HKIE Civil Division International Conference 2012
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APPLICATION OF ARTIFICIAL GROUND FREEZING METHOD FOR TUNNEL CONSTRUCTION IN HONG KONG – A CONSTRUCTION CASE IN HARBOUR AREA TREATMENT SCHEME STAGE 2A

Chris K W Leung[1], Rupert K Y Leung[2], Anson K K Cheung[3], W L Chan[4]

Abstract

The works under Contract DC/2009/05 of the Drainage Services Department (DSD), the Government of the Hong Kong Special Administrative Region (SAR), includes two parts of interconnection tunnel. Part A tunnel uses soft ground TBM method and Part B tunnel uses hand mining method. Instead of conventional grouting method, artificial ground freezing is selected as the ground treatment for TBM break-through. Ground freezing is also adopted as a temporary measure for the Part B tunnel to strengthen the ground conditions around the tunnel for its construction.

This paper presents details of the design and construction of the ground freezing works for the TBM break-through and the mined tunnel. It also describes the laboratory testing for deriving the thermal and mechanical properties of the frozen soil necessary for the ground freezing design. In addition, the performance of the ground freezing system using brine is discussed and presented in the paper.

1. INTRODUCTION

There have been remarkable improvements to the water quality in the Victoria Harbour since the commissioning of Harbour Area Treatment Scheme (HATS) Stage 1 in 2001. The Government of the Hong Kong SAR is now implementing HATS Stage 2A under which sewage currently being discharged to the Victoria Harbour from the eight preliminary treatment works at northern and south-western Hong Kong Island will be intercepted and conveyed to the Stonecutters Island Sewage Treatment Works (SCISTW) by a deep tunnel conveyance system for centralized treatment before discharging to the sea. A new main pumping station will be built at SCISTW to draw the sewage from the deep conveyance system. To enhance the overall reliability and flexibility of the HATS conveyance system, an interconnection tunnel linking the existing main pumping station (constructed under HATS Stage 1) and the new main pumping stations at SCISTW will be provided (see Figure 1). Excavation for the new main pumping station and construction of the interconnection tunnel are both carried out under the Contract DC/2009/05. The works commenced in September 2009 and is now reaching the final stage of construction.

The interconnection tunnel is about 4m in diameter, 250m in length and is mainly founded in soft ground at about 30m below ground. The tunnel consists of two sections. The major

[1] Site Agent, China State – Shanghai Tunnel Joint Venture, 29/F, China Overseas Building, 139 Hennessy Road, Hong Kong, Email: chriskwleung@cohl.com
[2] Director, Hyder Consulting Ltd., 47/F, Hopewell Centre, 183 Queen's Road East, Wan Chai, Hong Kong, Email: rupert.leung@hyderconsulting.com
[3] Resident Engineer, Ove Arup & Partners Hong Kong Ltd., Level 5, Festival Walk, 80 Tat Chee Avenue, Kowloon Tong, Kowloon, Hong Kong, Email: anson.cheung@arup.com
[4] Engineer, Drainage Services Department, HKSAR Government, 5/F, Western Magistracy, 2A Pok Fu Lam Road, Hong Kong, Email: wlchan@dsd.gov.hk

section of about 235m in length (Part A Tunnel) starts from the new Valve Chamber (used as a TBM Launching Shaft during construction) and ends at the Inlet Chamber of the new Main Pumping Station. The remaining section of the interconnection tunnel (Part B Tunnel) connects the new Valve Chamber to the Riser Shaft of the existing Main Pumping Station (see Figure 1).

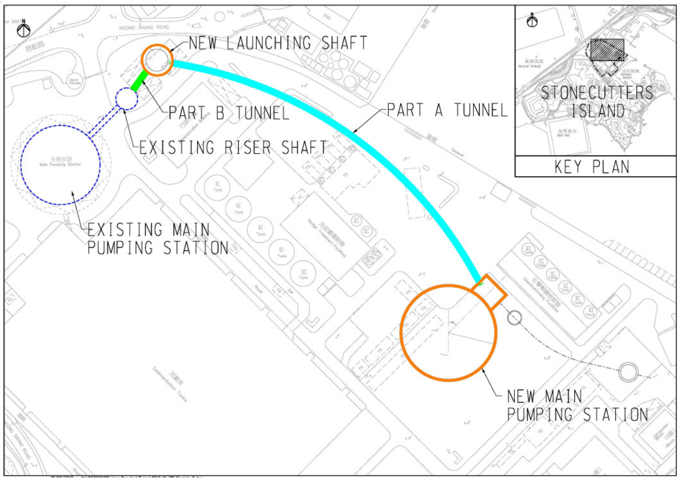

Figure 1 – Site Location Plan

2. DESCRIPTION OF WORKS

Ove Arup & Partners Hong Kong Limited (Arup) and China State – Shanghai Tunnel Joint Venture (CSSTJV) were appointed by DSD as the Engineer and the Contractor respectively for the Contract, with Hyder Consulting Limited (Hyder) acting as the Contractor's Designer to carry out the design of the Interconnection Tunnel.

