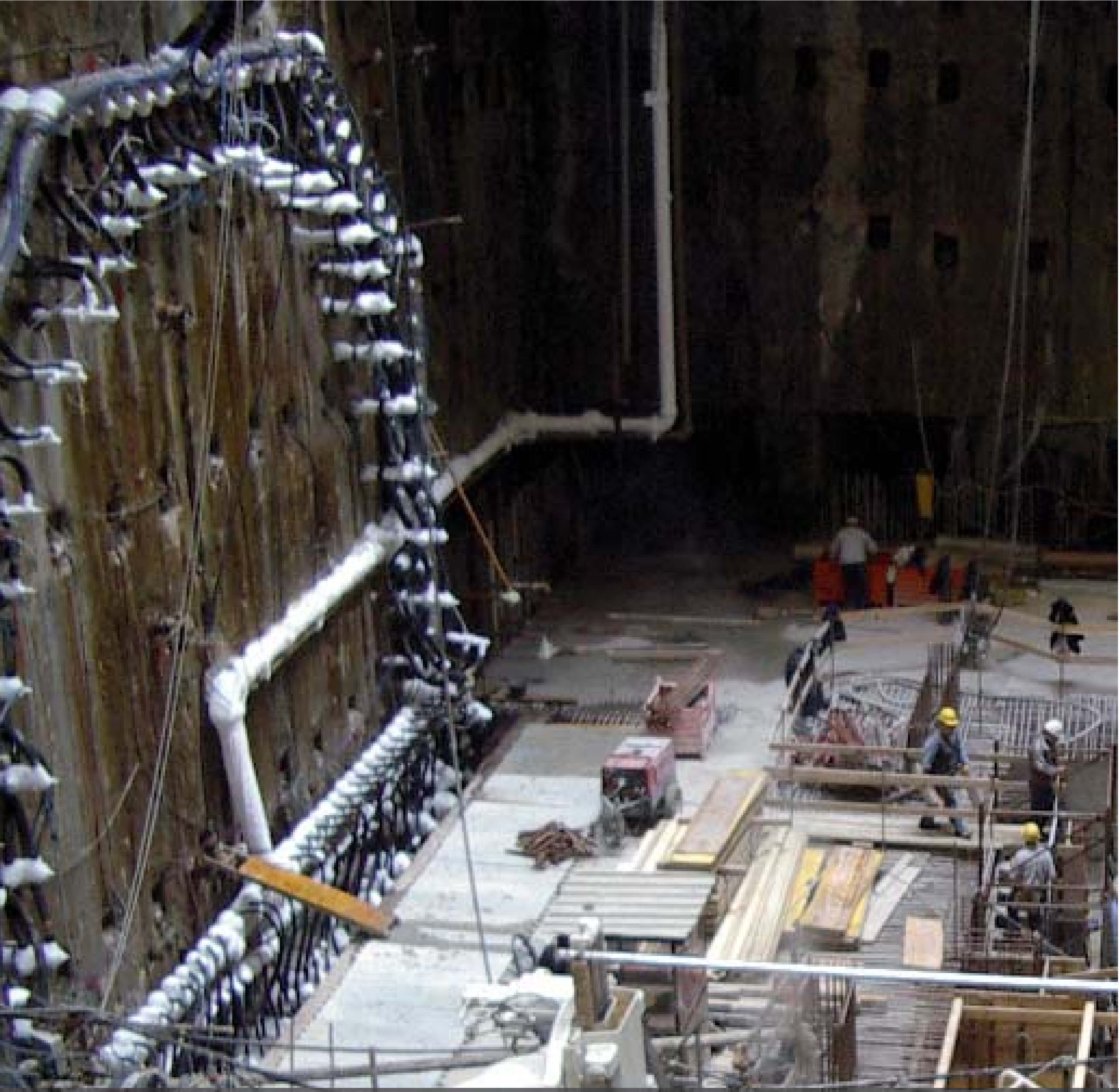
TECHNOLOGY

Artificial ground freezing

TREVI

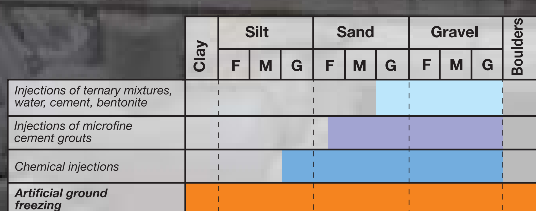


Artificial ground freezing (AGF) is used for waterproofing and/or temporary consolidation to support the excavation of tunnels, shafts and cross passages under the water table in loose soils or fractured rocks.

