AGS (HK)

香港岩土及岩土環境工程專業協會
ASSOCIATION OF GEOTECHNICAL & GEOENVIRONMENTAL SPECIALISTS (HONG KONG)

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TUNNEL CONSTRUCTION GUIDELINES
04 - GUIDANCE NOTE ON GROUND FREEZING CONSTRUCTION

ARTIFICIAL GROUND FREEZING DEVELOPMENT

Artificial ground freezing (AGF) is a mature construction technique used worldwide in both city and coal mining construction. The AGF method is used to provide temporary support of excavations. Ground freezing has more than 100 year's history and it was first used in shaft construction in England and Germany in the 19th century. The table below has indicated the development of artificial ground freezing (AGF).

Development of AGF in Worldwide

Year	LOCATIONS
1862	The technique was first used in a coalfield in South Wales in England
1883	German engineer F.H.Poetsch invented the method and used in the shaft construction in mining operations and obtained the patent of this technology
1928	Russia started to use the ground freezing method in mining operations
1955	China began to use the ground freezing technology for shaft construction
1992	Artificial ground freezing became a popular construction technique used in railway project in China
Nowadays	Artificial ground freezing is being widely used in different construction areas over the world

Table 1 - AGF Development

Development of AGF in Hong Kong

Projects in Hong Kong involving the use of AGF (in terms of freezing methods)

- Ground freezing by Liquid Nitrogen Coolant
  Harbour Area Treatment Scheme (HATS) Stage 1
- Horizontal ground freezing by brine system
  Contract No. LDB 201 Sheung Shui to Chau Tau Tunnel
  Contract No.DC/2009/05
  HATS Stage 2 Construction of the Interconnection Tunnel and Diaphragm Wall for Main Pumping Station at Stonecutters Island Sewage Treatment Works. (Horizontal ground freezing employed at mine tunnel)
- Contract No. 703
  MTR West Island Line-Sheung Wan to Sai Yin Pun Tunnels
- Contract No. 704
  MTR West Island Line - Sai Ying Pun and Hong Kong University Stations and Sai Ying Pun to Kennedy Town Tunnels
- Vertical ground freezing by brine system
  Contract No.DC/2009/05
  HATS Stage 2 Construction of the Interconnection Tunnel and Diaphragm Wall for Main Pumping Station at Stonecutters Island Sewage Treatment Works. (Vertical ground freeing employed at the launching shaft as well as for TBM break-in and out)

Typical applications of Ground freezing technology:

Excavation and lateral support
Cross Passage
Stabilization of soil for TBM launch or retrieval
Mining

GENERAL PRINCIPLE

The principle behind ground freezing is the use of refrigeration to convert in-situ pore water into ice to strengthen the soil and to form an impermeable barrier. Ground freezing is carried out by installing and interconnecting a series of freezing pipes around the intended excavation. Figure 1 offers a clear scheme of vertical freezing pipe and coolant flow.

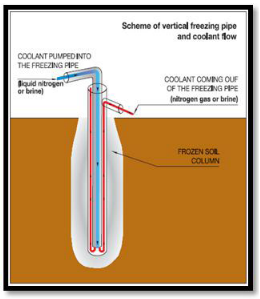
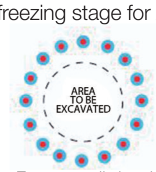


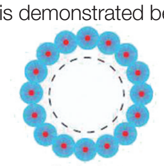
Figure 1 - Scheme of vertical freezing pipe and coolant flow

The coolant (liquid nitrogen or brine) is pumped down to the bottom of the central freezing pipe and went through the annulus of the coaxial freezing pipes. If nitrogen is being used as the coolant, it will be vented to atmosphere directly. For brine, it will be pumped through the connection pipes to cool down by the evaporator of a freezing unit, and will then be returned to the brine tank or recirculated to the freezing pipes again for the freezing process.