CSSTJV and Hyder proposed to construct the Part A Tunnel using an earth pressure balance tunnel boring machine (TBM) and the Part B Tunnel by hand mining method. In parallel, the design and fabrication of the TBM was carried out in Shanghai, and in late 2011 the TBM was delivered, assembled and lowered to the Launching Shaft ready for the break-through operation.

For the TBM break-through, artificial ground freezing (AGF) technique using brine as the freezing agent was adopted to form a block of frozen soil in front of the tunnel eye of the Launching Shaft. This block of frozen soil gained significant strength and was practically impermeable such that stability of the ground and minimum water ingress into the Launching Shaft were ensured when the TBM cut into the soil layer behind the diaphragm wall (D-wall) at the tunnel eye location of the Launching Shaft. Details of the AGF design and construction procedures for the Part A Tunnel are explained in later sections of this paper.

The hand-mined tunnel, AGF technique was also used to form a cylindrical shaped frozen soil zone along the Part B Tunnel alignment. After the frozen soil gained sufficient strength and was checked to be water tight, hand mining would be carried out. Temporary steel ribs were also designed to be installed as excavation proceeded. Shotcreting, grouting and the construction of permanent lining would follow after completion of the tunnel excavation. Details of the AGF design and procedures for Part B Tunnel are also explained in later sections of this paper.

3. GROUND CONDITIONS

Series of ground investigation had been carried out in the design stage and construction stage of the project to provide comprehensive site-specific geological information for design. Figure 2 shows the geological profile in the vicinity of the launching shaft.

The materials encountered underground are briefly described as follows:
Fill – Medium dense, slightly silty fine to coarse SAND to very sandy clayey SILT, with some

angular to subangular fine to coarse gravel sized rock fragments.

Marine deposit (MD) – Firm to stiff, slightly sandy silty CLAY with occasional angular to subangular fine gravel sized rock and shell fragments.

Alluvuim (ALL) – Medium dense to dense, clayey silty fine to coarse SAND or stiff to very stiff, sandy silty CLAY, with some subangular to subrounded fine to medium gravel sized rock fragments.

Completely Decomposed Granite (CDG) – extremely weak to very weak, very sandy clayey SILT to slightly clayey silty fine to coarse SAND, with some fine to coarse gravel sized rock fragments.

The materials expected to be encountered at the location of TBM break-through from the launching shaft and the Part B tunnel, where artificial ground freezing was carried out, are essentially alluvial clay and sand, with marine deposits at the tunnel crown.

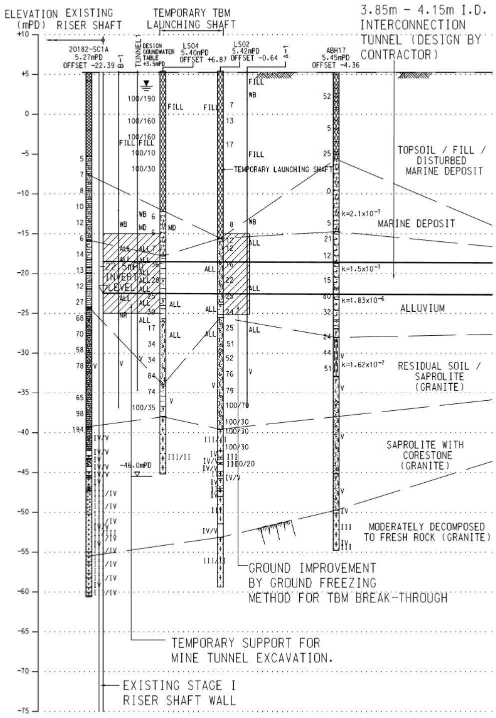

Figure 2 - Geological Profile

4. COMPARISON WITH OTHER GROUND TREATMENT METHODS

There have been a couple of cases in Hong Kong where AGF was adopted for mined tunnel adit construction in soil. For TBM break-in/break-out, there is no record that the technique has been applied locally. Permeation grouting and jet grouting, of which local specialist contractors have the expertise and experience, have been more commonly adopted. AGF nevertheless is a well established ground treatment technique in some other parts of the world, and one of the partners of the contracting joint venture for this contract, Shanghai Tunnel, has undertaken a number of tunneling projects in China using AGF.

