THE ARTIFICIAL GROUND FREEZING TECHNIQUE APPLICATION FOR THE NAPLES UNDERGROUND

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Abstract

The extension of the Naples underground between Piazza Dante and the *Centro Direzionale* (office district) on Line 1 includes 5 stations. The stations, driven partly by using bored tunnelling methods through the Neapolitan yellow tuff, were subject to unusually high heads of water for projects of this type due to the presence of the natural water table.

Given the extreme difficulty of injecting the material surrounding the excavation, the problem of waterproofing it during construction was solved for four of the stations by employing artificial ground freezing (AGF) methods.

The main characteristics of this ground treatment are presented in the text along with the main problems and solutions adopted during the project and the significant aspects of this experience which constitutes one of the major examples, at least in Italy, of the application of AGF technology.
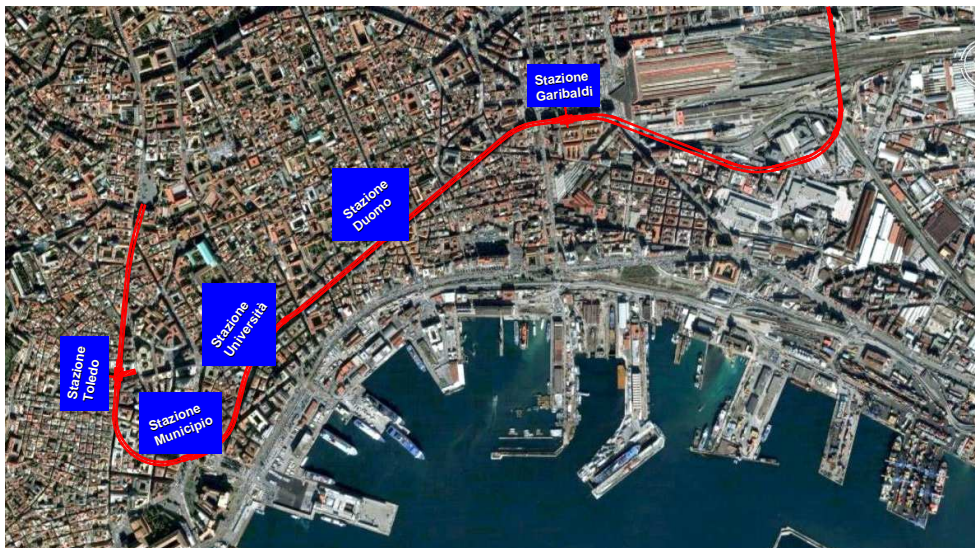
1.   Introduction

The extension of Line 1 of the Naples underground between the current end of the line at Piazza Dante and the *Centro Direzionale* (office district) passes beneath a very heavily urbanised area of the city. It was not therefore possible to use "cut and cover" design methods large enough to fully contain the platforms of the five stations along the route [1].

The standard design employed for stations therefore consisted of a rectangular central shaft of approximately 40 m x 20 m with the shorter side running parallel to the centre line of the tracks. Four platform tunnels were then excavated with a length of around 45 m (2 for each direction) to give platforms of 110 m.

Another four inclined tunnels were also constructed, again from the shaft, to allow passengers to reach the platforms (Fig. 2).
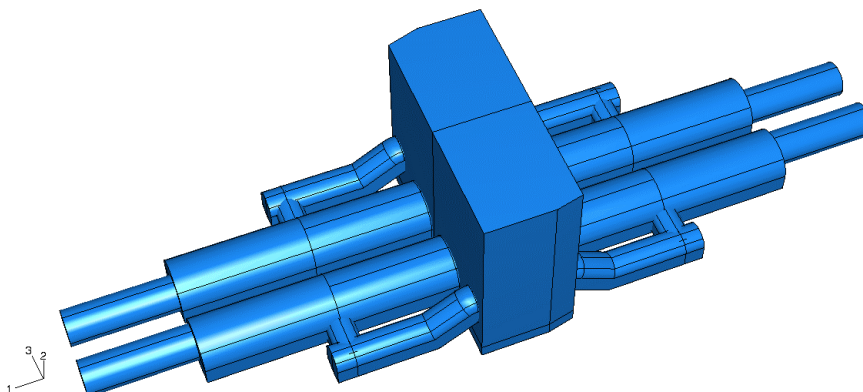

Fig 2 Functional drawing of a "standard station"

The vertical geometry of the alignment was designed to position the two bores of the railway tunnels within the tuff stratum which, in the section in question, is met at around 25-30 m below ground level. Furthermore, the nearness of the alignment to the coast causes the water table to reach levels relatively close to the surface. Consequently the bored tunnel excavation for the stations are subject to substantial heads of water.

