APPLICATION OF GROUND FREEZING FOR MINED TUNNEL IN T226 MARINA BAY STATION

Sim Zhan Rui

Land Transport Authority, Singapore, Email: Sim_Zhan_Rui@lta.gov.sg

Immediate Supervisors:
Mr Esen Sze (Project Manager Tunnelling)
Mr Ramesh Nair (Deputy Director Tunnelling)

ABSTRACT: Thomson-East Coast Line (TEL) is a fully underground Rapid Transit System which is approximately 43km long with 31 stations that will provide greater rail connectivity. With the integration of six existing station as interchanges, further enhances public transport accessibility. T226 Marina Bay Station is one of the interchange station that will link North-South Line(NSL), Circle line and Thomson East Coast line. In T226 Marina Bay Station, pedestrian link way that allows pedestrians to commute between the North-South Line and Thomson East Coast line and the two stacked mined tunnels connecting Shenton Way Station to Marina South Station were constructed directly below Circle Line and North-South Line tunnels. The close proximity poses great challenges to construction works under the existing live tunnels without disruption to daily operation of MRT. Furthermore, termination of the existing North-South Line piles had to be carried out for the construction of link way and mined tunnels. With limited space available and for the works to be carried out safety, innovative engineering solutions had to be adopted, which sees the birth of the Ground Freezing method in the Rail Construction history of Singapore. This paper summarizes T226 approach of Ground Freezing in the construction of mined tunnel. It also serves as a reference as to how Land Transport Authority pushes engineering boundaries and creating history in the Rail Construction of Singapore.

1. INTRODUCTION

This paper focuses primarily on the construction of T226 stacked mined tunnels under both North-South Line and Circle Line tunnels. Ground Freezing method was implemented to terminate and prevent the flow of water into the lower tunnel excavation site via the formation of 2 rows of continuous ice walls, keeping water away from the confines of Diaphragm Walls and the ice walls. The length of the stacked mined tunnels was approximately 44 metres. The upper bound tunnel was constructed at a depth of 20 metres, while the lower bound was at 40 metres deep.

The geology in which the Thomson-East Coast Line stacked tunnels were to be constructed consist of weak ground types Marine Clay, Estuarine Clay and the weaker layers of Old Alluvium (OA). While it could have been thought to be straightforward ground treatment for the stacked tunnels, it was never the case especially at the interfacing layers of weak and strong OA at the tunnel axis level.

Where the stronger layers of OA render the ground treatment ineffective in terms of permeability, water ingress from the sides become an engineering situation to tackle and work on. Adopting a risk-adverse and vigilant approach, the Ground Freezing method had won favour to safeguard smooth execution of the tunnel works without impact to the existing Live MRT tunnels.

