Application of Artificial Ground-Freezing to Construct a Passenger Interchange Tunnel for the Subway Line 14 in Paris, France

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***Abstract*—**Artificial ground freezing (AGF) technique is a well-proven soil improvement approach used worldwide to construct shafts, tunnels and many other civil structures in difficult subsoil or ambient conditions. As part of the extension of Line 14 of the Paris subway, a passenger interchange tunnel between the new station at Porte de Clichy and the new Tribunal the Grand Instance has been successfully constructed using this technique. The paper presents the successful application of AGF by Liquid Nitrogen and Brine implemented to provide structural stability and groundwater cut-off around the passenger interchange tunnel. The working conditions were considered to be rather challenging, due to the proximity of a hundred-year-old existing service tunnel of the Line 13, and subsoil conditions on site. Laboratory tests were carried out to determine the relevant soil parameters for hydro-thermal-mechanical aspects and to implement numerical analyses. Monitoring data were used in order to check and control the development and the efficiency of the freezing process as well as to back analyze the parameters assumed for the design, both during the freezing and thawing phases.

***Keywords*—**Artificial ground freezing, brine method, case history, liquid nitrogen.

I. Introduction

The Greater Paris ("Grand Paris") development plan involves the construction of a 3600 m tunnel between Saint-Lazare and Clichy Saint-Ouen, with two new stations (Pont Cardinet and Porte de Clichy). This is a complex project due to the dense urban environment where the construction takes place and the limited working area available.

The extension of the Line 14 is part of the above mentioned development plan, and it includes the construction of a passenger interchange tunnel between the station of Porte de Clichy (PCY) and the exit shaft of the Tribunal de Grande Instance (TGI). Considering the ground and groundwater conditions at site, as well as the proximity of a hundred-year-old existing service tunnel of the Line 13 (BL13), to be kept in service during construction, and the urban environment (i.e. dense presence of utilities), AGF was the preferred technique to provide construction in a safe work environment, structural stability, and tunnel excavation in dry condition (i.e. groundwater cut-off around the tunnel).

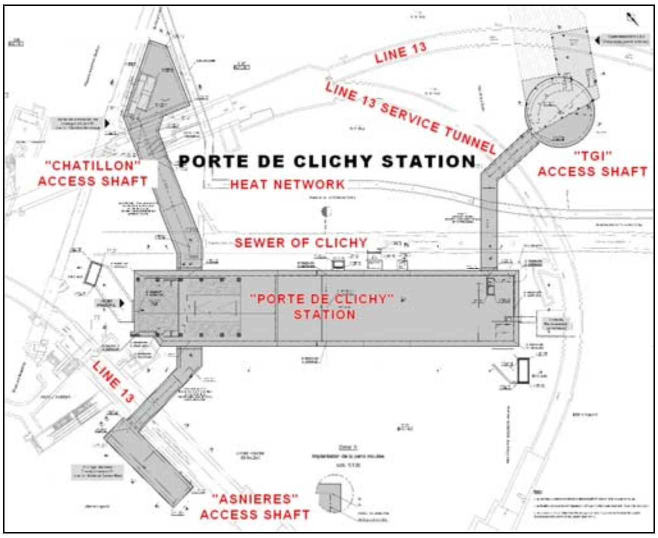

Fig. 1 Plan view of PCY station

II. Soil Profile and Geotechnical Characterization

The soil profile is comprised of made ground covering the Limestone horizon, known as Calcaire de Saint-Ouen (CSO) ranging from El. 26.8m to El. 18m a.s.l.. This horizon overlies variably cemented layers of fine to medium silty sand and sand, known as Sables de Beauchamp (SB). The Calcaire de Saint-Ouen is an Upper Bartonian lacustrine deposit, characterized by decomposed limestone and Marl bands with different degrees of cementation. It is a very stiff material with a high consistency index (>1). The SB is an Eocene deposit, with fines content ranging from 10 to 30% in the upper portion. Based on different tests, the expected permeability for both the CSO and the SB is of the order of $1x10^{-4}$ - $1x10^{-5}$ m/s. These values appear rather high for both horizons, but can be explained on a macroscale by considering the variable degree of cementation for the SB layer and the presence of fractures and fissures in the CSO, that give rise to a horizontal permeability higher than the vertical one. The groundwater table lays around 10.5 m below ground level (El. 22 m a.s.l.).

