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Artificial ground freezing application for tunnelling works in Hong Kong

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ABSTRACT: Artificial ground freezing (AGF) is a soil stabilization technique carried out by continuously refrigerating the soil and converts pore water to ice. The objectives are to create a water seal and strengthen the soil. The effectiveness of freezing depends on the presence of pore water to create ice, cementing the particles and increasing the strength of the ground to achieve the design strength. The AGF technique has been successfully applied in several tunnel projects in Hong Kong

1 INTRODUCTION

The principle of AGF is where refrigeration of the ground converts pore water to ice, binding together the soil particles as a form of improvement. The method involves a system of pipes consisting of an outer pipe and concentric inner feed-pipes. Freezing is then achieved by circulating a cooling fluid into the inner pipe and back up the outer pipe. During the process, heat is removed from the soil in a cylindrical pattern around freeze pipes. This process produces a column of frozen soil for each tube. The columns continue to expand until they intersect with each other. From here, the frozen mass will expand outwards creating a wall or solid ring of frozen soil. The formed ice ring will be virtually impermeable and the soil/ice structure will have greatly enhanced strength so that excavation work can proceed safely in dry condition.

2 DEVELOPMENT OF ARTIFICIAL GROUND FREEZING IN HONG KONG

2.1 Harbour Area Treatment Scheme Stage 1

The Hong Kong SAR Government is carrying out the Harbour Area Treatment Scheme (HATS) to reduce the water pollution in Victoria Harbour. In Stage 1 system, sewage is collected from the eastern end of Hong Kong Island, Tseung Kwan O in the eastern Kowloon and urban Kowloon to a central enhanced sewage treatment facility at the Stonecutter's Island via a network of deep tunnels and shafts. A short adit with a length of 31m was constructed between a pumping shaft and a riser shaft by using

pipe jacking method at Kwun Tong (Figure 1). TAM grouting was first chosen as the ground treatment method. After the completion of TAM grouting from the surface, a concrete disc at tunnel eye was formed through closely spaced drill holes at its perimeter. During an attempt to lift the concrete disc out, a sudden rush in of sand and water occurred. The lifting works were stopped and a steel beam was installed as a prop to prevent the concrete disc from falling down, causing a catastrophic ground loss. Several options were considered for dealing with this flooding issue and finally AGF was chosen as the best solution to ensure weathertightness.

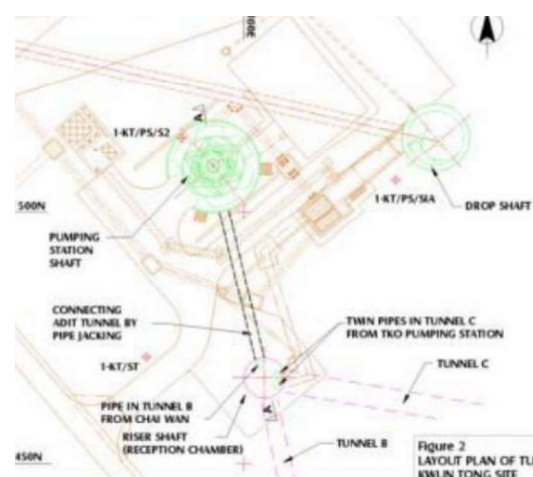


Figure 1. layout plan of tunnels at Kwun Tong site (Leslie et al. 2002)

The aim was to freeze a block of soil of approximately 1m thick around the tunnel eye in the diaphragm wall so that the concrete disc can be removed safely and the TBM can be launched. 7 boreholes were drilled from the ground surface with

a diameter of 195mm down to approximately 24m deep for the installation of freezing pipes (Figure 2). 2 additional boreholes were drilled on either side of the freeze pipes to install thermocouples for monitoring the rate of temperature reduction during active and maintenance freezing period. Another thermocouple was placed in a hole drilled in the concrete wall near the center of the tunnel eye.

