GROUND FREEZING COMBINED METHOD FOR URBAN TUNNEL EXCAVATION

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ABSTRACT

The construction of Powisle station of Metro Warsaw Line 2, in Poland, required the execution of two shafts next to an urban road tunnel adjacent to the Vistula River. The shafts were linked by three conventionally mined tunnels to be excavated 10 m below the water table level, into an upper sandy and sandy silty layer and a lower stiff clayey stratum. After a failed dig attempt under the protection of jet grouting and forepoling, it was decided to deal with the tunnels excavation problem by using the ground freezing technique as a temporary, non-polluting geotechnical treatment, keeping in service the upper road tunnel. The planning of the activities and the executive phases had a significant importance for the success of the work. For work scheduling reasons the mixed system was adopted, i.e. using both the liquid nitrogen system and the brine freezing method. The freezing process management, with a real time evaluation of the soil temperature measured by thermometric strings and an accurate monitoring of the overlying road tunnel structure, allowed the tunnel excavation and lining stages to be performed under difficult conditions, without water leaking from the frozen ground shell, within the expected times and saving extra costs.

INTRODUCTION

The new Underground Line 2 in Warsaw connects the eastern and western part of the town. One of the most critical interferences was the under passing of the Vistula river and of the Wislostrada motorway tunnel, a very congested motorway along the western bank of the river, with the construction of the new station Powisle. The construction of the station required the excavation of two shafts, using the top-down system with the creation of intermediate slabs while deepening the excavation.
The shafts were used for the extraction of four Tunnel Boring Machines (TBMs), two approaching from the Vistula river side (east-side) and two approaching from downtown (west-side); in order to connect the two shafts was foreseen the realization of three tunnels, two for the underground lines and the central one for the exchanging passenger platform. These tunnels were underpassing the "Wislostrada Road Tunnel" and interfered with this tunnel foundation, which consisted of diaphragm walls (DW), the "barrettes" (Figure 1).
Due to the variable geological conditions at the site, the first excavation stage, with a temporary underground support constructed of horizontal jet grouting columns and forepoling, caused the North tunnel face failure, that required an immediate filling of the empty cavities with lean mix concrete under the Wislostrada tunnel slabs. Thereafter, the recovering attempt with the grout injections could not be completed because of the development of heaves induced on the tunnel structures (Bringiotti et al. 2016).
In those conditions the tunnel excavation with traditional technologies appeared to be very problematic, with high risk for the structural safety of the Wislostrada tunnel. This would have meant longer duration for the works and higher costs for the General Contractor as well as for the city Council.
In light of this, the artificial ground freezing appeared to be the best solution. It was proposed to create a shell of frozen soil around the tunnel excavation profiles in order to ensure a safe excavation of the tunnels, using the mixed ground freezing method with Liquid Nitrogen (LN) and brine. Collecting all the

information about the occurred failure and with an accurate additional ground investigation, times and costs could be predicted with a very moderate fluctuation due to unexpected occurrences.

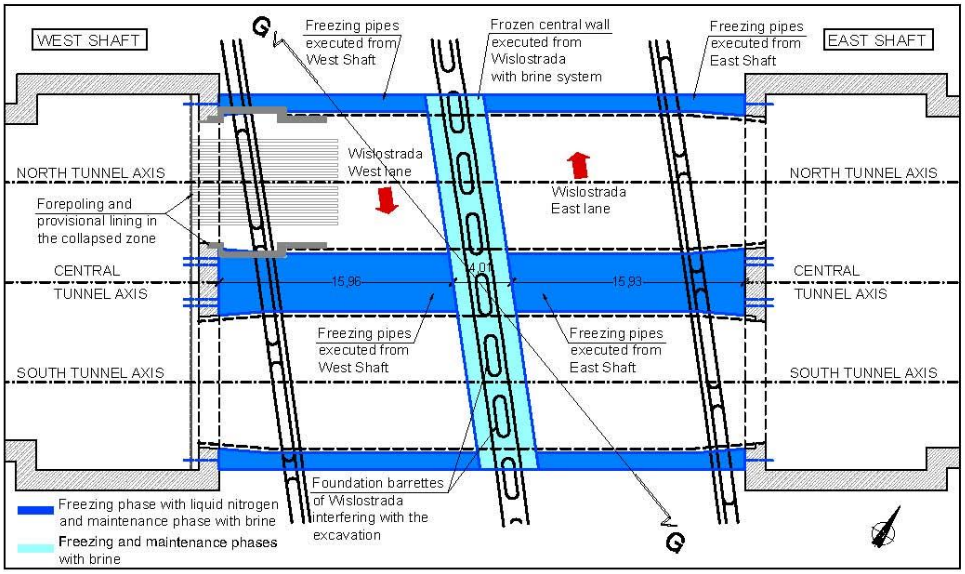

Figure 1: Powisle Station Plan View

GEOLOGICAL CONDITIONS

The ground conditions encountered during the site investigations have been interpreted from the Cone Penetration Tests (CPTs), Drilling Parameters Test (DPTs) and Seismic Tomography records. The ground investigations confirmed a variable complex stratigraphic layout due to the effect of collapsing during the excavation of the North Tunnel and the ground treatments executed before and after it (Figure 2).