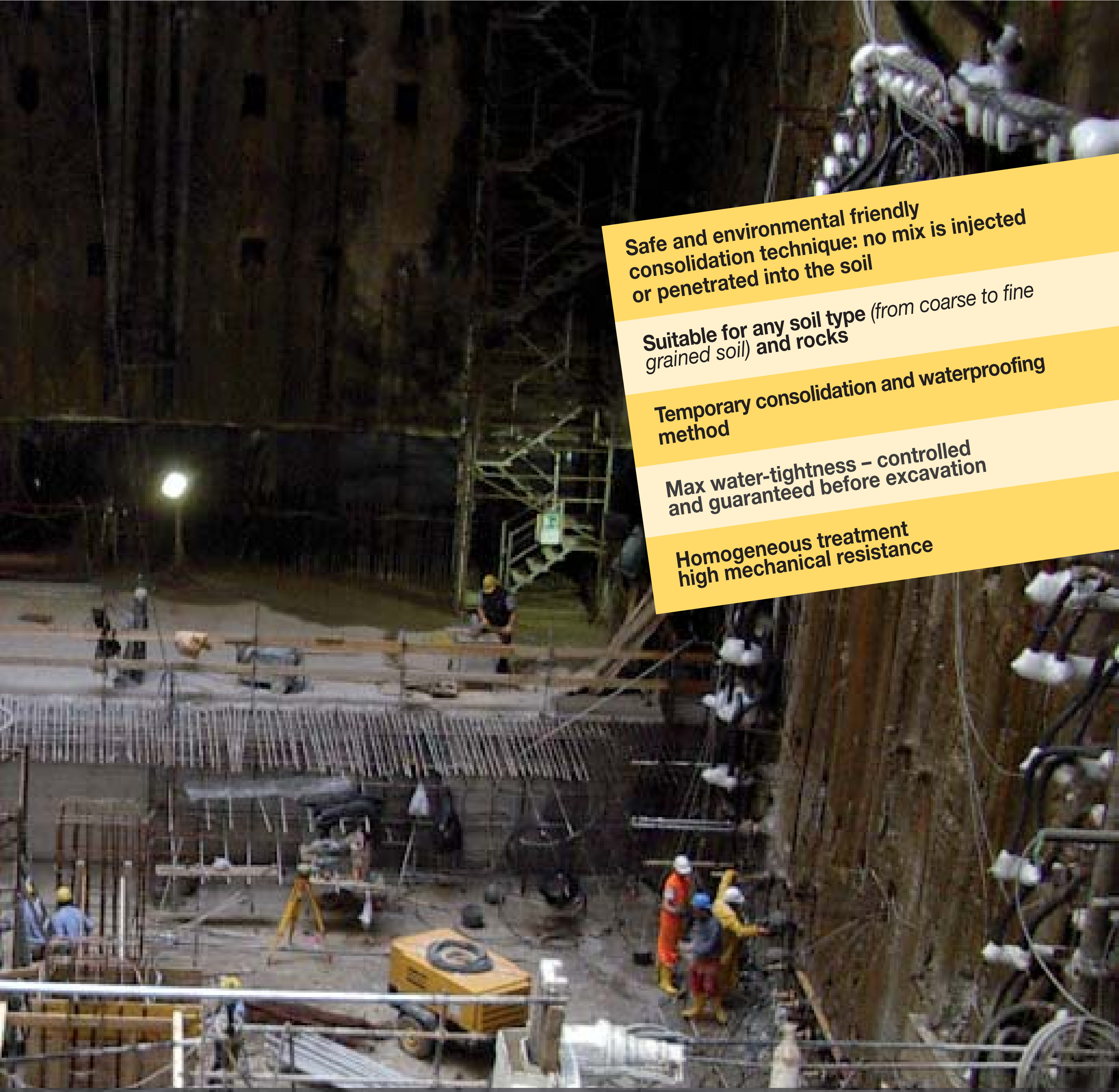
Artificial ground freezing has been used for decades, mainly in Northern Europe since the 70s.

The main advantages and features that make AGF different from other consolidation and waterproofing technologies are the following:

- *AGF is safe and environmentally-friendly, as no product is injected or penetrated into the ground; the water naturally present in the ground is frozen by means of cooling agents that never enter in direct contact with the soil or groundwater, thus avoiding any contamination or pollution of aquifers. Once the procedure is completed, thawing occurs naturally.*



- *AGF is suitable for any soil type (from coarse to fine grained soil) and rocks.*
- *Ground freezing is a temporary consolidation and waterproofing method.*



Safe and environmental friendly consolidation technique: no mix is injected or penetrated into the soil

Suitable for any soil type *(from coarse to fine grained soil)* **and rocks**

Temporary consolidation and waterproofing method

Max water-tightness – controlled and guaranteed before excavation

Homogeneous treatment high mechanical resistance

- *If properly executed, AGF allows to:*

  - reach water-tightness, whereas the other consolidation methods can only reduce the natural permeability of the soil with an efficiency strongly dependant on soil type and grouted materials, and with an extent and quality that cannot be guaranteed beforehand.

  - obtain a homogeneous treatment, with no weak points or planes. High mechanical resistance is achieved.

In case of excavations in loose or cohesive soil under the water table, and in the presence of high water heads (tens of metres) - especially when working in urban settings, AGF is the most suitable technique, and sometimes the only possible solution to ensure the highest level of safety.
In these situations it is of the outmost importance to avoid any risk of rushing out and discharge of spoil and water under pressure inside the boreholes, resulting in dramatic consequences for the works under construction, the workers and existing overlaying structures.

Technology

Thanks to the recent buy-out of Rodio and its know-how, the Trevi group proposes comprehensive services for every AGF project including:

- **Geotechnical, geognostic and hydrogeological analyses and investigations;**
- **Analysis and evaluation of the most suitable method** from a technical and economic point of view, by assessing various options and geometries;
- **Thermal analysis and sizing of frozen soil body**, by defining the cooling power and the time needed to reach the requested thickness and temperatures.
- **Intervention execution**, from the preliminary phases of drilling and installation of freeze pipes and thermometers, to the installation and management of refrigeration systems and liquid nitrogen tanks.
- **Monitoring, analysis and management of temperatures.**

The **limits of application** are the following:

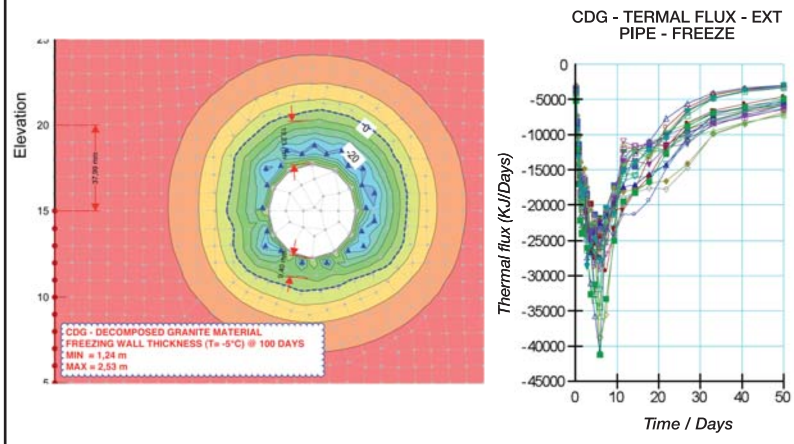
- **every layer to be frozen must have a suitable moisture content**
- **the flow rate of groundwater to be treated must be lower than preset thresholds.**

The **major application fields** are:

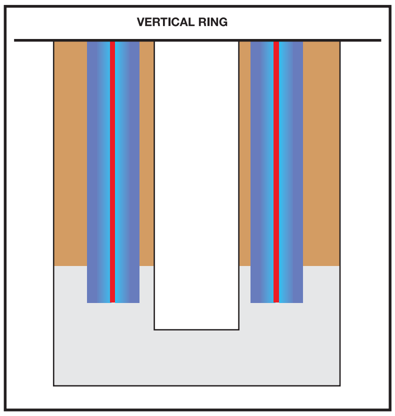
- tunnelling, shafts and by-pass tunnels
- underpinning and excavation protection
- cryogenic coring to sample loose non-cohesive materials, the ground remaining undisturbed.