Table 1: Comparison of Ground Treatment Methods

Property	Permeation Grouting	Jet Grouting	Artificial Ground Freezing
Strength	Some improvement	UCS up to 2MPa	CS up to 2 to 3.5MPa
Uniformity	Heavy reliance on workmanship	Heavy reliance on workmanship	High certainty
Permeability	10^{-7} to 10^{-8}m/s	10^{-8} to 10^{-9}m/s	Virtually impermeable
Environmental Impact	Potential contamination by grout	Potential contamination by grout	Less
Soils applicable	Granular soils	Clayey and silty soils	Can be applied in full range of soils

Apart from the availability of expertise, one important consideration for adopting AGF in this Contract was the anticipated heterogeneity of the soil to be encountered at the locations of TBM break-through and the mined tunnel. It was considered that AGF would provide more certainty in terms of the strength and water-tightness performance of the treated soil zone when compared to grouting methods. Table 1 summarizes a comparison of AGF with permeation grouting and jet grouting.

5. DESIGN CONSIDERATIONS

General design considerations for AGF are summarized as follows:
Groundwater Level – Completely submerged condition is a pre-requisite of AGF. In this project, with the lowest groundwater level at +1.0mPD and tunnel crown level at -18.0mPD, the tunnel is completely submerged and hence AGF is applicable.

Soil Material – AGF is considered generally effective in improving the strength of silty, clayey and sandy type of soil materials but less effective for bouldery soil though cut-off effect would still be achieved. The soil materials encountered along the tunnel alignment are mainly clayey, silty to sandy. Therefore the use of AGF in this case would likely to be more effective.

Salinity – Salinity affects the freezing point of water and hence the saturated soil materials. It also affects the mechanical properties of the frozen soil. Laboratory testing has been carried out on frozen in-situ soil samples to determine the thermal and mechanical properties of the soils.

Groundwater Flow – Groundwater flow affects the shape and time for formation of the frozen soil. In significant groundwater flow, more energy will be required to create the design frozen soil block. Groundwater flow has been monitored through the reading of piezometers in this case and found insignificant.

Frost Heave and Thaw Consolidation – With the existence of some sensitive building structures along the tunnel alignment, frost heave and thaw consolidation need to be considered. In view of this, laboratory testing to determine frost heave and thaw consolidation ratios has been carried out for the heave and settlement assessment.

5.1 Design Consideration of AGF for TBM Break-through

Figure 3 shows the arrangement of the AGF works at the TBM break-through from the launching shaft. Vertical freezing pipes installed from ground level were used to form the frozen soil block in front of the soft-eye in the launching shaft. Apart from preventing groundwater inflow that might lead to ground loss and flooding of the launching shaft, the improved frozen ground by AGF also served as a screen wall outside the soft eye zone of the launching shaft against the external ground and hydrostatic pressure such that the soft eye of the D-wall cofferdam could be broken off in advance of TBM launching.

Thermal analysis, as shown in Figure 4, was carried out using finite element software ANSYS to determine the arrangement of vertical ground freezing pipes and the heat flow rate required for choosing suitable freezing units. The arrangement of the freezing pipes was designed to enable the formation of an ice wall with sufficient thickness reaching the designed temperature. Finite element software PLAXIS was employed for stress analysis to verify the competence of the frozen soil zone against the external ground and hydrostatic pressure with the absence of D-wall at soft-eye zone. The stress diagram of the PLAXIS model is illustrated in Figure 5.