As is known, tuff is a soft volcanic rock with good mechanical characteristics. Nevertheless the presence of irregular fractures which formed as the pyroclastic matrix cooled and running mainly vertically through it affects the secondary permeability to such an extent that excavation without prior waterproofing treatment is not possible.

The permeability of non fractured tuff is, however, relatively low and this makes grout injections on the scale required particularly costly, above all because they would have to be performed by drilling from the surface. As a consequence, the method employed in the tunnel design was that of artificial ground freezing.

Holes were drilled horizontally from the station shafts, parallel to the tunnel alignment, for considerable lengths (up to a maximum of 65 m. approx.). Freezer pipes were inserted into those boreholes into which cooling fluid was injected to draw heat from the ground and freeze the groundwater until the design thickness for the treated ground was reached.

Finally, the frozen volumes of ground were closed crosswise to each tunnel with an end barrier in order to stop water seeping through from the tunnel face. In some cases these barriers were created using freezing techniques with vertical boreholes drilled down from the surface. In other situations, however, the barriers were created by using chemical grout injections again from the surface with MPSP technology.

2. Geology and hydrogeology

2.1. General background

The geotechnical characterisation of the ground tunnelled was the end result of extensive survey campaigns which commenced in 1978 and, having been resumed several times, are still continuing.

The stratigraphy identified by the surveys consists of urban deposits at the surface which reach down to thicknesses of up to 10 m. These deposits are the result of urban construction in Naples which goes back to classical times as is also borne out by the important archaeological finds made during the excavation of the station shafts. At greater depths the stratigraphy presents a succession of pyroclastic deposits formed approximately 12,000 years ago. These deposits, which are generally loose at the higher levels are termed *pozzolana,* while at deeper levels they are cemented (but have the same mineral composition) to form a soft rock known as *yellow Neapolitan tuff.*

The presence of fractures which formed as they cooled running mainly vertically through this rock was of particular importance for the bored tunnel excavation under the water table. The permeability of tuff with these fractures is in fact two orders of magnitude greater than that of non fractured tuff and the factures can constitute, at least potentially, a dangerous pathway of communication between the tunnels in the tuff and the subsequent layers of loose ground*.*

2.2 Geotechnical characteristics of the ground

During the surveys already mentioned a substantial number of samples were taken including undisturbed samples at various depths which were subjected to *in situ* and laboratory tests to determine the geomechanical parameters [2][3][4].

Laboratory analysis included measurements of the shear strength using triaxial compression tests under drained conditions, determination of the natural specific weight and of porosity and more recently strength tests on frozen ground at different temperatures. For example *in situ* tests were also performed to determine permeability using the Lugeon method. It is well known that in terms of deformability, tuff presents linear elastic behaviour under the levels of stress found at the depths at which excavation takes place.

A summary of the most important characteristics of yellow Neapolitan tuff is given in table 1.

Characteristic	Average value
Dry specific weight, γ_d [kN/m^3]	11-12
Saturated specific weight, γ_{sat} [kN/m^3]	16-17
Water immersed specific weight, γ' [kN/m^3]	6-7
Porosity	0,55
Permeability, k [cm/s]	10^{-4}, 10^{-5}
monoaxial compression resistance [MPa]	3,0
Drained cohesion, c' [MPa]	0,8 – 1,0
Friction angle, φ' [°]	27° - 28°
Young modulus, E' [MPa]	1500
Poisson coefficient, ν'	0,3
Ko	0,5

Table 1 Tuff properties

The pozzolana was also investigated with laboratory tests on samples taken at different levels and with *in situ* tests.

The linear interpolation of the results of the triaxial tests gives an inclination which corresponds to an angle of friction of 40°, while t he CPT and SPT gave very scattered results which suggest that a conservative value of 35° should be assumed for the angle of friction.

Finally, chemical analyses were conducted on samples of water taken from the ground in order to measure their salt content. A high concentration of salt will lower the freezing point and consequently have the effect of influencing the mechanical properties of the frozen ground.

The analyses found an NaCl content of around 0.19-0.22 g/l, and a total salt concentration of 0.72-0.86 g/l. These levels of salinity are not, however, sufficient to significantly alter the freezing temperature of the saturated ground.