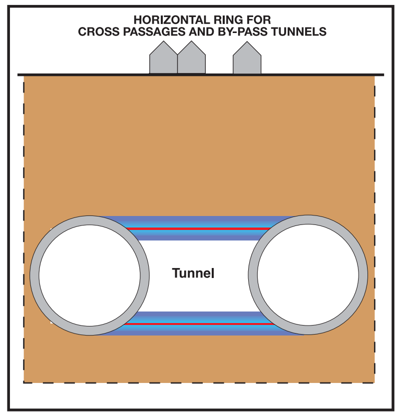
Depending on the positioning of freezing pipes, different shapes and structures of frozen soil can be created. Standard intervention patterns are indicated below:

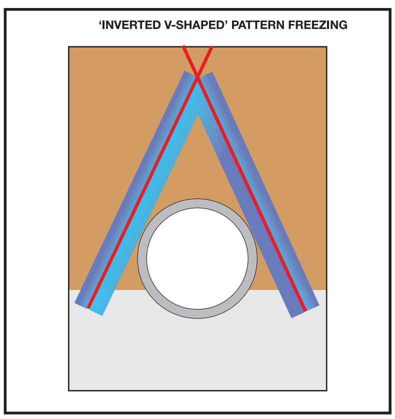
- **circular pattern of vertical cylinders** used to bore shafts from the ground level, either socketed or not into the watertight substrate;
- **circular pattern of horizontal cylinders** used to bore tunnels or cross passages from shaft or trench;
- **vertical partition** used as bottom plug for closed-end tunnels;
- **'inverted V-shaped' pattern**, used to protect horizontal tunnels needing waterproofing and consolidation at the top of the crown and side walls only (invert in watertight layer);
- **truncated-cone shaped circular pattern of cylinders** used for "head to head" joints between two tunnels or relay in case of very long interventions;
- **'trestle-shaped' pattern** used for underpinning and excavation next to pre-existing structures.

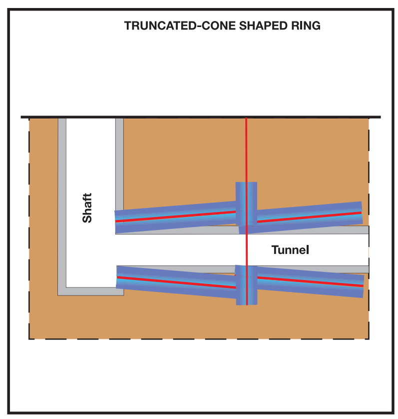


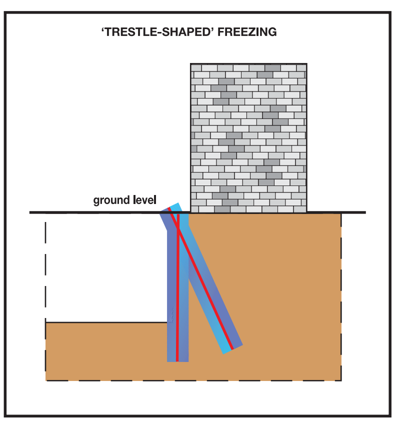
Thermal analysis

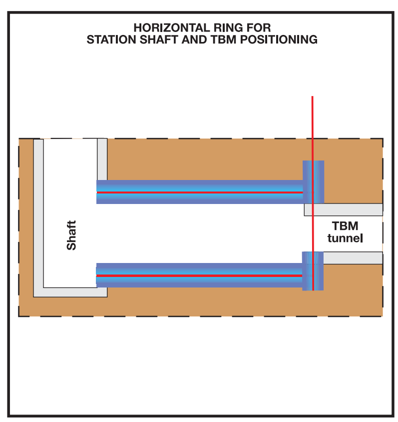




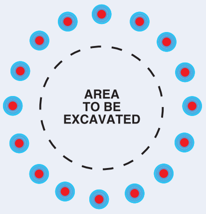




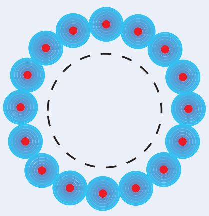




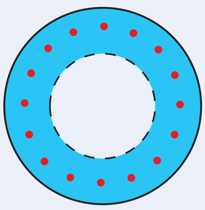
FREEZING STAGES



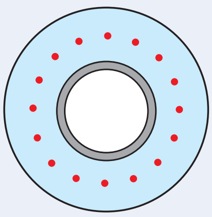
Freezing stage
the frozen wall develops



Freezing stage
gaps between frozen
columns are closed



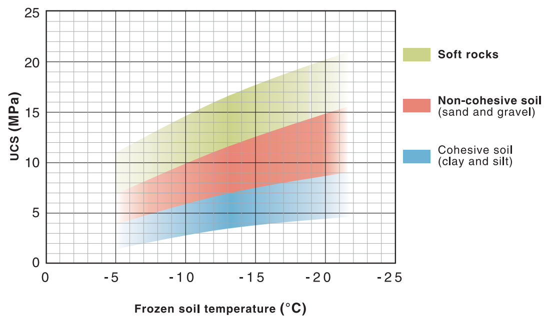
Freezing stage is completed
Design thickness and
temperature are reached