In the upper part of the ground profile, below the superficial backfill materials, medium sand with a thickness of 5 m, overlies fine silty sands up to 10 m, and approximately sandy silts up to 13 m. Below this depth, a layer of plastic clay with slight silty content can be found, up to a depth of approximately 18 m. The contact surface between the clay and silty layers is very irregular and is leaning towards south-east; the ground water table is located approximately 2 m below the "Wislostrada Road Tunnel" and all tunnels are completely immersed into ground water (Lombardi et al. 2015).

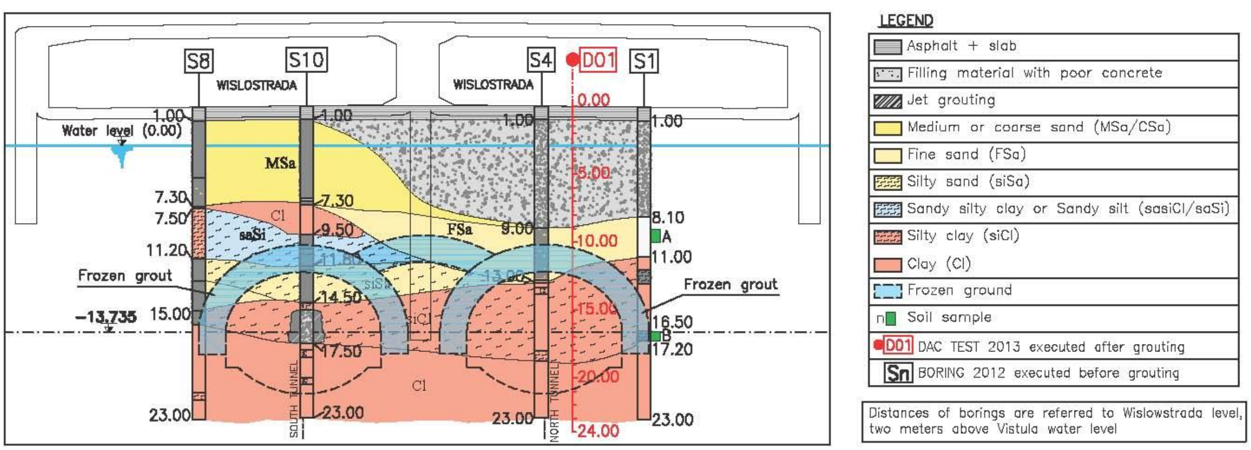

Figure 2: Soil Stratigraphy and Geological Investigation – Section G-G

The tunnels arches have been excavated through the sandy and silty sand layer, whereas almost one-third of the abutments and the inverts are located in the clay. The ground freezing was extended only to the upper sandy-silty layers and only 2 m into the lower clay layer, being this last tight and strong enough to sustain the stress created by the excavation of the tunnels.

GROUND FREEZING METHODS

Frozen soil is a four-phases-mixture comprising mineral grains, ice, water and air. This technology can be applied in nearly all ground conditions regardless of soil permeability and grain size to increase the strength and tightness of the natural ground. Applying ground freezing as a temporary reinforcement measure, only the natural physical characteristics of the soil and the water are used. The impact on the environmental system is very low: groundwater contamination risk due to cement and chemical grouting is dramatically reduced, limited only to drilling and pipe embedment works.
In this project, two different ground freezing technologies were applied:

- Liquid nitrogen method (open system)
- Brine freezing method (closed system)

Liquid nitrogen freezing method

Liquid nitrogen is obtained by air distillation, and it is transported by truck to the site in special tanks, where it is kept at a temperature of -196°C and at a pressure not exceeding 2-3 bars (-196 °C is the state-change temperature of nitrogen under atmospheric pressure). Usually, the liquid nitrogen is stored on site in double-walled storage tanks (under vacuum), where it retains its physical properties until use.
The high cryogenic efficiency of the liquid nitrogen allows quick formation of the frozen structure in only 5-10 days, depending on soil conditions, groundwater temperature, and the distance between pipes, and enables management of scenarios, such as the presence of underground water streams (Figure 3).

