Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World – Anagnostou, Benardos & Marinos (Eds)

Ground freezing for cross-passages in Milan Metro Line 4

G. Lunardi, G. Cassani & M. Gatti
Rocksoil S.p.A., Milan, Italy

A. Pettinaroli & P. Caffaro
Studio Ing. Andrea Pettinaroli, Milan, Italy

G. Pirro
MetroBlu S.p.A., Milan, Italy

A. Celot
Webuild S.p.A., Milan, Italy

ABSTRACT: The paper presents the application of the ground freezing for the construction of the cross-passages in the downtown stretch of the Milan Metro Line 4. The design requirements of the ground freezing, as well as the materials and equipment used will be described in detail; the design criteria will be focused by means of analytical and FEM analyses, concerning the thermal and static behavior of the frozen ground during excavation. The monitoring system to follow up and calibrate the freezing process will be illustrated too. Finally, some aspects and detailing deriving from the jobsites and construction process will be described, which represent a lesson learned very useful for future applications.

1 INTRODUCTION

Metro Line 4 crosses Milan with a length of about 15 km, from west to east, crossing the downtown up to Linate Airport. The running tunnels have been bored using EPB-TBM and segmental lining. For the central section, from “Tricolore” Station to “Coni Zugna” Station, two TBM machines with a diameter of 9.15 m have been used, to include the platforms of the stations; the connections with the station shafts are provided by cross-passages, three for each platform. Further cross-passages are located for the access to ventilation and escape shafts, two for each of them. The excavations for the shafts reach to the depths of up to 30-35 m, in very poor geotechnical conditions, mainly represented by sand, gravel and silty sand. The piezometric heads are very high too, up to 15-20 m above the cross-passages’ crown. Considering the difficult geotechnical and groundwater context, the technology of ground freezing, coupled with a pre-treatment by injection of cement mixture, has been designed to perform the excavation of the cross-passages in safe conditions. The project provides 42 cross-passages, located in eleven jobsites (5 stations and 6 ventilation and escape shafts); so, an extensive use of the AGF method has been applied, allowing to refine an “industrialization process” of the technology for the first time in Italy and among the most significant in the world. The civil works were carried out by “Metro Blu”, made up 100% by Webuild, which operates on behalf of the EPC contractor “CMM4”. The project was performed by Rocksoil, supported by Pettinaroli Engineering.

DOI: 10.1201/9781003348030-247

2 CROSS-PASSAGES' LAYOUT AND LOCATION

The stations in the central stretch of the metro line (named S. Ambrogio, De Amicis, S Sofia, Sforza Policlinico and S. Babila) and the ventilation and escape shafts (named S Vittore, De Amicis, Ticinese, Vettabbia, S Calimero and S Damiano) do not interfere with the line tunnels, because of their narrow dimensions planned to minimize the impact of their construction on the road network of the downtown of Milan. Therefore, the tunnels will run beside the structures and will be connected by means of short cross-passages to be excavated by conventional method. The number of cross-passages is 6 for each station (generally 4 dedicated to the transit of passengers and 2 also to the ventilation pipes passages in the lower part of the section) and 2 for each shaft, for the transit of passengers in emergency situations. Their dimension is variable according to their function, with excavation area varies from about 15 m^2 to 38 m^2, while the length is normally ranging between few meters up to 10m; just one cross-passage, at Vettabbia Shaft, reaches an higher length of around 18 m. Figure 1 shows a plan of the stations and shafts position into the Milan urban context; the works are distributed along an inner ring, called *Cerchia dei Navigli*, from S. Damiano Shaft to S. Vittore Shaft. The figure points out the high number of jobsites, spread over about 3.5 km. The cross-section of the cross-passages are visible in Figures 3 and 4.