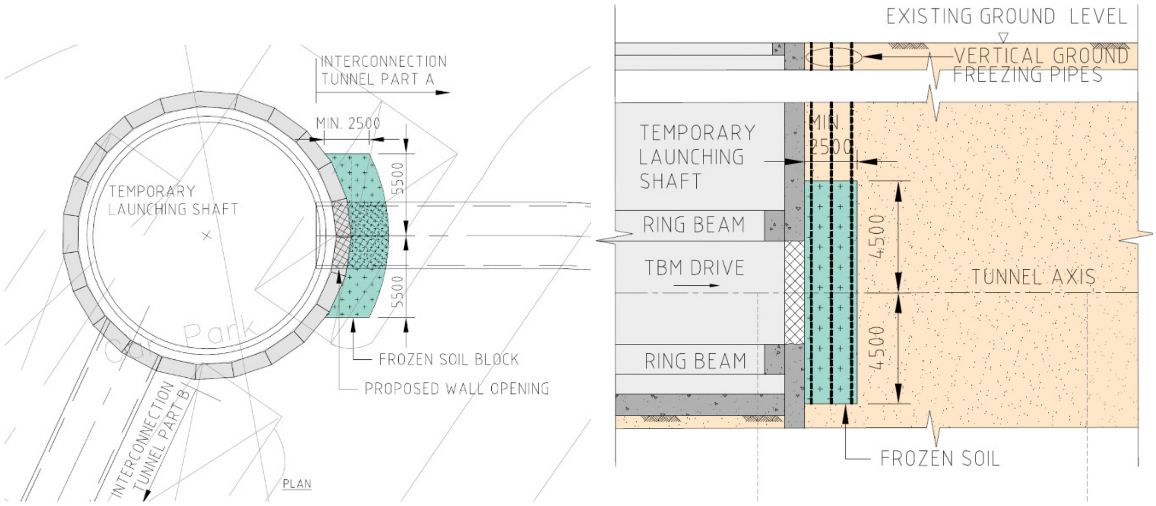

Figure 3 – Artificial Ground Freezing at TBM Break-through from Launching Shaft

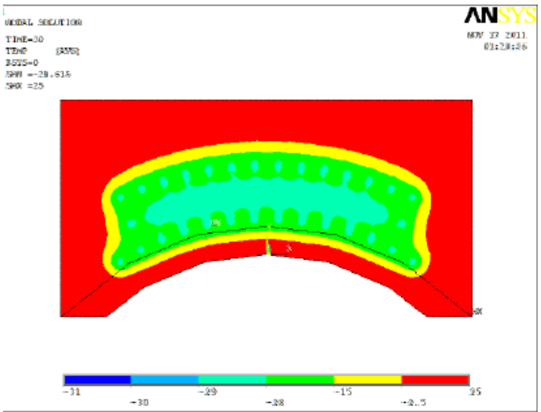

Figure 4 – Temperature Field of Frozen Soil Wall at Day 40 of Active Freezing

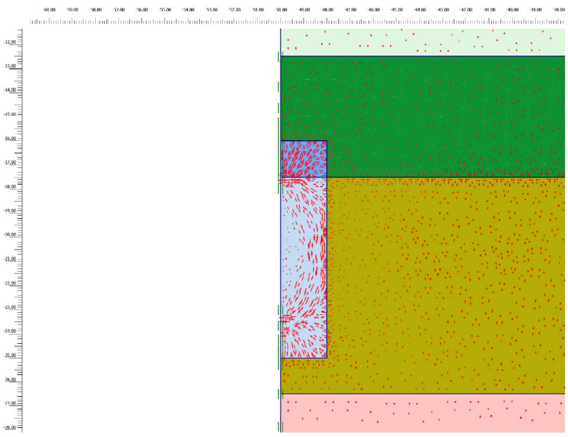

Figure 5 – Principal Stress Diagram of the Frozen Soil Wall from PLAXIS Model

5.2 Design Consideration of AGF for Mined Tunnelling

Figure 6 shows the arrangement of AGF works for construction of the hand-mined tunnel. Two layers of freezing pipes were installed in shape of rings around the adit excavation to withstand the overburden pressure, and to provide a dry yet safe working environment for the workers. In conventional design of mined excavation in soft ground tunnel, horizontal forepoling pipe piles are required as temporary support to the ground during excavation prior to erection of structural steel ribs/lattice girders. The frozen soil ring, which provided structural support by utilizing hoop action, allowed the omission of the forepoling works. Structural steel ribs though were still provided to control creep deformation of the mined opening prior to installation of permanent lining.

Similar to the design for TBM break-through, both thermal analysis to determine the freezing pipe arrangement and heat flow rate, and stress analysis to verify the thickness of frozen soil ring, had been carried out. Figures 7 and 8 illustrate the two analyses.

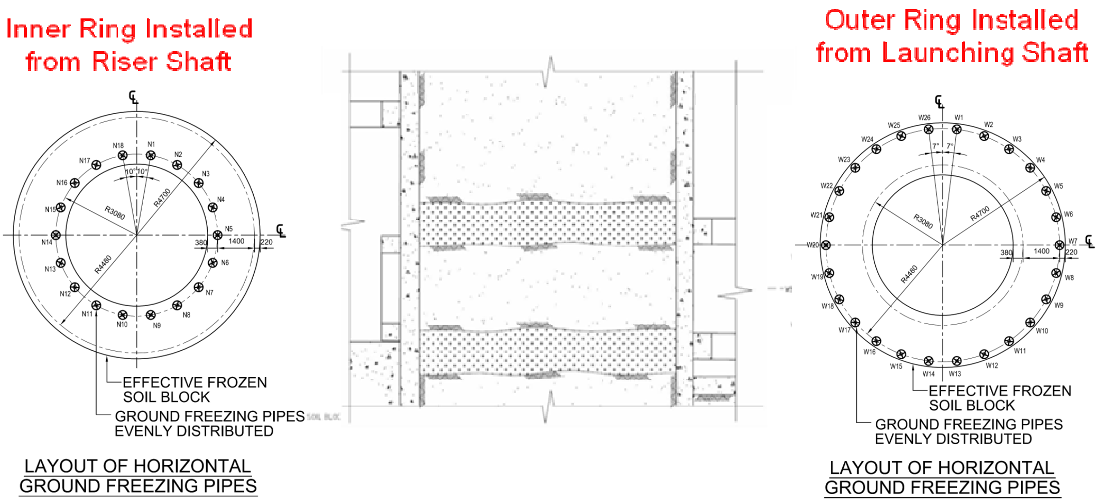

Figure 6 – Arrangement of Artificial Ground Freezing for Part B Tunnel Construction

