

## Analysis of artificial ground freezing in the Pari-Duomo platform tunnel of the Naples metro

S. Papakonstantinou, E. Pimentel & G. Anagnostou  
 ETH Zurich, Switzerland

**ABSTRACT:** The method of artificial ground freezing in a horizontal direction was employed to ensure stability and waterproofing of the platform and escalator tunnels in the Università station of the Naples underground. The paper presents the temperature histories monitored within the ground during the freezing process. Furthermore, it discusses the importance of the mineralogical composition of the ground and shows that the temperatures monitored can be numerically interpreted using the FREEZE code, a thermo-hydraulic software developed at the ETH Zurich. The thermal conductivity of the ground – a key parameter in modeling artificial ground freezing – can be estimated reasonably accurately by numerical back analysis when not known. FREEZE software is also a powerful tool for analysing field data for cases involving non constant temperatures within the freeze pipes.

### 1 INTRODUCTION

The extension of Line 1 of the Naples underground passes through 5 stations. Each station consists of a rectangular central shaft, 4 platform tunnels with a length of approximately 50 m each and 4 escalator galleries connecting the platform level with the first slab above the rails (Colombo *et al.* 2008). As the tunnel alignment is at a distance of only 230 m from the coastline, the water table is close to the surface, leading to significant piezometric heads. The method of artificial ground freezing in a horizontal direction was employed as the most suitable method for ensuring stability and waterproofing of the platform and escalator tunnels. Figure 1 shows part of the Pari-Duomo platform tunnel in the Università station. Its construction was completed prior to the excavation of the tunnel for the underground line using an EPB shield between the Università station and the Duomo station.

The present paper reports on the temperatures monitored during the freezing process as well as on their numerical interpretation using the FREEZE code, a thermo-hydraulic software developed at ETH Zurich (Sres 2009).

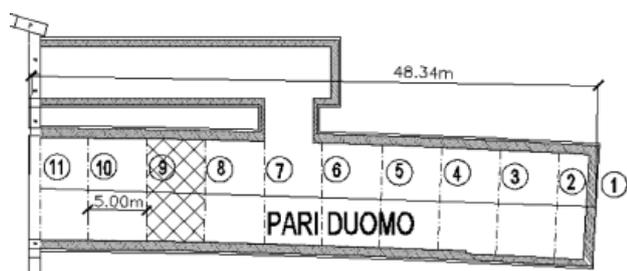


Figure 1. Plan of a part of the Parti-Duomo platform tunnel.

### 2 GROUND PROPERTIES

The ground consists mainly of tuff and occasionally, in the upper part, pozzolana. The platform and escalator tunnels were driven through the yellow tuff of Naples, a material exhibiting an increased secondary permeability due to the presence of an irregular pattern of vertical cracks when met. Tuff is a cemented soft volcanic rock, a pyroclastic flow deposit stemming from a multi-phase eruption occurring during the last 12,000 years in the region of Naples (De Gennaro & Langella 1996). Among the various tuff minerals, volcanic glass was dominant. When interacting with alkaline water at temperatures of 200–300°C, volcanic glass changes into zeolites. Zeolite has a very low thermal conductivity (Jakubinek *et al.* 2007, Murashov & White 2002) which has been measured at 0.12 W/mK for a ground temperature of 18°C (Murashov & White 2002). The degree of zeolitisation in the Naples yellow tuff is irregular and variable – mainly between 50–70% (De Gennaro *et al.* 2005) – which means there is a variable content of zeolite minerals. The thermal conductivity of the ground depends greatly on the thermal conductivities and fractions of its minerals (Johansen & Frivik 1980):

$$\kappa = \kappa_1^{n_1} \kappa_2^{n_2} \kappa_3^{n_3} \dots, \quad (1)$$

where  $\kappa_i$  and  $n_i$  denote the thermal conductivity and the volume fraction of the mineral  $i$ , respectively, while  $\kappa$  is the thermal conductivity of the mixture.

