Geotechnical Aspects of Underground Construction in Soft Ground – Yoo, Park, Kim & Ban (Eds)
 ISBN 978-1-138-02700-8

Geotechnical control for artificial ground freezing works in tunnel projects in Hong Kong

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ABSTRACT: Artificial ground freezing has been used successfully for ground treatment to facilitate construction of tunnels and adits and break-in and break-out operations in TBM drives in soft ground in a number of tunnel projects in Hong Kong. Many of these projects are constructed in densely populated urban areas with difficult ground conditions. In the interest of public safety and to manage and control the risk involved, artificial ground freezing works, which form part of the tunnel works construction, are subject to geotechnical control exercised by the Geotechnical Engineering Office of the Civil Engineering and Development Department. The geotechnical control for artificial ground freezing works in government tunnel projects in Hong Kong exercised at different stages of the projects and some of the geotechnical control measures and practices applied to a recently completed project are presented in this paper.

1 INTRODUCTION

In Hong Kong, tunnel works construction is subject to geotechnical control by the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) of the Government of the Hong Kong Special Administrative Region (HKSAR). The control, which aims to protect public safety, is exercised under the Buildings Ordinance and the mandate given in Environment, Transport and Works Bureau Technical Circular (Works) No. 15/2005 (ETWB, 2005a) for private and government tunnel projects respectively. The railway projects undertaken by the Mass Transit Railway Corporation Limited are also subject to the same geotechnical control, either under an Instrument of Exemption granted by the Building Authority or an Instrument of Compliance granted by the Director of Highways, using the same technical standards. The development of geotechnical control for tunnel works in Hong Kong is outlined in Pang & Woodrow (2009) and Pang (2010).

A number of major tunnel projects for drainage, sewage, railways, roads, etc., have been/are currently being constructed in Hong Kong. The tunnels are usually constructed in the congested and densely populated urban areas with difficult ground conditions. To facilitate construction of the tunnels and adits and break-in and break-out operations in TBM drives in soft ground in these projects, artificial ground freezing (AGF) has been used (AGS (HK), 2013; Leung et al, 2012; Tsang et al, 2012a; Tsang et al 2012b). Both brine and liquid nitrogen have been used as the freezing agent. The AGF works, which form part of the tunnel works construction, are subject to the same geotechnical control requirements.

In this paper, the geotechnical control for AGF works in government tunnel projects in Hong Kong at different stages of the projects is presented. Reference is made to the geotechnical considerations and some of the geotechnical control measures and practices that have been applied to a recently completed project. While the process of geotechnical control for private tunnel projects under the Buildings Ordinance is different, the same geotechnical considerations and control requirements apply.

2 GEOTECHNICAL CONTROL FOR ARTIFICIAL GROUND FREEZING WORKS

2.1 *Background*

GEO's audits on tunnel works cover all stages of the works,including any AGF works, from geotechnical design to site supervision and risk management during construction, where the proposed works pose a significant risk to public life or property. In all stages, GEO maintains close liaison with the project department and its consultants to agree the schedule and priority of submissions to GEO, provides feedback on the proposed design scheme prior to the design submission, and clarifies and resolves technical issues arising from the geotechnical control process.

For government tunnel projects, GEO's responsibility is to audit the geotechnical aspects of the proposed works and the standard of works implementation in the interest of public safety. GEO focuses primarily on public safety issues and checks that due diligence has been exercised by the parties responsible, in the design audits and site audits. The project department and its consultants will deal with the contractual implications and ensure consistency in making changes to the contract documents. GEO's audits do not change the authority, duties, responsibilities and liabilities of the project department and its agents responsible for the project.

The key items examined during the various stages of geotechnical control of AGF works are discussed in the sections below.

2.2 *Feasibility study*

In this early stage of a government tunnel project's development, GEO (serving as the Government's geotechnical advisor) advises the project department on the geotechnical requirements to be included in the consultancy brief. These include employment of adequate suitably experienced and qualified geotechnical design staff as well as geotechnical site supervision staff, specification of minimum qualification and experience requirements for such staff, requirement for systematic identification of the geotechnical risks, adequate and timely geotechnical investigation and risk assessments, etc. In reviewing the feasibility study report, focus is given to difficult ground conditions and major geotechnical hazards likely to be encountered in the project, performance limits of sensitive receivers affected, the scope, extent and adequacy of ground investigation (GI) works required, funds and time allowed for the GI works, geotechnical studies required to support the reference design to manage and reduce uncertainties and risks, construction method related hazards and risks, buildability of the risk mitigation works, etc.

