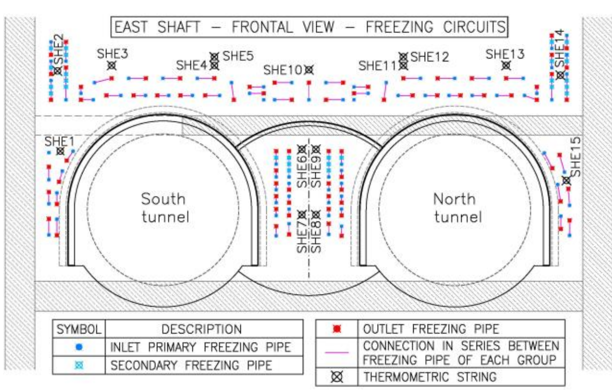


Figure 5. Freezing pipes circuits and thermometric strings layout in East shaft.

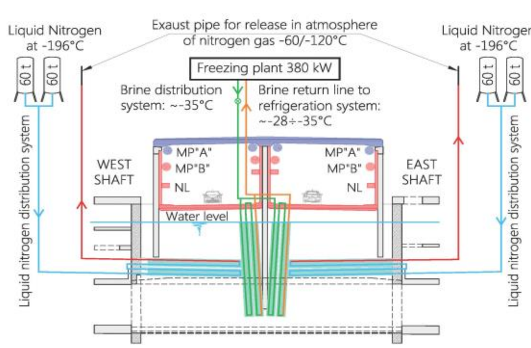


Figure 6. Freezing plants installed on site for direct (Liquid Nitrogen) and indirect (brine) method.

interfering with the tunnel, RC lining cast in the central part of the tunnel.

In Figure 7 operations are described in chronological order. The NW tunnel was excavated first, followed by the NE side. Operation on the SE side started in parallel with the NE side, so that excavation occurred only when the adjacent tunnel was lined with reinforced concrete or not excavated. The central tunnel excavation started only after the curing of the other tunnels linings.

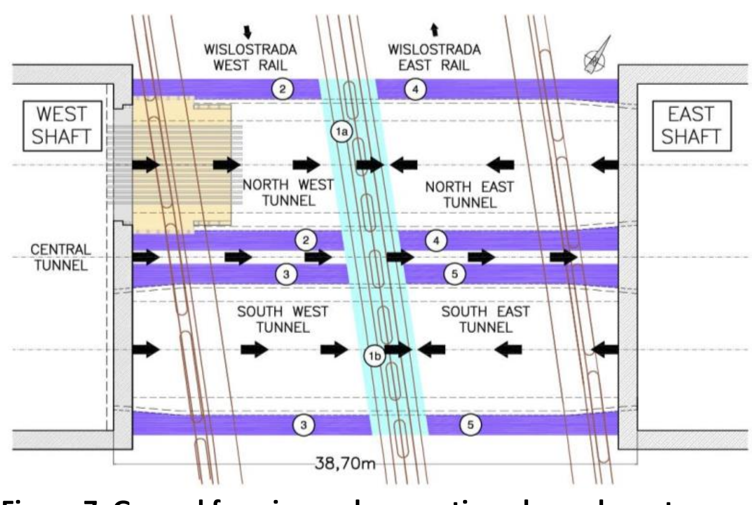
Ground freezing process

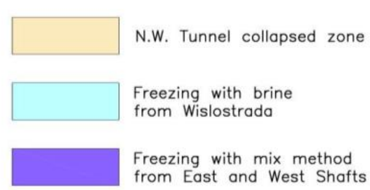
Ground temperatures were monitored with the temperature sensors. Charts in Figure 8 show the evolution of temperature versus time in the central vertical frozen wall (3 sensors of thermometric chain WE14) and in the arch zone of the NE tunnel (6 sensors of SHE12) respectively. The central vertical circuits were fed from WS only with brine, while the arch zone of the NE tunnel was fed with the mixed system.