The variable amount of the zeolite minerals results in a variable thermal conductivity of the ground to be frozen. The quartz content in the zeolitised cemented tuff of Naples is small (Shuaib 1954) and was assumed to be 0.15. Pozzolana, a loose material, predominantly

Table 1. Geotechnical and thermal ground properties.

Property	Tuff	Pozzolana
Porosity $n$	0.55	0.51
Mineral density $\rho_s$ [kg/m <sup>3</sup> ]	2718	2392
Dry density $\rho_d$ [kg/m <sup>3</sup> ]	1223	1172
Wet density $\rho_{wet}$ [kg/m <sup>3</sup> ]	1733	1682
Unfrozen ground (at 16°C)		
Thermal conductivity $\kappa_{unfr}$ [W/mK]	0.492	0.273
Heat capacity $c_{v,unfr}$ [kJ/m <sup>3</sup> K]	3227	3020
Permeability $k$ [m/s]	10 <sup>-5</sup>	10 <sup>-6</sup>
Frozen ground (at -50°C)		
Thermal conductivity $\kappa_{unfr}$ [W/mK]	1.106	0.578
Heat capacity $c_{v,unfr}$ [kJ/m <sup>3</sup> K]	1735	1633

consisting of ash and pumice resulting from volcanic fall-outs, is encountered occasionally. The amount of quartz (a crystalline mineral, rarely met in volcanic pozzolana) in Naples pozzolana is assumed to be zero. Pozzolana has also a very low thermal conductivity. The properties of the two materials are listed in Table 1. The given tuff values apply to a zeolite content of 0.65 and a quartz content of 0.15. As discussed later in this paper, these mineral contents produce the best match between the theoretical predictions and the temperatures monitored *in situ* above the invert. The permeability values are given only for the sake of completeness as there is no seepage flow in this ground.

The unfrozen water content of the ground was determined on the basis of the power law of Tice *et al.* (1976) with the constants  $\alpha$  and  $\beta$  taken equal to 0.03 and  $-0.574$ , respectively (like a silty ground).

### 3 ARTIFICIAL GROUND FREEZING METHOD

The artificial ground freezing method was applied with liquid nitrogen and occasionally, i.e. when maintenance was necessary, with brine. In the numerical interpretation of the field measurements only the liquid nitrogen freezing was considered because temperature data were not available for the phases with brine. The temperature data were obtained from the company Trevi SA.

The freezing by liquid nitrogen involves the coolant entering a freeze pipe which consists of two concentric pipes at a temperature of  $-196^\circ\text{C}$ . The outer pipe is closed at the end, while the inner one is open. After reaching the deepest point of the inner pipe, the coolant returns and passes through the opening between the inner and outer pipe. At this moment, the liquid nitrogen turns into gas as it extracts heat from the ground around the pipe due to heat transfer by conduction. At the exit of the pipe, nitrogen gas is released into the atmosphere at a temperature between  $-120$  and  $-80^\circ\text{C}$ , which can be regulated.

36 freeze pipes with 50 m length and 76 mm outer diameter were installed in a horizontal direction in the upper part of the planned tunnel and 19 freeze

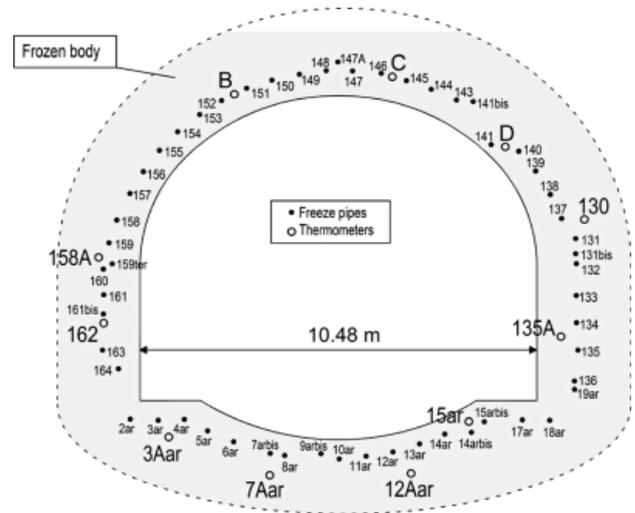


Figure 2. Initial cross section 11 with the installed freeze pipes and the thermometer chains.