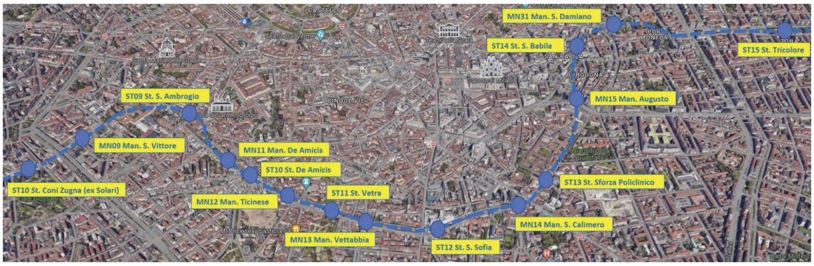

Figure 1. View of the sites' location of stations and shafts.

3 GEOTECHNICAL CONTEXT AND GROUNDWATER CONDITIONS

The soils under Milan are part of sedimentary deposits, belonging to the fluvio-glacial Wurm period, consisting of sandy gravel with local lenses of fine silty sand. On top, it is present a surficial layer, characterized by anthropogenic filling with coarse grain size, having a thickness variable between 1 and 3 meters, that doesn't affect the excavation. The cross-passages are located 28-34 m belove the ground level. At this depth, the grain size curves show an average presence of 50% of sand, 30% of gravel and 15-20% of silts with clay; as a matter of fact, the random inclusion of layers with higher percentage of fine granulometry, and thickness varying from few centimeters up to 1-2 meters, can represent a critical issue on respect to grouting technologies to be carefully investigated. The relative density of the deposits is between 50% and 70%, with N_{spt} values, derived by standard penetrometer tests (SPT), ranging between 20 and 40 (unit weight in the range 19-21 KN/m^3). The soil mechanical properties vary in the following ranges: friction angle between 33° and 38°; nil cohesion; modulus of deformability increasing with depth, from 20-30 MPa on the surface up to 150-300 MPa at the depth cross-passages. The permeability values are included in the range between $8 \cdot 10^{-6}$ m/s and $1 \cdot 10^{-4}$ m/s, hanging on the granulometric distribution. Finally, the groundwater level lies in average around 104-105 m above the sea level; the ground level is about 118 m a.s.l., so that the water table level lies 13-15 m below the ground level. referring to the to the invert excavation level of cross-passages, ranging from 84 to 92 a.s.l., the hydrostatic head is very high, from 12 m up to 18 m, corresponding to 1.2-1.8 bar.

4 ARTIFICIAL GROUND FREEZING - DESIGN CRITERIA

To excavate the cross-passages in safe conditions, it's necessary to guarantee both core-face and cavity's stable conditions (Lunardi, 2008), as well as it should be avoided draining water during the excavation phases. It is very important to operate in static groundwater conditions, to prevent any subsidence phenomena at ground level and the risk of seepage with dragging material inside the excavation. This issue has been carefully considered, as the excavations must be carried out into an urban context, in presence of several historical and residential buildings. For this reason, it was designed to excavate the cross-passages under the protection of a soil grouting and artificial ground freezing treatment. Soil grouting by permeation, using the TAM "*tube-a-manchette*" method (Tornaghi, 1978), is a technique commonly used in Milan, which allows to improve the mechanical properties of ground and reduce its permeability; by the injection of cement mixture, coupled with silica mixture, for soil thicknesses of 3.0-4.0 m around the cavity, it's possible to support and waterproof the excavation profile. This technique may not be fully effective in the presence of layers with non-negligible percentage of fine soil, coupled with high hydrostatic level; it runs the risk that in very locally layer of soil, not perfectly grouted by injection due to their low permeability, start seepage phenomena stressed by the high-water pressure. The above-described conditions are often present along the metro line 4, that reaches depths up to 30-40 for the first time in Milan; so it was decided to combine the permeation grouting with the freezing technology.