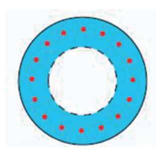
The freezing stage for AGF is demonstrated below:



The Frozen wall develops



Gaps between frozen columns are closed



design thickness and temperature are reached

Ground freezing is adaptable to practically any size, shape, or depth of excavation or structure and may be used in any moist soil or rock formation, regardless of structure, grain size or permeability. Figure 2 offers a useful guide to the suitability of the various geotechnical methods according to soil types and permeability values. It will be noted that the only method unrestricted by soil grain size is ground freezing.

Besides the suitability for all soil strata, artificial ground freezing is also an environmentally friendly method, owing to the non-toxic nature and reversibility of the treatment. The formed ice wall is completely impermeable and with high strength which is associated with a low construction risk and provides a safe working condition.

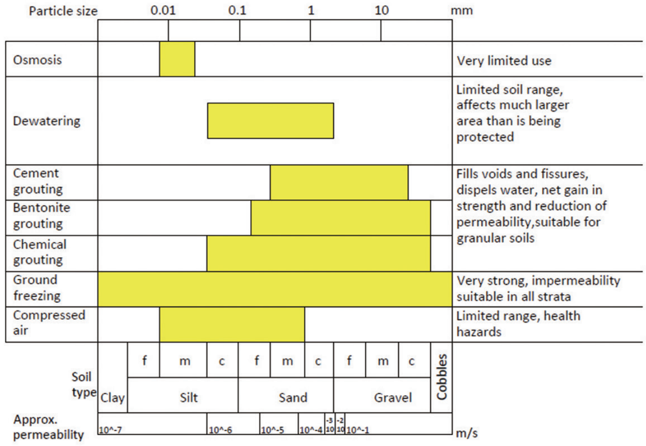


Figure 2 - Applicability of geotechnical processes according to soil type

TYPES OF COOLING AGENTS

There are two types of cooling methods in terms of the cooling agent used:

- Ground freezing with Brine
- Ground Freezing with Liquid Nitrogen

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

Ground freezing with Brine

Brine freezing is typically used for large, longer-term applications and it is the most commonly used cooling agent.

In practice, brine is cooled to temperatures between -28°C to -35°C and is then pumped into the freeze pipes through the delivery pipes. When flowing out of the freeze pipes, the warmer brine (due to absorption of heat from the ground) is returned to the refrigeration system through the return circuit. The brine is re-refrigerated and re-circulated into the freeze pipes for a new cycle.


Figure 3 - Refrigeration Compressor

The system relies on the refrigeration power generated by the difference between inlet and outlet temperatures of the brine in the refrigeration system. (Refer to Figure 4)

Compared to Liquid Nitrogen, the Brine has the following characteristics:

- lower operating costs
- more complex in terms of installation, operaton, management and maintenance of the refrigeration systems
- lower refrigeration power and longer freezing times
- limited scope of application in case of moving groundwater

Ground freezing with Liquid Nitrogen

Liquid nitrogen freezing acts more quickly than the brine system and has been used effectively for short interventions and emergency use.

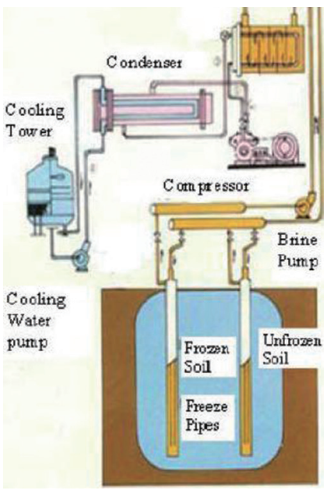


Figure 4 - Schematic diagram of brine freezing

As a deep-cold liquefied gas, liquid nitrogen, which has a condensation temperature of -196°C, is pumped into the freezing pipes from the distribution system (system for delivering liquid nitrogen from the storage tank to the freezing pipes). The liquid nitrogen gets warmer as it absorbs 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. (Refer to Figure 5) Compared to Brine, liquid nitrogen has the following characteristics:

- higher refrigeration power
- shorter freezing times
- simple freezing system
- wider range of applicability in case of moving groundwater

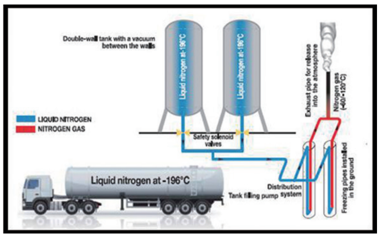


Figure 5 - Schematic diagram of liquid nitrogen

Figure 6 - Ground freezing with liquid nitrogen

COMPARISION BETWEEN TWO COOLING AGENTS

Characteristics of two cooling agents

	Quality	Liquid Nitrogen	Brine
Execution of Freezing	Physical condition of coolant	Liquid / Vapor	Liquid
	Minimum temperature achievable (theoretical)	-196°C	-28°C ~ -35°C
	Reusability of coolant	Impracticable	Standard
	Control of system	Simple	More complicated
	Shape of freeze wall	Often irregular	Regular
	Temperature profile in freeze wall	Great differences	Small differences
	Frost penetration	Fast	Slow
	Impact on freeze wall in case of damage to freeze pipe	None	Thawing effect
	Noise	None	Little

Table 2 - Characteristics of Liquid Nitrogen freezing and Brine freezing

Applications for two cooling agents

Ground Freezing Applications	
BRINE	**LIQUID NITROGEN**
• Shafts • Horizontal tunnels • Large, circular open excavation • Tunnel crown support	• Mining of small connectors • Stabilization of soil for TBM launch or retrieval • Emergency Cases

Table 3 - Applications for Liquid Nitrogen freezing and Brine freezing

GROUND FREEZING CONSTRUCTION SEQUENCES

The following steps describe a general construction sequence for ground freezing.

Site Preparation

- to ensure the surface water is collected and drained away from the proposed excavation
- to consider the utility lines that traverse the frozen zone or are located in close proximity to the frozen zone
- to consider the backup generating and refrigeration plant capacity

Freezing pipes installation

- spacing of the freezing pipes is based on engineering experience and thermal analysis is needed for verification of the final freezing pipe spacing
- it is important that alignment of all freezing pipes be verified after their installation
- installation of a freezing pipe in a drilled hole requires a hole larger than the diameter of the pipe
- grouting techniques are needed for backfilling the annular void between the pipe and drill hole in some cases. Cement grouting is preferable and practice demonstrates that cement grouting does not handicap freezing pipe withdrawing

Installation of coolant plant and coolant distribution manifold

- ground freezing coolant plants should routinely be capable of rapidly achieving and maintaining suction temperatures between -30°C and -40°C
- ground freezing coolant plants normally consists of condenser, brine water pump (if ground freezing with brine), cooling water pump and cooling tower
- a coolant distribution system is normally assembled in a series-parallel configuration
- In practice, for brine agent, the difference between the inlet and outlet temperatures should not exceed 2°C and the return temperature for each group of freezing pipe should not exceed 1.5°C

Instrumentation

- The recommended sensors for monitoring ground temperatures are called thermocouples (Refer to Figure 7) together with appropriate digital thermometers (Refer to Figure 8). Thermocouples are highly durable and accurate , which are adequate for field applications. They are inexpensive, tough, and easy to install.

Figure 7 - Thermocouple

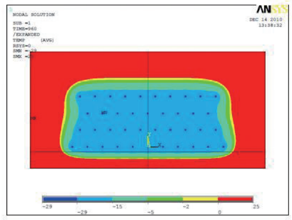
Figure 8 - Thermometer

Excavation and simultaneous protection of exposed frozen earth structure

- To reduce the impact of frost heave during ground freezing in case that the frozen wall is designed in a closed form, pressure relief holes are provided.
- Thaw grouting can be applied after 10~15 days of the natural thawing. A circle of grouting holes can be installed where each circle contains 6 number of grouting holes. Once the frozen wall has completely thawed and without any further grouting, measure the ground settlement for one month, if the ground settlement is less than 0.5mm in half a month, thaw grouting can be stopped.