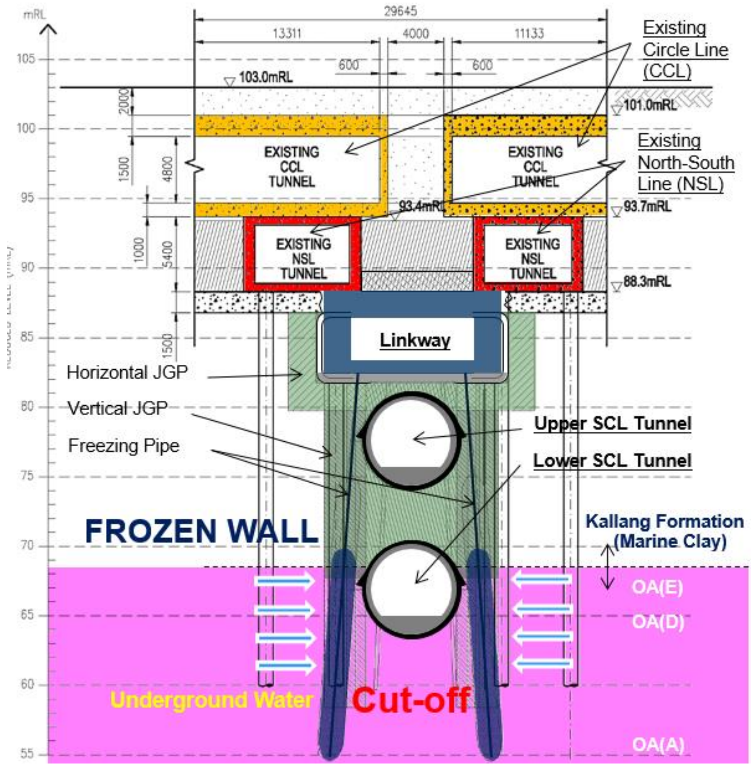

Figure 1. Overview of T226 Ground Improvement

1.1 *The Prelude to Ground Freezing and the Mining works for the Stacked Tunnels*

Before Ground Freezing works could commence, tedious stages of ground improvement works had to be carried out. The spaghetti of Live MRT tunnels were in the way of a straightforward approach to ground treatment. In order to ensure an effective all-round treatment, 4 phases of vertical JGP and 2 phases of horizontal JGP were carried out. This would ensure that the new pedestrian linkway, upper tunnel and crown of lower tunnel could be constructed in well treated ground.

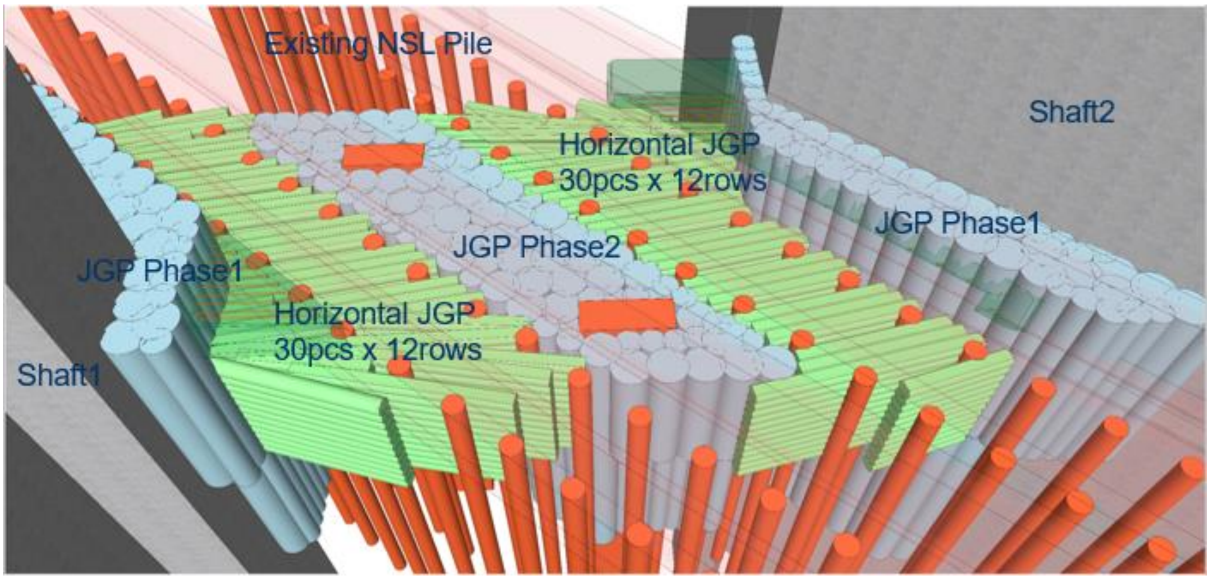

Figure 2. Vertical and Horizontal JGP for Adit Mining

The pedestrian linkway not only served its purpose of underpinning the NSL live MRT tunnels, but it also provided a stronghold, for the safe execution of Ground Freezing works. The adits were constructed via the use of Rectangular Shield Open face Tunnelling Machines. The use of horizontal JGP ensured that the tunnelling works were carried out in well treated ground. Subsequently, various stages of mined excavations allowed for the transfer slab and temporary base slab of the pedestrian linkway to be constructed, to pave the way for Ground Freezing works.