4.1 *The artificial ground freezing (AGF) technology*

The technique of artificial ground freezing (AGF), in this specific case executed and managed directly by Webuild, consists in freezing the water included in the ground by transferring frigories. This is achieved through the passage of a cooling fluid (nitrogen or brine) through steel probes embedded in the ground, arranged according to the geometry of the ice wall to be created (Sanger and Sayles, 1979; Pettinaroli et al. 2016, Lunardi et al., 2019). The effect of freezing is to perfectly waterproof the soil and to improve its mechanical characteristics, which strength depends directly on the temperature reached in the ground. The freezing process has two main phases: a) the initial "freezing phase", where the soil is intensively cooled until it reaches the designed temperature in all control point, so to create the defined frozen soil thickness; b) the "freezing maintenance phase", during which the inflow of frigories is calibrated to guarantee the preservation of the frozen soil thickness for the timing necessary, in this case, to excavate the cross-passages and to complete the works by casting the final lining. Two freezing methods can be adopted: the "open system" using the nitrogen as coolant, or the "closed system", using the brine. For the current works the first method have been used, to reduce as much as possible the freezing time. The "closed system", by using brine, has been adopted just at "Vettabbia" shaft; the high length of these cross-passages would have required a larger amount of nitrogen delivery in few days, not available on the market at the moment of the works. In Figure 2, a conceptual layout of the "open system" is reported; the layout for the "closed system" are conceptually similar, except for the fact that the brine, that comes out of the probes at a higher temperature than the initial one, is sent to a chiller where it is cooled again and then sent back into the circuit, to repeat the cycle.

4.2 *Design concept*

Due to the above-described conditions, the design of the treatments for the cross-passages excavation has been approached by coupling the freezing technology and the soil permeation grouting.

The grouted soil thickness, injected via TAM by cement and silica grouts, supports the ground pressure (so to reduce the frozen soil thickness needed), while the frozen shell guarantees just the watertightness of the excavation and supports the hydrostatic pressures, avoiding thus any risk of seepage and dragging. Moreover, the action of the permeation grouting on the soil is to homogenize the freezing diffusion in the ground and to reduce possible deformation effects during the defrosting phase after the stop of the freezing process. Three typical geometrical sections have been defined for the cross-passages, due to their functionality: one for the cross-passages of the services shafts (internal *gabarit* 3.60m×4.25m); two for the cross-passages of the stations: one

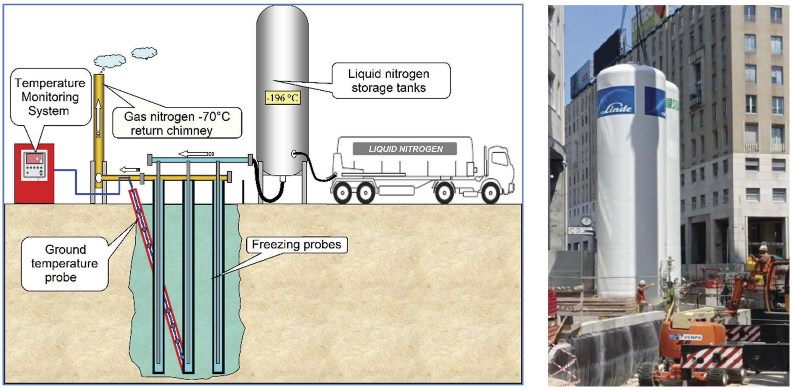

Figure 2. Conceptual layout of the "open system" for ground freezing. S.Babila Station jobsite.

