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Artificial Ground Freezing for Cross Passage Construction

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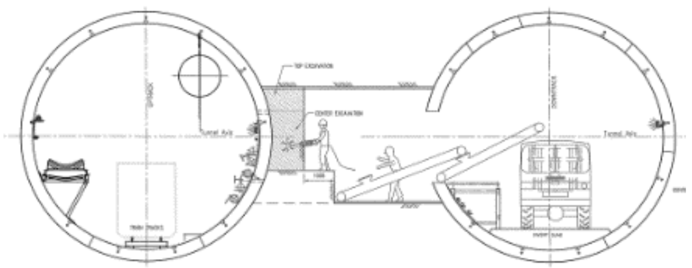
ABSTRACT: Artificial ground freezing (AGF) is a soil improvement method carried out by continuously refrigerating the soil and converts pore water to ice. The effectiveness of freezing depends on the presence of pore water to create ice, cementing the particles and increasing the strength of the ground to achieve the design strength. The AGF freezing technique has been successfully applied for cross passage (CP) construction in soft ground between twine bored TBM tunnels. The method involves installation of freezing pipes around the cross passage opening. Freezing is then achieved by circulated a cooling fluid into freezing pipes and 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 creating a solid ring of frozen ground. 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. The major objective of this paper is to describe the key considerations for design and construction of AGF applied for cross passage construction. Discussion on the importance of instrumentation monitoring to check the development of ice ring will be provided.

1 INTRODUCTION

1.1 *Construction of cross passage (CP) between twin bored TBM tunnel*

The construction of CP, especially in soft ground, between the twin bored TBM tunnel is one of the most high-risk construction activities for tunnelling projects. The CP is generally constructed using traditional mining techniques to create a link between two tunnels, as shown in Figure 1. Depending on the ground conditions, different ground treatment methods can be implemented.



- Carry our ground treatment works
- Open main tunnel segmental lining
- Excavation of CP by mined method
- Shotcrete the excavated roof and walls to acts as a temporary support
- Continue excavation and shotcrete, stage by stage, until reaching the receiving end
- Apply smoothing concrete before the installation of waterproofing membrane
- Spray permanent shotcrete or cast in-situ concrete to form the CP permanent structure
- Construction of collar structure between the CP and main tunnel

Figure 1. Typical construction of cross passage.

1.2 *Application of AGF for cross passage excavation*

When ground treatment cannot be carried out from the ground surface due to site constraints or environmental concerns, AGF is generally considered one of the best ground treatment methods to be adopted from inside the tunnel for cross passage excavation in soil. The ground freezing method is very reliable in achieving design strength and watertightness. 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 feedpipes. 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.

2 KEY DESIGN CONSIDERATIONS FOR GROUND FREEZING WORKS

2.1 *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.

2.2 *Types of cooling agent*

Brine freezing is typically used for large, longer-term applications. Brine temperatures of -25°C or less are typically sufficient for most projects. 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 is 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.

3 DESIGN OF AGF FOR CROSS PASSAGE CONSTRUCTION

3.1 *Ground freezing design*

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 2.

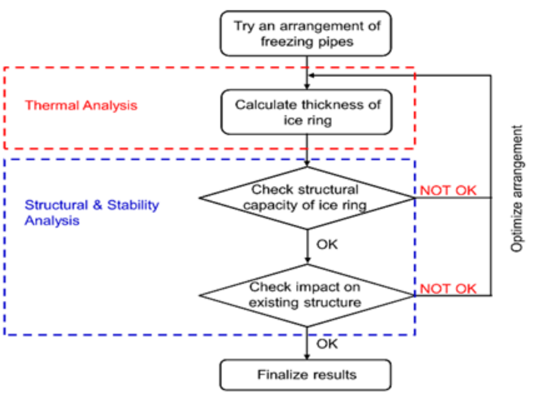


Figure 2. Proposed procedure of ground freezing design

3.2 *Thermal analysis*

The thermal analysis can be carried out by 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 and temperature at boundary of the model should be set as the ambient temperature. On the other hand, the temperature at the locations of the freezing pipes is reduced progressively from ambient temperature to -28°C for brine and -196°C for liquid nitrogen.