2.3 *Design, risk management and site supervision*

2.3.1 *Project layout plan*

In the submission to GEO, an outline of the proposed AGF works, including the site location, area/volume of the ground to be treated, etc., is required tobe provided. Details of the sensitive features (e.g. old/historical buildings, adjacent foundation piles, etc.) in the vicinity that could affect or be affected by the proposed works, their tolerance to ground heave and settlement and pressures generated by the AGF works need to be provided. In some cases, deformation control criteria instead of stability requirements may govern the design.

2.3.2 *Geotechnical review, including ground investigation*

For design of AGF works, boreholes are carried out within the proposed treatment zone and well below the planned excavation depth, to provide sufficient samples for soil classification and strength tests (on both undisturbed unfrozen and frozen samples), and for establishing the thermal properties of the soils. To assess the variability of the soil strata to be frozen, continuous sampling carried out through a zone about twice the thickness of the AGF zone is recommended.

The frost susceptibility of the soils, expressed in terms of the segregation potential of the soils (Harris, 1995), would need to be assessed. The parameters for evaluating such potential, such as particle size distribution, type of fines (e.g. active platey clay minerals or rounded soil particles), etc., have to be obtained from the GI works.

Sufficient groundwater and soil samples have to be collected for testing the salinity of the pore water which would have an impact on the frost development and design of the freezing scheme. In addition, in-situ ground permeability tests would need to be carried out and sufficient groundwater monitoring stations installed for assessing the groundwater regime (present pore pressures and seepage gradient) and the hydraulic conductivity of the soil strata to be frozen.

Cross-sections showing the geological and hydrogeological conditions, including changes in soil strata, location of any suspected cavities, position of the phreatic surface and its fluctuation range have to be provided. The suitability of using AGF would have to be assessed, based on information of the ground and groundwater flow conditions collected.

A schedule of laboratory tests for unfrozen and frozen soil samples, including unconfined compression, tensile and triaxial tests and tests to determine creep behaviour, frost heave and thaw consolidation characteristics and thermal properties, is also required to be provided. Due to lack of special equipment for testing of frozen soil samples locally, the soils samples have to be sent overseas for testing. The time required for arranging and carrying out the tests would need to be allowed for in the project programme. Relevant testing standards should be specified for the tests carried out, in particular for frozen soil samples. The testing standards for frozen soils that have been used include the Chinese standards MT/T593-1999 and GB/T 50123-1999 and the American standards ASTM D5520, D5334 and D7300.

2.3.3 *Risk management plan, risk register and risk treatment plan*

The risks to life and property associated with the works must be identified, classified and documented (ETWB, 2005b). For the risk items identified, the parties responsible for managing the risks and details of the risk management strategy (i.e. measures to be taken to control/avoid the risks at the planning, design and construction stages, and the persons to be assigned the responsibility for taking action and making timely submissions of adequate quality to GEO at each stage) are required to be included.

2.3.4 *Geotechnical assessment and design of temporary support*

In the design of AGF, stability analysis for the proposed temporary support and thermal analysis to determine the freeze pipe arrangement and the time and energy needed to form the frozen soil wall at the temperature required would need to be carried out. Numerical method is often adopted, and the software used is required to be validated. In the analyses, the ground model,together with the parameters used and the boundary conditions assumed taking into account the proposed freezing/excavation/support sequence, etc., need to be provided. Sensitivity studies are required to determine the range of ground performance to be expected (e.g. vertical/lateral ground deformations). Due consideration of the creep effect of the frozen soils on tunnel stability is necessary. The need for standby plant and equipment and/or temporary support (e.g. shotcrete lining or steel ribs) as contingency/emergency measures in case of freezing plant failure or excessive creep should be considered. Results of the analysis with graphical output have to be provided to demonstrate the adequacy of the thickness and strength of the frozen ground to prevent instability and excessive deformation, as well as the temperature variation across the frozen zone with respect to the time of freezing. In cases where the proposed AGF zone and underground openings are close to existing foundation piles, a soil-structure interaction analysis may be required to estimate the possible loss of structural and geotechnical capacities of the piles and building structures affected.

If the underground openings involve complicated shape and non-linear alignment, the ground freezing scheme and the associated construction details have to be designed to ensure the complete closure of the freezing ring/wall and the interfaces between the freezing ring/wall and the existing underground structures.