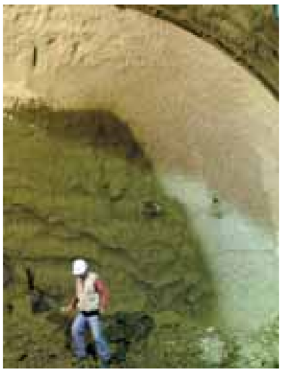


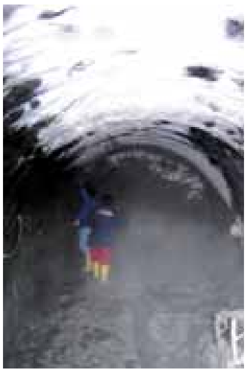
Maintenance stage

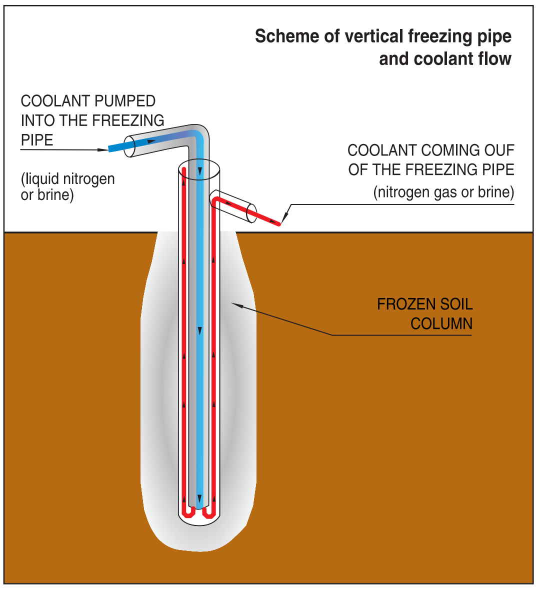
The AGF process involves freezing water within soil volumes, at a preset temperature, based on a known pattern, by extracting heat from the ground through special heat exchangers named freezing pipes.
Soil cooling is obtained by circulating a low temperature liquid within the soil volume to consolidate: heat is extracted and dissipated.

Freezing alters the hydraulic properties of soil or rocks *(making them watertight)*, as well as the mechanical features. The compressive strength of frozen soil varies according to soil or rock type and increases as temperature decreases. The values generally applied are between -5 and -20°C; the corresponding strength values range between 3 and 20 MPa.
The correct measurement of mechanic, hydraulic and thermal properties of soil is crucial to the reliable calculation of freezing time, refrigeration power and capacity needed to achieve the design values.









Scheme of vertical freezing pipe and coolant flow

Physical soil properties (mechanic and hydraulic)

- natural unit weight (gamma n)
- solid unit weight (gamma s)
- dry unit weight (gamma d)
- water content (w)
- saturation degree (Sr%)
- granulometric analysis and mineralogic composition
- salinity
- water table temperature
- water table velocity
- soil permeability coefficient (k)

Thermal soil properties

- thermal capacity (C)
- thermal conductivity (K)

AGF involves the following stages:

Freezing stage: heat is extracted from the ground and a frozen ground wall is created with thickness and temperature set forth in the project.

Maintenance stage: the flow of heat extracted is appropriately regulated to prevent further development of the frozen volume and avoid the deterioration of the features achieved in the previous stage *(thawing)*.

Depending on the coolant used, two methods can be adopted:

- **liquid nitrogen freezing, also named 'open circuit' or 'direct' method**: the coolant (*compressed gas in a liquid state – temperature -196°C)* circulates in an open circuit and after passing through the freezing pipes is released to the atmosphere in the gaseous state;
- **brine freezing, also named 'closed circuit' or 'indirect' method**: the coolant *(calcium chloride brine with freezing point between -40 °C and -50 °C)* is pumped through the freezing pipes at a temperature of - 30/-35°C: as heat is extracted from the ground the brine gets warmer and returns to the refrigeration system to be re-cooled and re-circulated into the circuit.

Choosing either one of the two methods mainly depends on economic factors and jobsite logistics, as well as the time needed to freeze the soil volume.
The average freezing power *(calculated in terms of electric power or amount of nitrogen)* needed to freeze one cubic metre of soil with 30% water content can be estimated as follows:

Indirect ground freezing *(brine)*
50 - 150 kWh/m^3

Direct ground freezing *(liquid nitrogen)*
1.000 ÷ 2.000 l/m^3

During maintenance stages, cooling powers and nitrogen volumes are generally reduced by 40-60%.

The refrigeration power ranges above stated, do not take into account local factors, related to the peculiarities of each project, such as abnormal soil or water temperature, high salinity, length and type of insulation of the coolant distribution system and the inactivated lengths of freezing pipes to calculate the heat losses.