The WE14 sensor required about 33 days to reach the target temperature of about -30° at 0.3m from the axis of the freezing wall, and during the maintenance stage, the temperature had minimal variation around this value. In SHE12, the freezing stage with LN required 6 days to reach the target value; subsequently the maintenance stage was started, initially with LN (12-24 hours cycles of LN pumping followed by a 24 to up to 130 hours resting time, until a stabilization was reached at about -15°C. Finally the maintenance was switched to brine. The daily evaluation of the temperatures allowed, for each tunnel, optimization of the LN freezing and maintenance stages duration in close cooperation with the site manager who organized the transport of LN to the site.

Another type of chart was used for evaluating the thermal ground behaviour during the works: the sensors' temperatures were plotted versus distance from the freezing pipes. On the same chart, the theoretical curve obtained from a model giving the thermal gradient in the soil surrounding a freezing pipe was plotted. The model assumes that the temperature influence radius of a freezing pipe in the ground is 3 times the freezing radius (Sanger and Sayles 1979). Knowing the natural ground temperature (+18°C due to the previous grouting), the temperature of the surface of the freezing pipe (-80°C in case of LN freezing fluid; -35°C in case of brine), and fixing as a design input to have -6°C in the ground, at a distance of 0.6m from the pipe axis, the *target thermal gradient* has been plotted.

Under these conditions a thickness of 2.0m of the frozen ground wall was reached (Balossi Restelli et al. 2011) according to the structural requirements.





	Start freezing	Start maintenance	End of casting
1a – Wislostrada	03-12-2013	22-01-2014	16-04-2014
1b – Wislostrada	04-12-2013	22-01-2014	02-05-2014
2 – N.W. Tunnel	20-12-2013	05-01-2014	05-03-2014
3 – S.W. Tunnel	30-12-2013	11-01-2014	25-03-2014
4 – N.E. Tunnel	14-01-2014	25-01-2014	02-04-2014
5 – S.E. Tunnel	31-01-2014	09-02-2014	30-04-2014
Central tunnel	Included in other tunnels (NW–SW–NE–SE) freezing		13-06-2014

Figure 7. Ground freezing and excavation phases layout.

Figure 9 shows these values for the NE tunnel. The first diagram was plotted at the beginning of the freezing process, when the sensors showed almost the same temperature. After 10 days the freezing was completed (second chart).

The demolition of the diaphragm wall of the shaft started five days later, under LN maintenance, with the temperatures shown in the third chart. The last diagram shows temperature during the casting of the arch, under maintenance with brine.

The daily evaluation of temperature data, available online and updated every 60 minutes by the control unit on site, allowed management of the freezing process in real time, in its critical phases: switching to maintenance, start of diaphragm wall shaft demolition and of tunnel excavation, cutting of the freezing pipes under WS, and interruption of the brine maintenance.

Tunnels excavation and lining execution

The table in Figure 7 summarizes the excavation phases. During the excavation it was possible to compare the stratigraphy at the face of the tunnels with the design prediction derived from the investigations and a good accordance was observed. Figure 10 shows the sandy silty layer of the upper half of the section, frozen in the upper part, as well as the lower clay. The blue lines indicate the boundaries of the layers.

Soil freezing allowed fast and precise excavations and face stability.

Figure 11 shows the jet grouting columns carried out from the East shaft before the collapse, encountered during the excavation of the first part of the tunnel.

The excavation of the tunnels was stopped 2m before reaching the position of the reinforced concrete *barrettes* of the WS, surrounded by two rows of vertical steel freeze pipes.

After the temporary concrete lining of the tunnel was placed, it was necessary to cut the frozen wall in order to uncover the *barrettes*' lateral surface.

The orientation of the freezing pipes is shown in Figure 12. The ones within the tunnels had to be shortened. The brine circulation was interrupted, the pipes emptied out, and a special sealing plug was placed 50cm above the cut.

Figure 13 shows the excavation of the central tunnel in the proximity of the last *barrette* to be demolished. On the right side the deactivated freezing pipes are visible.