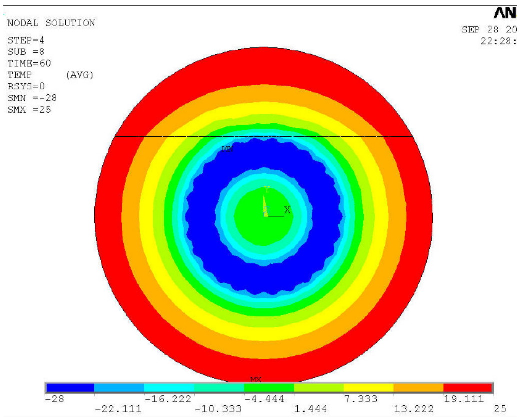

Figure 7 – Temperature Field of Frozen Soil Ring at Day 60 of Active

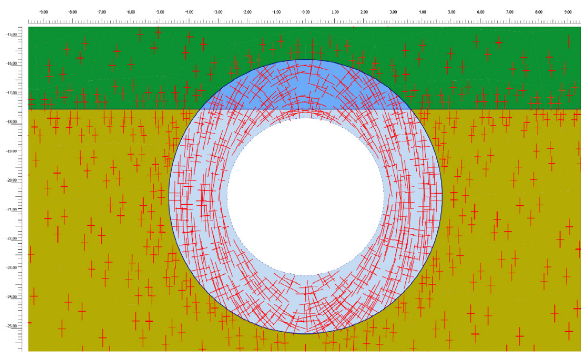

Figure 8 – Principle Stress Diagram of the Frozen Soil Ring from PLAXIS Model

6. DERIVATION OF DESIGN PARAMETERS

Design parameters, both for thermal and mechanical properties, were obtained from laboratory testing. Thermal properties included freezing point temperature, unfrozen and frozen specific heat capacity, and conductivity of soil at a range of temperature, while mechanical properties included frost heave and thaw consolidation ratios, uniaxial compressive strength (UCS), Young's modulus, and creep strength at a range of temperature. The laboratory tests were performed according to PRC Standard for Soil Test Method (National Administration of Quality and Technology and Department of Construction, 1999) and Standard for Coal Mining Industry (Department of Coal Industry, 1996). Test results of UCS and thermal conductivity of the soils are summarized in Figures 9 and 10.

Adopted design parameters are listed in Table 2. In general, the testing results showed that frozen soil strength is reduced by half under creep and showed relatively large thaw consolidation ratios. The design of ground freezing works has to take these two behaviours into consideration.

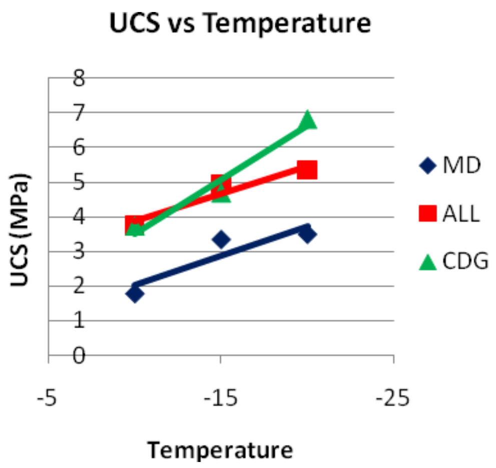

Figure 9 - UCS of Soils at Different Temperatures

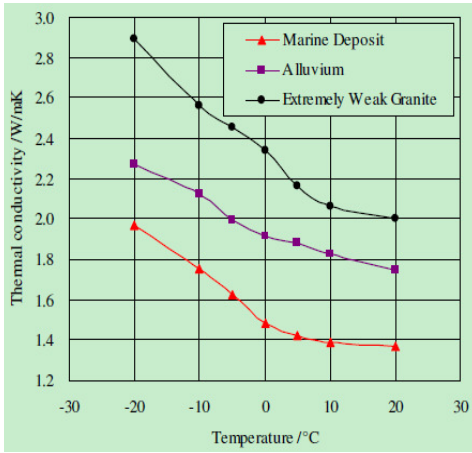

Figure 10 – Thermal Conductivity against Temperature

Table 2: Adopted Design Parameters of Soils

Soil	UCS (MPa)	Young's Modulus E50 (MPa)	Creep Strength (MPa)	Young's Modulus under Creep Stress(MPa)	Frost Heave Ratio	Thaw Consolidation Ratio
Frozen Marine Deposits	2.0	160	1.0	21	1.18%	13.00%
Frozen Alluvium	3.5	315	1.75	36	5.10%	8.65%