pipes were installed underneath the invert. The orientation of the boreholes was controlled by the horizontal directional drilling method. The growth of the frozen body was monitored by temperature sensors located along chains parallel to the freeze pipes. 7 thermometer chains were installed in the area around the planned tunnel and above the invert and 4 thermometer chains underneath the invert. Each chain has 50 m length and consists of a set of thermometers located at intervals of 5 m. The temperatures were automatically recorded every 30 minutes. Figure 2 shows the location of the freeze pipes and of the thermometer chains at the first cross section (section 11 in Figure 1). Despite the use of the horizontal drilling method, deviations up to 30 cm from their initial location occurred for the freeze pipes in the other sections.

### 4 MODELING METHODOLOGY

Due to uncertainties over the stratigraphy of the ground, the numerical calculations were carried out in 2D for some cross-sections of the platform tunnel (sections 11, 8 and 5 in Figure 1) and by assuming homogeneous ground with the material constants of Table 1 (tuff for the tunnel cross-sections 11 and 8, pozzolana for the cross-section 5). The computational domain models a rectangular region of  $18.1 \times 16.7 \text{ m}^2$  around the tunnel and consists of 1,361,920 finite elements. Due to the absence of temperature measurements for the freeze pipes underneath the tunnel invert, only the area above the invert was modeled. For the section 11, the locations of the freeze pipes were taken according to the cross section shown in Figure 2 while for the sections 8 and 5 they were considered with the deviations from their initial location in section 11.

The initial conditions were taken according to the temperature of the ambient ground ( $16.1^\circ\text{C}$ ). Additionally, some separate calculations for an initial ground temperature of  $8.3^\circ\text{C}$  were performed on account of

the initial temperature of the thermometer chain 135A, which was measured 8.3°C.

In the calculations for cross-section 11, for which the freeze pipe temperatures are directly measured, the hourly measured values of each freeze pipe were taken into account as time-dependent boundary conditions. The temperatures of the freeze pipes for the other cross-sections were determined by linear interpolation between the exit temperature and the entrance temperature of  $-196^{\circ}\text{C}$ . At the outer model boundaries, a no heat flow condition was applied.

The numerical calculations were carried out by using the finite element FREEZE code developed at ETH Zurich for performing thermo-hydraulic simulations of artificial ground freezing (Sres 2009). The Euler backward iterative procedure was selected as the convergence method for calculating heat transfer along the model. Each time step simulates 1 hour of ground freezing. A total of 960 time steps were therefore calculated in order to map a freezing period of 40 days. Within this time period the developing frozen bodies connected together, thus forming a closed ice wall.

## 5 NUMERICAL INTERPRETATION

### 5.1 Tunnel cross-section 11

The interpretation of the monitoring results is based upon a comparison of the computed ground temperatures with those obtained from the thermometer chains B, 158A and 135A (see crown, left wall and right wall, respectively, in the cross-section of Figure 2). Four computations were carried out with different mineral compositions (zeolite and quartz content) and thus different thermal constants, in order to calibrate the model. For the purpose of comparison, an extreme case with unzeolitized tuff (i.e. a zeolite content of 0 in the tuff) was also calculated.

Figure 3a shows the measured temperature history of thermometer chain B as well as the four computed histories. The best match with the in-situ temperature was achieved for a high zeolite content of 0.65 and a quartz content of 0.15. In the neighbourhood of thermometer station B, a closed ice wall was formed in 4.5 days, reaching a thickness of 1 m after 11.5 days.