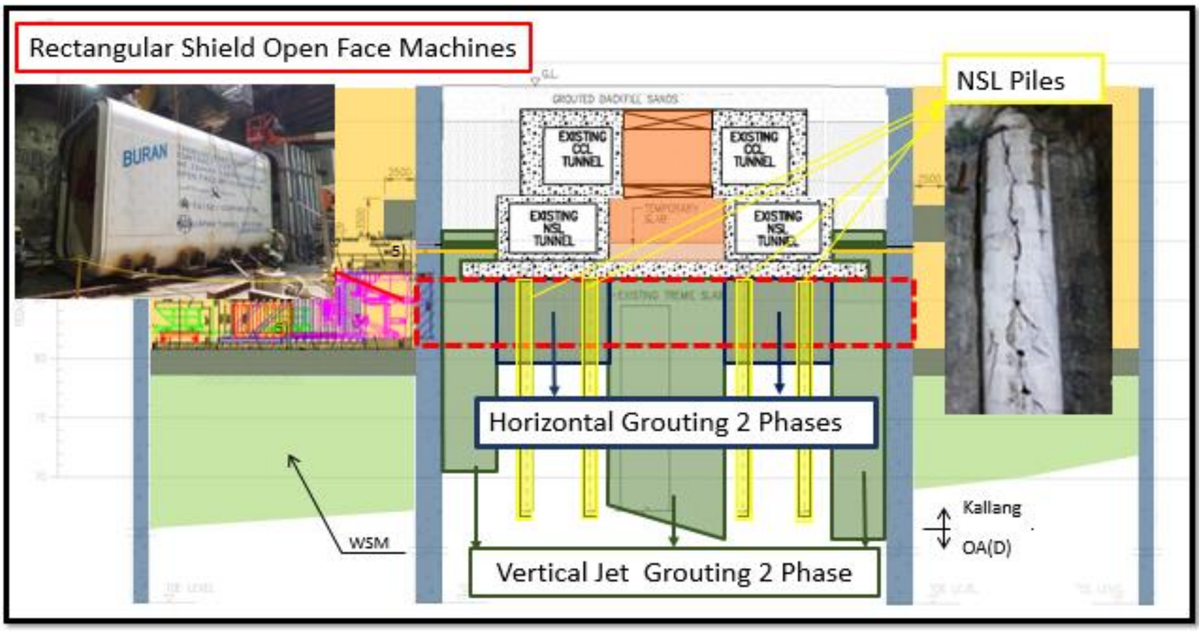

Figure 3. Underpinning of North-South Line

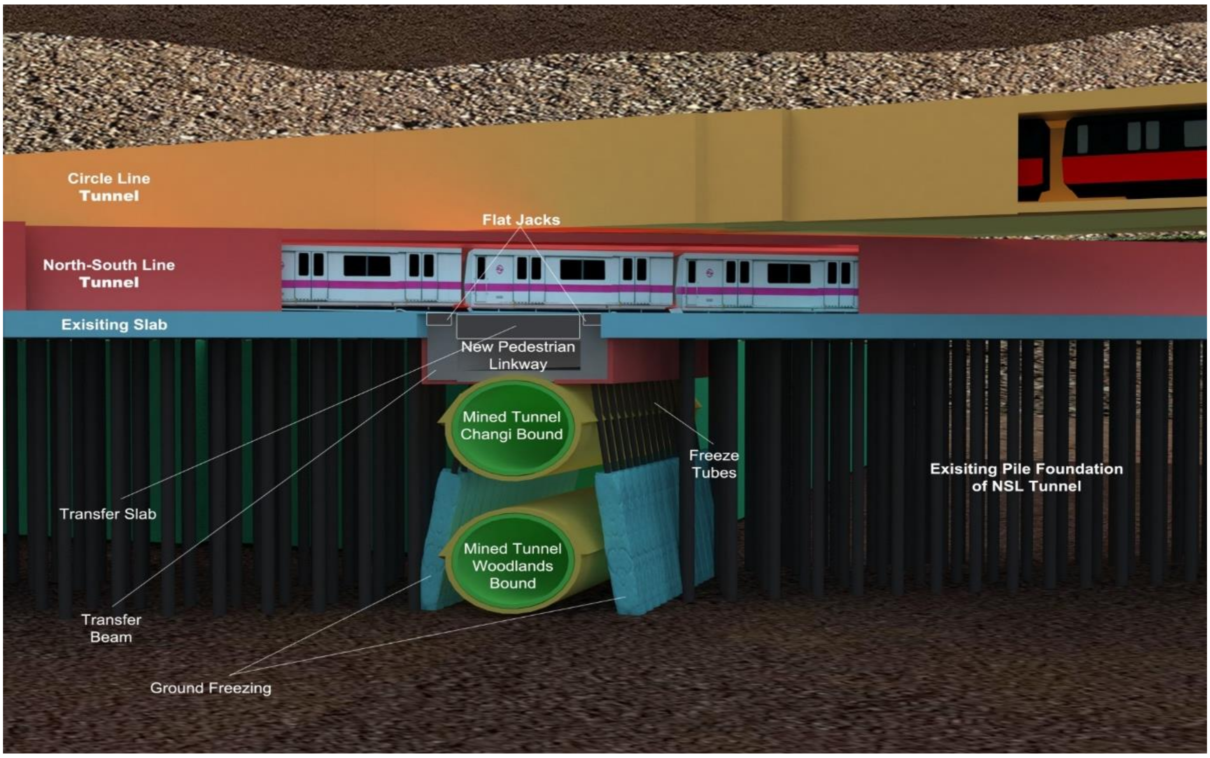

Figure 4. Overview of T226 Project

1.2 *Geological profile of T226*

The geology which upper bound tunnel had to be constructed in consists mainly of highly permeable Sand and soft Marine Clay while the lower bound tunnel had a mixed geological condition of a harder, sandier and permeable Old Alluvium layer and Marine Clay.