2.3. Mechanical characteristics as a function of temperature

As mentioned previously, the frozen ground through which the tunnels were driven consisted basically of tuff and pozzolana.

It must be considered that the properties of the tuff degenerate appreciably in the transition layer between the tuff and loose soils where a different material is found termed "*cappellaccio*".

Tests to measure the extent to which the mechanical characteristics were a function of temperature were therefore performed on a number of samples taken from the three layers described: tuff, "*cappellaccio*" and pozzolana.

Monoaxial compressive strength tests were performed at temperatures of -10°C. and -20° C. The results, summarised in table 2, co nfirmed the well known tendency of monoaxial strength to increase as temperature decreases.

Campione No.	Profondità [m dal p.c.]	materiale	Tem-peratura [°C]	Densità secca ρd [t/m³]	Resistenza a compressione monoassiale σ [MN/m²]	Deformazione a rottura ε [%]	Modulo tangente E_T [MN/m²]
15937-1	19,10 - 19,54	pozzolana	-10	1,52	8,3	11,0	628
15939-1	21,60 – 22,10	pozzolana	-10	1,49	7,9	13,1	220
15942-1	28,10 – 28,66	cappellac.	-10	1,11	6,4	8,9	475
15942-k2	28,10 – 28,66	cappellac.	-10	1,08	7,0	9,3	280
15944	31,60 – 31,81	tufo	-10	1,04	12,3	1,9	1382
15951	40,90 – 41,20	tufo	-10	1,01	11,7	1,6	1045
15937-2	19,10 – 19,54	pozzolana	-20	1,61	14,6	7,5	1128
15939-k2	21,60 – 22,10	pozzolana	-20	1,44	14,0	12,8	711
15954-k1	29,40 – 29,90	cappellac.	-20	1,21	10,2	15,6	629
15942-k3	28,10 – 28,66	cappellac.	-20	1,14	10,5	3,3	1218
15948	37,62 – 37,90	tufo	-20	1,09	17,9	2,1	1345
15949	39,53 – 39,80	tufo	-20	1,10	17,7	1,9	1463

Table 2 Results for the mono-axial compression tests for temperatures of -10°C and -20°C

3.   The artificial ground freezing technique

The primary purpose of artificial ground freezing is to draw heat from the ground until its temperature falls below the freezing point of the groundwater in it (freezing stage) and then to maintain the temperature level reached by appropriately regulating the flow of heat extracted until excavation and construction operations have been completed (maintenance stage).

The ground is cooled by making refrigerant fluid circulate through frozen pipes set in the ground consisting of two concentric pipes. The outer pipe is closed at the end while the inner tube is open. Generally the refrigerant fluid enters the inner tube and reaches the deepest point. On its return journey after passing through the opening between the two tubes, the refrigerant fluid draws heat from the ground.

There are two methods of freezing available [5]: the indirect method (or brine method) and the direct method (with liquid nitrogen).

The indirect method (Fig. 4) is based on a closed process and requires the use of industrial refrigeration plant, which feeds a closed circuit. The refrigerant is sent to and returns from freeze pipes through insulated delivery and return pipes.

The warmer brine returning from the freeze pipes is cooled again and sent back to the freeze pipes. Brine freeze pipes generally consist of a steel outer tube and an inner tube of either steel or polyethylene (the steel used is highly resistant to low temperatures). The refrigerant liquid consists of a water solution of calcium chloride (brine) cooled to a temperature of between -25 and -40°C.
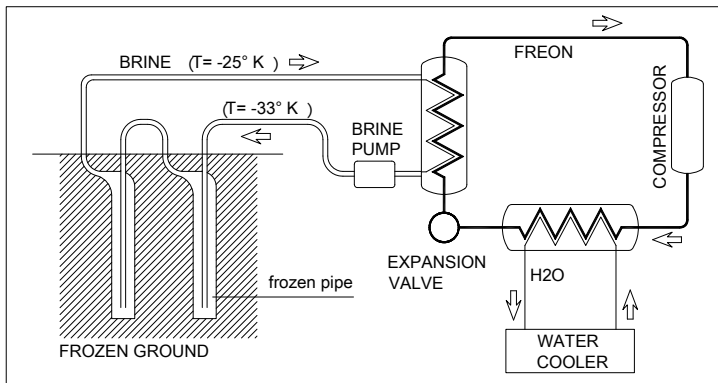
Fig. 4 Schematic diagram of indirect freezing (with brine)