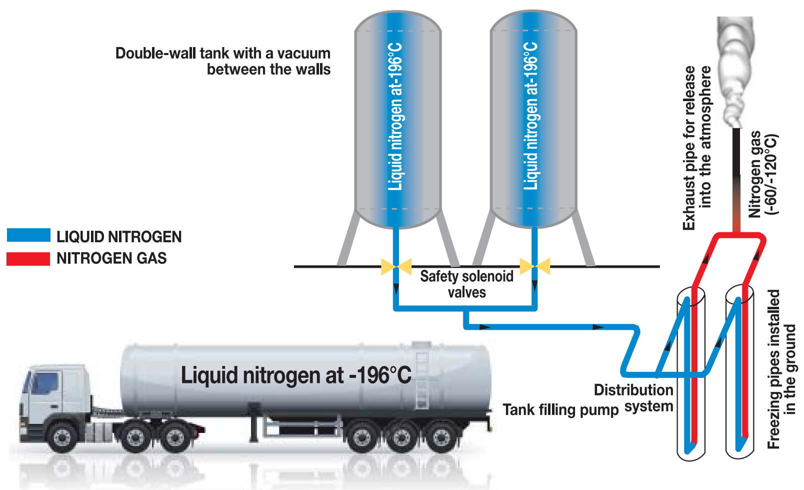
Ground freezing with liquid nitrogen

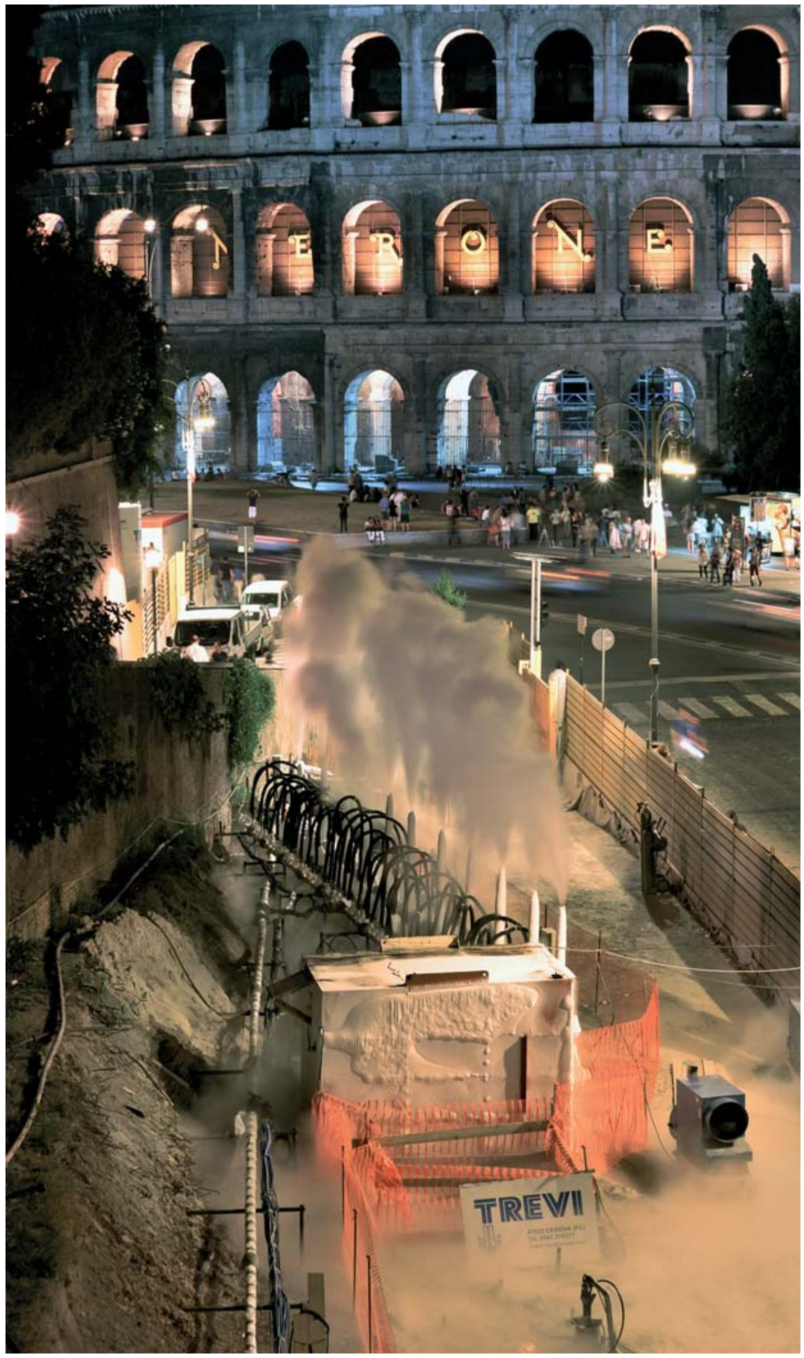
Ground freezing with liquid nitrogen is especially suitable for the following applications:

- **short interventions**
- **small volume** *(up to a few hundred cubic metres of soil)*

Nitrogen is a non-toxic and non-flammable gas that makes up to 78% of air.
Liquid nitrogen at a temperature of -196°C is pumped into the freezing pipes through the distribution system. Nitrogen gets “warmer” as it absorbs the heat from the ground and reaches the outlet of the freezing pipes through the return circuit, to be released to the atmosphere as a gas.
In addition to the refrigeration power resulting from change from liquid to gas state, the system also exploits the refrigeration power generated by the heat drop from the gas evaporation temperature and the temperature of the gas released to the atmosphere. The temperature of nitrogen gas at the pipe outlet is a good compromise between cost-effective gas exploitation and intervention timing: temperature usually ranges between -60 °C and -120 °C.
In AGF with liquid nitrogen, materials traditionally used in the cryogenic industry are commonly adopted *(copper and stainless steel)* to prevent any risks of breakage due to cold temperature, as they ensure higher resistance to cold brittleness. Moreover, the nitrogen delivery pipes and connection pipes between the delivery system and pipe inlets are insulated with suitable material.
The nitrogen freezing system is made up as follows:

- **one or more double-wall tanks** fitted with evaporation system and liquid nitrogen compression system, which allows to feed the freeze pipes with no need for pumping systems
- **freeze pipes** in which liquid nitrogen circulates and evaporates
- **distribution system** delivering liquid nitrogen from the tank to the freeze pipes, and after change to gas state within the pipes, to the exhaust for release to the atmosphere.