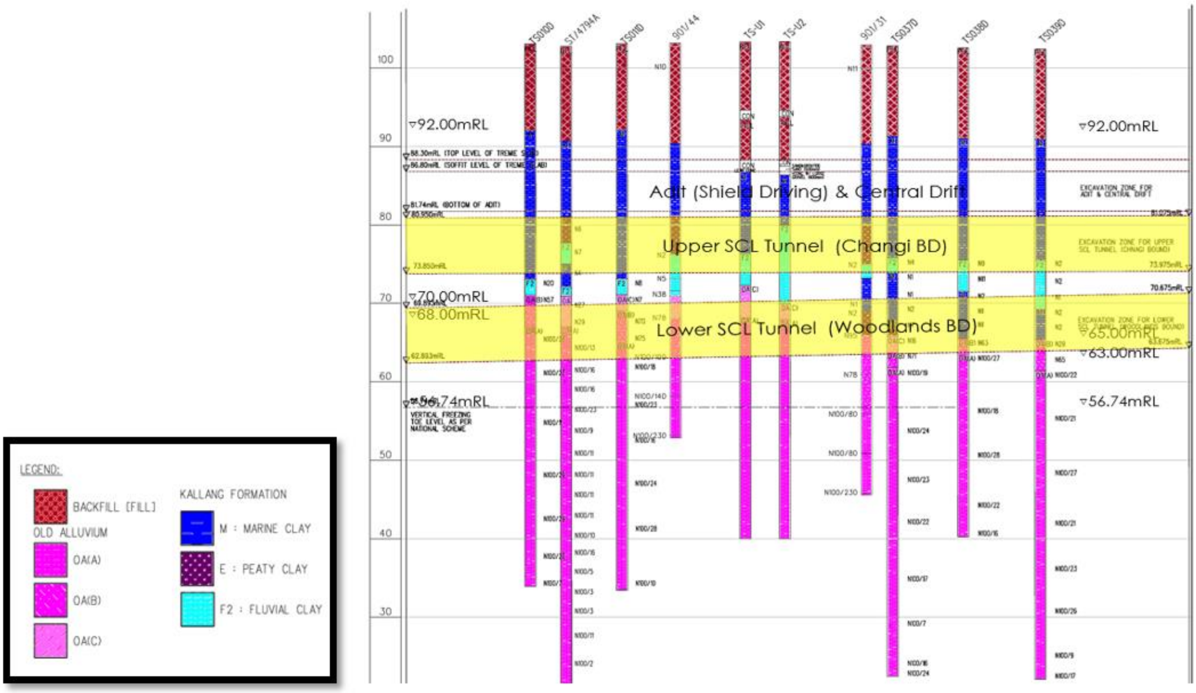

Figure 5. Geological Profile of T226

2. STAKEHOLDERS

One of the critical stakeholder for this tunnelling works was SMRT Corporation. When the project was first tabled to SMRT Corporation, the engineering team of SMRT was shaken at the massive works which would be carried out as it included cutting off the piles which support the NSL live MRT tunnels. Intense coordination meetings were carried out between the LTA and SMRT teams to ensure all aspects of the works were considered for application and approval of such NSL piles termination work. We let the stakeholder understand the contingency measures we have on hand, which can be immediately activated, in the unlikely event of a failure.

At the meetings, we engaged SMRT proactively, doing our best to let them understand and have confidence in our engineering solutions. Proactive updates and communication were provided to the stakeholder, allowing close communication in the unlikely