The direct method on the other hand is based on an open process (Fig. 5). The refrigerant liquid consists of liquid nitrogen at -196°C. The liquid nitrogen is sent directly to the freeze pipes through insulated pipes. The two concentric tubes which form the freeze pipes are generally made of copper or stainless steel. The liquid nitrogen evaporates as it passes through the freeze pipes. It draws heat from the ground as a result of both its change of state (thermal shock) and the difference between the inlet and outlet temperatures. The gas produced is released and dispersed into the atmosphere at a temperature of between -100° C. and -60° C.
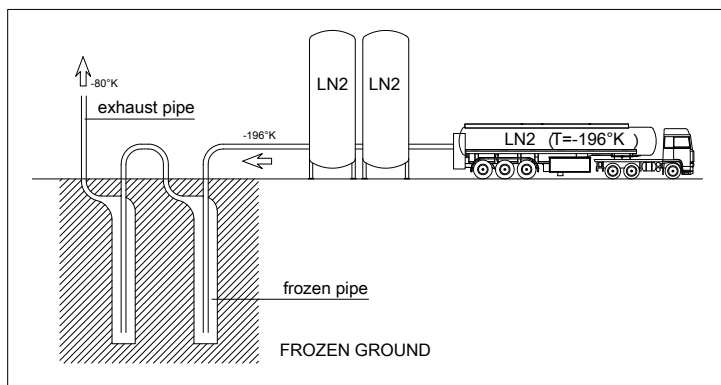

Fig. 5 Schematic diagram of direct freezing (with liquid nitrogen)

It is possible to use a combination of the two procedures described or to alternate the use of them to freeze the same ground as long as the freeze pipes are suitable for the circulation of both refrigerant fluids. One possibility that is sometimes exploited is to use the direct method for the freezing stage and the indirect method for the maintenance stage.

The choice of which freezing procedure to adopt is based on a series of operational and economic design factors: the mechanical characteristics required by the design of the frozen ground, the time available for the freezing stage, the length of the maintenance period, the logistic conditions, etc..

4.   Design decisions

4.1.   geometry of the freeze pipes

A geometry consisting of a single row of freeze pipes around the entire perimeter of the tunnel cross section was adopted for freezing the platform tunnels.

The theoretical distance between centres of the pipes was set at 0.75 m. to allow for admissible tolerances in drilling the boreholes of 0.5%. Since the length of the pipes is generally 50 m. the maximum admissible deviation reaches 0.25 m If the theoretically possible case occurs of two boreholes which deviate to the maximum in opposite directions then a distance between centres of between 0.25 m and 1.25 m is possible.

While bringing the pipes closer together does not create any significant problems, if they are too far apart it could make it impossible to create joints between the cylinders of ice that are formed around two adjacent pipes which would leave a "hole" in the frozen ground. Discontinuities like these constitute a potential danger to the maintenance of freezing during excavation because they could allow water to seep in at normal temperatures which would inevitably cause the surrounding ice to gradually melt.

Where the tuff was encountered at a lower depth than that of the crown of the tunnel, which left the upper part of the excavation in the pozzolana, a double row of freeze pipes were installed in order to obtain a thicker band of ice so that the treated ground could perform structural as well as water-proofing functions.

4.2.   The freezing technology employed

The treatment employed for the stations in question was performed by adopting the two freezing techniques described in section 3 primarily because of the high degree of porosity (55%), which translated into large quantities of water in the ground to be frozen. More specifically:

- The direct method was adopted for the freezing stage with the insertion of liquid nitrogen into the freeze pipes at a temperature of -196℃.   The pressure at which it was pumped in was regulated as a function of the temperature of the outlet vapour which was maintained at between -60° C. and -100°C.

    This stage continued until the design objectives were reached, defined as the creation of a frozen wall with a temperature of $\leq$ -10° C. and a minimum thickness of 1 m. This was the equivalent of obtaining a temperature of $T \leq$ -10°C. at a distance of 0,50 m from the freeze pipe s.

- The following maintenance stage was normally performed using the indirect method, by circulating a saturated solution of CaCl in the pipes at a temperature of around -30° maintained by a refriger ating system with a total output of 500 Mcal/h (600 KW/h).

It is worth noting that the temperature around the freeze pipes can be estimated by integrating the Fourier equation which, with polar co-ordinates and assuming

stationery conditions (because of the extremely slow propagation of the isotherms) gives:

$$T(r) = A \cdot \ln \frac{r}{B}$$ where r is the distance from the pipes

and where A and B can be calculated, in the case of freezing using the indirect method, by assuming that the temperature on the border of the pipe is the same as that of the brine (-30°C) and that the value for T at 0.50 m is -10°C.