7. GROUND FREEZING FOR TBM BREAK-THROUGH FROM LAUNCHING SHAFT

7.1 Construction Sequence

The overall construction sequence of TBM break-through from the launching shaft is summarized as follows:

i. Install three rows of vertical drillholes from existing ground for installation of ground freezing pipes. The three rows of holes were spaced at 1m and the holes within each row were spaced at 0.8m.
ii. Start the ground freezing process using brine water system. The target brine temperature was -28°C. The target soil temperature was -16°C.
iii. After the temperature of the soil had reached the target temperature, manually remove the portion of the D-wall at the location of TBM launching.
iv. After the opening was made, position the TBM with the cutter face pressed against the exposed face of the frozen soil block. Fill the excavation chamber of the TBM with conditioned soil muck.
v. Lift the ground freezing pipes at the breakout area to above the tunnel crown, with the freezing operation maintained throughout the operation.
vi. Progressively drive the TBM through the frozen soil block. Carry out cement grouting around the outside of the TBM shield through the pre-installed grout tubes.
vii. Install the first ring of segmental lining and carry out annulus grouting.

viii. Gradually increase the temperature of the ground freezing pipes for pipe extraction. While the ground freezing pipes were being extracted, carry out permeation grouting to control the thaw settlement.

7.2 Instrumentation and Monitoring

At the location of the TBM break-through, thermocouple sensors were installed to monitor the temperature of the frozen soil. Figure 11 shows the arrangement of the thermocouple sensors. Five vertical steel pipes (T1 to T5) were installed for measuring the temperature changes. At each location, six thermocouples were installed vertically at intervals of 2 m from the top to the bottom line of frozen zone except monitoring point T5 where, in order not to cause any conflict with the TBM during launching, the steel pipe was designed to terminate above the crown level of TBM and only two thermocouples were installed. In total, 26 thermocouples were installed.

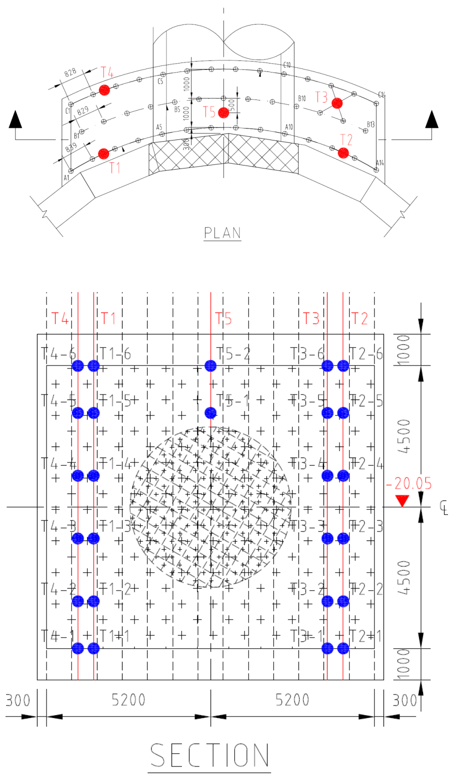

Figure 11 – Arrangement of Thermocouples at TBM Break-through at Launching Shaft

In addition, ground settlement monitoring and groundwater monitoring devices typical for underground excavation were installed.

7.3 Precautionary Measures

The following precautionary measures were in place for the TBM break-through operation:

i. A mechanical rubber seal was installed around the collar of TBM launching (Photo 1), and greased steel brushes were installed within the collar (Photo 2) as secondary measures to prevent groundwater inflow from the frozen soil block. They also served as additional measures to control inflow when the TBM cutter face passed through the frozen soil zone.

ii. Grout tubes were installed around the collar to allow emergency grouting in case of significant

Photo 1 – Collar and Mechanical Seal at TBM Launching

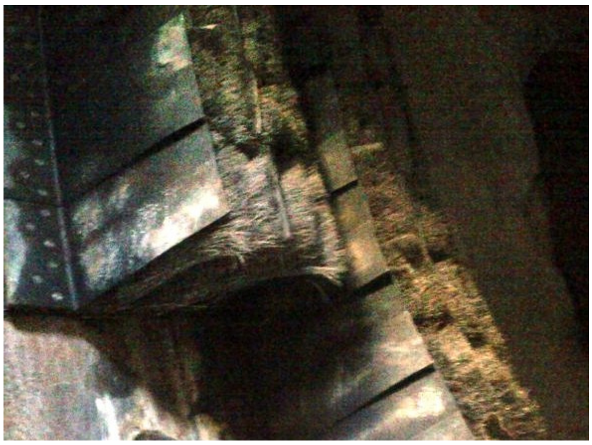

Photo 2 – Greased Brushes within Collar

leakage.

iii. The thermocouple sensors were used for continuously monitoring of the temperature of the frozen soil block during the pipe lifting operation and the TBM break-through operation.