The thickness of freeze wall will be one of the input data for structural analysis. Generally, it is usually defined as the distance between two -10°C or -15°C isotherms. The other important output is the active freezing period which should be tally with 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 and adverse impact due to breakdown of plants could be minimized.

3.3 *Structural analysis*

The structural analysis could also be conducted by 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 also 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 is thus assigned to the frozen zone to simulate the thaw consolidation.

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

3.4 *Typical ground freezing design and arrangement of the ground freezing pipes*

Based on the design approach as described in the previous sections, a typical ground freezing design with consideration on the dimensions of cross passage opening and main tunnel diameter is shown in Figure 3.

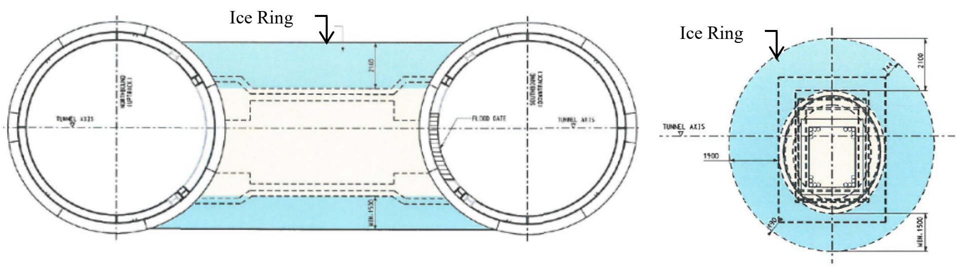


Figure 3. Design of ice ring

The key design of ice ring is summarized below:
- The design thickness of ice ring is 2.1m (top) / 1.9m (side) / 1.5m (bottom)
- The design temperature at the boundary of defining the ice ring thickness is -10°C.
- Strength of ice ring: the minimum and maximum compressive strength of ice ring is1.5MPa and 3MPa respectively.
- 48 numbers of freezing holes are designed around the cross passage opening to form the ice ring.

The arrangement of ground freezing pipes to form the required ice ring is shown in Figure 4.

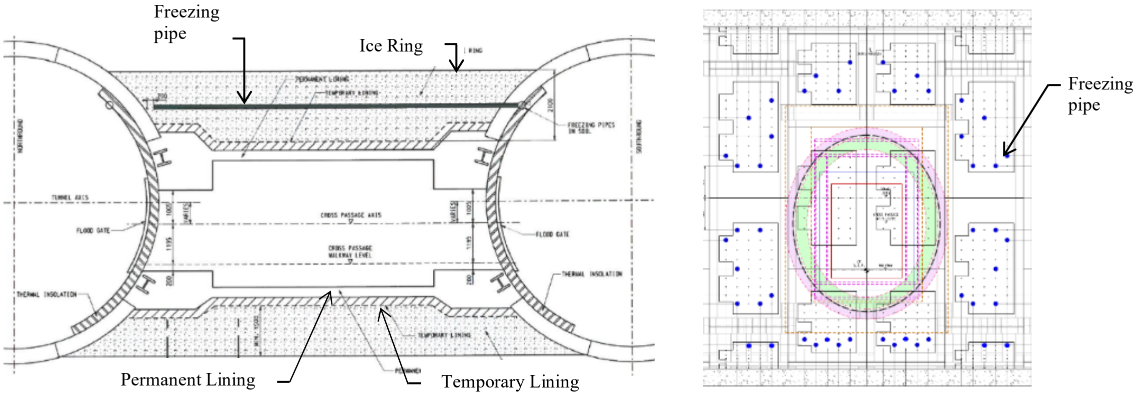


Figure 4. Arrangement of freezing hole on tunnel segment

4 CONSTRUCTION OF AGF WORKS

4.1 *General arrangement*

The construction of AFG works is described by a project with 6 cross passages (CP1-CP5 and CP8) for AGF works between the up-track and down-tack tunnels. To achieve a safe and fast track construction, the 6 cross passages are divided in to two groups for AGF such that the works for each group can be carried out simultaneously in a streamlined manner. The construction arrangement is illustrated in Figure 5.