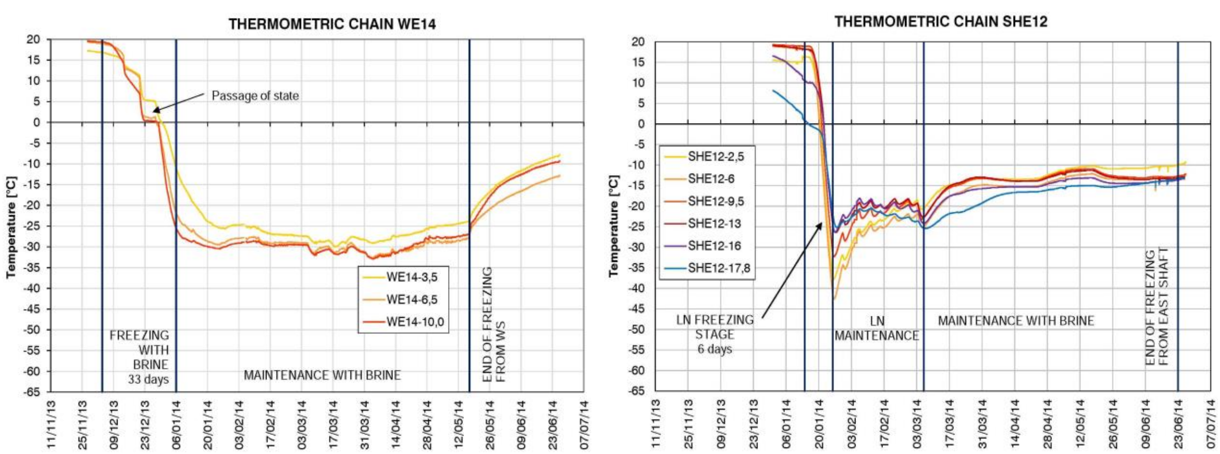


Figure 8. Ground temperature evolution in thermometric chains WE14 and SHE12.