event of a catastrophic failure at the North-South Line tunnels. During the course of our tunnelling works involving the Rectangular Shield Machine and Mined Tunnels, we sent daily updates (including Sundays and Public Holidays) to SMRT to keep them closely informed as the works proceeded 24 hours every day.

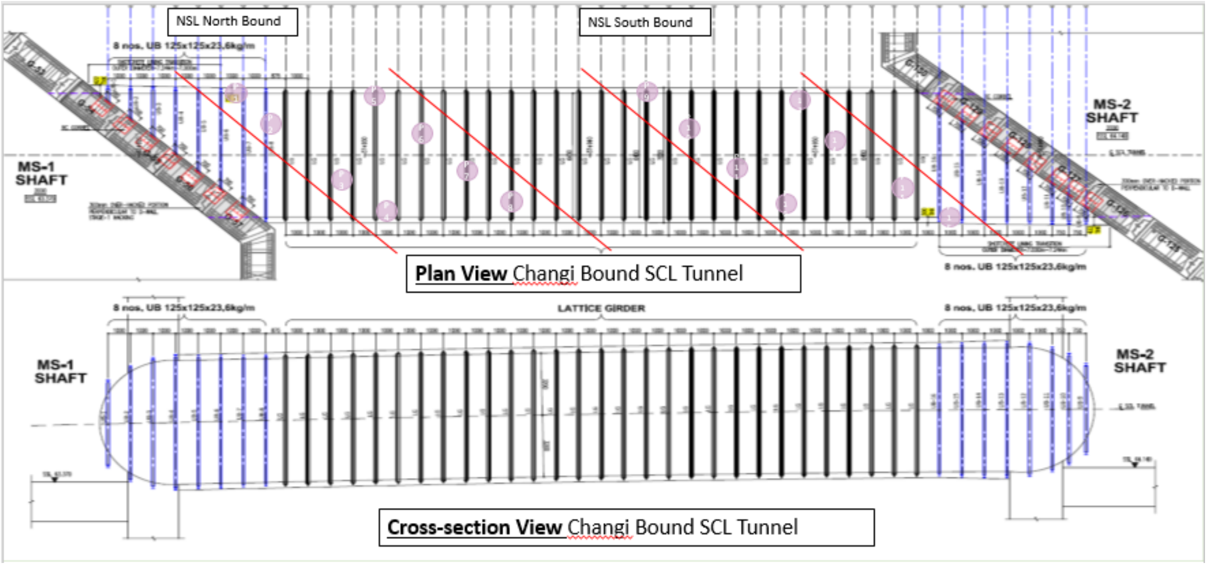

Figure 6. Temple of SMRT Updating

Our main concern will be causing any damage to the existing operating tunnels, therefore intensive Instrumentation monitoring had to be carried out to ensure safe operation for our stakeholder. Live prims were installed in both NSL and Circle Line, where it provides a live time monitoring. This will reflect any potential movements caused by our construction activities that takes place under the tunnels. The readings were monitoring closely and discussed in daily meeting to ensure all works were carried out safely and a strong reason why the stakeholder can set their mind at ease with our works.

