ARTIFICIAL GROUND FREEZING FOR TBM BREAK-THROUGH – DESIGN CONSIDERATIONS

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ABSTRACT

Artificial ground freezing (AGF) has been widely adopted in Shanghai, China, as the ground improvement method for break-through of tunnel boring machines (TBM) from their launching shafts and into their receiving shafts. In Hong Kong, AGF application has in the past been limited to the construction of mined adits and cross-passages between tunnel bores. In one of the construction contracts under the Harbour Area Treatment Scheme (HATS) Stage 2A, the contractor has initiated to adopt AGF for the first time in Hong Kong using brine for TBM break-through. Under the contract, a tunnel about 4m in diameter and 250m in length is to be constructed inside Stonecutters Island Sewage Treatment Works at 30m below ground in marine deposits, alluvium and decomposed granite by TBM to connect a new pumping station to the existing pumping station. This paper presents the design considerations for the application of AGF using brine for TBM break-through. It details the thermal and stress analyses required to confirm the viability of the construction method, and the laboratory testing required for derivation of the necessary thermal and geotechnical parameters of the soils.

1 INTRODUCTION

Contract No. DC/2009/05 is one of the HATS Stage 2A contracts being implemented by the Government of the Hong Kong Special Administrative Region to improve the water quality in the Victoria Harbour. This construction contract was awarded by the Drainage Services Department to a joint venture of China State Construction Engineering (Hong Kong) Limited and Shanghai Tunnel Engineering Company Limited (CSSTJV). Works under this contract consist of construction of an interconnection tunnel, and of a diaphragm-walled cofferdam for the main pumping station at Stonecutters Island Sewage Treatment Works. Hyder Consulting Ltd. was appointed by CSSTJV to carry out detailed design for the construction of the 4m diameter interconnection tunnel which comprises Part A Tunnel 236m in length excavated by TBM, and Part B Tunnel 14m in length excavated by hand-mining. AGF was employed as the ground improvement method to facilitate TBM break-through from the launching shaft. Figure 1 shows the site layout.

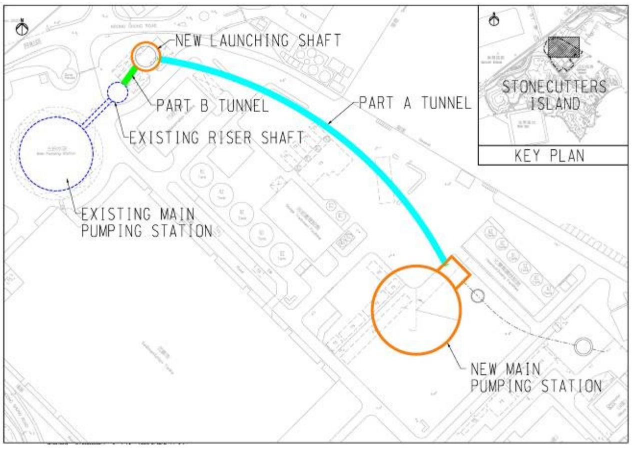

Figure 1: Site Location Plan

This paper presents the detailed design, covering both the thermal and stress analyses, and the required laboratory testing for the application of AGF using brine for TBM break-through. Thermal analysis was carried out to estimate the freezing energy and time needed to achieve a frozen zone down to a designated temperature. As some of the vertical freezing pipes had to be lifted prior to TBM break-through, an assessment was also made of the temperature change with time after those pipes were removed. Stress analysis was carried out to confirm stability of the soil mass with the soft-eye cut out in the diaphragm-wall of the launching shaft. Assessment of the effects of frost heave and thaw consolidation with the help of numerical modeling is also discussed.

2 SITE GEOLOGY

The site is formed by reclamation with a ground level of about +5.5mPD. The interconnection tunnel is situated at approximately 30m below ground level and the encountered geology at TBM break-through from the launching shaft includes Marine Deposits and Alluvium, as shown in Figure 2 and described below:

Marine Deposits - firm to stiff, slightly sandy silty CLAY with occasional angular to subangular fine gravel sized rock and shell fragments;

Alluvium - 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.

The design groundwater level is at 2m below existing ground level.