standard dedicated only to the passengers (internal *gabarit* 5.25m×5.50m) and another higher section to allow also the ventilation pipes passage (internal *gabarit* 5.70m×8.0m). The permeation grouting treatments, preliminarily executed via TAMs, were carried out by operating differently from site to site: usually from the street level performing a subvertical geometry of the sleeved pipes; in some other cases working from inside the shafts (in case of interferences with the buildings foundations, or if the site dimensions in surface do not allow to operate efficiently), with a sub-horizontal geometry of the holes, that required the use of blow-out preventer. Differently for AGF treatments sub-horizontal freezing probes have been used, with a geometry designed to channel the stresses all around the excavation profile and make the tensile stresses in the frozen ground null or negligible (less than 0.5 MPa). The structural calculation was carried out considering a frozen ground wall having the mechanical properties reachable at temperature not higher than -10°C into its whole thickness: this value, that defines the thickness of the frozen shell, has been adopted as the design temperature target, to be considered during freezing process. The ground having temperature included in the range between -10°C÷-2°C collaborates on the stabilization of the ground too, especially around the contour of the digging profile, to ensure that no oversize sections and/or releases occur during the excavation steps. Figure 3 shows the typical freezing probes layout used for the cross-passages of the shafts. 26 freezing probs are provided,15 drilled from the shaft, in the upper part of the section, and 11 drilled from the tunnels, in the lower part of the section (where the shaft's slab prevents drilling), as showed in the right scheme. For the control of the temperature in the ground during the freezing process, several chains of thermometric sensors are inserted into probes placed besides the freezing lances pattern. Figure 3 shows 4 thermometric probes (red colored) placed in the crown zone and 3 in the invert zone. Each sensor is connected to the dedicated automatic unit that collects the temperature measurements at prefixed time intervals, allowing to control also from remote the thermal behavior of the soil during the treatment. The required thickness of the frozen shell with temperature below -10°C was equal to 1.00 meter, both in crown and in the invert.

Figure 4 illustrates the layout of the probes for the two typical passages section of the stations. The scheme on the right refers to the smaller cross-passages, similar to the one used for the shafts: 26 freezing lances and 7 thermometric probes, to create a 1.00 m thick efficient frozen wall. For the bigger cross-passages, 40 freezing lances and 9 thermometric probes are provided; due to the bigger dimensions, the thickness of the frozen efficient wall varies from 1.00 m in the crown to 1.30 m in the sides, and from 1.30 m and 1.80 m in the invert, assuming a curvilinear shape thanks to the freezing pipes position. All the drillings for the probes were executed from inside the stations. The interaxis between adiacent freezing probes is 0.80 m. The drillings have been executed using a blow out - preventer system, to prevent any leakage of material due to the hydraulic load.

The geometry of the drillings have been planned into a 3D geometrical model containing the geo-referenced position of both the 2 line tunnels as well as the stations and the shafts. The boreholes lengths have been carefully defined in order to guarantee the effective connection between the frozen soil wall and the tunnel, without damaging the tunnel segmental lining. Each drilling

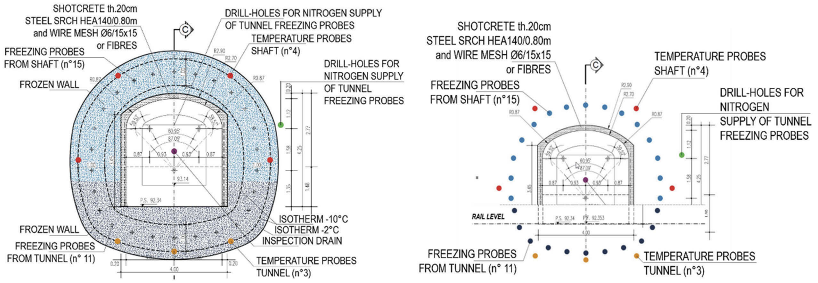

Figure 3. Shaft's cross-passages. Layout of the freezing probes (in blue) and thermometric probes (in red).

has been measured by a non-magnetic gyroscopic instrument (Gyro-type or similar) to control direction and to give a 3D mapping of their position. In the case of greater deviations, integrative probes have been executed, in order to guarantee a regular formation of the soil frozen wall.

4.3 *Material and equipment*

Both freezing systems, using LN as well as Brine, have been studied directly by Webuild and built under its supervision. The freezing probe consists of an external, AISI 304 stainless steel pipe and an internal coaxial copper pipe. Each probe has been positioned inside a Ø88.9 mm steel pipe. A freezing head, connected to the two coaxial pipes allowed to feed the internal pipe with the cooling fluid, at a temperature of -196 °C, and to release the gaseous nitrogen to the discharge line, at temperature of about -60÷-80 °C. The annular space between the external tube and the freezing probe has been filled with a cement mixture (C/W≥1), to avoid the presence of empty sections that may work as insulation. The heads of the freezing probes will be controlled by an on/off electro-valve, able to manage the nitrogen flowrate during the process. Ø60 mm steel pipes, embedded in the ground, are equipped with thermometric probes; they include a thermometric chain composed by a set of thermometric sensors placed along the pipe at prefixed position, suitable for obtaining monitoring sections at different distance from the diaphragm wall.