The AGF intervention was carried out predominantly in the SB horizon, with a frozen annulus around the intersection between the crown of the excavated tunnel and the existing

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slab of the tunnel BL13 in the CSO horizon, as shown in Fig. 2.

III. Laboratory Tests

Laboratory tests, on unfrozen and frozen soil samples, were carried out to establish the basis of design for hydro-thermal-mechanical aspects. The investigation program comprised two phases: (1) Index testing and Thermal behavior of soil, (2) Mechanical behavior for the two layers that will be frozen (Calcaire de Saint-Ouen and SB). In detail, the specific tests carried out were:

- Phase 1:
  - Classification of soil material (grain size distribution, Atterberg limits, moisture contents and densities, specific gravity, salinity)
  - Frost heave tests
  - Frost pressure tests
- Phase 2:
  - Unconfined compression test (UCS) in unfrozen and thawed conditions
  - UCS in frozen conditions at T=-10 °C and T=-20 °C
  - Uniaxial creep test (UCT) in frozen conditions at T = -10 °C and T = -20 °C
  - Triaxial compression tests in frozen conditions at T = -10°C and T = -20 °C

To model heat conduction phenomena, the thermal soil properties such as heat capacity and thermal conductivity were also investigated. The heat capacity of a multi-phase soil system has been determined as the weighted arithmetic mean of each individual soil component. Thermal conductivity of frozen and unfrozen soil was determined by Johansen's method [9], [10]. Johansen's equations are based on geomechanical soil parameters, such as dry density, moisture content and grain-size distribution (determined during Phase 1), water content (calculated assuming that the soil is fully saturated). Table I summarizes the set of material properties, determined through the above mentioned laboratory tests, that were implemented into the thermal numerical analyses discussed in Section V.

IV. AGF Technique

The basic concept of AGF technique is that the ground and in situ pore water is frozen in order to create an impermeable frozen ground mass with improved compressive strength [3], [6], [7], [13]. The method involves two phases: The freezing phase (1) corresponding to the extraction of the heat from the ground, until its temperature falls below the freezing point of the groundwater, and the maintenance phase (2), intended to assure the designed temperature level is retained with time. The ground is cooled by making a refrigerant fluid circulate through regularly spaced freezing pipes.

There are two available freezing methodologies: The so called indirect method (or brine method) and the direct method (with Liquid Nitrogen).

TABLE I
Material Properties from Laboratory Test Results

Quantity	Unit	SB (low fines) [A]	SB (higher fines) [A]	CSO (max) [A]
Dry density	[t/m^3]	1.705	1.705	1.48
Natural water content	[%]	21.0	21.0	30.0
Fraction of particles <0.02 mm	[%]	8.0	21.0	50.0
Unfrozen Thermal Conductivity	[kcal/h/m/°K]	1.85	1.42	1.23
Frozen Thermal Conductivity	[kcal/h/m/°K]	3.04	2.35	2.29
Unfrozen Heat Capacity	[kcal/m^3/°K]	702	702	743
Frozen Heat Capacity	[kcal/m^3/°K]	522	522	520

[a]The values reported for CSO, SB (low fines) and SB (higher fines are average values.

Liquid Nitrogen (LN_2) was the methodology adopted for this site for the freezing phase. The cooling medium is the LN_2, pumped directly into the freeze pipes at -196 °C. It is an open process, by which heat is extracted from the soil through direct vaporization of the cryogenic fluid LN_2 along the length of the freeze pipes. This freezing method requires that all the materials used in this process are suitable for such low temperatures (i.e. copper or stainless steel).