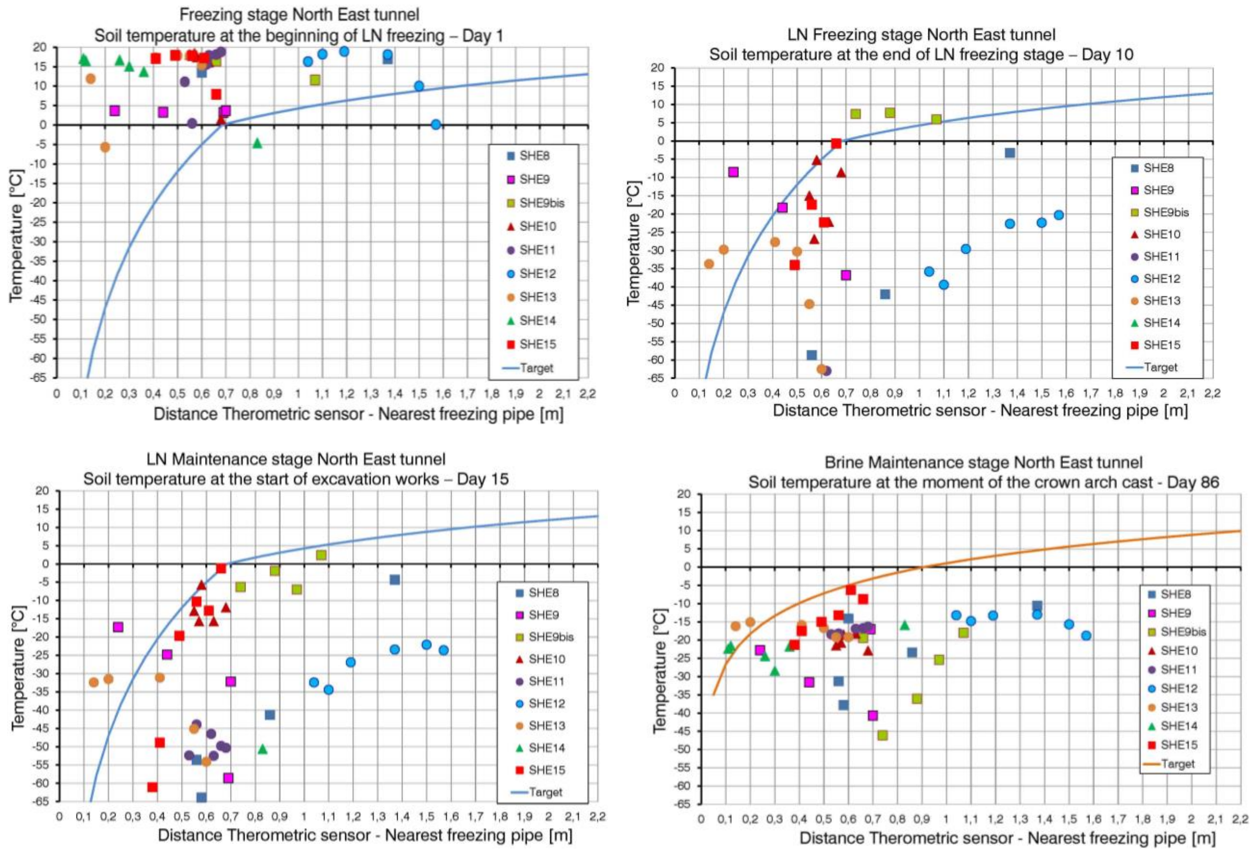


Figure 9. Ground temperature vs. sensor distance from the freezing pipe at different times of the works.

Monitoring system

A topographic monitoring system, installed inside the WS, gave information about the displacements of the structure above the frozen tunnels. Figure 6 shows a monitored section.

The top beam (in blue) was monitored with mini-prism MP"A". Two U-shaped structures (in red), placed beneath the top beam, can move with oscillation of the water table influenced by the Vistula River, close to the road. These structures were monitored with mini-prisms and a manually read with levelling staff. Four sets of mini-prisms and levelling staffs were installed in each monitored section.

Figure 14 shows the movements recorded in two section, close to the West shaft and to the East shaft. Zero displacement refers to the end of the grouting operations carried out after the collapse.

After that, a relaxation of the ground was observed. The injections performed during the drilling phase from the shaft, in order to embed and seal the tubes of the freezing pipes, caused an uplift of the WS structures: 16mm on the West side, 10mm on the East side.

Also the freezing stage with nitrogen resulted in an evident uplift. This was higher in the zone of the d-wall above the West tunnel (chart on the left), where a large placement of lean mix concrete was made after the collapse. This filling worked as a stiff plate lifted by the swelling frozen soil. The heave was 48mm on the West, about 35mm under the centre of WS, and 22mm on the East side (chart on the right).

The effect of the excavation combined with the reduced temperatures with the maintenance of the freezing led to a settlement of 44mm in the West side, 54mm in the central zone, and 28mm in the East side.

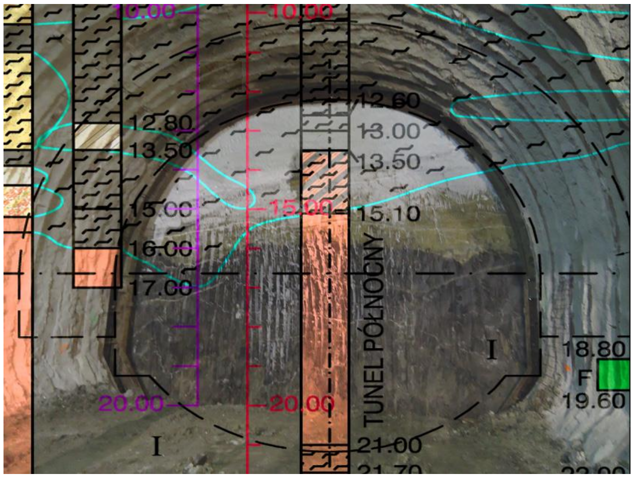


Figure 10. The design stratigraphy overlaying the North East face tunnel at 12th rib.

Figure 11. Face of the South East tunnel at 4th rib.