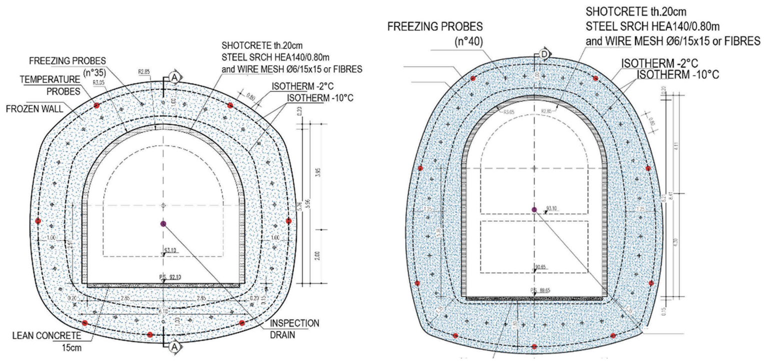

Figure 4. Layout of the freezing and thermometric probes of two typical Station's cross-passages.

The distance between the sections varies around 1,5 and 2 m. In the core-face of each cross-passages, 3-4 drainages have been drilled, and equipped with one pressure gauge. As described in the further chapter 6, the drainages are used for the evaluation of the proper completion of the initial freezing stage. In the "close system", the coolant flows only in the liquid state, at a predetermined inlet temperature: around -33°÷-35°C using a brine with a freezing point around -50 °C.

4.4 *Field test and control*

The freezing of the first two cross passages of San Damiano shaft was used as a field test, with the aim of calibrating some design details (for example the probes interaxis, chosen equal to 0.80 m after the field test completion), as well executive aspects (materials and procedures), verifying also more in detail the freezing stage time and the amount of needed nitrogen. For both cross-passages the freezing treatment worked regularly, allowing to execute the excavation in dry and safety conditions, as well as the final waterproofing placement and the following RC lining cast (See Figure 5). This experience gave several results, especially the implementation of procedures regarding the delicate connection zone between the freezing wall and the line tunnel, such as the provisional insulation of this area, and the check of the freezing process evolution by using a thermal camera from the excavated tunnel. The volume of nitrogen consumed was not proportional to the amount of frozen ground, compared to previous experiences, but greater, due to the relative reduced length of the cross passages and the consequent freezing pipes, thus dissipating part of the cryogenic energy applied.

Figure 5. The test field at S.Damiano shaft – The insulation installed inside the line tunnel; the freezing portal in the shaft; the cross-passage excavation up to the segment line tunnel.

5 DESIGN ANALITICAL AND NUMERICAL ANALYSES

To design in detail the freezing technology, both statical as well as thermal analysis have been performed. Preliminary, laboratory investigations were executed, at the “GroutFreezLAB” Laboratory of Bicocca University, to test the frozen ground thermal and mechanical properties, the latter at temperature of -10°C: more in detail, UCS tests defined a compressive strength of 5.0÷5.5 MPa for frozen sandy-gravel soil and 4.5÷5.0 MPa for frozen sand and silty-sand soil; Brazilian Tests defined a tensile strength of 1.0÷1.5 MPa.

Finite Different Method FDM analyses, by FLAC, have been developed to investigate the static behavior of the grouting-freezing system. For grouted soil a cohesion of 175 kPa, coupled with an elastic modulus three times the natural one, has been adopted. For frozen soil a cohesion of 300 kPa, on safety side, has been used. The 2D analysis is based on the confinement-convergence method, reducing progressively a system of internal forces to simulate the step-by-step excavation. Forces are released 100% on grouted and frozen soil, with a conservative approach, without considering pre-lining (see Figure 6, left). The results showed stress distribution complaint with the strength’s material (with safety factor equal to 2); no plasticization took place, with convergence and excavation lifting less than 10-15 mm. The tensile stress is less than 0.3-0.4 MPa.