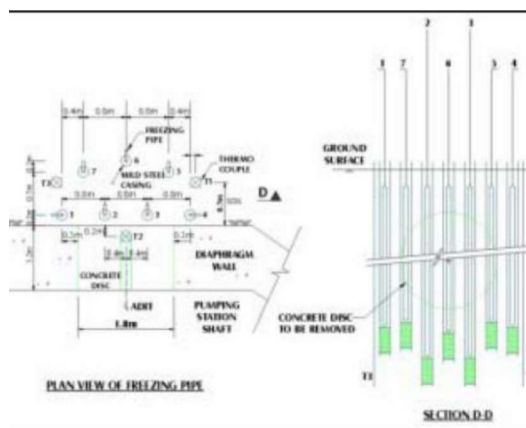


Figure 2. Arrangement of freezing pipes (Leslie et al. 2002)

The freezing continued for 4 days when the design temperature of below -10°C was achieved and verified by the thermocouples, indicating a satisfactory block of frozen ground has formed behind the tunnel eye. The concrete disc at the tunnel eye was removed and a stiff rubber sealing ring was bolted around eye. After the tunnel eye and the support frame for the sealing ring were in place, the TBM was lowered and moved into position and launching works started. Immediately after the tunnel face was supported by the TBM, the removal of freezing pipes was carried out. The TBM launching operation was then successfully carried out, indicating that use of liquid nitrogen in AGF could effectively strengthen the ground and provide an impermeable barrier.

2.2 Lok Ma Chau project (Contract No. LDB 201)

Lok Ma Chau project is an underground railway link including twin bored TBM tunnels of 3.7 km length with twelve cross passages.

Three cross passages were located within the Mai Po marshes area which is a haven for thousands of migratory birds during autumn and winter. The Environmental Protection Department requested that no work, site area, and instrumentation be installed from the ground surface within the Mai Po marshes Area. Ground freezing was finally chosen as ground treatment method from inside the tunnel for the construction of three cross passages.

It was reported by Martin et al. (2005) that 32 freezing pipes, 4 instrumentation holes, and 5 piezometers were installed (Figure 3). They were all carried out horizontally from the completed tunnel. Brine, as the cooling agent was circulated via the

double tube freezing pipes with inner tube of 40mm and outer tube of 60mm. The active freezing period was 5 to 7 weeks while the maintenance period was approximately 6 weeks. The thawing period was approximately 8 weeks. It was noticed during the active freezing period that water-tightness of the icing was reached only after 10 days which is largely prior to the necessary strength was reached.

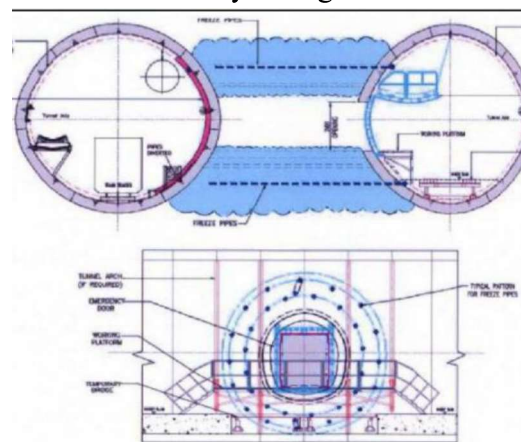


Figure 3. Typical section of the cross passages constructed by using ground freezing method (after Martin et al. 2005)

2.3 HATS Stage 2A

The Harbour Area Treatment Scheme (HATS) 2A comprises a 3.9 m internal diameter interconnection tunnel, connecting the existing and the proposed pumping stations. The tunnel consists of two portions (i.e. Part A and Part B tunnels). The Part A tunnel is 236 m in length and is built by an Earth Pressure Balanced TBM. The Part B tunnel is 14 m in length and is constructed by hand mined method. The TBM was launched from the shaft near the existing pumping station to the inlet chamber of the new pumping station (Figure 4). Ground freezing was chosen as the soil improvement method for not only TBM break through but also for the construction of Part B tunnel.