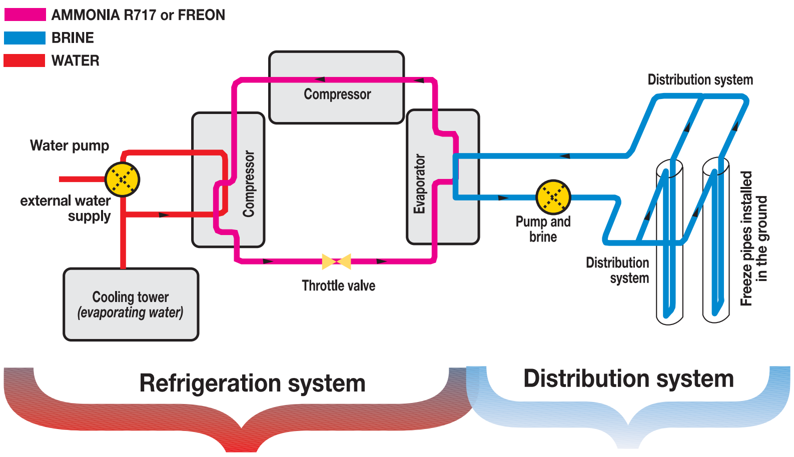




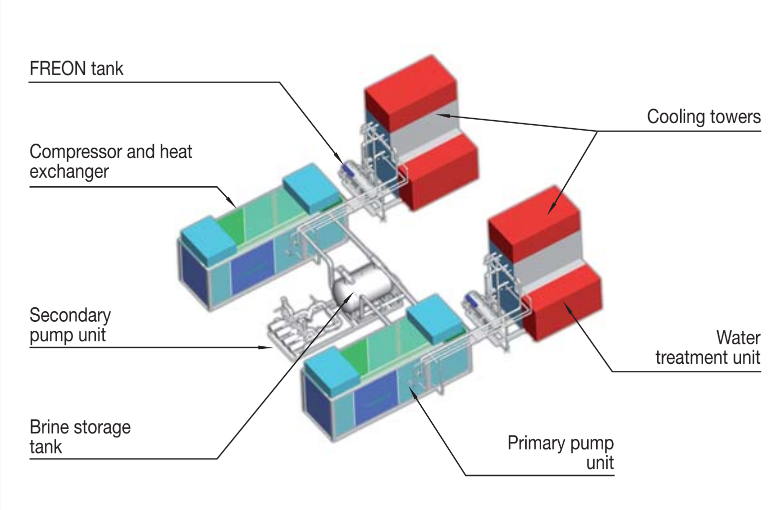
With respect to indirect freezing method (brine), the direct method (liquid nitrogen) has the following features:

- **high refrigeration power**
- **shorter freezing times** *(usually 2-7 days)*
- **simple freezing system** – lower set-up cost
- **use of higher quality materials** traditionally used in the cryogenic industry *(stainless steel and copper)*
- average **low temperatures are easily reached in the ground**, thus ensuring high strength
- **wider range of applicability in case of moving groundwater** *(water flow rate < 8 m/d)*
- **higher cost** due to continuous nitrogen consumption *(namely in case of large and long-lasting treatments)*
- **application problems in tunnels** on lengths of more than 500-800 m.

Ground freezing with brine



Scheme of brine refrigeration system



Ground freezing with brine is especially suitable for the following applications:

- **long lasting projects** requiring frozen ground to be maintained for more than one month;
- **large volumes of ground to be frozen** - more than 500 cubic metres.

Brine *(water solution of calcium chloride)* is cooled to a temperature between -28 °C and -35 °C, by exchanging heat with the coolant inside the refrigeration system, usually ammonia or Freon.
Brine is pumped into the freezing pipes through the delivery pipes. When flowing out of the freezing pipes, the "warmer" brine (due to absorption of heat from the ground) is returned to the refrigeration system through the return circuit to be refrigerated and re-circulated into the freezing pipes for a new cycle.

The system relies on the refrigeration power generated by the difference between inlet and outlet temperatures of the brine in the refrigeration system. This temperature difference usually ranges between 3 and 5°C.
As it is the case for liquid nitrogen, also in the brine freezing method, materials with high resistance to cold brittleness are generally used to prevent breakages due to cold temperatures. Steel is commonly used, instead of higher quality materials such as copper or stainless steel. The brine delivery/return pipes and connection pipes between the delivery/return systems and freeze pipe inlets are insulated with suitable material.

The brine freezing system is made up as follows:

- **industrial refrigeration system** *(ammonia or Freon are generally used as refrigerants)* and brine pumping system
- **freezing pipes** for brine circulation
- **distribution system delivering brine** *(coolant)* from the refrigeration system to the freeze pipes and vice versa.

With respect to direct freezing method (liquid nitrogen), the indirect method (brine) has the following features:

- **lower operating costs** for large and long-lasting treatments
- **higher start-up costs** of the refrigeration system
- **complex system** in terms of installation, operation, management and maintenance of the refrigeration systems
- **lower refrigeration power and longer freezing times** *(usually 20 ÷60 days)*
- **limited scope of application** in case of moving groundwater *(water flow rate < 2 m/d)*