The indirect method was the methodology adopted for the maintenance phase. The brine method is a closed process that requires the use of a large primary refrigeration plant, connected to a secondary coolant system. For this project, the closed circuit consisted of brine continuously circulated through a distribution manifold placed on the ground surface and refrigeration pipes installed into the ground. The brine, usually a calcium chloride solution, is cooled by the freezing plant, typically at -25 °C to -35 °C, and pumped into the closed circuit. The warmer brine returning from the freeze pipes through the insulated surface manifold system is then re-cooled and re-circulated into the closed circuit.

The choice of the freezing method depends on a number of different factors, such as the available time, the geological and groundwater conditions, the volume of the ground to be treated, the design requirements, and many others [1], [2], [4], [5], [11], [12], [14].

In the project presented herein, the use of Liquid Nitrogen in the first freezing phase was necessary to minimize the time required (target 5 days) to achieve a continuous frozen wall of the desired thickness.

V. Work Plan and Design of Freezing System

As already mentioned, the freezing system at PCY was required to provide a water cut-off and structural stability. This required the realization of a pseudo-cylindrical structure of frozen soil, with a minimum thickness of 1.5 m, around the passenger interchange tunnel. In order to achieve the above mentioned project objectives, the design involved the following actions (see Fig. 2 for clarity):

a. Preliminary grouting operation around the existing tunnel BL13 to fill any void around it and to seal the tunnel from any water entrance (there was evidence of existing leakage from the tunnel lining).

b. Formation of a plug shield, by means of Jet-grouted columns and grouting treatment beyond the existing tunnel BL13.
c. Installation of horizontal freeze pipes, up to about 18 m long, drilled under blow up preventer (BOP) from the access shaft TGI to the plug shield (lower part) and to the contact of the existing BL13 (upper part).
d. Installation under BOP of a screen of short inclined freeze pipes to seal the interface between the ground, the existing BL13 and the plug shield.
e. Insulation at the shaft wall and inside the tunnel BL13 to minimize any heat sources.

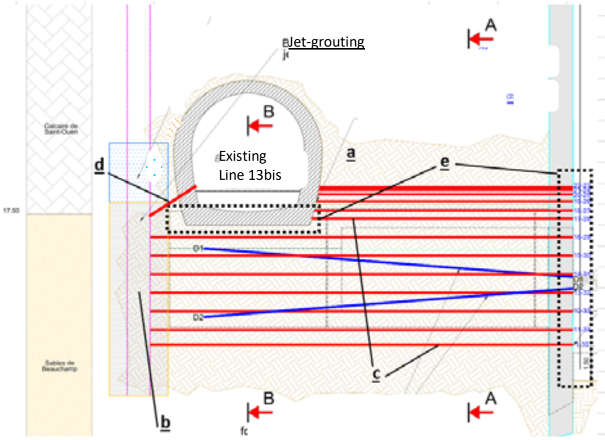
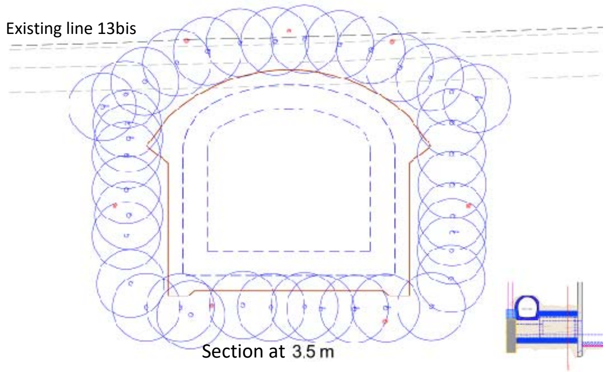


Fig. 2 Longitudinal profile of AGF intervention

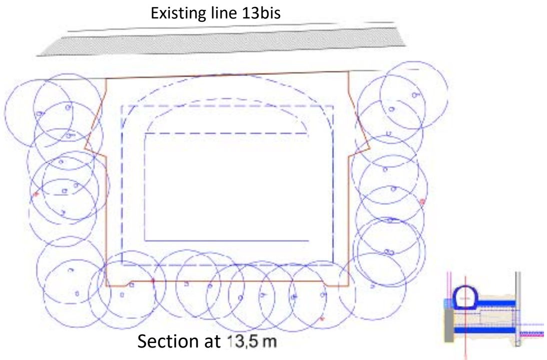
After the installation, all the pipes were surveyed with a high precision degree in order to verify the as-built layout, to evaluate the need for additional freeze pipes (i.e. if the deviation between two pipes was such to affect the AGF execution), and to assess the distance between temperature sensor chains and the closest freezing pipes in order to properly interpret the monitoring data.