As the tunnel level is at water bearing sandy Alluvium strata, ground improvement at that level is required to avoid ingress of soil and groundwater into the shaft when the diaphragm wall is removed. AGF was applied as the ground treatment method using brine as cooling agent. A rubber packer fixed on a one-way hinged steel plate and two rows of steel wire brush with grease injection ports were also installed to ensure the watertightness (Figure 5). The frozen block, steel wire brushes and rubber packer form a robust water-stop system during the TBM launching.

The frozen soil block was formed by circulating -28°C brine solution in three rows of freezing pipes in staggered pattern from ground level down to the bottom level of the frozen block. The spacing of the pipes was 0.8m to 1m and the active freezing period is 40 days. Figure 6 shows the design of the frozen soil block. After all the temperature monitoring

readings reached the design temperature, water tightness of the frozen block was checked by a probe hole through the diaphragm wall. The diaphragm wall at the tunnel eye was then broken-off. There was no sign of any water ingress after diaphragm wall break-off and the frozen block was completely water-tight at this stage

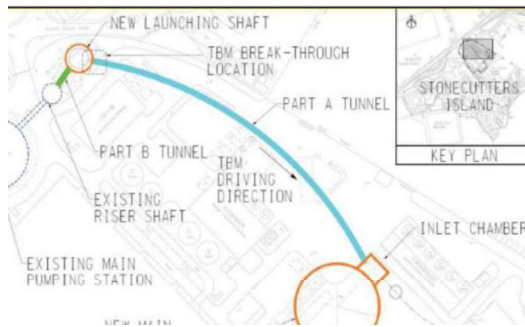


Figure 4. Tunnel layout plan (after Tsang et al. 2012)



Figure 5. One-way rubber packer (left) and steel wire brushes (right) (after Tsang et al. 2012)

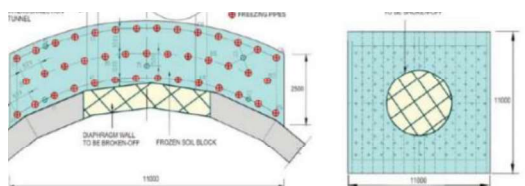


Figure 6. Frozen soil block plan (left) and elevation (right) (after Tsang et al. 2012)

AGF was also selected as the soil improvement method again to form a frozen soil ring in Alluvium and Marine Deposits as the temporary support for the construction of Tunnel B. The temporary support of the tunnel comprises a 2 m thick frozen ring and steel rib installed every 600 mm. The frozen soil ring would be formed by 2 rows of freezing pipes surrounding the tunnel using brine solution system. The temporary support and horizontal freezing pipes layout are shown in Figure 7.

Based on the thermal analysis, there were 44 freezing pipes used and the estimated active freezing duration was 60 days. Pressure relief holes would be

installed to release the water pressure developed within the frozen ring and also to check the condition of ring closure. It can be inferred that a confined frozen ring is formed when the water pressure within the ring increases. Excavation would commence when the readings at the thermal couples indicate that the temperature of the frozen ring reaches the design requirement. The advance length is 600 mm and steel rib would be installed for each advance length. Steel plate would be installed between steel rib and thermal insulator would be mounted onto the steel plate. During excavation, the soil temperature was closely monitored using the thermal couples.

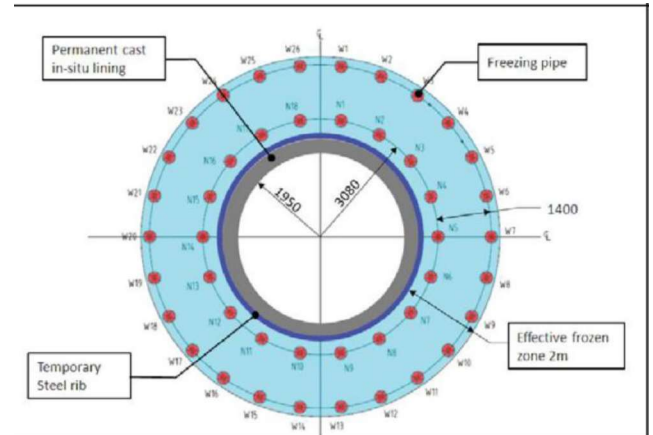


Figure 7. Tunnel temporary support and horizontal freezing pipe layout (after Tsang et al. 2012)

2.4 West Island Line project (Contract WIL No. 703)

During the construction stage of WIL Contract 703, it was confirmed that several steel sets were likely in the alignment of TBM up track tunnel which posed an obstruction to the TBM. To remove the steel set prior to the TBM excavation, AGF was adopted to stabilize the 30 m gallery in mixed ground.