Figure 3b shows (for a zeolite content of 0.65 and quartz content of 0.15 in the tuff), the temperature histories of stations 158A and 135A on the left and right tunnel sidewalls, respectively. In the neighbourhood of these thermometer chains, the closure time was 2.5 and 4 days, respectively, and the ice wall became 1 m thick after 11.5 and 8 days, respectively. It can be observed that the temperature of stations 158A and 135A at the times of the ice wall closure in their vicinity are above  $0^{\circ}\text{C}$  as the ice bodies had not yet reached them. The calculated temperatures at the thermometer chain 135A agree well with measured temperatures, while a difference of  $10^{\circ}\text{C}$  exists for the thermometer chain 158A.

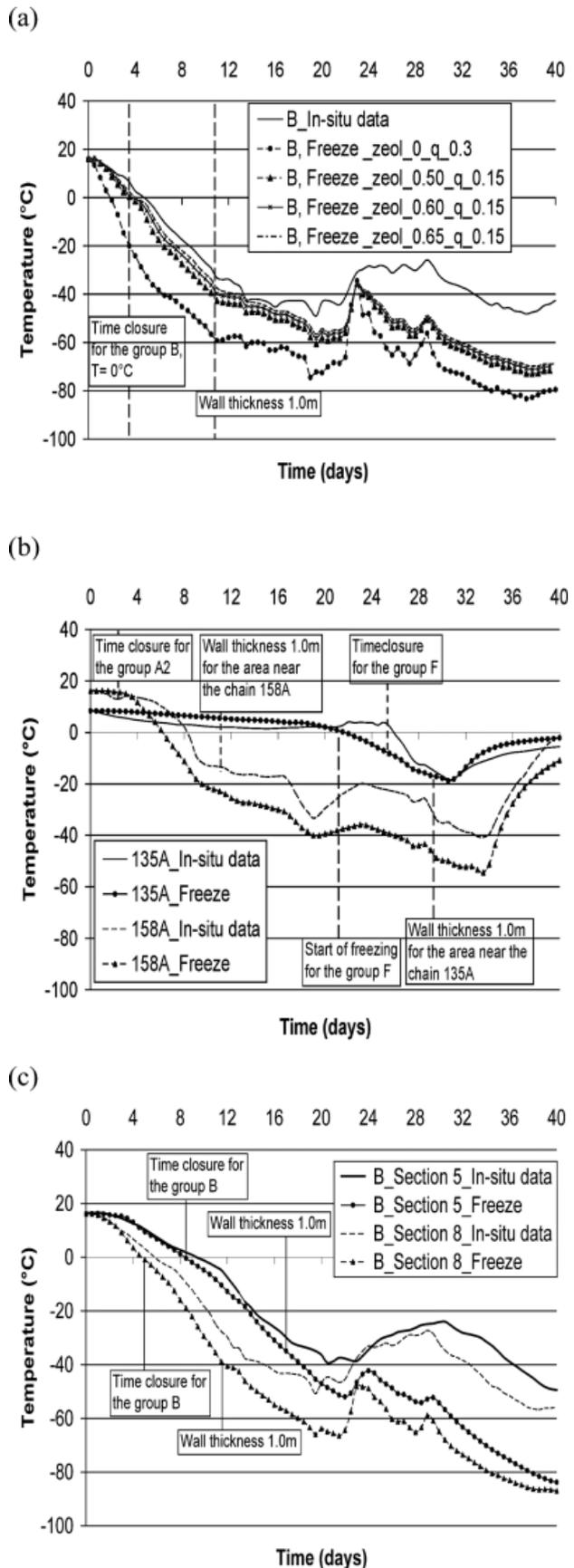


Figure 3. (a) Measured temperature history of the thermometer chain B at section 11 as well as calculated histories for different mineralogical compositions; (b) Temperature histories for thermometer chains 158A and 135A at section 11; (c) Temperature histories for thermometer chain B at sections 8 and 5.