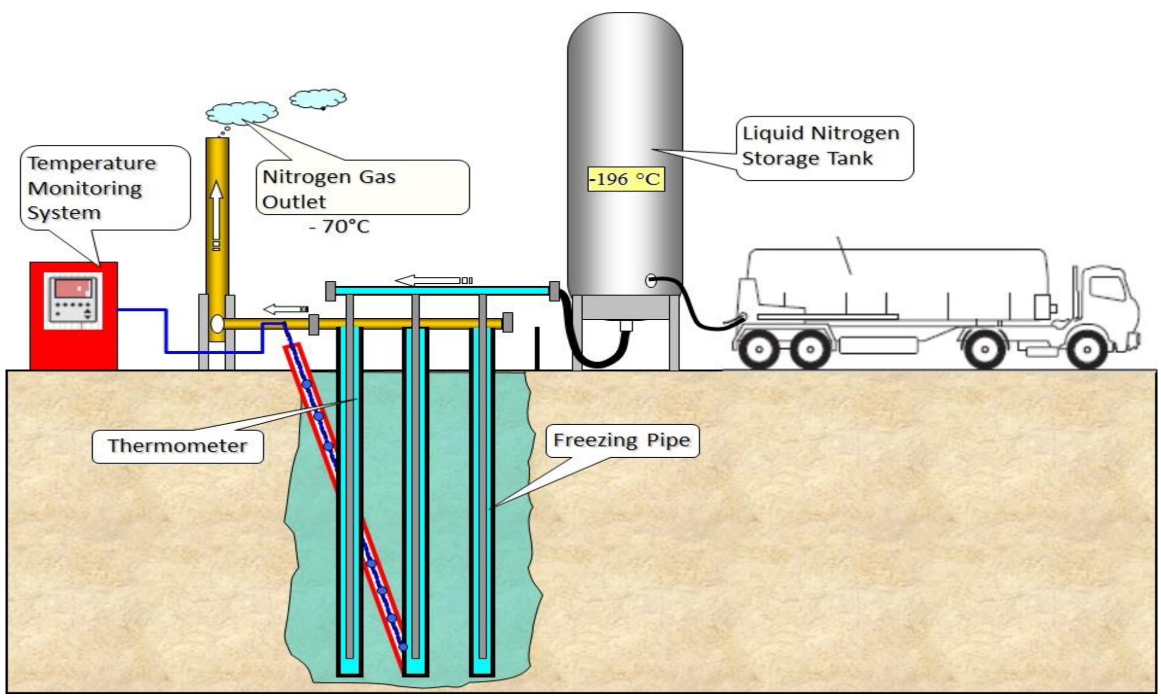

Figure 3: Principle Scheme of the Liquid Nitrogen Freezing System

Brine freezing method

Inside dedicated freeze units (chillers), the brine (a solution of calcium chloride and water) is cooled to a pre-defined temperature and afterwards is pumped through the freezing pipes in a closed circuit and back to the chillers. The primary cooling agent, usually ammonia, circulates inside the freezing plant. The brine is used as a cooling agent that circulates through the freezing pipes (the so called secondary cooling agent). By changing the salt concentration in the solution, different melting points can be achieved. A basic requirement for brine freezing is an absolutely tight circuit (Figure 4).