As shown in Fig. 3 and 4, three freeze pipe layouts were adopted due to the presence of the existing tunnel. Layout A comprised of 18 m long freeze pipes, installed around the side wall and invert of the tunnel to be excavated, and 11 m long freeze pipes, installed at the crown as close as possible to the existing tunnel lining. All freeze pipes had a spacing of about 0.80 m. Layout B, is representative of the zone where the service tunnel BL13 passed under the tunnel to be excavated (about 7 m long), thus 26 freeze pipes, 18 m long, were installed around the side wall and invert. The maximum distance between the existing slab and the closest freeze pipe was kept to 0.5 m. Layout C represents the section with the inclined freeze pipes to seal the interface beyond the existing loop tunnel, as shown in Fig.4.

The design process included the evaluation of the time needed to achieve the desired frozen wall thickness, and it required setting a benchmark to verify the monitoring data during the freezing process (in order to capture potential anomalies occurring during the process). To achieve this goal and verify the adequacy of the design, extensive 2D thermal analyses were carried out with the support of a finite element software.



(a) Layout A



(b) Layout B

Fig. 3 As-built layout of freeze pipes – (a) Layout A, 3.5m from the shaft – (b) Layout B, 13.5m from the shaft TGI

The numerical model considered the freeze pipes with a convective heat transfer, coolant characteristics and coolant flow/rate to compute the actual heat removal from each freeze pipe. The heat removed is a function of ground temperature, coolant temperature, coolant flow/rate and pipe geometry. The key model input parameters are: the freeze pipe geometry, the heat flux boundary condition of the pipes (in this case a constant temperature of -196°C was used for the primary freezing pipes, and a constant temperature of -35°C was used for the brine), the ground temperature (varying between 18°C to 40°C in the proximity of the jet-grouting columns, also see [8]). The boundary conditions of the model assumed a constant temperature equal to the ground temperature before the freezing process. Further, where applicable, air ambient temperature was simulated (i.e. at the surface of the existing tunnel BL13 towards the opening, after the tunnel excavation phase occurred, etc.). It is noted that all analyses were performed assuming no water flow, which was consistent with the actual groundwater conditions having negligible velocity.

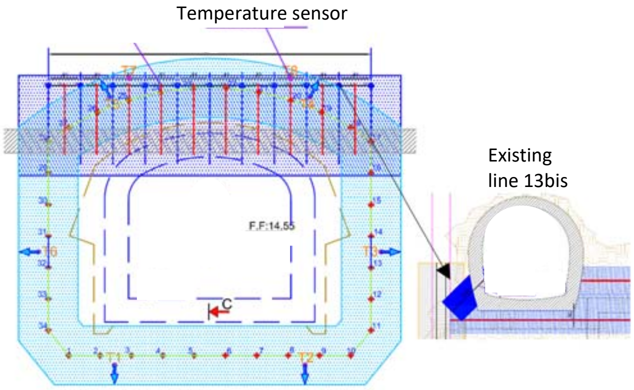


Fig. 4 Theoretical layout of freeze pipes – Layout C

In the design stage three phases were modeled to account for: (1) AGF by Liquid Nitrogen (5 days), (2) simultaneous conversion of all freezing pipes from Liquid Nitrogen to brine for maintenance phase, (3) tunnel excavation while AGF maintenance is ongoing (phase 2 and 3 combined correspond to 90 days of freezing maintenance). Three sections were analyzed corresponding to Layout A (Fig.3), Layout B (Fig.3), and Layout C (Fig.4). Layout B was modeled to simulate the existing tunnel as a cavity with air and a temperature above zero on the intrados of the lining.