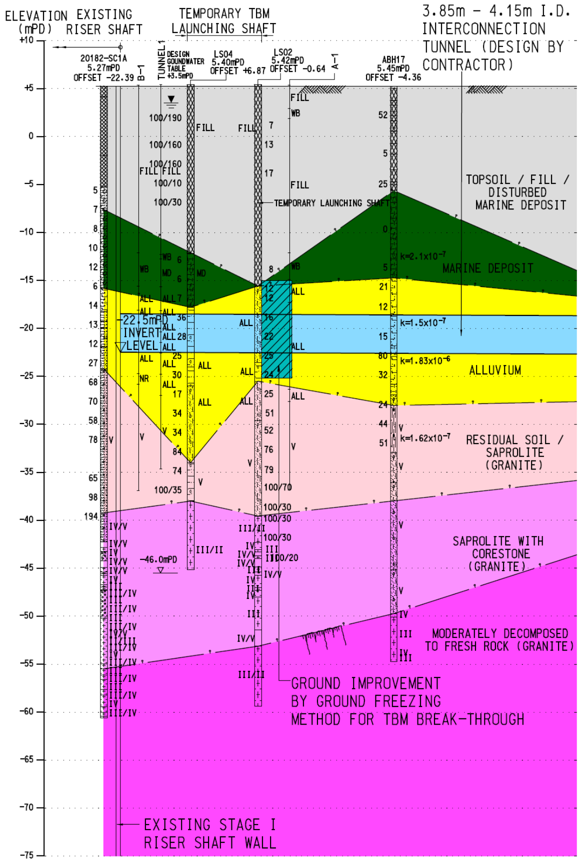

Figure 2: Geological profile

3 DESIGN CONSIDERATION

General design considerations for AGF are as follows:

Groundwater Level – Soil with sufficient moisture content 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 the soil around it is saturated;

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 at the locations where AGF was applied vary from clayey, silty to sandy;

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 needed 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.

4 LABORATORY TESTING

Laboratory tests were performed on soil samples retrieved from the site to obtain the mechanical properties of frozen soils and thermal properties of soils in both the non-frozen and frozen states. The tests were carried out in accordance with the Chinese national code GB/T50123-1999 Standard for Soil Test Method (土工试验方法) and Chinese code for coal mining industry MT/T593-1999 Testing for Physical and Mechanical

Properties of Artificially Frozen Soil (人工冻土物理力学性能试验). Table 1 gives a summary of the tests performed.

Table 1: Summary of laboratory testing

Test	Details
Unconfined compression	2 tests each at -10ºC, -15ºCand -20ºC for each soil type
Creep	For each soil type, one test each for each combination of temperature (-10ºC, -15ºC, -20ºC) and stress level (0.3q, 0.4q, 0.5q, 0.7q)*
Freezing temperature	2 tests for each soil type
Frost heave	2 tests for each soil type
Thaw settlement	2 tests for each soil type
Thermal conductivity	One test each at 20ºC, 0ºC, -5 ºC and -20ºC for each soil type
Specific heat capacity	One test each at 20ºCand -10ºC for each soil type

*q is the peak axial stress or axial stress at axial strain of 20% if there is no peak.

The unconfined compression tests were carried out with specimens cut from Mazier soil samples. Compression was applied at a rate of 1% strain/min. until an axial strain of 20%. Figure 3 shows a typical stress-strain curve of the test. Whilst the test standard defines the strength as the peak stress or the stress corresponding to 20% strain if no peak is experienced, a more conservative approach of taking the stress at which the specimen began to yield as the strength was adopted in arriving at the design values.

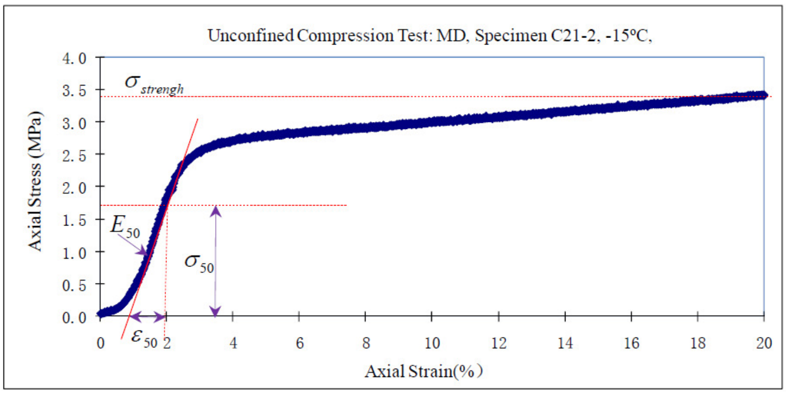

Figure 3: Typical stress-strain curve of unconfined compression test

In the creep test, compression was applied at a rate of 1% strain/min to the required stress level and then maintained for 24 hours. Figure 4 shows a typical plot of the creep strain and strain rate against time. The tests results showed that at a stress level of 0.5q or lower, the strain of the tested specimens consistently came to be stable with time. Hence, 50% the design compressive strength is taken as the design creep strength of the soils. The creep modulus corresponds to the ration of the applied stress to the strain when stable.