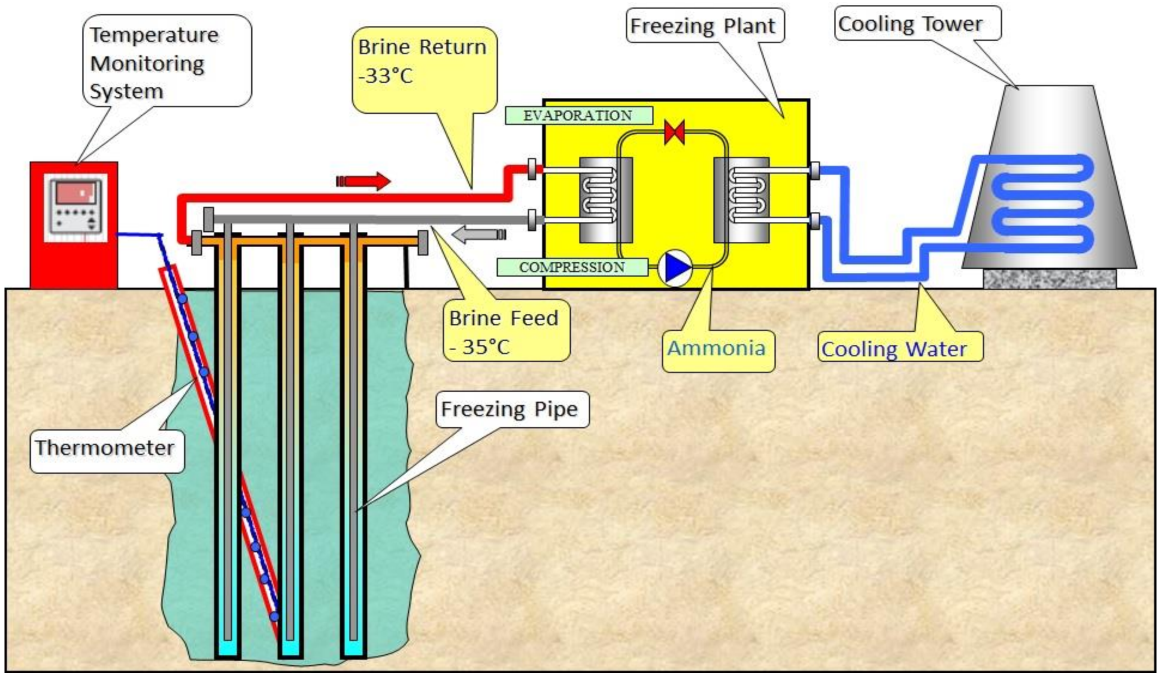

Figure 4: Brine Cooling System

THE PROJECT

The project involves the excavation of the tunnels from each shaft, followed by the demolition of the central DW panels of the Wislostrada tunnel. The ground freezing treatment was used to create a double vertical frozen wall on the sides of this alignment operating from the fast lanes of the Wislostrada, as well as to create a frozen shell surrounding the crown and the sides of each semi-tunnel operating from the two shafts. The works commenced in the Wislostrada Tunnel where due to the safety rules, it was possible only to use the brine method, both for the freezing and for the maintenance stage, and where the sub-vertical drillings were easier to be carried out (Figure 5).
Drillings from the shafts required more time because the pattern of the holes was more complex and the main part of the freezing pipes were horizontal, but the presence of the existing intermediate slab required some sets of inclined holes in order to allow a complete connection between the frozen ground column originated from each pipe. Moreover, the drilling had to be performed against hydrostatic pressure (about 9 m above the tunnel crown) (Figure 6).