8. GROUND FREEZING FOR HAND-MINED TUNNEL SECTION

8.1 Construction Sequence

The overall construction sequence of hand-mined Part B tunnel would be as follows:

i. Install two rows of horizontal freezing pipes – the inner row from the existing Riser Shaft and the outer row from the TBM launching shaft - around the proposed adit. The two rows of pipes were 1.4m apart and the holes within each row were spaced at 1m.

ii. Start the ground freezing process using brine water system. The target brine temperature was -28°C. The target soil temperature was -16°C.

iii. After the temperature of the soil reached the target temperature, carry out probing from the riser shaft to ascertain no water leakage through the frozen soil.

iv. Make an opening in the D-wall from the launching shaft.

v. Excavate and advance for 0.6m. Install the first steel rib.

vi. Excavate a further 0.6m and install the next steel rib. Repeat until the D-wall of the Riser Shaft was reached.

vii. Make an opening on the D-wall of the riser shaft. Strengthening work of the D-wall would be completed in advance.

viii. Apply shotcrete to the steel ribs.

ix. Construct the permanent adit tunnel lining.

x. Gradually allow the temperature of the ground freezing pipes to rise. Backfill the pipes with crement grout.

8.2 Instrumentation and Monitoring

For the Adit Tunnel, thermocouple sensors were installed from both the TBM launching shaft and the existing riser shaft to monitor the temperature of the frozen soil. Figure 12 shows the arrangement of the thermocouple sensors.

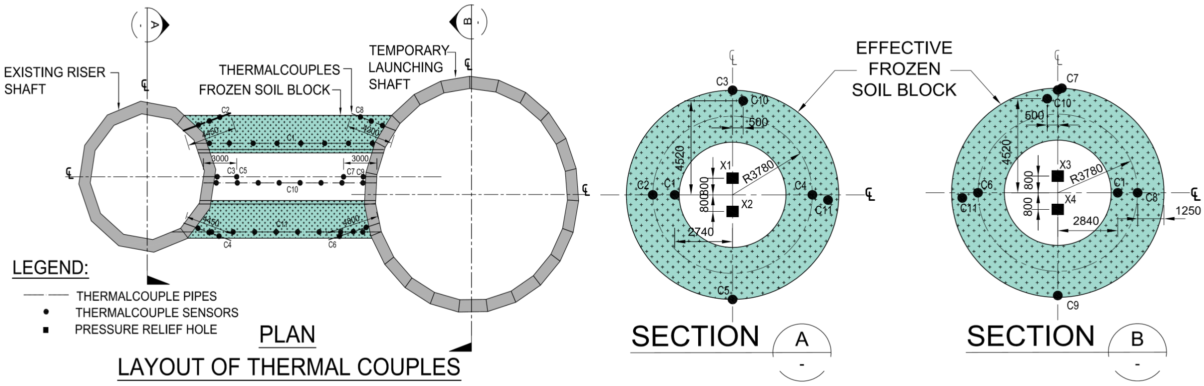

Figure 12 – Arrangement of Thermocouples for Part B Tunnel Construction

8.3 Precautionary Measures

As a precautionary measure, a flood door each capable of withstanding full hydrostatic pressure is to be installed at the opening at the Riser Shaft and Launching Shaft. In event of failure of the ground freezing causing significant inflow, the doors can be closed to prevent further inflow and hence excessive drawdown and settlement, so that mitigation measures can be implemented subsequently.

9. GROUND FREEZING SYSTEM AND PERFORMANCE

9.1 Description of the Ground Freezing System

Two freezing technologies are available in the construction industry, either using liquid nitrogen or brine. In this Contract, the brine system was selected and thus no pressurized storage tank was required, and less ground disturbance and frost heave would be induced as compared to the liquid nitrogen system. Using of brine is known as an indirect method. Unlike liquid nitrogen system, the brine system is not injected into the ground to freeze the soil directly. The freezing system using brine is a closed circuit system, as compared to an open end system in the case of using liquid nitrogen. The system using brine typically requires the use of industrial refrigeration plants.

The freezing station, located adjacent to the Launching Shaft, was equipped with three refrigeration units (Photo 3) for ground freezing for the launching of TBM and the hand-mined tunnel section. During the freezing operation, only two of the refrigeration units were running, whilst the remaining one served as a back-up. Two insulated pipes, respectively for delivery and return of brine, which is a calcium chloride solution, were laid from the station to the freezing zone (Photo 4). Tees were installed at both the delivery and return pipes at the location of freezing zone and each of the tees serves a group of two to three freezing pipes.

Typically, the brine was cooled down to a temperature of between -25°C and -40°C in the refrigeration plant. Then it was sent to the proposed frozen zone and the warmer brine returning from the return pipe was cooled again and sent back to the delivery pipe, forming a closed circuit. The cooled brine running through the freeze pipes continuously drew heat from the ground until the state of water changed from liquid to solid and the required temperature is reached.

Photo 3 - Refrigeration Plant

Photo 4 – Insulated Delivery and Return Pipes

9.2 Performance of the Freezing System

Figure 13 shows the monitoring results prior to TBM break-through.