In the tests for frost heave ratio, temperature of soil specimens were brought down to below their freezing temperature and the change in height of the specimens was measured. Likewise, in the test for thaw consolidation ratio, frozen soil specimens were allowed to thaw and the reduction in height of the specimens was measured.

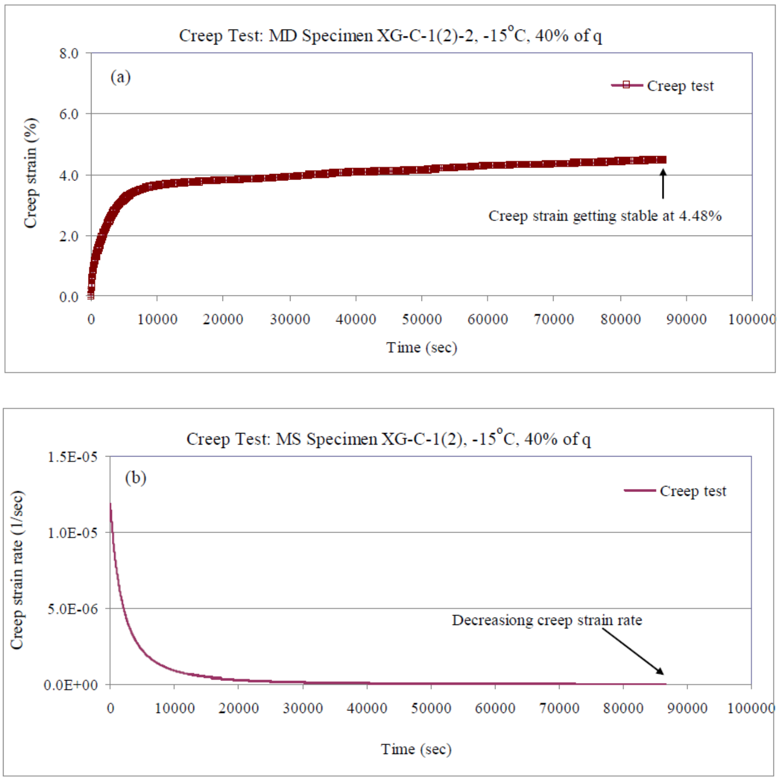

Figure 4: Typical strain-time & strain rate-time plots of creep test

Tables 2 and 3 summarize the values of the mechanical and thermal properties adopted in the design.

Table 2: Design values of mechanical properties

Soil	UCS* (MPa)	Young's Modulus E_{50} (MPa)	Creep Strength (MPa)	Creep Modulus (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%

* at temperature of -15˚C

Table 3: Design values of thermal properties

Soil	Freezing Temperature (˚C)	Specific heat capacity kJ/(kg ˚C)		Thermal Conductivity W/(m K)			
		In-Situ	Frozen	-20˚C	-5˚C	0˚C	20˚C
Marine Deposits	-1.71	2.14	1.28	1.966	1.628	1.485	1.367
Alluvium	-1.84	1.48	1.04	2.272	1.993	1.916	1.746

5 CONSTRUCTION ASPECTS AFFECTING THE DESIGN

Figure 5 shows the configuration of the ground freezing work for TBM launching. Key aspects affecting the design are discussed as follows.

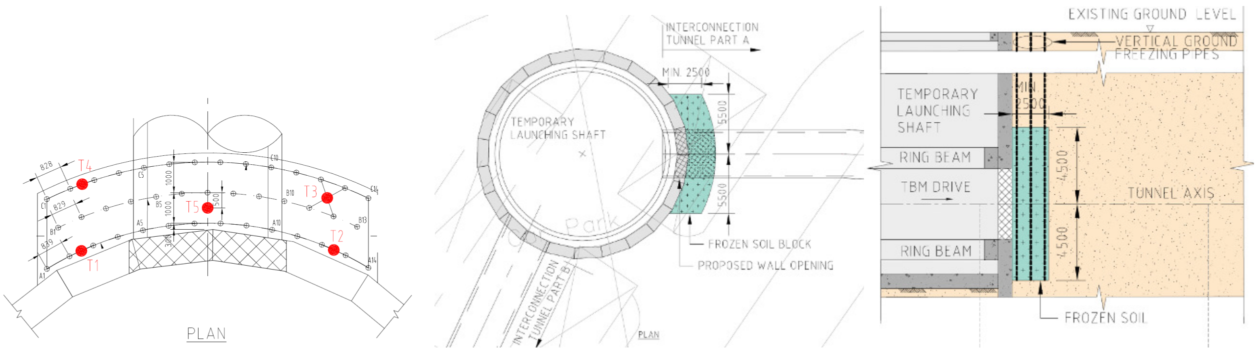

Figure 5: Configuration of the Frozen Soil Wall for TBM Launching

Use of brine as freezing agent

Two artificial ground freezing systems are available in the construction industry, using either liquid nitrogen or brine. In this project, a closed circuit freezing system using brine was adopted. Brine lowered to a temperature of -28°C using industrial refrigeration plant was circulated into freezing pipes installed in the ground in a regular pattern. The target was to form a 2.5m thick frozen block with a temperature of -16°C in front of the TBM break-through.