There were total 22 nos. of freezing holes for installation of freezing pipes and 5 nos. of monitoring holes for installation of thermal sensors. All the holes were drilled sub-horizontally or inclined with a length of 33 m.

Freeze tubes in the form of two concentric pipes were inserted into the drill holes. To avoid introducing obstruction to the subsequent TBM drive, the tubes were made from HDPE (high density polyethylene). The brine solution was circulated at temperatures between -25°C to -30°C . It took roughly 8 weeks to achieve the designed ice wall thickness, which varied from 0.5 m for rock to 1.7 m for soil based on the thermal analysis. Eventually steel grossing 700kg was successfully removed without impact to the operating railway or third parties.

Due to obstruction of the existing structure in the tunnel alignment, the TBM cutter head was not able to excavate up to the permanent structure. This

meant that there was a span 2m long between the TBM shield and permanent structure that required support during the excavation. A pipe pile canopy system together with grouting had been envisaged to support the soft and weathered materials at tunnel crown. However, after the success of the ground freezing for the gallery excavation it was suggested to reuse the freezing plant to further reduce the construction risks of material ingress and associated settlement.



Figure 8. Gallery excavation (after Polycarpe et al. 2012)

The innovative design required a total of 15 steel freeze pipes to form a pipe roof, however 16 were placed acting as the structural component taking up the soil and water load, as they were steel they had to fall outside the TBM excavation. The frozen soil formed an ice canopy to act consolidate the strata around steel pipes and prevent water ingress and associated ground destabilisation at the crown.



Figure 9. Freezing in COB for tunnel break-out and connection (after Polycarpe et al. 2012)

2.5 Express Rail Link Contract No. XRL826

The Guangzhou-Shenzhen-Hong Kong Express Rail Link will provide high speed rail services between Hong Kong and Guangzhou, and a connection to the national high-speed passenger rail network. The Contract no. XRL 826 is the first Hong Kong section, connecting the boundary at Shenzhen River and Mai Po. Similar to the problem encountered in Contract LBD 201 of Lau Ma Chau project, all the six cross passages were located within the Mai Po Marsh Area and no work, site area, ground investigation and instrumentation be allowed in the area.

The purpose of the freezing pipe arrangement is to form a 2m thick ice ring around excavation area. Based on previous experience, the coverage of a single freezing pipe with a reasonable active freezing

period is approximately a circle with a diameter of 1m. Hence, two rows of freezing pipes are considered in the present case for generating the proposed 2m ice ring. The center to center distances of the freezing pipes are controlled around 1m. The proposed arrangement of freezing pipes is shown in Figure 10. There are total 42 nos. of freezing pipes in the proposed arrangement.

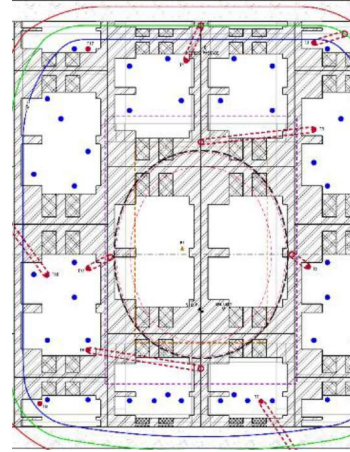


Figure 10. Arrangement of freezing pipes and monitoring instrumentation

3 KEY DESIGN CONSIDERATIONS FOR GROUND FREEZING WORKS

3.1 General

Site characterization is always the most important element for successful implementation of all underground engineering projects, including AGF projects. The type of soil encountered and the ground water condition must be accurately investigated to ensure an appropriate design. In particular, for AGF projects, the thermal properties of encountered soils and their mechanical properties after frozen should be tested. A high groundwater velocity (i.e. > 2 m/day, Harries 1995) may erode the ice ring at the same time it is being formed, yielding discontinuities of ice ring and hence longer active freezing period. High salinity sites would cause degradation of freezing temperature and lower frozen strengths. However, as salinity increases, frost heave, thaw settlement, and heaving force will decrease (Hu et al. 2010). Besides soil and groundwater properties, further considerations may include ambient air temperature, project timescale constructability and construction risks.