Once the constants have been calculated the temperature curve for the case in question shows, amongst other things, that the isotherm T=0°C. has been pushed to 1.55 m from the centre line of the freeze pipes.

This result was confirmed qualitatively by the works performed in Naples. In fact the formation of frost on the face in the frozen zones showed temperatures of below zero even at considerable distances from the pipes, at least on the inner side of the cross section clearly visible on the face (Fig. 13).

Fig. 13 Face in tuff with freezing of a substantial thickness of ground clearly evident

As excavation of the tunnel proceeded, a marked tendency of the ground to heat was observed mainly in the crown, because volumes of ground at low temperatures had been removed. The problem was solved by again pumping nitrogen into the pipes adjacent to the more critical zones. It was therefore necessary to adopt both the direct and indirect freezing systems simultaneously during the maintenance stage for periods which often lasted until the final linings of the tunnels were placed

5. Drilling and monitoring of boreholes

From a technological viewpoint one of the most difficult challenges was that of drilling horizontal boreholes with a length of 50 m. or longer, while containing deviations within the rigorous design tolerances.

To cope with the problem, a method was developed, based on drilling technology used in the oil industry, which made it possible to "steer" the drill bit during drilling to correct for deviations if they should occur.

5.1. Steered drilling

This method, known as "horizontal directional drilling" (HDD), is based on the use of a drill-bit with a special "chisel" geometry (see Fig. 14) which advances theoretically in a straight line when rotating, but which can be made to turn in a given direction if it is percussion operated (not rotating).

The direction of the deviation is orthogonal to the plane of the chisel and the orientation of this plane is measured continuously by the equipment and displayed to the operator on a special monitor.
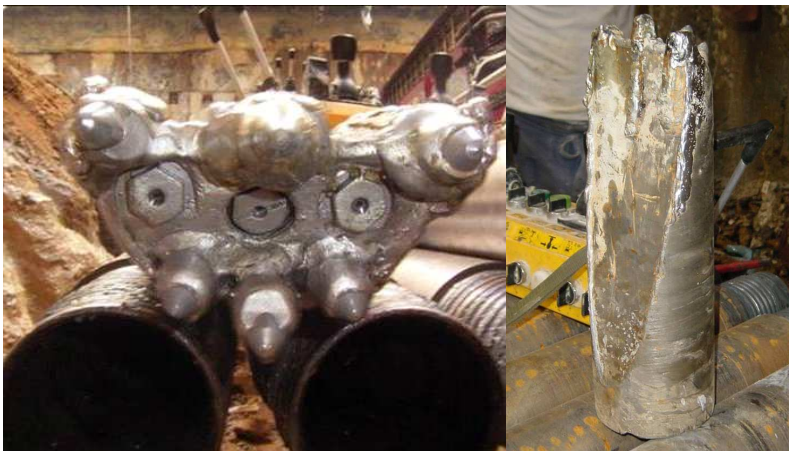

Fig. 14 Drill bit for drilling using HDD technology

The problem of locating the drill bit in the ground as drilling proceeds was solved by using the interference of a sensor fitted directly on the cutter head with a magnetic field artificially induced in the surrounding ground.

The depth of the operations from the surface of a few dozen metres was found to be too great for a magnetic field to be induced by a network of conductors placed on the surface. The problem was nevertheless solved by placing an electric cable inside a special borehole located, for example, in the centre of the row of freeze pipes above the crown.

The magnetic interference made it possible to measure vertical and horizontal distance from the cable just mentioned. It was therefore necessary, before proceeding, to measure the geometry of the service borehole using optical inclinometric methods (described in greater detail later in the article).

6. Temperature monitoring

6.1. data acquisition

The temperature range was monitored constantly by placing thermometer chains consisting of a string of thermometers set at intervals of 5 m starting from the station shaft walls in appropriately drilled boreholes. Generally the thermometer chains, 3 in the tunnel invert and 6 around the uprights and crown of the tunnel, have a length of 50 m and therefore connect 11 measurement points.

Consequently the frozen ground is monitored by 99 thermometers altogether from which the data is acquired by a unit connected to software which is programmed to record readings every 30 minutes.