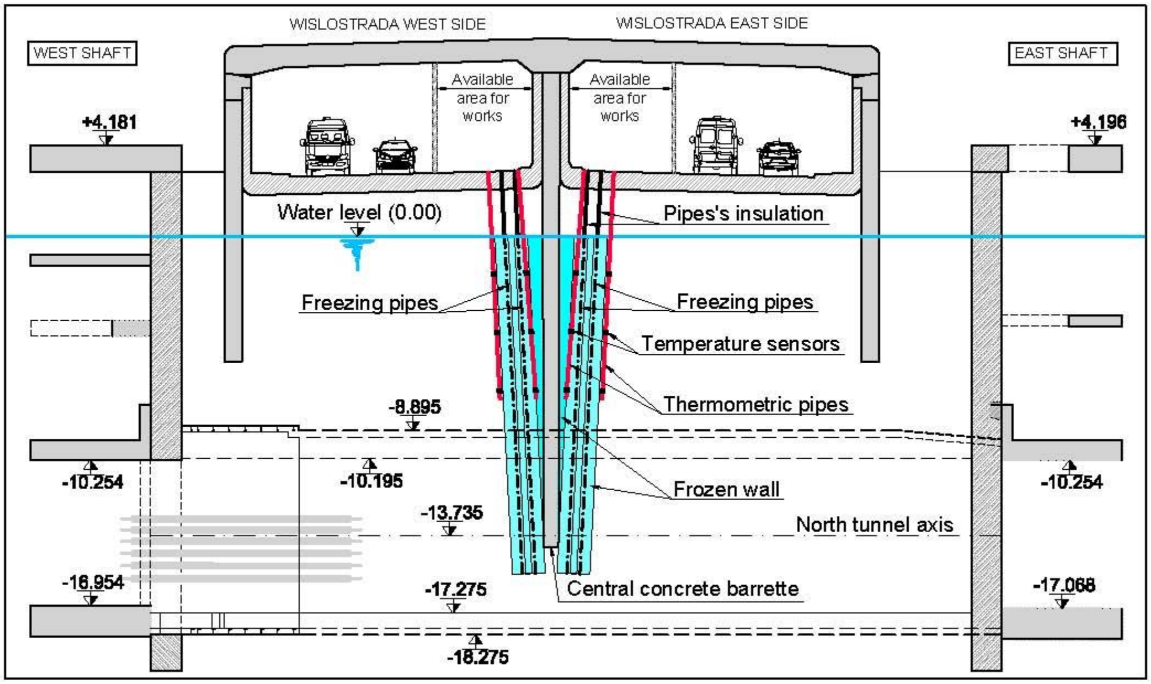

Figure 5: Working Area Wislostrada

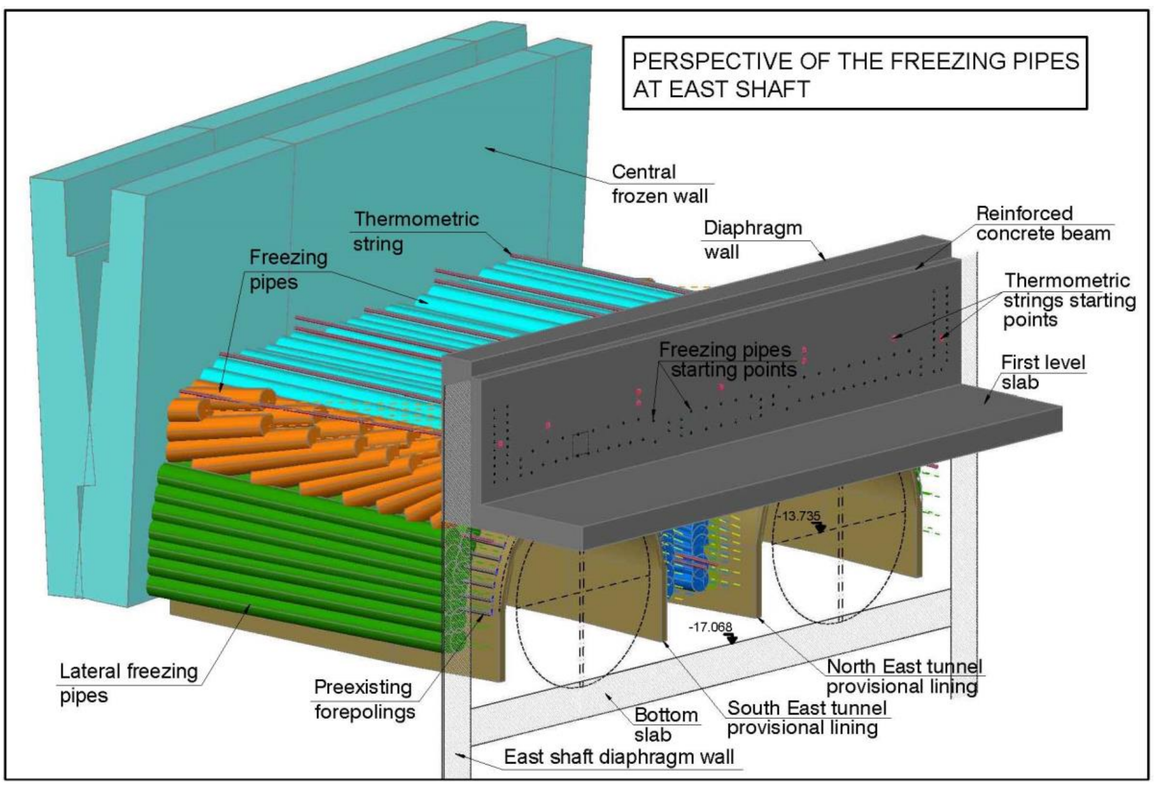

Figure 6: Working Area Shaft

Based on site conditions, a decision was made to freeze the ground using the quicker LN system, and then to proceed with the maintenance using the brine system. The use of the two methods allowed the contractor to synchronize the freezing stage of the wall and of the tunnels, optimizing the costs.
The project envisaged in any zone two lines of pipes in order to obtain a ground frozen wall with a minimum thickness of 1.80 m, where temperature was below or equal to -6°C.

CONSTRUCTION METHOD

The activities started with the drilling of freezing holes. One of the two most important and delicate points of ground freezing works is the precision of the drilling pattern; it has been realized with a very low tolerance, (<1%), in order to have a correct distance between freezing lances. The drilling deviation was expected mainly due to the presence of steel bars and concrete inserts, mostly in the North-West tunnel (the zone of the collapse). During the drilling stage every freezing lance was measured with a laser optical system, called Maxibor; the data were examined in order to check in the design 3D-model the possibility to have a theoretical gap in the frozen body. Finally, it was necessary to install a few additional pipes; the total amount of the latter has been approximately less than 10% of the total amount of pipes foreseen (Figures 7).
The drilling parameters had been recorded in order to check the presence of residual voids (not encountered) and to confirm the geological profile, particularly the upper level of the stiff clay layer in the zone of the invert arches of the tunnels. As a consequence of this, two new freezing lances were added at the base of one of the tunnels side.
In those cases, co-operation between the designer and the drilling company allowed for making quick decision and to avoid time loss in the work program.
The total amount of drilling meter was around 11,100 m, with a length varying between 5 and 19 m and a vertical angle of up to 34°.