3.2 Types of cooling agent

There are two types of cooling agent generally used:

- Brine
- Liquid Nitrogen.

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

cooling agent recently. Brine temperatures of -25°C or less are typically sufficient for most projects. Commercial brines designed specifically for use with AFG are also available. The corresponding freezing pipe is a double concentric pipe system for circulation of brine. The outer pipe has a closed end while the inner pipe has an open end. The brine was pumped into the inner pipe from the freezing units and circulated back at the open end of the inner pipes. On its way back through the annulus between inner and outer pipes, the brine absorbed the heat from the ground. Liquid nitrogen freezing acts more

quickly than the brine system and has been used effectively for short interventions and emergency use. Liquid nitrogen boils at a temperature of -196°C and may be used in the place of a generic coolant. Due to the extremely low temperature of liquid nitrogen, freezing soil in contact with liquid nitrogen occurs much more quickly. Therefore, complete freezing can be accomplished much faster. However, due to its higher cost, this is usually reserved for emergency stabilization, short-term freezing, and small-volume projects.

3.3 Properties of frozen soils in Hong Kong projects

Mechanical property tests for frozen soil include unconfined compression testing, creep testing, frozen heave and thaw settlement testing, and tension tests. To predict active freezing period, thermal parameters such as thermal conductivity and specific heat capacity are required. Thermal conductivity (W/mK) is the amount of heat flowing through a unit area in a unit time under a unit temperature gradient while specific heat capacity ($\text{kJ/kg}^{\circ}\text{C}$) is the amount of heat required to raise the temperature of a unit weight of substance by 1°C . For evaluation of the stability of the excavation which is supported by artificial ground freezing treatment, the mechanical properties of frozen soils (i.e. Young's Modulus, shear strength and uniaxial compression strength) at anticipated freeze temperature are also required.

Due to the limited database, the parameters used in Hong Kong projects seem scattered with each other. These may be due to the properties of frozen soil may depend on its original properties. In addition, the tests were carried out in different laboratories according to different guidelines. Hence, further inputs are required to establish a mature and complete database of frozen soil properties for Hong Kong local use.

Table 1. Summary of thermal properties of frozen soil in Hong Kong projects

Soil	Project	Specific Heat Capacity ($\text{kJ/kg}^{\circ}\text{C}$)		Thermal Conductivity (W/mK)	
		Unfrozen	Frozen	Unfrozen	Frozen
Fill	Express Rail	3.20	2.20	1.99	3.93

		Link Contract No. 826			
		Express Rail Link Contract No. 826			
Marine Deposit	West Island Line Contract No. 703	3.10	2.20	1.40	2.66
	HATS 24 Stage 2A Contract No. DC/2009/05	4.30	2.60	1.37	1.69
	Express Rail Link Contract No. 826	3.10	2.20	2.33	4.23
Alluvium	HATS 24 Stage 2A Contract No. DC/2009/05	2.96	2.08	1.75	2.06
	Express Rail Link Contract No. 826	3.10	2.20	2.35	4.24
CDG	West Island Line Contract No. 703	3.00	2.20	2.12	3.54
Decomposed Volcanic	Lok Ma Chau Spur Line LDB 201	2.80	2.00	2.10	3.70