Several thermal numerical analyses have been performed too, studying some 2D typical cross sections for each cross passages with the FEM software Geostudio TEMP-W, with two main topics: a) to define the temperature target to be reached in each thermometric sensors for both freezing and maintenance phases, considering the real position of the freezing and thermometric probes, as obtained after the directionality control; b) to give an approximative evaluation of the time necessary for reaching the temperature targets during the freezing phase. The thermal analyses have been developed and calibrated on the basis of the results of the freezing trial fields carried out in San Damiano shaft; several back-analyses of the first two cross-passages treatments have been implemented to set-up the most effective thermal parameters and boundary conditions to be assumed for frozen and unfrozen soil and for

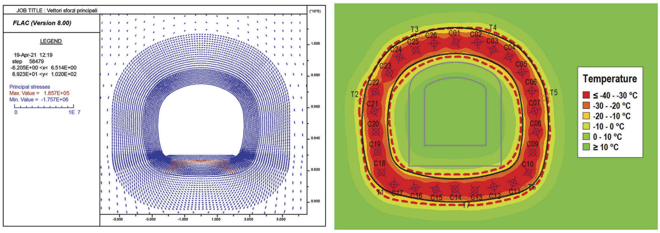

Figure 6. FDM analysis: stress distribution in the grouted and frozen soil after excavation (left). Thermal analysis: temperature distribution at the completion of the freezing stage (right).

freezing pipes; Figure 6 (right) shows the predicted distribution of the temperature at the moment of the completion of the frozen soil wall.

6 TEMPERATURE MONITORING SYSTEM AND CONTROL PROCEDURE

The ground freezing treatments in all the cross-passages have been carried out through 3 main stages: 1) the initial freezing stage of the ground, managed by controlling the evolution of the temperature in soil, until the target values were reached. 2) the check of the effective completion of the freezing stage, performing a drainage test, to authorize the start of the excavation works. 3) the stage of the maintenance of the frozen soil wall during the excavation and the following operations, with control in real-time of the temperatures in the ground. The control of temperature has therefore a key role in the AGF management. A dedicated digital platform, created specifically by Webuild, allows to view in real time the temperature data recorded and collected in specific sections and diagrams. Figure 7 (left) shows one of these sections, where it is possible to see, depending on the color shown, the effective achievement of the target (green or red color). Due to the short extension of the cross passages, the freezing probes are connected in series, to optimize the total probe length per group, between 20 m and 30 m considering the use of LN as coolant. The distribution of the nitrogen to each group is performed by means of an electro-valve on/off system controlled by an automatic unit. The setting of the valves position is managed based on the temperature of the gaseous nitrogen released by each group. Figure 7 (right) shows a screen shot of the control panel of the automatic system.

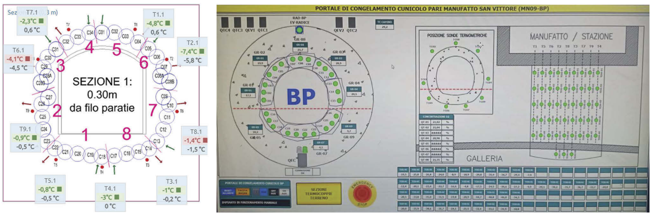

Figure 7. Screen shot of the temperature control platform showing the current temperatures and the targets in each thermometric sensor (left) - Control panel's typical screen shot to manage the nitrogen outlet (right).