Partial removal of diaphragm wall prior to TBM launching

It was intended to remove the part of the diaphragm wall of the launching shaft facing the TBM prior to TBM launching for facilitating the launching operation. The frozen soil block thus should have the capability of withstanding the soil and water pressure acting from the back of it.

Partial extraction of ground freezing pipes prior to TBM launching

Prior to TBM launching, the ground freezing pipes falling within the drive of the TBM had to be partially extracted to above the tunnel crown level in order not to obstruct with the TBM drive. After the pipe extraction, the frozen block had to remain frozen for at least 72 hours to allow the TBM launching operation.

6 THERMAL ANALYSIS

The finite element software ANSYS was employed for 2-D thermal analysis. This analysis helped determine the arrangement of the ground freezing pipes and estimate the time and energy required to form the frozen soil wall to the design temperature. The analysis algorithm is based on the heat balance equation from the principle of conservation of energy. Latent heat associated with phase change from non-frozen to frozen state was taken into consideration.

The input data for thermal analysis include geometry, thermal conductivity and enthalpy at different specific temperature, and boundary conditions. The initial temperature and temperature at boundary of the model were set at 25°C and the temperature at the locations of the freezing pipes was reduced progressively from 25°C to -28°C. According to the analysis results as illustrated in Figure 6, the frozen soil wall with temperature lower than -15°C could be achieved in 20 days of active freezing. The average heat transfer rate obtained from the analysis was 435kJ/hour·m^2. The refrigeration system was required to have a heat exchange capacity of at least 435kJ/hour·m^2 multiplied by total contact area and a factor of 1.3 to account for heat loss.

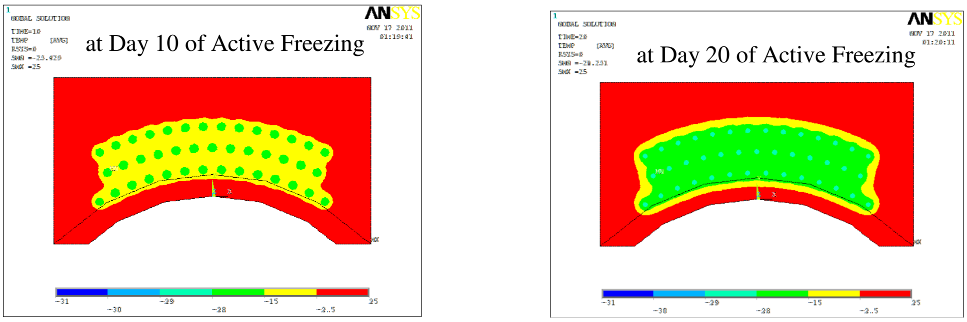

Figure 6: Temperature field of active freezing from ANSYS analysis

To simulate the effect of pipe extraction to the overall temperature of the frozen soil block, the action of circulating warm water to defrost the freezing pipe was modeled. Due to heat diffusion, the defrosted region was frozen again and returned to -15°C by the surrounding frozen soil as illustrated in below Figure 7.