Table 2. Summary of mechanical properties of frozen soil in Hong Kong projects

Soil	Testing Temp. ($^{\circ}\text{C}$)	Project	UCS (MPa)	Young's Modulus (MPa)	Design	Design
					Creep Strength (MPa)	Creep modulus (MPa)
Clay	-5	Express Rail Link Contract No. 826	1.9	45	0.2	30
	-10		3.1	145	0.5	100
	-20		6.9	325	0.9	210
Marine Deposit	-15	HATS 24 Stage 2A Contract No. DC/2009/05	2.0	160	1.0	21
	-10	West Island Line Contract No. 703	3.8	121	0.9	--
Alluvium	-15	HATS 24 Stage 2A Contract No. DC/2009/05	3.5	315	1.75	36
	-10	West Island Line Contract No. 703	5.0	162	1.3	--
Metasiltstone	-5	Express Rail Link Contract No. 826	2.1	175	0.4	165
	-10		6.3	300	0.7	250
	-20		6.4	680	1.3	665
Decomposed Volcanic	-10	Lok Ma Chau Spur	2.4	142	--	--
	-15	Line LDB 201	2.5	166	--	--
	-5		2.8	172	--	--

4 DESIGN PROCEDURE

4.1 General

The ground freezing design is an iterative procedure. An initial arrangement of freezing pipes is estimated based on previous experience as the initial trial. With this arrangement, both thermal analysis and structural analysis are carried out. The flow chart of ground freezing design is shown in figure 11.

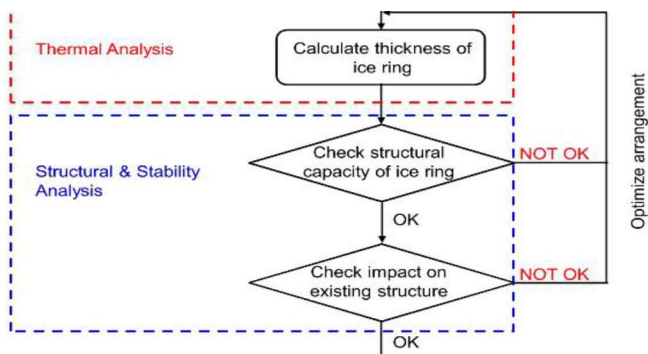


Figure 11. Proposed procedure of ground freezing design

4.2 Thermal analysis

The thermal analysis can be carried out by using different commercial finite element software, such as ABAQUS, ANSYS and TEMP/W. This analysis aims to determine the ice ring thickness against time with the predetermined arrangement of the ground freezing pipes. The analysis algorithm is based on the heat balance equation from the principle of conservation of energy.

The input data for thermal analysis include geometry, thermal properties of surrounding soil and boundary conditions. The initial temperature at boundary of the model should be set as the ambient temporary. On the other hand, the temperature at the locations of the freezing pipes was reduced progressively from ambient temperature to -28°C for brine and -196°C for liquid nitrogen. The thickness of freeze wall which is usually defined as the distance between two -10°C or -15°C isotherms will be input for structural analysis. Due to long period of active freezing, it should be carefully considered in the construction program. In order to tackle some emergency issues, a 24-hour stoppage time is suggested to be considered in the model so that the thickness of freeze ring could be determined conservatively to address the impact on breakdown of plants.

4.3 Structural analysis

The structural analysis could also be conducted by using commercial finite element software, such as ABAQUS, ANSYS and PLAXIS. The structural capacity of the freeze ring determined in the thermal analysis will be assessed. The analysis should consider the characteristic

behavior of frozen soil, including frost heave and thawing settlement. To consider the effect of frost heave, usually a positive volume strain is assigned to the frozen zone to model the expansion effect caused by formation of ice lenses. On the contrary, a negative volume strain was thus assigned to the frozen zone to simulate the thaw consolidation.

The structural analysis could provide the internal forces of temporary support (i.e. temporary steel ribs) and subsequent structural design. In addition, the impact of ground freezing works on adjacent existing structures and utilities could also be investigated.

5 CONCLUSION

The ground freezing technique has been successfully applied in the tunnel construction in Hong Kong in the past 20 years. In this paper, the application history of ground freezing technique in Hong Kong is described, including the purposes and construction details. In particular, the soil thermal properties and frozen earth strength properties in different projects are summarized and compared. It is found that further inputs are required to establish a mature and complete database of frozen soil properties for Hong Kong local use.

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