It was also possible to associate its distance from the nearest freeze pipe with each measurement point by measuring the geometry of the boreholes that house them.
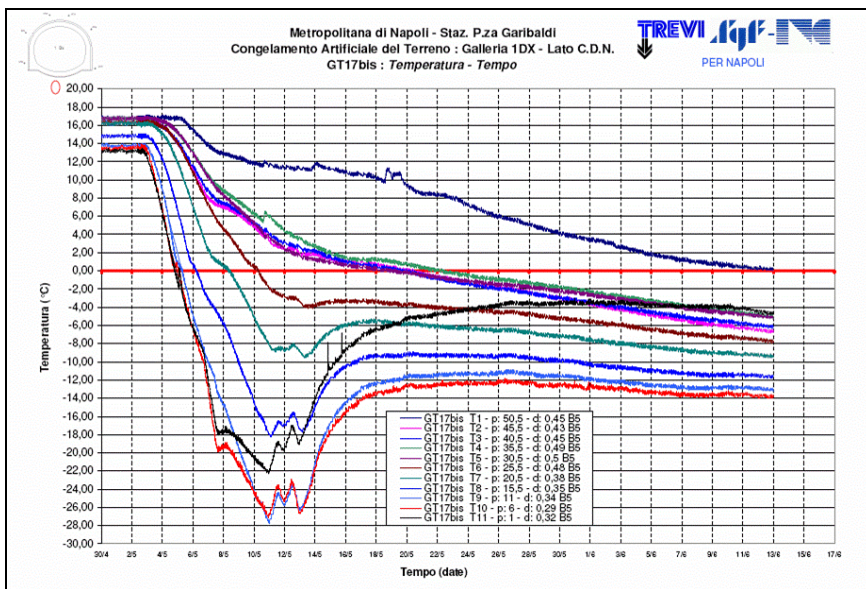

Fig. 17 Time temperature curves generated from data acquired from thermometers installed along the axis of the tunnel invert of one of the Garibaldi Station tunnels. Pumping of liquid nitrogen started on 3rd May and on 13th May, after the temperature had reached around -20° C. along the half of the thermometers closest to the station shaft tunnel walls, the maintenance stage began with brine which brought the temperatures together at around -10°C.

It was finally possible to plot the temperature against time on a graph for each thermometer with its associated distance (Fig. 17). The representation not only gives an immediate view of the temperatures reached on any given date, but also the gradient over time. It must, however, be considered that the position of a measurement point affects the reading considerably. Those thermometers located

closest to the freeze pipes record cooling much earlier than those farthest from it.

The curves like the one shown must therefore either be interpreted "intelligently", or, as an alternative, systems were studied to process the results obtained to give values that are normalised with respect to the distance between the sensors and the freeze pipes.

6.2. Methods of representing the temperatures measured graphically

We mention two of the techniques for normalising curves used in Naples. Both are based on the consideration already mentioned that the relationship of temperature to distance from the freeze pipes is that of a logarithmic function.
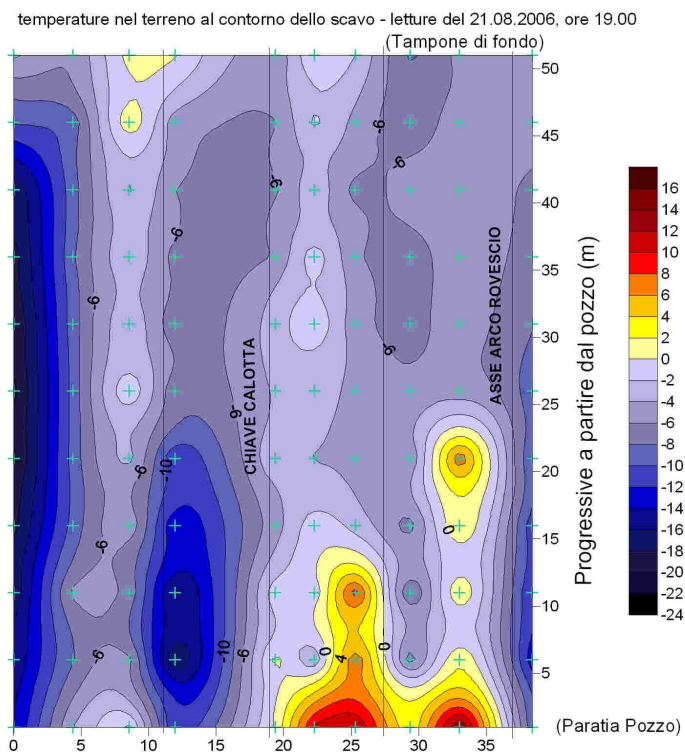

Fig. 18 Iso-temperature on the surface at 0,50 m from the freezing pipes .