The effect of groundwater flow and salinity of groundwater on the additional freezing energy or alternative freeze pipe arrangement needed, and of ground heave/settlement during freezing/thawing on the sensitive facilities in the vicinity would need to be assessed.

2.3.5 *Monitoring and contingency plans*

Details of the instrumentation monitoring for heave, settlement, groundwater pressures, freezing agent temperature, ground temperatures (i.e. those measured along the installed thermocouples), tunnel convergence and the alert-action-alarm (AAA) limits on typical cross and longitudinal sections, together with the contingency/emergency measures to be taken at each respective AAA limit, are required to be provided. Frequency of monitoring and the timing for the monitoring data to be conveyed to the person responsible for managing the risks for his review and decision on implementing the contingency/emergency measures when the AAA limits are exceeded are also required. It is important that the contingency/emergency measures proposed can be implemented sufficiently quickly, if needed, to prevent loss of life/injury, damage to property, disruption to traffic and services.

2.3.6 *Quality site supervision plan*

Details of the key resident site staff employed and curriculum vitae of the competent person responsible for the AGF works have to be provided. The key persons in the consultants' and the contractor's team who are responsible for managing the geotechnical risks and who have the authority to give consent to commence the excavation and to instruct the risk mitigation works on site are also required to be identified. The designer of the AGF works is required to critically review the design during construction.

2.3.7 *Design drawings*

Excavation and lateral support plans showing details and construction sequence of the works, checking of drilling accuracy for freeze pipes, monitoring to verify the design assumptions, safety-critical hold points for design review, contingency measures and provision of standby emergency staff, plant and equipment, and site supervision requirements, including provision for emergency management are required to be provided.

2.4 *Prior to/during construction*

2.4.1 *Construction programme*

All the key activities and the duration for each activity need to be shown. The time allowed for freezing has to follow that specified in the design. Adequate time for carrying out a review of the temperature distribution of the frozen soils prior to excavation has to be allowed for in the programme.

2.4.2 *Method statement*

Details of the type of freezing agent used (e.g. brine or liquid nitrogen), including delivery, storage, etc. have to be specified. A plan showing the location of the refrigeration plant on site, including the estimated quantities of freezing agent to be used, backup generating and refrigeration arrangement, etc., has to be provided. Method for drilling and installation of freeze pipes, including tolerance criteria for alignment and orientation for the installed freeze pipes need to be specified. In Hong Kong, directional drilling techniques are commonly adopted for installation of freeze pipes. The works have to comply with the relevant Construction Site Safety Regulations, Dangerous Goods Ordinance and the Fire Services Department and Labour Department requirements.

The planned time for freeze pipe installation, formation of ice ring, excavation and support installation cycle, thawing, in compliance with the design, need to be specified clearly. A check on the extent and effectiveness of the freezing process before commencing excavation has to be carried out.

The criteria for commencing thawing, the person responsible for making the decision on commencement of thawing, the approval procedures under the contract, and the need for undertaking a performance review prior to and after thawing need to be provided.

2.4.3 *Site inspections and site supervision reports*
Inspections by a geotechnical engineer who is familiar with the design of the AGF works, with adequate supervision from the project department/consultant supervising the contract, are required to be made at regular intervals and at critical stages of the AGF works. He would be required to inspect all critical items of the works and take timely follow-up actions to ensure adequate quality of the works and no adverse impact on life and property. He would be required to check that the design assumptions are valid and that the works are being carried out as specified in the accepted design, and to continue to advise the Contractor/Engineer or his Representative of the actions needed. His inspection records and reports have to be made available for GEO's audit inspection. Contents of the report have to include construction progress, monitoring results, as-built locations and spacing of freeze pipes, predicted/actual monitoring results of the nearby monitoring stations (including temperatures, and piezometric, ground and building responses), and plots of monitoring results of the specialist works (such as the temperature measurement of thermocouples versus time at different locations along the radius of the frozen annulus, including the AAA limits, and ground movements monitoring plots with the settlement troughs of predicted volume losses). A critical review of the construction problems encountered, the contingency/remedial measures adopted and the validity of the design assumptions based on the latest information collected, are required to be included. Anticipated geotechnical problems for the upcoming works and the planned contingency measures, including actions to be taken when the monitoring results approach the AAA limits, also need to be examined.

2.5 *Prior to completion of works*

Prior to completion of the AGF works, the following are required to be submitted to GEO for record:

(a) the geotechnical performance review carried out and the monitoring/survey data obtained for the AGF works; and
(b) the geological and hydrogeological data collected.