As the freezing stage starts, the evolution of the temperature in each thermometric sensor is continuously controlled by comparing the recorded data with the prediction given by the thermal model in the same point. Once the temperature targets are achieved in any thermometer, a drainage test is performed for checking the effective watertightness of the frozen soil wall. The drainages are equipped with a pressure gauge and a closing valve. Before the start of the freezing, the valves are opened to measure the initial flow rate of water. During the freezing phase (with closed valves) it has been often verified that the pressure in the gauge has increased as the frozen wall continuity has been formed. Finally, when the temperature targets are achieved, the valves are opened again to measure the residual water flow rate from the drains (Figure 8, left). If the freezing is effectively completed, the residual flow rate gradually reduces as the flow of the water contained in the core-face, closed by freezing, is running out. In few cases, the residual flow rate, through one or more drains, settle to a constant value, showing a weakness still present in the frozen wall; in those cases, it is often visible a perturbation (even an increase) in the temperature chart of one or more thermometers, allowing to detect the position of the critical weak zone. Close to it, it has been necessary to feed the probes intensively with the LN. Once the excavation of the cross-passage was started, the frozen soil wall must be maintained: LN is delivered to the freezing circuit in average for 8 hours per night, the flow rate to the probes is optimized by observing the effective temperature in the soil. A typical temperature evolution during freezing and maintenance phases is reported in Figure 8, right.

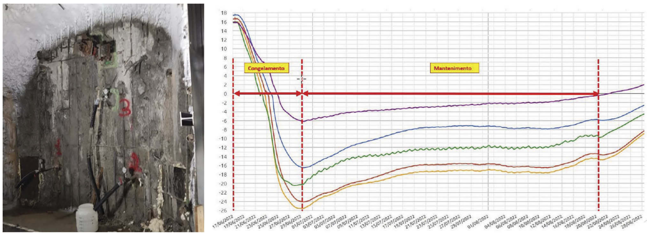

Figure 8. Drainage location in the core-face and drainage test (left). Typical temperature evolution during the freezing and maintenance phase measured by thermometric sensors (right).

7 CONSTRUCTION PROCESS AND JOBSITES' FEEDBACK

It can be stated that the freezing phase lasted around 7-10 days, depending on the length of the cross-passages and on the local conditions encountered (such as local residual water flow, close to the tunnel lining or to the diaphragm wall). This residual water flow has, occasionally, led to a longer freezing stage (up to 12-13 days). For Vettabbia Shaft, where close system by brine was used, the freezing stage lasted 35 days. Once freezing has been completed, the diaphragm walls of the shafts were carefully demolished, preventively mounted a special metallic carter to protect the nitrogen distribution circuit. The excavation of the cross-passages has been executed by single steps of 1.00 m, followed by the placement of a steel rib embedded in a layer of shotcrete. The final delicate step was then the excavation of the intersection between the cross-passage and the main tunnel, due to the particular and problematic contact nail. At the end of these operations, the waterproofing system all round is placed. Finally, the cast of the foundation slab of the cross passage is made, followed by the sides and the crown lining, both using reinforced concrete.

About the safety conditions linked with the use of LN, it can be noticed access to people into the tunnels has been strictly denied during the circulation of liquid nitrogen along the circuit (initial freezing stage, night-time maintenance stage). In addition, air oxygen concentration sensors have been installed at the base of the stations and the shafts, as well as in the stretch of the line tunnel involved in a freezing process: a stronger series of emergency procedures must be rapidly adopted if alarm threshold is reached.

REFERENCES

Balossi Restelli A., Pettinaroli A., Rovetto E., 2016. Combined ground freezing application for the excavation of connection tunnels of Centrum Nauki Kopernik Station - Warsaw Underground Line II. *Proceedings of World Tunnel Congress 2016* – San Francisco

Lunardi G., Cassani G., Gatti M., Bellardo L., Palomba A. 2018. Brenner Base Tunnel & Isarco River Underpass Section: several technical and operational solutions. *Gallerie e Grandi Opere Sotterranee* n° 125, Marzo 2018 pp.33–44. ISSN-0393-1641.

Lunardi, P. 2008. *Design and construction of tunnels, analysis of controlled deformations in rock and soils (ADECO-RS)"*, Springer-Verlag Berlin Heidelberg.

Sanger, F.J., Sayles, F.H. 1979. Thermal and rheological computations for artificially frozen ground construction. *Engineering Geology*, 13, pp. 311–337.

Tornaghi, R., 1978. Iniezioni. *Atti del seminario su consolidamento di terreni e rocce in posto nell'ingegneria civile*, 26-27 May 1978. Stresa.