Further, the impact of different factors on the AGF results was investigated. In particular sensitivity analyses accounted for:

- Eventual pipe deviation from the designed geometry.
- Different brine and Liquid Nitrogen temperatures to optimize the efficiency of the system.
- Different moisture content and thermal properties of the two horizons to account for pre-grouting operations.
- Different time frame for the starting of AGF by brine for the short inclined freeze pipes.
- Different ground temperatures along the longitudinal profile of the ground to account for the jet-grouting hydration reaction (jet-grouted columns have been installed about 6 months prior to commencement of AGF works).
- Switch-off of the refrigeration plant and observation of thawing with time.

The results of these analyses showed that the closure of the ice wall with a minimum thickness of 1.5 m would occur within 5 days of AGF by Liquid Nitrogen for all scenarios, after which the maintenance phase would start (following the conversion of the freezing pipes from LN_2 to brine). Further, the design defined to start AGF by brine method for the short inclined freeze pipes one week prior to commencing the LN_2 process for the main works to guarantee the continuity and closure of the frozen ground.

VI. Ground Freezing Process and Monitoring Data

The freezing process is a highly specialized technique that requires a continuous and carefully designed monitoring system, in order to check the evolution of the process.

In this project the monitoring system was implemented to detect ground temperature, groundwater levels, outlet temperature of Liquid Nitrogen and inlet and outlet temperatures of brine.

The recorded freezing parameters were processed and interpreted in order to follow the freezing process during its development. In particular:

- Ground temperature was observed versus time for each sensor of a chain. As an example, Fig. 5 shows the typical ground temperature development as detected by the temperature sensor T3.
- Ground temperature was observed vs depth, as shown in Fig. 6.
- Ground temperature was also observed vs distance between the sensor and the closest freeze pipe, an example is shown in Fig. 7. It is observed that the formation and speed of development of the frozen body is strictly dependent on the distance from the freeze pipes and the type of material.

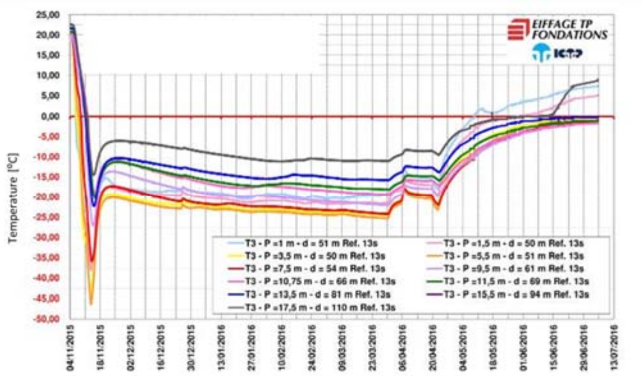


Fig. 5 Ground temperature vs time as detected by T-sensor T3

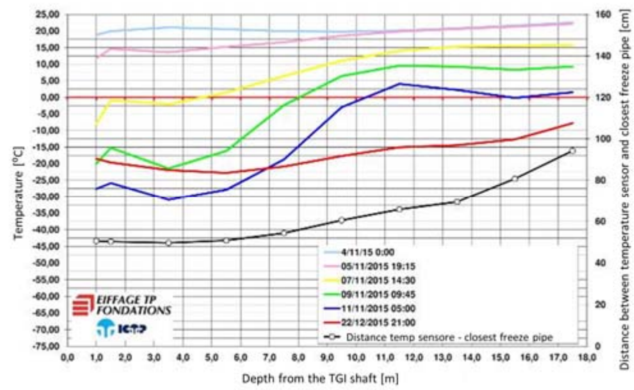


Fig. 6 Ground temperature vs depth

By observing the ground temperature vs time diagram in Fig. 5, it is possible to observe the rapidity, 1 to 2 days, with which the ground reaches extremely low temperatures (-30°C to -55°C, depending on the distance from the freezing pipe and the temperature sensor detecting the temperature) with the use of LN_2. After the spike it can be observed that the temperatures rise up quickly and thereafter stabilize around -10°C to -20°C, this phase corresponding to the conversion of the freezing pipes from LN_2 to brine. Afterwards, the ground temperature start decreasing again at a much lower rate and the system stabilized at a constant temperature.