If the environmental conditions, the temperature measured and the distance of the thermometer are then taken for each separate measurement point and if it is assumed that the surface of the pipe is the same as that of the brine (or equal to that of the nitrogen vapour discharged into the atmosphere during the direct freezing stage) then the temperature can be calculated at any distance (e.g. 0.50 m) and for each measurement point. In reality the method is more complex and takes account of the difference between the two logarithms for T as a function of distance: one is valid for temperatures < 0° C. and the other for temperatures > 0°C. [7].

This is because both the coefficient of thermal diffusion and the specific heat of water are different in its liquid and solid states.

If we project the surface that surrounds the pipes at a distance of 0.50 m from them onto a plane and interpolate the temperature values calculated for each sensor, then the consistency of the ground can described for any instant in time in the form of a thermograph or, if the values calculated at two different times are subtracted, the change in temperature over that period of time can be seen.

A different method of graphical representation was developed for the thickness of the ice in the different sections in which the thermometers are positioned. Firstly each thermometer is associated with the closest freeze pipes (which are then grouped into as many groups as there are sensors for each section).

Subsequently the distance at which the temperature is -2° C. (assumed as the limit for freezing) is calculated for each measurement point using the same procedure described for creating the thermographs.

Finally the actual geometry of the freeze pipes in the section considered is represented taking account of the deviations measured and each freeze pipe is surrounded by a circle with a radius that is the same as the distance for the temperature T=-2°C.
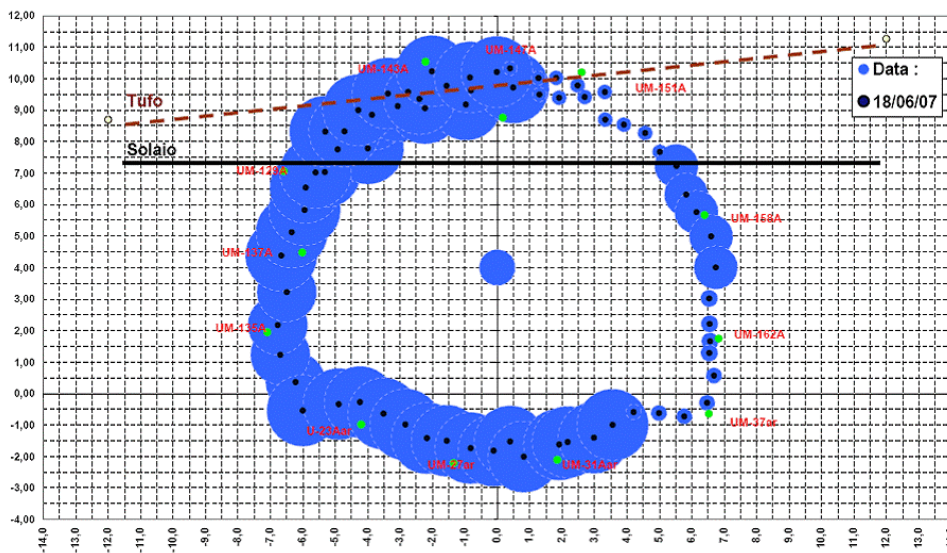

Fig. 19 Graphic representation of the thickness of the frozen ground in a given cross section of tunnel which takes account of the borehole deviations

7.   The station tunnels: actual times and consumption

The consumption recorded was relatively variable. The reasons are to be sought in the greater or lesser difficulty with freezing maintenance as a result of the different degrees of fracturing in the tuff on the different construction sites.

An additional factor was the number of refrigerant units available on construction sites. A larger available freezing capacity meant there was less need to circulate liquid nitrogen during the maintenance stage and vice versa. Average consumption for the freezing stage only was around the 1700 l/m^3 of frozen ground.

8.   Conclusions

The excavation of the platform tunnels for the stations on the section of the Naples underground under construction was performed after first performing artificial ground freezing (AGF).

The project, which is still in progress, demonstrated the great complexity of this operational technique and technology which is one of the reasons why it was very difficult to predict the actual effectiveness of the ground treatment at the design stage. Aspects such as the nitrogen consumption, the time required to reach the target temperatures and the power consumption during the maintenance stage were affected by many factors some of which, such as the speed of seepage into the ground and the degree of fracturing in the tuff, are not fully measurable or controllable during construction operations.

The objectives achieved are therefore even more impressive and are the result of commitment and teamwork by the consulting engineers, Rocksoil and MM, the general contractors; the specialist contractors, Trevi and the Icotekne consortium, the client Metropolitana di Napoli S.p.A. and the City of Naples.