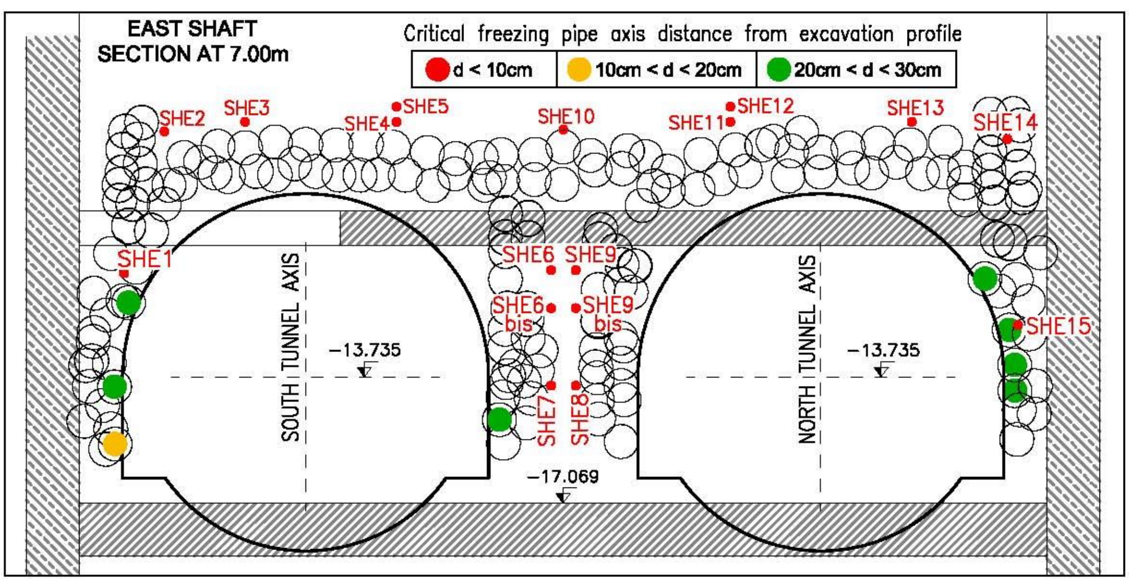

Figure 7: Deviation Freezing Pipes

The second most important point of the ground freezing works was the temperature monitoring system. The control of the ground temperatures was made through direct readings using temperature sensors introduced at different positions into thermometric pipes. These were placed at different sections and distances from the axis of the freezing pipes, in order to verify with the highest possible precision, the thermal gradient of the frozen ground. The data were recorded every hour and transmitted to a central read out unit and recorded. All data were displayed in graphical and numerical form in a dedicated website for authorized staff (Figure 8).