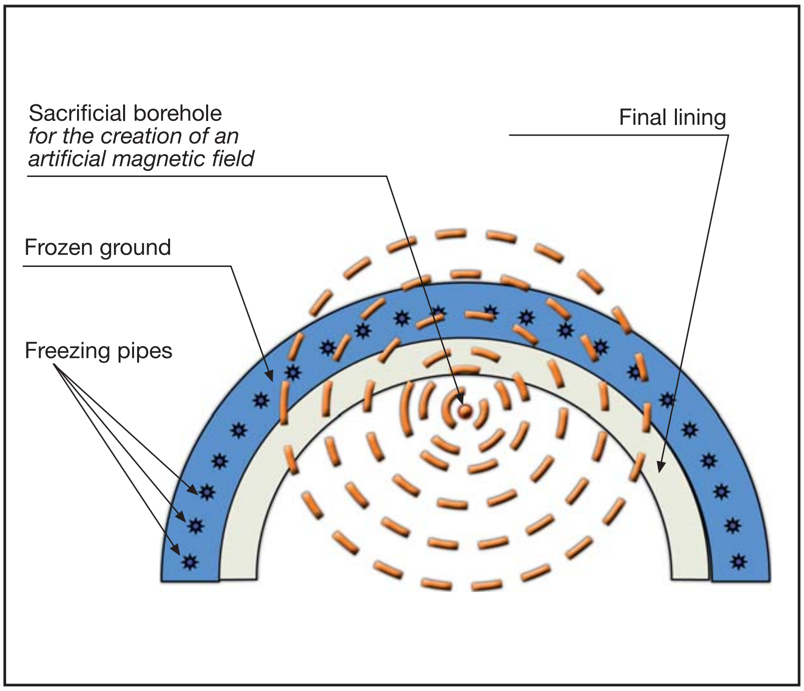
Mixed nitrogen-brine freezing system

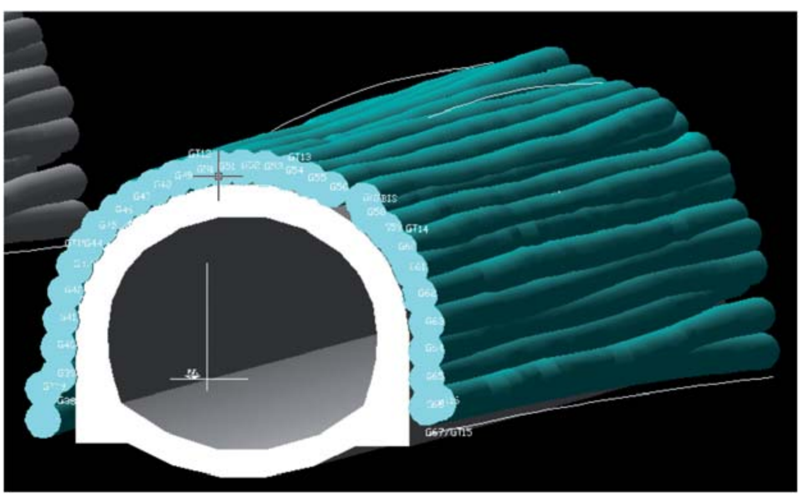
The mixed nitrogen-brine freezing system combines the advantages of the two methods described above.
By implementing some changes and replacing a few components, it is possible to use the same freezing pipes to circulate nitrogen first and brine later, or vice versa.
These special pipes must not be subject to cold induced brittleness, as any leakage of brine from the freezing pipes – when performing brine freezing – causes soil contamination and hinders freezing.
As a result materials with high resistance to cold induced brittleness suitable for cryogenic use are adopted.
The patterns and ratios between freezing pipe sections shall be specially designed and manufactured to maximize heat exchange.

The main features of the system are the following:

- **Possibility to use nitrogen for freezing stage and brine for maintenance stage**, to take advantage of the pros and cons of each method.
- **Versatility of use**: at any time it is possible to choose the freezing method, with short conversion times.
- **Improved safety**, as nitrogen can be used in the event the following problems occur:
  - pattern and/or incorrect positioning of freeze pipes
  - non-homogeneous soil
  - unexpected water flows and flow rates
  - broken freeze pipes.

Directional drilling





To ensure homogeneous ground freezing, proper freeze pipe positioning is crucial. The pattern and distance between the pipes must be respected throughout the length of the same, which means no deviation beyond the design tolerances is admitted.

To tackle the situations in which conventional drilling is risky or impossible, the Trevi group has designed and adopted the innovative directional drilling method **TDDT *(Trevi Directional Drilling Technology)***, based on the already known **HDD *(Horizontal Directional Drilling)***.

A number of *"dedicated"* control and guide systems have been developed to ensure accurate and rapid measuring, in order not to slow down drilling. The method involves the creation of a reference system based on an artificial magnetic field with known coordinates. A measuring device is installed on the drilling string: it detects and measures the string coordinates with respect to the artificial magnetic field. Depending on the drilling evolution being measured and preset deviation tolerances, any corrections are made by means of special asymmetric tools.

This system has been tested and successfully implemented in the construction of some **underground stations in Naples**. The project involved the use of ground freezing for the realization of station tunnels. **TDDT with max deviation lower than 0.4% has been used to drill the boreholes for the installation of 55m-long freezing pipes.**

Monitoring and controls

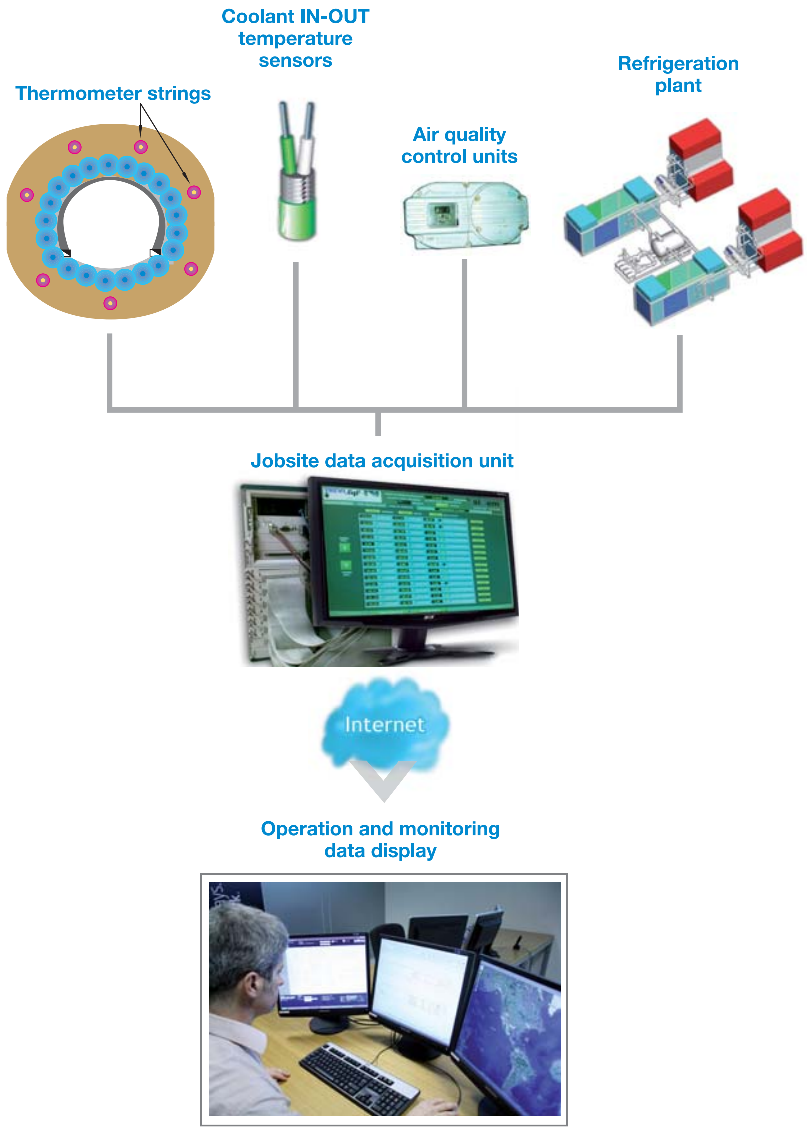
To control ground freezing and maintenance stages, it is important to constantly monitor soil temperature variations over time.