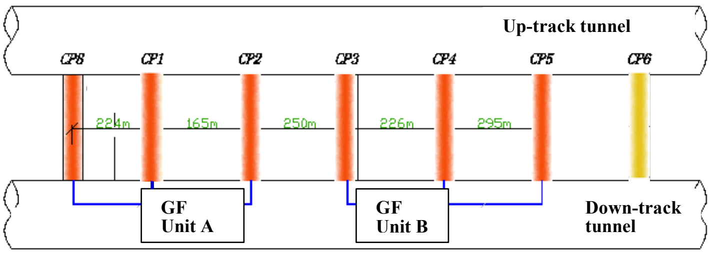


Figure 5. Layout plan for the grouping of cross passage

4.2 *Construction methodology*

The first step is to drill holes for installing freezing pipes and thermometers in the freezing zone of cross passage. At the same time, cooling stations are installed. Once the freezing pipes and cooling stations are installed, freezing works can be started to strengthen the soil. After the design freezing time, the ground freezing is verified by instrumentation monitoring to check if the performance requirements of ground freezing works are achieved. Subsequently, the tunnel segmental lining can be removed and excavation of cross passage can be carried out stage by stage with installation of temporary support. Upon excavation of the entire cross passage is completed, a waterproofing layer will be laid against the temporary lining. Finally permanent lining will be cast.

4.3 *Construction of freezing hole and installation of freezing pipes*

The drilling of freezing holes is carried out according to the below steps:

(1) Setting up of the drilling rig and equipped with the grouting pump.

(2) Special type ϕ89 drill rods equipped with guiding function drill bit and oblique sensor are used with recirculate water flush rotary drilling.

(3) Measurement of the drilling direction is carried out at 2m interval using Gyro inclinometer. Adjustment of the drill bit direction is carried out according to the measured inclination. Measurement of derivation is checked again when the design depth of drilling is reached.

(4) When drilling the freezing pipe reach to the design depth, pull back the drill rod and filling the hole with grout is carried out concurrently until the whole drill rod is retrieved out. Close the blow out preventor to prevent leakage of grouting.

The installation of the freezing pipes is carried out as below:

(1) The freezing pipes is connected by using of threading, when the casing is threaded tightly, the pipe joint is weld manually to ensure concentricity and strength.
(2) Install freezing pipe on drill rig and carry out drilling. Connect the freezing pipe one by one until drilling depth is reached.
(3) Install the liquid supply tube inside the freezing pipe, then weld the freezing pipes end cap, return liquid steel tube and the final connection hose.

4.4 *Installation of the colling stations*

Cooling station is installed in the tunnel between CP1 and CP2 to support the freezing works of CP1, CP2 and CP8, another cooling station is installed in the tunnel between CP3 and CP4 to support the freezing works of CP3, CP4 and CP5. The general arrangement of the cooling system is shown in Figure 6.

Due to poor ventilation inside the tunnel, cooling water circulation system of the cooling station include cooling tower, water pump and water tank are be installed at the ground near TBM launching shaft. The circulation system of the cooling station including cooling pumps, brine water pump and brine water tank are installed inside the tunnel as shown in Figure 7.

Cooling station platforms are set up at one side of tunnel, the width and length of the platform is approximately 2.8m and 40m respectively. The main equipment to be installed at the cooling station platform include cooling plan, brine water tank, brine water pump, power distribution cabinets and cables.