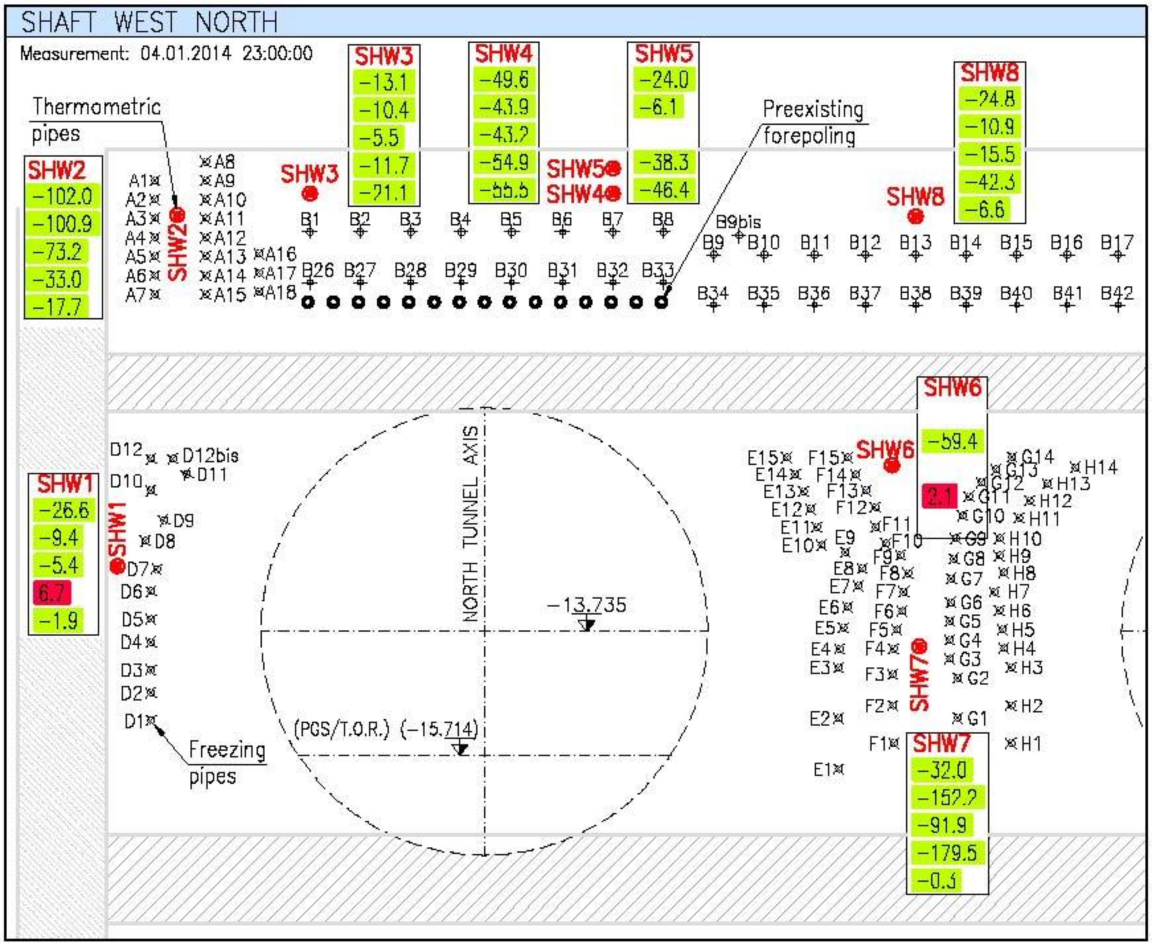

Figure 8: Temperature Monitoring System (Temperature in Degree Celsius)

The freezing stage commenced with the double vertical wall, operating from the Wislostrada with the brine method (Figure 9). It took about 40 days to reach the design thickness. Then, from the shafts, the freezing of each semi-tunnel was performed, starting from the north-west tunnel side. The thickness of the frozen body was reached in an average of 10 days. In the NW tunnel, due to the presence of disturbed soil (lean concrete, steel, former injections), the freezing stage took 15 days with more consumption of LN than the other tunnel (approximately 20%) (Figure 10).

During the freezing stage with LN the soil temperature reached -60 degree Celsius; the thermometric strings were located at a distance between 0.3 and 0.6 m from the closest freezing pipe. Using this data and the correlation between distance and ground temperature, it was possible to estimate that the frozen wall created had a thickness of 1.8 to 2.0 m (Sanger and Sayles 1979).

Figure 9: Brine Circuit

Figure 10: LN Circuit

THE EXCAVATION STAGE

Once the freezing stage with LN was completed, the temperature was maintained during the excavation stage by circulating brine in the same pipes used for the liquid nitrogen. The swap of the circuit took approximately three days for tunnel; the methodology was decided between the designer and the company, to minimize the loss of frozen body volume.

During the maintenance stage with brine, the four semi-tunnel excavations were performed with the traditional method, using a hydraulic hammer and rotary cutting head. The tunnel on the northern side was completed first, followed by the southern tunnel.
Once reached the Wislostrda central DW, the vertical freezing pipes, executed from the Wislostrada Tunnel, were shortened; the cutting position was obtained comparing the detected position of the freezing pipes and the topographically surveyed tunnel excavation profile. The shortening sequence was defined in order to minimize the interruption of the brine circulation into the closed circuit. The freezing groups to be closed were excluded from the circuit and, after the shortening reattached to the main circuit (Figure 11).
Ground temperatures were monitored daily during the excavation activities. Using the brine for maintenance stage, the frozen wall remained stable without significant variations in the average soil temperatures.