## 5.2 Tunnel cross-sections 8 and 5

Figure 3c compares the temperature histories measured at the location of the thermometer chain B with the calculated temperatures. It should be noted that the constants for section 8 were then equal to those back-calculated from the section 11 measurements.

The formation of a closed ice body in cross-section 5 (in the neighbourhood of thermometer chain B) takes 3.5 days more than in the cross-section 8. This occurs because the ground at the section 5 consists of pozzolana which has a lower thermal conductivity than the zeolitised tuff at the section 8. For the same reason, the time needed for achieving an ice wall 1 m thick in section 5 is 5 days longer than in section 8.

## 6 CONCLUSIONS

A numerical study of the artificial ground freezing method employed in the Pari-Duomo platform tunnel of the Naples underground project was conducted using the FREEZE code. A back analysis was necessary in order to determine the thermal conductivity of the ground. The main conclusions of this study are as follows:

The thermal conductivity of the ground is a key parameter in modeling the artificial ground freezing and can be estimated reasonably accurately by a numerical back analysis when not known.

FREEZE software can be used as a powerful tool for interpreting *in situ* temperature monitoring data for cases involving the use of liquid nitrogen and where there are non constant temperatures within the freeze pipes.

In pozzolana, ground freezing develops more slowly than in the zeolitised tuff due to the lower thermal conductivity of pozzolana.

## ACKNOWLEDGEMENTS

The authors wish to extend their gratitude to the Federal Road Office (FEDRO/ASTRA) of Switzerland for providing financial support for the research project and to Mr. Di Salvo, TREVI SA, for providing monitoring data.

## REFERENCES

- Colombo, G., Lunardi P., Cavagna, B., Cassani, G. & Manassero, V. 2008. The artificial ground freezing technique application for the Naples underground. In V.K. Kanjlia et al. (eds), *World Tunnel Congress 2008; Proc. Underground Facilities for Better Environment and Safety, Agra, 22–24 September 2008*. New Delhi: Central Board of Irrigation & Power.
- De Gennaro, M. & Langella, A. 1996. Italian zeolitised rocks of technological interest. *Mineralium Deposita* 31: 452–472.
- De Gennaro, R., Cappelletti, P., Cerri, G., De Gennaro, M., Dondi, M. & Langella, A. 2005. Neapolitan Yellow Tuff as raw material for lightweight aggregates in lightweight structural concrete production. *Applied Clay Science* 28: 309–319.
- Jakubinek, M.B., Zhan, B. & White, M.A. 2007. Temperature-dependent thermal conductivity of powdered zeolite NaX. *Microporous and mesoporous materials* 103: 108–112.
- Johansen, O. & Frivik, P.E. 1980. Thermal properties of soils and rock materials. In P. E. Frivik et al. (eds), *Proc. 2nd Intern. Symp. on Ground Freezing, Trondheim, 24–26 June 1980*. Amsterdam: Elsevier B. V.
- Murashov, V.V. & White, M.A. 2002. Thermal properties of zeolites: effective thermal conductivity of dehydrated powdered zeolite 4A. *Materials Chemistry and Physics* 75: 178–180.
- Shuaib, S.M. 1954. A study of minerals in a sediment core from the gulf of Naples. *Clay minerals* 12(2): 170–176.
- Sres, A. 2009. Theoretische und experimentelle Untersuchungen zur künstlichen Bodenvereisung im strömenden Grundwasser. *PhD Thesis ETH Zurich*, Nr. 18378.
- Tice, A.R., Anderson, D.M. & Banin, A. 1976. The prediction of unfrozen water contents in frozen soils from liquid limit determination. *U.S. Army Cold Regions Research and Engineering*. Laboratory Report CRREL 76–8.