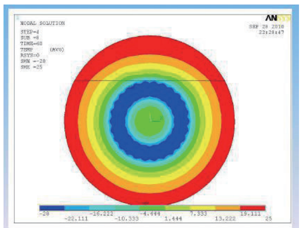
Thermal Analysis (Results based on DC/2009/05 project)

- Thermal Analysis is used to determine the ground freezing pipes arrangement and estimate the time and energy required to form the frozen soil wall to the design temperature. The model evaluates the required freezing time as related to freezing pipe spacing, coolant temperature and coolant flow rates.
- According to the analysis results as listed in Figure 9, a -15°C frozen soil wall is developed in 40 days for vertical ground freezing and 60 days for horizontal ground freezing (Refer to Figure 10)



Temperature field at 40 days
-15°C frozen soil wall is developed

Figure 9 - Vertical ground freezing

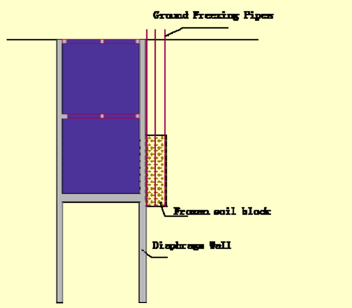


Temperature field at 60 days

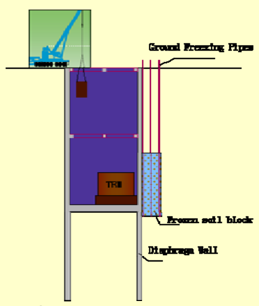
Figure 10 - Horizontal ground freezing

The construction sequences of vertical and horizontal ground freezing is based on a current completed project, Contract No. DC/2009/05. This project has involved both vertical and horizontal ground freezing. (Refer to the following drawings)

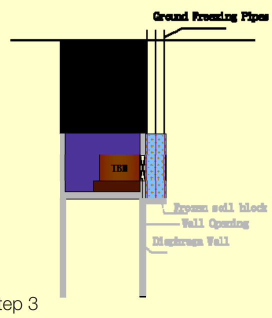
Typical Vertical Ground Freezing Construction Sequences
(Reference from DC/2009/05 Project)



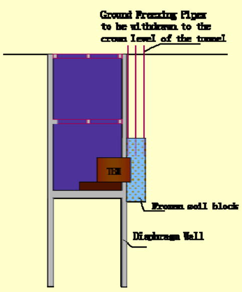
Step 1
- Install all vertical ground freezing pipes from existing ground
- Carry out ground freezing



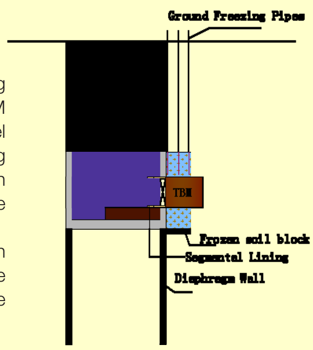
Step 2
- Carry out ground freezing
- TBM assemble



Step 3
- Make opening on diaphragm wall of launching shaft
- Erect TBM to break-up position
- Water stop need should encase the TBM

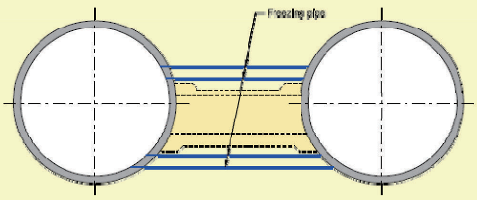


Step 4
- Withdraw the ground freezing pipes at the proposed TBM breakout area to the crown level of the tunnel and restart freezing to ensure watertight function (destroyed by the freezing pipe lifting operation)
- The frozen soil shall maintain the minimum performance requirement throughout the entire TBM breakout process