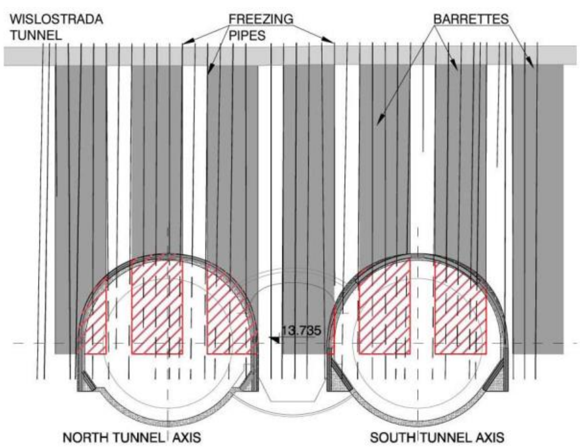


Figure 12. Scheme of the freezing pipes to be shortened under WS for the further cut of the barrettes.

Figure 13. Central tunnel in the proximity of the last barrette to be demolished. On the right side the deactivated freezing pipes.

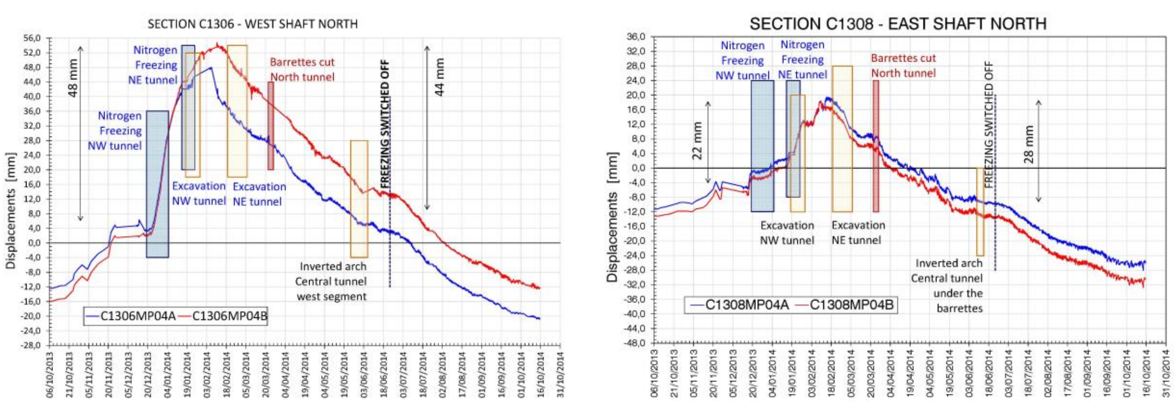


Figure 14. Wislostrada displacement diagrams.

After the deactivation of the freezing, a residual, rather homogeneous settlement was observed: 20mm on the West side, 18mm in the middle, 20mm on the East side. After four months from the end of the freezing the settlement trend seemed to be almost finished.

Finally the West side structures of WS went back to their initial position; the East side had a global settlement of 13mm; the central zone had a global settlement of 20mm. This was considered acceptable by structural engineers.

CONCLUSIONS

The freezing Direct Method with liquid nitrogen allowed to accelerate the freezing time of tunnel shells, whose pipes required more time to be installed compared to pipes drilled from WS. In this way, when pipes installed from the two shafts were completed, the vertical frozen end-wall in the centre of WS was ready, thus saving time for the construction.

Despite the interference of the shaft slabs, previously drilled forepoling and grouted columns, in general there was a good correspondence between theoretical pipes design and the actual layout. The directional control and hole surveying was extremely important to evaluate any excessive distance between freezing pipes that may slow down or even compromise the formation of frozen ground in that area.

It was very important to perform daily temperature evaluation in order to cease the freezing phase with LN so as to save time and money and reduce ground heave. Moreover the management of the Direct Method maintenance required constant temperature supervision in close cooperation with the site manager who organizes the transport of LN to the site.

During several on-site inspections the excellent behaviour of the excavation face as a result of soil freezing was observed.

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