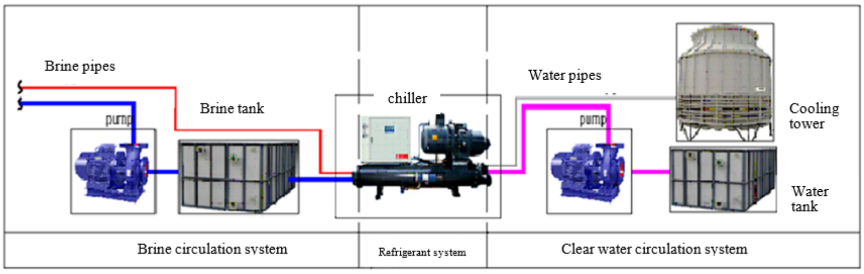


Figure 6. Illustration of cooling system

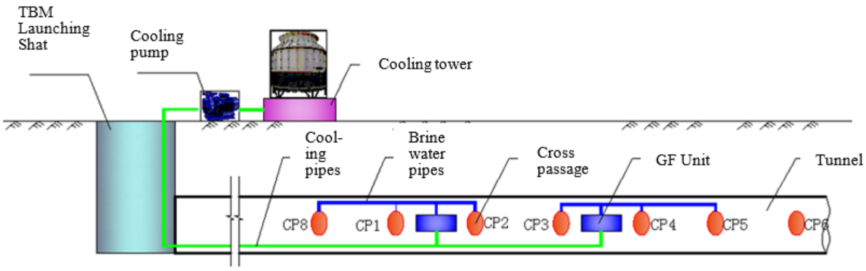


Figure 7. On-site arrangement of cooling stations

4.5 *Piping system installation*

(1) The pipes are connected with flange connection and the brine water pipes inside the tunnel are support by the steel bracket installed on the segment in order not to affect tunnel access.
(2) Testing equipments such as pipeline valves, pressure gauges and thermometer are required to be set up on the brine water and cooling water pipes.
(3) Once brine water pipes are installed, water tightness test is carried out for maintaining testing pressure of 0.6MPa for 15 minutes.
(4) The connection between the brine water feeding pipe and the freezing pipe are provided by high pressure rubber house. Valves are installed at both inlet and outlet of feeding pipe at each to control the flow.

4.6 *Insulation works*

(1) The evaporation parts of cooling station and low temperature pipe are insulated. Brine water tank and brine water pipes are insulated with 50mm thick insulation material. Brine water pipe insulation material are wrapped by plastic film.
(2) Insulation on tunnel segments at both sides of cross passage: Since the heat loss on concrete tunnel segments surface is relative easier than soil layer, in order to enhance the effectiveness of ice ring at the tunnel segment, insulation measures are provided at the surface of segments at both ends of cross passage to reduce heat loss.
(3) The insulation layer are provided at the tunnel segments surface affecting the ground freezing works.
(4) For area where end of freezing pipes are in touch with tunnel segments, additional freezing pipes are provided at surface of tunnel segments. Insulation layer are provided at the surface of tunnel segment at the ice ring development area to reduce heat loss.

4.7 *Freezing operation*

(A) Freeze System Testing
Testing and commissioning are carried out after all equipments are installed. During testing, pressure, temperature and other operation parameters are adjusted to suit the technical requirements of equipment. After testing and commissioning, the system can be operated for active freezing.

(B) Active Freezing Stage
This stage is the formation of ice ring period. During the active freezing stage, instrumentation monitoring is carried out to check if the ice ring is closed and achieve the design thickness. The main technical specifications are as follow:
(1) Brine water temperature during the active freezing stage ranging from -25 °C ~ -30 °C.
(2) The flow rate of single freezing hole shall not less than $5m^3/h$;
(3) The temperature of brine water for 7 days of active freezing should dropped below -18 °C. The temperature of brine water for 15 days of active freezing should dropped below -24 °C. The temperature of brine water to drop to -30 °C before excavation.
(4) The temperature difference between feeding pipe line and return pipe line of brine water shall be less than 2°C.
(5) The design freezing time is about 45 ~ 50 days, if brine water temperature and flow rate do not meet the design requirements, active freezing time should be extended.

(C) Maintenance Freezing Stage
Maintenance freezing stage is maintenance period of ice ring. When the ice ring meeted the design requirements, it can be changed to maintenance freezing stage.
The temperature of maintenance freezing stage is about -28 °C ~ -23 °C. The freezing time is based on progress of cross passage excavation and construction of permanent structure.

4.8 *Excavation and installation of primary support*

Before commencement for opening the tunnel segments, information on monitoring data of thermal sensors, prizometer and probe holes are reviewed. Table 1 showed the technical requirements to be met before excavation.