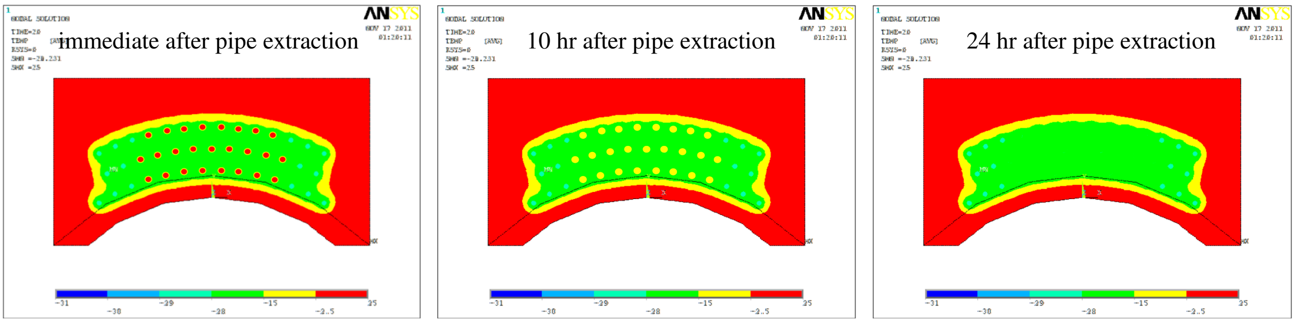

Figure 7: Temperature field of freezing pipe extraction from ANSYS analysis

7 STRESS ANALYSIS, FROST HEAVE AND THAW CONSOLIDATION CONSIDERATION

According to the TBM break-through sequence, a local 5m diameter opening (soft eye zone) would be made on the diaphragm wall of the launching shaft. In advance, a 2.5 thick frozen soil wall that had reached the design temperature and achieved the target supporting strength had to be formed immediately outside the opening. After the soft eye zone was broken off manually, the soil and hydrostatic pressure would be retained by the frozen soil wall spanning across the opening. Analysis was carried out using PLAXIS 2D. The frozen soil was modelled using Mohr Coulomb's failure criteria with undrained shear strength S_u taken as 0.5 x creep compressive strength. With a factor of safety of 2 applied, the undrained shear strength of frozen marine deposits and frozen alluvium were taken respectively as 250kPa and 437.5kPa. Two analysis cases using two different sets of Young's modulus had been carried out with one considering the short term loading effect using E_{50} and another one considering the long term loading effect using creep modulus. In view of the relative large frost heave and thaw consolidation ratios, the ground movement and associated impact to the existing building structures including their foundations were also assessed using PLAXIS 2D. To consider the effect of frost heave, a positive volume strain was assigned to the frozen zone to model the expansion effect caused by formation of ice lenses. To mitigate excess settlement caused during the thawing process, permeation grouting through the grout ports pre-installed in the TBM tunnel lining was proposed. A negative volume strain was thus assigned to the frozen zone untreated by permeation grouting to simulate the thaw consolidation. Models for these analyses are shown in Figure 8.

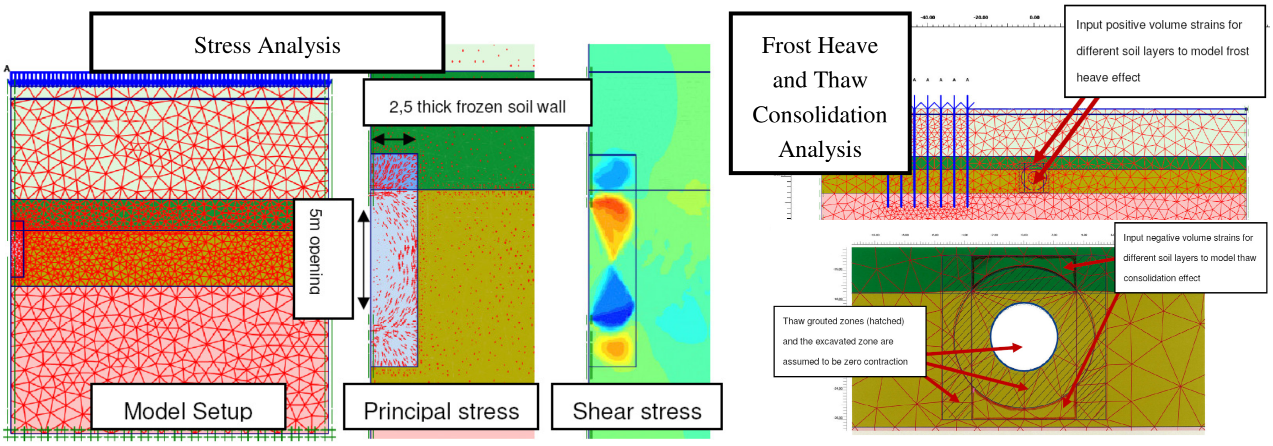

Figure 8: Stress, Frost Heave and Thaw Consolidation Analysis

8 CONCLUSION

It was the first time in Hong Kong to employ AGF using brine as ground improvement method for TBM launching. The application in Contract No. DC/2009/05 has proven that AGF can be used to strengthen various types of soil provided that it is supported by careful planning, comprehensive laboratory testing and rigorous design. In the detailed design, thermal and mechanical properties of the soil including the frost heave and thaw consolidation were all considered. The TBM was launched successfully in January 2011 and this has set a benchmark of using AGF to improve the in-situ ground for TBM launching in Hong Kong.

ACKNOWLEDGEMENTS

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