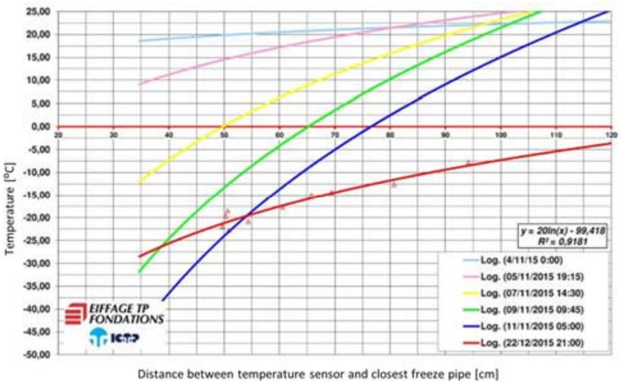


Fig. 7 Ground temperature vs distance between sensors and the closest freeze-pipe

Fig. 6 shows the trend of temperature along the pipes. The comparison of the reported curves is useful to understand if there are factors affecting the heat transmission.

Finally Fig. 7, ground temperature vs distance between sensors and the closest freeze-pipe, allows the determination of the physical radius of the frozen soil column and the growing of the columns dimension with time.


Fig. 8 Freezing phase by Liquid Nitrogen (direct method)

During pre-grouting operations, carried out prior to start the AGF phase, it was observed that a higher volume of grout was injected than expected. This result could indicate the high presence of voids and inter connected fractures in the ground. There was also evidence of existing leakages from the hundred-year-old masonry tunnel lining (with decompressed ground and cavities with water flow at the tunnel lining interface). For these reasons, the pre-grouting operation could have made the ground locally more heterogeneous than it was originally. However, monitoring data were in agreement with the design, and after 5 days of freezing by LN_2 (Fig. 8), the conversion of the freeze pipes from LN_2 to brine began. This operation took place over 3 days, under continuous injection of LN_2 up to the completion of the conversion.

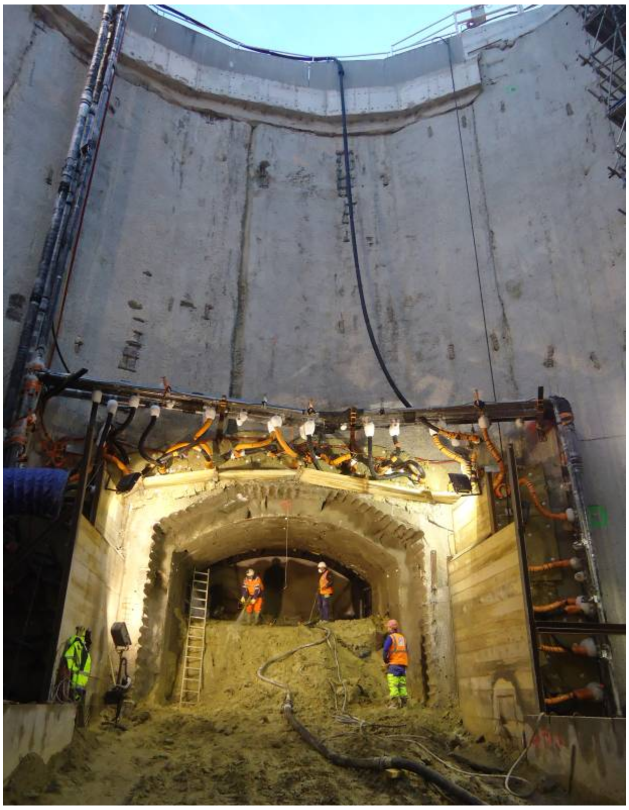


Fig. 9 Passenger Interchange Tunnel excavation front with AGF maintenance ongoing


Fig. 10 AGF showing the frozen ground behind the steel sets in place (temporary support)

Prior to the start of excavation operations (Fig. 9), the continuity of the frozen ground and consistency with the design was verified through piezometers inside and the outside the tunnel. The piezometers were used to monitor the drawdown during pumping test. The recorded data confirmed that the frozen ground wall provided a water cut-off.