Table 1. Technical requirements for commencement of excavation

Item	Requirement	Method
Ice Ring Thickness	Design Values	Using mapping method
Ice Ring Temperature	-10°C	Thermocouple temperature monitoring
Brine Water Temperature	-28～-23°C	Monitored with thermometer, thermocouple
Brine loop temperature different	Within 5°C	Monitored with thermometer, thermocouple

Temperature difference between feeding and return pipes	Within 2°C	Monitored with thermometer, thermocouple
Piezometer	0.15MPa increment of water pressure	According to reading of pressure gauges, no water and mud outflow

Excavation work can be started after confirmation with the result of instrumentation monitoring and probe holes drilling. The tunnel segment can be cut and removed, excavation of CP is carried out by top heading and benching method. Temporary support of steel ribs and shotcrete are applied.

In view of relatively high strength of the frozen soil and strong ice ring formed by ground freezing method, the excavation advance can be carried out between 0.5 ~ 0.8m. The condition of ground freezing is reviewed with the exposed ground during excavation and instrumentation monitoring. The excavation advance and temporary support can be adjusted to suit the actual ground condition to ensure safety of works.

4.9 *Waterproofing installation and construction of permanent structure*

Hydrophilic strip and embedded re-injectable grout pipe are provided at the interface between the tunnel segment and cross passage permanent support. After the excavation and temporary support for enlarged section at tunnel segment are completed, waterproofing membrane from tunnel crown, along the side walls and connected with membrane at the floor to form a closed waterproofing layer.

Permanent support in form of in-situ reinforced concrete are provided at cross passages. In order to minimize the number of construction joints, continuous casting of concrete are carried out after cross passage excavation and temporary support is completed. To improve the quality of concrete, concreting works are carried out in batches, grouting machine are used to fill up the voids in the concrete if necessary. Embedded water-stop are provided at the construction joints.

4.10 *Thawing and compensation grouting*

During the natural thawing, monitoring control system is performed to monitor soil temperature, settlement. Compensation grout is used to control ground settlement. Reserve grout holes in the concrete segment are provided in the mainline tunnels. Reserve grout holes at cross passage lining is arranged with 4 grout holes installed at 2m interval at each cross passage. The grout holes are staggered into two types as shown in the Figure 8. The acceptance of grouting works shall be based on the monitoring data of ground settlement and whether thawing is completed. Under the condition where thawing is completed with grouting not carried out, if the record settlement is less than 0.5mm in half-month period for continuous monitoring for a month. Compensation grouting can be stopped.

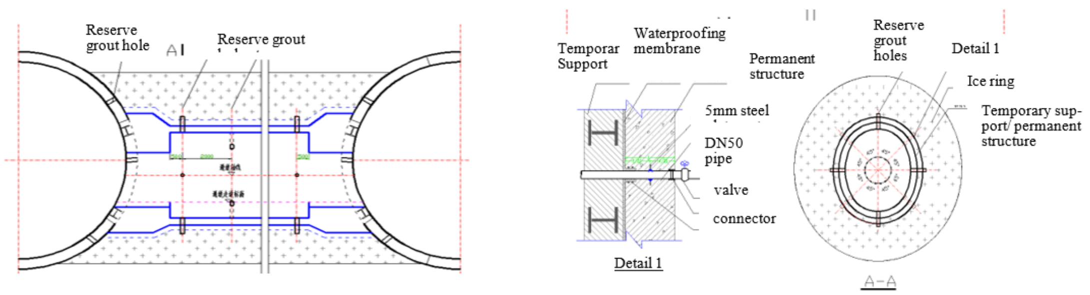


Figure 8. Grout holes installation and details

4.11 *Monitoring and control*

Temperature monitoring is carried out by installation of thermal couples, constantan wire is connected for transmitting signal. Thermal couples are located at the interface between ice ring and segmental lining, with typical spacing of 2m c/c.