3 CASE EXAMPLE OF APPLICATION OF GEOTECHNICAL CONTROL

3.1 *General*

Application of geotechnical control to the AGF works for a recently completed government tunnel project in Hong Kong is outlined below.

3.2 *Geotechnical review*

The site is underlain by fill, marine deposit (MD), alluvium, completely decomposed granite, followed by moderately decomposed granite to fresh rock. Handmining with AGF was used to construct a 14 m long, 3.9 m diameter tunnel at an invert level of −22.5 mPD.

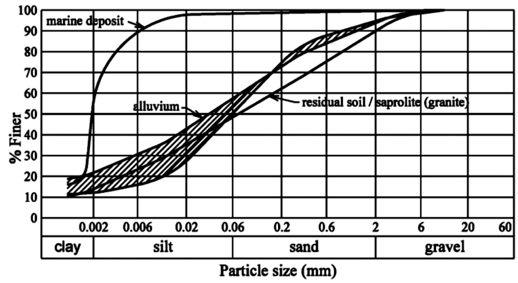

Figure 1. Particle size distribution.

Table 1. Properties of frozen soils at −15°C.

Material	UCS (MPa)	Young's Modulus E_{50} (MPa)	Creep Strength (MPa)	Creep Modulus (MPa)
MD	2.0	160	1.00	21
Alluvium	3.5	315	1.75	36

The soils to be frozen were mostly alluvium which was a silty or clayey sand to silty clay (Figure 1), in a fully submerged condition with a moisture content of 22 to 27%. AGF was assessed to be suitable for the ground and groundwater conditions encountered.

At this site, a groundwater flow of 0.12 m/day was recorded. This was less than the critical groundwater velocity of 0.19 m/day obtained using the equation by Sanger & Sayles (1979). The salinity of the groundwater was in the range of 10 g/l of NaCl (Andersland & Ladanyi, 1994) and was considered mild. Hence, the effect of groundwater flow and salinity of groundwater on the freezing temperature for the formation of the frozen wall was assessed to be minor.

3.3 *Geotechnical assessment*

Brine was used as a freezing agent for the AGF works, and the design temperature of the frozen soils was −15°C.

A series of laboratory tests on the unfrozen and frozen soil samples at the relevant stress and temperature ranges were carried out by the design consultants employed by the contractor to establish the strength parameters. Unconfined compression and tensile tests in the temperate range of −8°C to −20°C were carried out on the frozen soil samples. Unconfined compressive strength (UCS) and Young's Modulus (E_{50}) values obtained for the frozen soils at −15°C are given in Table 1. Creep tests were carried out on the frozen soil samples at different stress levels. At a stress level of 0.5 ∗ UCS, the strain remained fairly constant with time for the frozen soils. Hence, a creep strength of 0.5 ∗ UCS for the frozen soils was used.

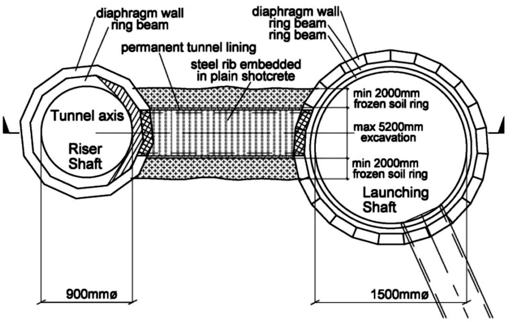

Figure 2. Plan view of tunnel.

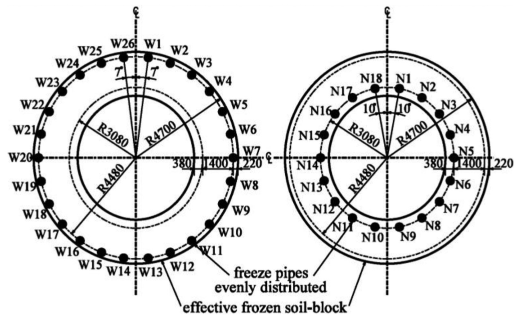

Figure 3. Layout of horizontal freeze pipes.

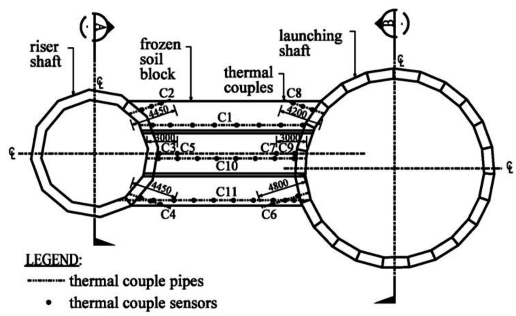

Figure 4. Arrangement of thermocouples for temperature measurement.