Tunnel excavation was carried out successfully in dry conditions, with a two-phase sequence: (1) tunnel crown and side excavation with 1m advance length and installation of temporary lining, (2) invert and installation of the base slab.

Fig. 10 shows a detail of the frozen ground behind the temporary excavation system. It should be noted that observing the ground vs temperature diagram, reported in Fig. 5, no significant temperature increase was observed during the excavation phase, tunnel temporary lining or permanent lining placement.

Furthermore, a series of thermal analyses have been carried out in order to back-analyze the monitoring data and evaluate the thermal behavior of the ground after switching off the refrigeration plant. The following monitoring data were implemented in the analyses:

- As-built layout of freeze pipes and temperature sensors for different cross section
- Outlet temperature of Liquid Nitrogen for each freeze pipes
- Monitored temperature as detected by the temperature sensors
- Construction records such as date of switching freeze pipes from Liquid Nitrogen to Brine, start of excavation, etc..

Seven phases were modeled to properly capture the major construction features: (1) AGF by Liquid Nitrogen, (2) (3) and (4) transition phases to convert freeze pipes from Liquid Nitrogen to brine over a time lapse of 4 days, (5) AGF by brine, (6) tunnel excavation while AGF maintenance is ongoing, (7) switch-off of the refrigeration plant and observation of thawing.

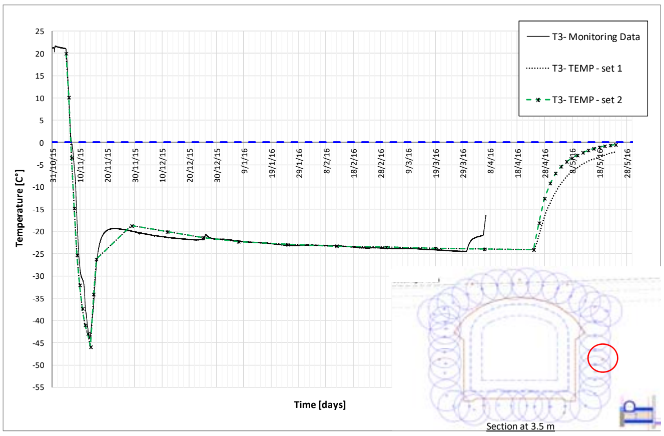


Fig. 11 Ground temperature vs time – back analyses results

The back analyses were carried out considering different sets of thermal material properties to best capture the monitored temperatures. As shown in Fig. 11, the parameters defined by these analyses are considered representative of a homogeneous equivalent ground that captures the main features of the treated material. Results also show that once the refrigeration plant is switched off the temperature rises quickly until reaching a temperature of about -1°C. However, this temperature refers to the temperature at the position of the T-sensors (about 0.2 to 1.1 m from the excavation perimeter). Although the frozen front near the perimeter of the excavation starts thawing quickly the frozen ground wall continuity has been shown to endure for more than a month after switching off the refrigeration plant.

VII. Final Remarks

It is well known that, when dealing with ground improvement techniques, soil freezing represents a rather unique solution for difficult soil and ambient conditions.

At the same time, this technique cannot be considered as a routine technique, because it requires expertise, both in the design and the execution, acquired with quite a large variety of projects in order to judge its capability and application for use on a given project.

In addition to this expertise, a properly designed monitoring system is of paramount importance. The monitoring system devises diagnostic parameters that can help to assess, in real time, the development of the freezing process or unexpected deviations, as provided by the observational method.

When adequately mastered and prepared, this technique becomes safer, more cost effective and efficient compared to other methods.

For all the above mentioned reasons, it is important in engineering practice to have a collection of well documented case histories. This paper is aimed to contribute in this respect, by showing how this technique was successful to solve a difficult condition during the excavation of the passenger interchange tunnel.

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