Perforated pipes with staggered slots are applied as piezometer as pressure relief tubes. Pressuremeter is installed at the end of the tube with cables connecting to the data logger. Pressure vale is provided at the head of piezometer, in case the internal soil pressure excesses the corresponding hydraulic pressure by 0.1MPa, the pressure relief valve is then be opened for pressure relieving purpose. The general layout of the instrumentation monitoring is shown in Figure 9.

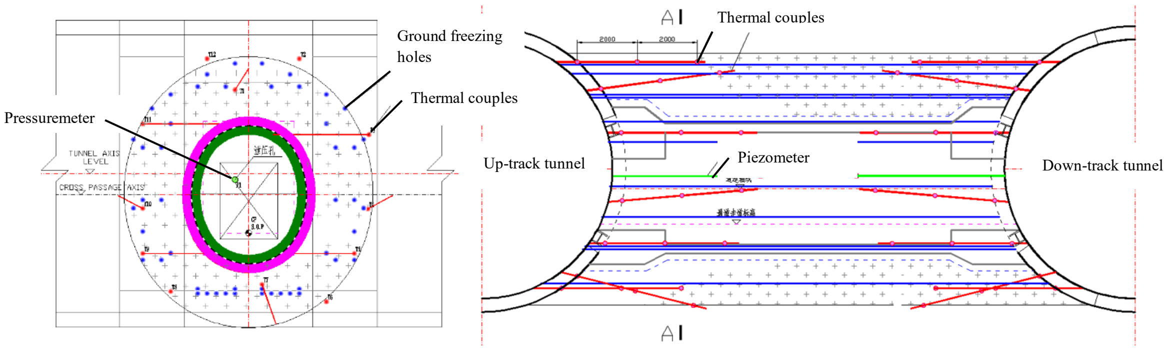


Figure 9. General layout of instrumentation monitoring

5 CONCLUSION

The construction of cross passage is one of the high-risk activities for tunnel construction. The AGF freezing technique has been successfully applied as ground improvement method for cross passage construction in soft ground between twine bored TBM tunnels. The key considerations for design and construction of AGF works for cross passages are presented in this paper. The ground freezing method is very reliable in achieving design strength and watertightness with careful planning, design and instrumentation monitoring of ice ring development.

6 REFERENCES

Andersland, O. & Ladanyi, B. 2004. *Frozen Ground Engineering (2nd ed.)*. Wiley and Sons, Hoboken, NJ.

Harris, J.S. 1995. *Ground Freezing in Practice*. Thomas Telford.

Martin, O., Storry, R., Harris, D. & Pegon, J.L. 2005. Ground Freezing in Hong Kong for Mining Cross-passages under Sensitive Ecological Area. *Underground Construction – 2005 Conference and Exhibition, 26 to 27 October*, London.

Pakianathan, L. J., Kwong, A., McLearie, D. D. and Chan, W.L. 2002. Pipe Jacking: Case Study on Overcoming Ground Difficulties in Hong Kong SAR Harbour Area Treatment Scheme. *Proceedings of Trenchless Asia 2002, 12-14 November 2002*, Hong Kong, UK Society for Trenchless Technology.

Polycarpe, S., Ng, P.L. and Barrett, T.N.D.R. 2012. Construction Risk Mitigation of the Tunnel to Station Connection Using Artificial Ground Freezing in the MTRCL West Island Line Contract 703. *Proceedings of HKIE Geotechnical Division Annual Seminar, 25 May 2012*: 137-146.

Tsang, L., Cheung, A., Leung, C. and Chan, W.L. 2012. Artificial ground freezing for TBM break-through – Construction. *Proceedings of HKIE Geotechnical Division Annual Seminar, 25 May 2012*: 125-130.

Tsang, L., Cheung, A., Leung, C. and Chan, W. L. 2012. Mined tunnel construction using artificial ground freezing technique for HATS 2A Project. *Proceedings of HKIE Geotechnical Division Annual Seminar, 25 May 2012*: 131-132.

Tsang, C.K., H.Z. Yu, C.S. Kong and Alan Hu 2019. Artificial Ground Freezing Application for Tunnelling Works in Hong Kong. *Proceeding of 13th Australia New Zealand Conference on Geomechanics, 1-3 April 2019.*