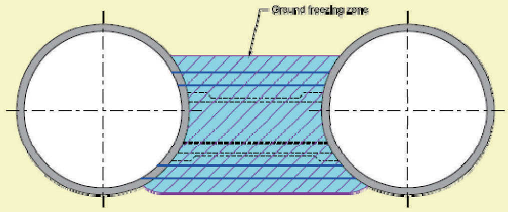


Step 5
- TBM breaks though the frozen block
- Install segmental lining and carry out annulus grouting when TBM moves forward
- Remove ground freezing pipes and carry out permeation grouting as contingency measures to thaw settlement as necessary

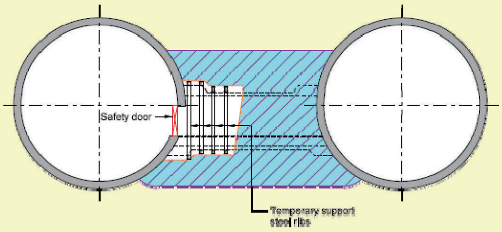
Typical Horizontal Ground Freezing Construction Sequences



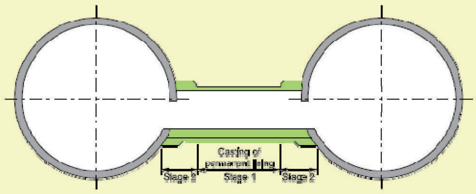
Step 1: Drilling of Freezing Pipes for double ring piped freezing
- Drilling from steel lining from one or both side of tunnel
- Use of double ring freezing to achieve required thickness
- Drilling with blow out preventer



Step 2: Setting up and Operation
- Setting up of condenser, brine tank, brine pump, clean water pump, cooling tower, power support control
- Keep active freezing for about 45 to 60 days with brine temperature of -28°C to -32°C to achieve ground freeze thickness of 1.5 m to 2 m
- Test Run of the system
- Monitoring of the temperature



Step 3: Excavation and Temporary Support
- Calculation for the temperature field to confirm the required average temperature and the thickness of the frozen wall
- Probe holes to inspect water ingress prior to excavation
- Safety door prior to excavation
- Steel ribs support with spray shotcrete lining as temporary support
- Thermal insulation layer applied between frozen soil and temporary support



Step 4: Construction of Permanent Support
- Concrete casting from the middle of Cross Passages
- Making connect with the tunnel lining in the final stage

REFERENCES

- Braun, B., Shuster, J. and Burnham, E. (1979). Ground freezing for support of open excavations. Eng. Geol. 13, 429-453.
- Harris, J.S. (1995). Ground freezing in practice. Pg 6, Fig 1.3, Applicability of geotechnical process according to soil type.
- Stoss K. and Valk, J. (1979). Uses and limitations of ground freezing with Liquid Nitrogen. Eng. Geol., 13, 485-494.
- Tsang, L., Cheung, A., Leung, C. and Chan, W.L. (2012). Artificial ground freezing for TBM break-through - Construction. Proc. of HKIE Geotechnical Division Annual Seminar, 125-130.
- Leung, R.K.Y., Ko, K.K.Y., Hu, H.B., Cheung, A.K.K. and Chan, W.L. (2012). Artificial ground freezing for TBM break-through - Design consideration. Proc. of HKIE Geotechnical Division Annual Seminar, 119-124.
- Tsang, L., Cheung, A., Leung, C. and Chan, W. L. (2012). Mined tunnel construction using artificial ground freezing technique for HATS 2A Project. Proc. of HKIE Geotechnical Division Annual Seminar, 131-132.
- Shuster, J.A. (1981). Engineering quality assurance for construction ground freezing. Eng. Geol., 18, 333-350.