The cooling history of thermocouples T1, T2, T3 & T5 shows that the temperature of all measured thermocouples consistently reached the freezing point in the first few days. After that the temperature drop slowed down as compared to the earlier days. Readings of the thermocouplers reached -25°C in three weeks after freezing started and then became steady with nearly no further temperature change.

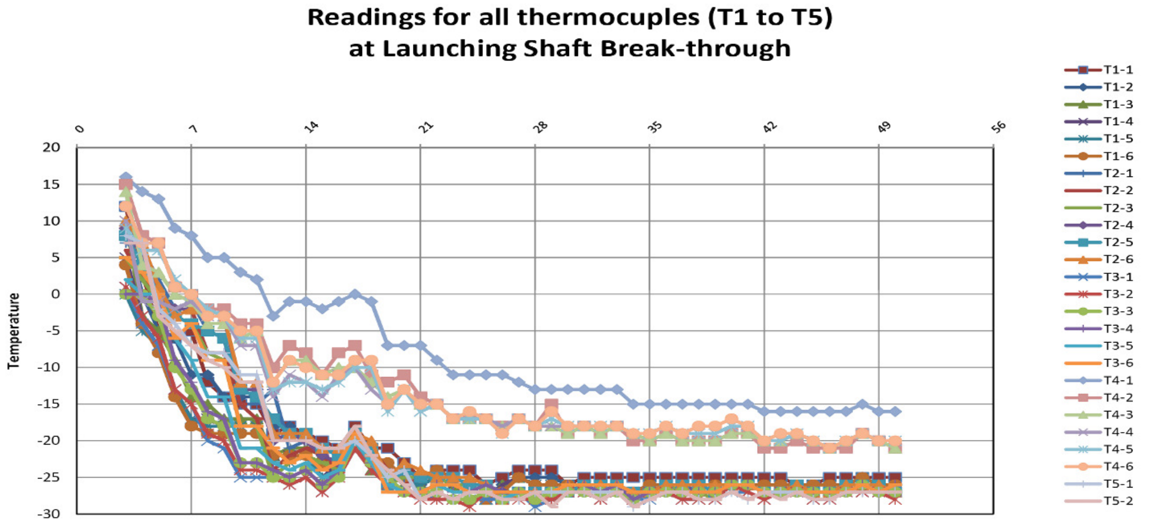

Figure 13 – Readings of Thermocouples at TBM Break-through from Launching Shaft

During the installation of the steel pipe at T4, boulders were encountered and, as a result, the steel pipe of T4 was installed slightly off vertical and inclined towards the outside of the frozen zone with an offset of 400mm at its toe. The temperature measured at T4 fell more slowly than the others. The readings of all thermocouples at T4 could not reach the freezing point (0°C) until a week later. After that, the temperatures recorded at T4 were always higher than the others. After a month's time it reached -15°C (design temperature), while the others could reach -15°C in a week's time.

In conclusion, the monitoring results show that the freezing operation was very effective and the design temperature of -15°C was reached within fourteen days, well before the estimated duration (i.e. 45 days). Hence, it is likely that the thermal conductivity of the frozen soil was conservatively estimated in the AGF design for this case.

Notwithstanding the frozen zone was located near the seafront (about 100m away), the temperature measurements did not show any tidal effect on the AGF.

10. DISCUSSIONS AND CONCLUSION

Comparing with ground treatment by grouting, which is more commonly adopted in Hong Kong for TBM break-in/break-out and minded tunnel construction in soft ground, AGF has the characteristics of not causing significant alteration to the ground properties after completion of the works. It is also more adaptive to different soil conditions, and capable of achieving strength improvement and ground water cut-off for soils of a wide range of particle size.

The experience of this technique in the HATS Stage 2A project has demonstrated that the use of brine as the freezing agent is a viable alternative to liquid nitrogen system, which was more commonly adopted in previous local projects. The experience gained also suggests that there are opportunities for a wider application of AGF in the construction industry in Hong Kong, such as support of excavations where installation of vertical retaining elements is impractical or difficult, construction of tunnels in soft ground with shallow cover, and temporary underpinning of existing structure, can be considered in the future.

Design of AGF requires knowledge of the mechanical and thermal properties of the frozen soil, for which the required testing facilities are not available in Hong Kong yet. In the case described above, the tests were carried out by laboratories in mainland China. It is hoped that as the method becomes more commonly adopted for local projects, such testing capability becomes available locally, and as the experience grows, properties of frozen soils in local conditions will become better understood.

Lastly, it must be stressed that effectiveness of AGF relies on continuous maintenance of the temperature of the frozen zone. The importance of close supervision and monitoring during the operation to ensure full compliance with the method statement and provision of contingency plan and measures cannot be overstated.

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12. ACKNOWLEDGEMENT

This paper is published with the kind permission of the Drainage Services Department, the Government of the Hong Kong Special Administrative Region.