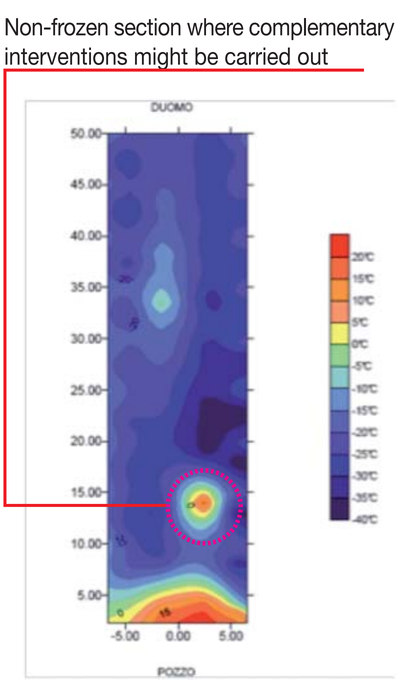
Temperatures are measured by thermometers placed inside drilled boreholes as long as the freezing pipes. The thermometers consist of a string of thermometers set at intervals of 3/5 m and placed along the contour of the frozen wall at known and measured positions.

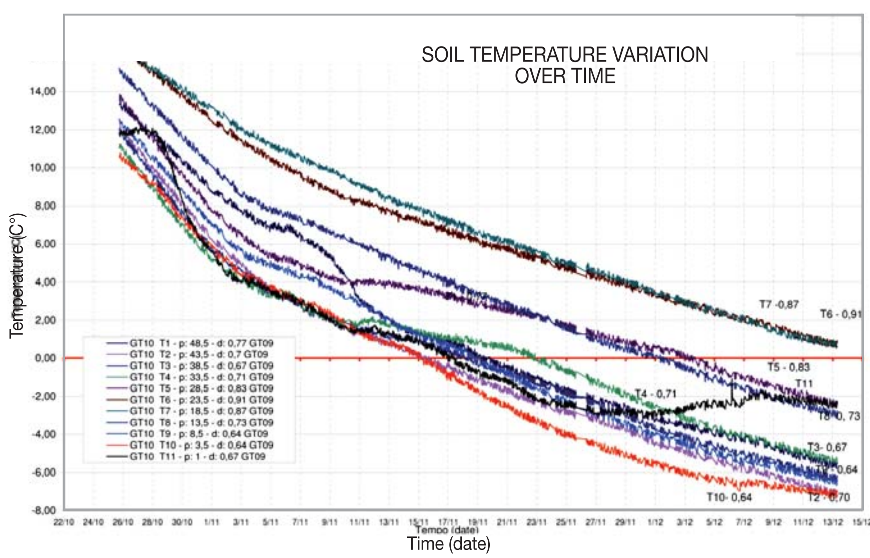
TREVI has specially developed a temperature measuring, display and management system.
The monitoring data as well as any abnormal data are sent via Internet to the operators and technicians, to allow for real time control and management of ground freezing.
The analysis of temperature variations based on time and distance from the freezing pipes allows to monitor the frozen wall as it develops, and to define with certainty when the process is completed.

Any abnormal data and areas of potential problems can be identified so as to perform early warning. As a result it is possible to highlight potential anomalies and problematic areas, therefore giving early warning to promptly react before the actual excavation takes place.

In the middle of the area to be frozen, observation holes are realized and fitted with a slotted pipe. By controlling water pressure it is possible to follow the development of frozen wall and formation of joints. The holes are also used as relief for water overpressure.







Case History

With the acquisition of Rodio, the Trevi group has also acquired the know how derived from a number of complex projects in which ground freezing proved to be a winning solution.
Some of the major projects realized over the last few years are described below.

2002-2003
SOPHIA SPOORTUNNEL (The Netherlands)
The project envisaged the realisation of 14 cross passages between the two tunnels of the Betuweroute freight railway – diameter 8.65 m, length 4.240 m, drilled by TBM. The cross passages have been excavated from 7 service shafts positioned at 520 m distance from one another, by realising a frozen wall having both hydraulic and structural function, as a temporary support to excavation walls until completion of internal concrete lining. The soil affected by the intervention mainly consisted of loose sands and clays under the water table. **Roughly 4,400 cubic metres of soil have been frozen using both liquid nitrogen and brine.**

1999-2000
CERN LHC project (France)
The project involved the drilling of 2 shafts to access the CERN underground tunnels. The shafts – 25m and 15m diameter, 70m depth – have been drilled by realising a 3-4m thick frozen wall having both hydraulic and structural function, as a temporary support to excavation walls until completion of internal concrete lining. The soil affected by the intervention mainly consisted of glacial deposits overlaying molasse bedrock made of marls and sandstones. **Roughly 25,000 cubic metres of soil have been frozen using the brine freezing method.**

2004-2009
NAPLES UNDERGROUND
Stations of Piazza Garibaldi, Università and Toledo (Italy)
The project involved the realisation of large rectangular shafts *(about 50 x 25 m)* up to 45 m depth. The platform tunnels were excavated from the shafts, as well as the inclined tunnels to allow passengers to reach the platforms – 50m length, in the presence of a 2-4m thick frozen wall having waterproofing and/or structural function for the ground being excavated, depending on geological conditions. The ground through which the tunnels were driven consisted basically of Neapolitan yellow tuff with different levels of fragmentation overlaid by a transition layer termed "cappellaccio". Pozzolana sands were found above these formations. The aquifer was at 10m from the ground level, through the tuff layer as well, in a complex system of sub-vertical fractures *("scarpine")*. Traditional drilling would have been risky or almost impossible; as a result TDDT *(TREVI DIRECTIONAL DRILLING TECHNOLOGY)* was chosen to drill the boreholes for the installation of the 55m-long freeze pipes – more than 40,000 m and max deviation lower than 0.4%. The complex surface situation in the Toledo station forced to excavate the station shaft misaligned with respect to the platform tunnels. As a result, an additional tunnel *(bypass tunnel)* was realized, from which the railway tunnels and platform tunnels were excavated. **Roughly 60,000 cubic metres of soil were frozen as a whole, mainly using the mixed method (liquid nitrogen for freezing and brine for maintenance).**

World leader in ground engineering, Trevi has been working for more than 50 years throughout the world, strengthening its ability to provide solutions to any ground engineering issues. Trevi works in the field of special foundation, soil consolidation, dam remedial works, tunnel construction and consolidation, marine works, rehabilitation and cleanup of contaminated sites and construction of underground automatic multi-storey car parks. Trevi is committed to continuous innovation and search for solutions to complex problems of civil engineering worldwide.
Experimenting cutting-edge technologies, entrepreneurship and investing in research and human resources are the strengths of a company based in more than 30 countries.

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