Thermal properties of the frozen soils in terms of freezing temperature, specific heat capacity and thermal conductivity were assessed.

As an integral part of the assessment, the freezing-thawing responses of the frozen soils were investigated. Samples were tested in a closed environment without water supply, and axial expansion was unconfined and measured. The length of the sample at the end of the freezing tests was taken as the initial length for the thawing test. Alluvium was found to have a frost heave of 5.10% and a thaw consolidation of 8.65%, as compared with 1.18% and 13.00% respectively for the marine deposit which overlain the alluvium. The frost susceptibility of these soils was assessed to be very low based on Andersland & Ladanyi (1994).

3.4 *Design of temporary support*

For the design of the AGF works, a 2,000 mm thick frozen soil ring was adopted, as shown in Figure 2. The stability and adequacy of the temporary support was assessed using the finite element software PLAXIS for a critical section of the mined tunnel. The parameters given in Table 1 were used. Both ultimate limit state (ULS) (assessment of the compressive and tensile stresses induced relative to the compressive strength and tensile strength respectively of the frozen ring) and serviceability limit state (SLS) (assessment of soil movement relative to the permissible limit) were examined. For the ULS analysis, a partial factor of 2.0 was applied to the soil strength parameters used.

44 freezepipes were proposed for the AGF works, as shown in Figure 3. Two rings of freeze pipes were used. The inner ring of pipes (N1 to N18) had a radius of 3,080 mm from the tunnel axis and the pipes were spaced at 1,070 mm. The outer ring of pipes (W1 to W26) had a radius of 4,480 mm from the tunnel axis and the pipes were spaced at 1,080 mm. Low carbon seamless steel pipes of 108 mm diameter × 8 mm thick with a pressure resistance larger than 0.8 MPa (1.5 × brine pressure) were used. Drain pipes for relieving pore water pressures developed in the soils enclosed by the frozen ring were also installed.

Thermal analysis using the finite element software ANSYS was carried out to assess the proposed freeze pipe arrangement and the time and energy needed to form the frozen soil wall at the design temperature. It was shown that after applying the freezing for 60 days, the average temperature and the thickness of the frozen ring reached −15.3°C and 3.8 m respectively, as compared with the target design soil temperature of −15°C.

3.5 *Monitoring and instrumentation plan*

The arrangement of the thermocouples for temperature measurement, as shown in Figure 4, was assessed and found to be adequate for measuring the temperature distribution and gradient in the frozen soils along the radial direction of the tunnel. Other aspects, such as the AAA limits, corresponding contingency/emergency measures to be taken at each respective AAA limit, frequency of monitoring, timing for the monitoring data to be conveyed to the person responsible for managing the risks and implementing the contingency/emergency measures when the AAA limits are exceeded, etc. were also examined.

3.6 *Method statement for excavation and support of the frozen ground*

In the method statement, tolerance was specified for the freeze pipes installed. The construction sequence, which involved safety door installation, probing ahead from the shaft to establish groundwater inflow and to obtain ground information, followed by excavation of 600 mm, installation of steel ribs and application of 175 mm thick shotcreting, was also specified. In addition, adjusting the temperature of the freeze pipes after the permanent lining installation or permeation grouting as a contingency measure to minimise thaw settlement was examined.

4 CONCLUSIONS

Tunnel works have become an integral part of engineering infrastructure in Hong Kong. Many of the tunnel projects are constructed in congested and densely populated urban areas with difficult ground conditions. AGF has been successfully used for ground treatment to facilitate construction of tunnels and adits and break-in and break-out operations in TBM drives in these projects. This part of the works can pose a high risk to life and property and is subject to geotechnical control by GEO. The control process is well established and covers all stages of the works from geotechnical design to implementation of the geotechnical design, site supervision and risk management during construction.

GEO has played a vital role in the geotechnical control and management of the geotechnical risk posed by construction of tunnel works, including AGF works, with the aim of protecting public safety.

ACKNOWLEDGEMENT

The authors would like to thank the Director of the Civil Engineering and Development Department and the Head of the Geotechnical Engineering Office of the Government of the HKSAR for the permission to publish this paper. Messrs Michael Yiu, Joel Wong, Darkie Lee and Leslie Tsang reviewed the paper and provided useful comments. Their contributions are gratefully acknowledged.

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