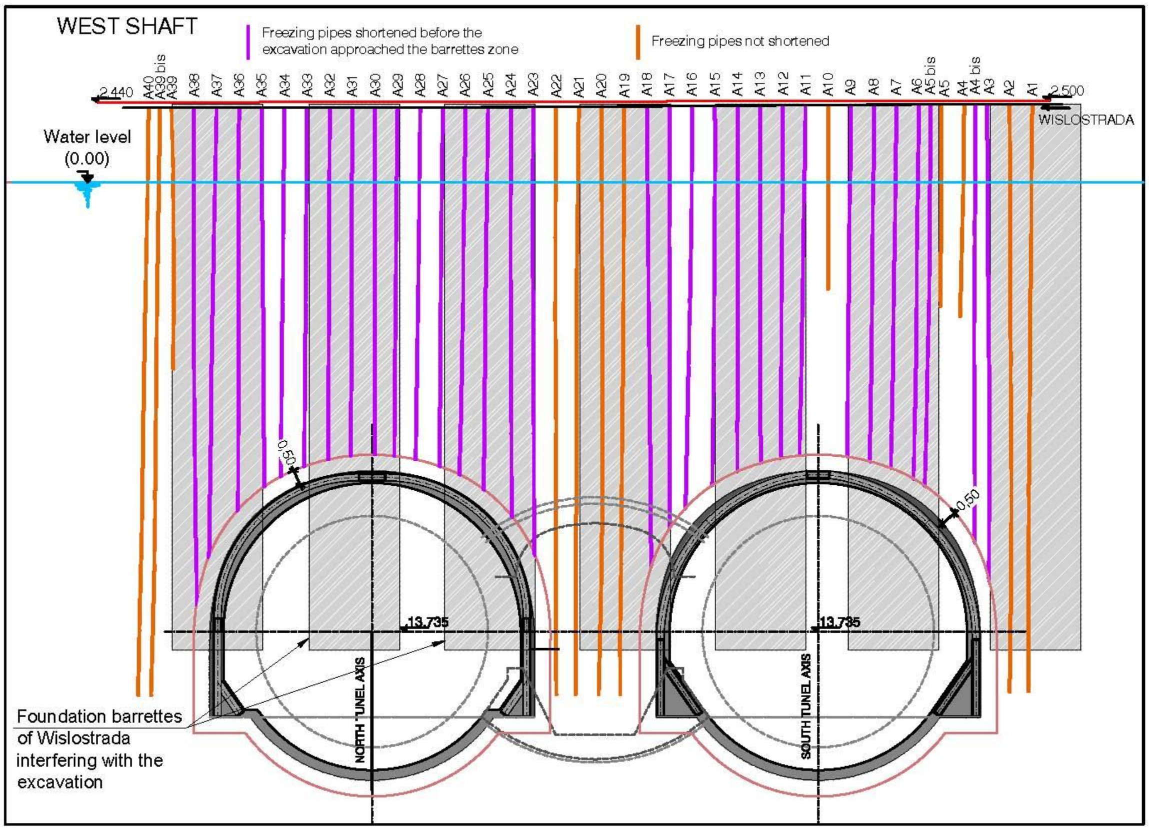

Figure 11: Shortening Freezing Pipes

Monitoring system of Wislostrada structures

A topographic monitoring system installed inside the Wislostrada Tunnel provided information about the displacements of the structure above the frozen tunnels, allowing to calibrate the operative parameter during the freezing process and especially during the maintenance process during, when tunnel excavations, foundation cuts and linings casts were carried out.
After an initial uplift produced both by drilling with cement and by the freezing stages, any relevant settlement during the excavation of the tunnels was not noticed. After four months from the completion of the excavation, the settlements varied from 0.0 mm to 20 mm, depending on the area (Balossi Restelli et al. 2016).

The freezing stage, excavation and, lining cast of each tunnel started gradually and were performed simultaneously. The drilling phase required 2 months. The completion of each tunnel, from freezing to lining, required 3 months. In total, the completion of all works lasted 9.5 months.

CONCLUSIONS

The construction of this underground station using artificial ground freezing as a structural temporary support proved to be the most successful method. The combined method using liquid nitrogen and brine allowed the required thickness of the frozen wall, and maintenance of this ground condition for the duration of the construction activities, to be achieved relatively quickly and cost-effectively.
In economic terms, in case of difficult conditions (i. e. under groundwater level works, in complex urban context), ground freezing can be considered competitive in cost with grouting of fine soils, and even more competitive in very fine soils wherein recourse to injection grouts is required. From an environmental point of view ground freezing can be a valid solution or a valid ground improvement technique as it is considered a non-polluting geotechnical process.
All three tunnels have been excavated on time without any disturbance to the traffic patterns inside the Wislostrada tunnel.
A strict collaboration between the designers and the contractor allowed for the different phases of the work to be completed without time loss or cost increases.
For its dimensions and degree of difficulty, this project can be considered an important achievement in the field of ground freezing techniques, particularly given the very high density area.

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