References

[1]   **Colombo G., De Risi A., 2008**. *Il progetto, lo scavo, ed il controllo delle gallerie di stazione della metropolitana di Napoli.* **Convegno Società Italiana Gallerie "le gallerie nelle infrastrutture di trasporto" – Verona. 5-6 March 2008**.

[2]   **Viggiani, C., Rippa, F., 1998. Linea 1 della metropolitana di Napoli, tratta Dante-Garibaldi, Relazione Geologica e Geotecnica.**

[3]   **CDM Jessberger Gmbh, 2004. Metro Napoli Line 1, Garibaldi Station; Laboratory investigations on soil samples in unfrozen and frozen condition – Test Report.**

[4]   **Colombo G., Cassani G., Sciotti A., 2004**. *Scavo meccanizzato in ambiente urbano: approccio e supporto progettuale. Il caso della linea 1 della metropolitana di Napoli.* Gallerie e grandi opere sotterranee, n. 74 (December 2004).

[5]   **Crippa, C., Manassero, V., Leoni, F., 2007**. *Il congelamento artificiale del terreno. Previsioni progettuali e monitoraggio in corso d'opera.* XXIII **Convegno Nazionale di Geotecnica. Padova – Abano Terme. 16-18 May 2007.**

[6]   **Sanger, F.J., Sayles, F.H., 1979. Thermal and rheological computations for artificially frozen ground construction.** *Engineering Geology*, **13 (1979) 311-337**.

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He worked with major Italian construction companies in the field of infrastructure of transportation between 1989 and 2000.

In this period he was involved as structural engineer, engineering manager, and project manager in many projects both in Italy and abroad.

In July 2000 he joined MM as Design Manager for underground works of Porto underground (Portugal).

In late 2001 he moved to Naples as Resident Engineer where he drove the realization of the extension of Line 1 of Naples Underground.

PIETRO LUNARDI

A civil engineer in the field of transport, he is one of the greatest experts in world on the design and construction of underground works, the creator of highly innovative solutions: the Cellular Arch, developed for the construction of the Porta Venezia underground station on the Milan Railway Link Line for which he was nominated "Man of the Year in the construction field" by the United States journal "*Engineering News-Record*"; shells of improved ground using jet-grouting techniques; full face mechanical precutting, face reinforcement using fibre glass structural elements; he devised and developed the revolutionary new approach to design and construction, known by the acronym ADECO-RS, which for the first time has made it possible to construct tunnels even in the most difficult geological-geotechnical and stress strain conditions with reliable forecasting of construction times and costs.

The author of more than 130 publications he has held more than 40 national and international conferences on the subjects of tunnelling and geo-engineering.

BRUNO CAVAGNA

Graduated in Civil Engineering, structural speciality, in 1972.

After several years of activity in the field of structural design, since 1988 he has been responsible of Civil Works of Metropolitana Milanese S.p.A., until 1993 when he become Technical Director of the same company.

He coordinated the structural design of line 3 of Milan Underground and the Milan Railway Link Line.

At present he is responsible of the design of line 1 and for

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Is design supervisor of all design activities for the extension of Milan underground.

GIOVANNA CASSANI

Technical Director of Rock Soil S.p.A. - Structural Civil Engineer.

As a project manager she has worked over the years on the design of numerous road, metro and rail tunnels.

She has participated in the most significant and important of the company's designs and projects, including the Venezia Station of Milan, constructed using Cellular Arch technology, the Tartaiguille Tunnel on the Lyon-Marseille G.T.V. line and more than 100 Km of tunnels for the new the Bologna–Florence high speed rail line.

She has been Technical Director of Rocksoil S.p.A. since July 2001.

VITTORIO MANASSERO

Graduated in Civil Engineering at Torino Polytechnic in 1982.

He immediately joined RODIO (geotechnical contractor) at the Engineering Department. In 1996 he became the Engineering Dept. Manager.

From 2004 to 2007 he was at the TREVI Design, Research and Development Department.

Since 2007 he is Technical Director at ICOTEKNE.

Member of Technical Committee for Micropiles European Code.

He published more than 25 technical papers on geotechnical engineering, with particular reference to the soil improvement techniques.

Areas of expertise: soil improvement by grouting, jet-grouting, artificial ground freezing; slurry walls, berlin walls, anchors and micropiles; tunnelling; landslide stabilization; VSM shafts; raise boring.