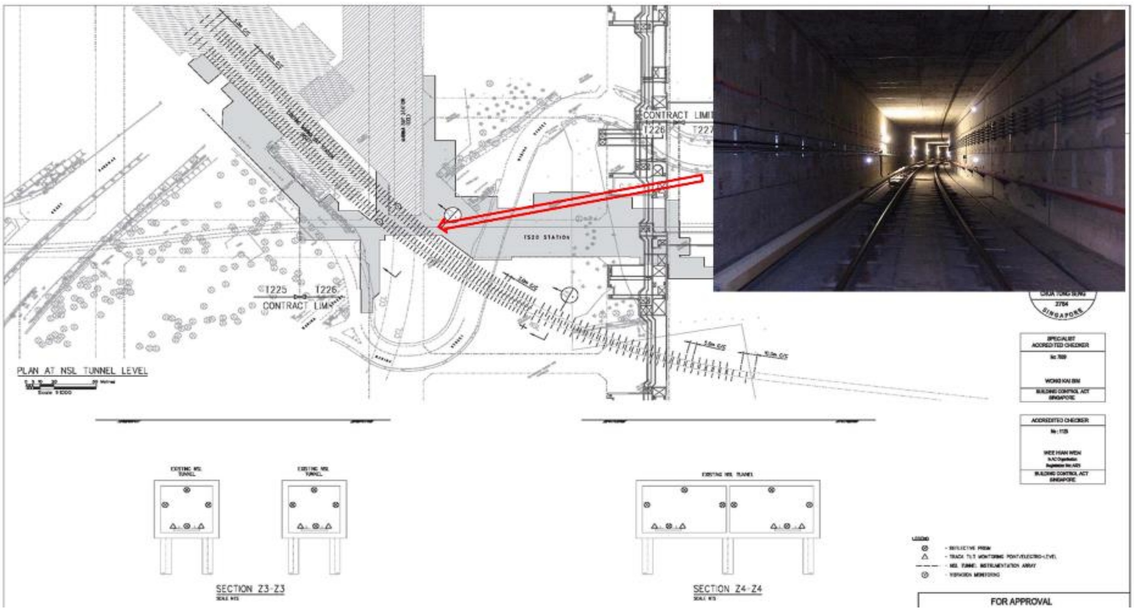

Figure 7. Real-time Monitoring for Existing NSL Tunnel

Besides the live tunnels, structures such as the linkway were also monitored with RX and LU.

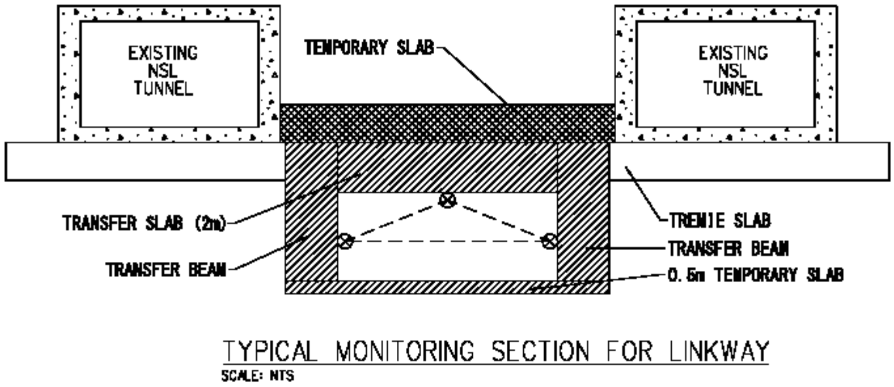

Figure 8. Convergence Monitoring for Linkway

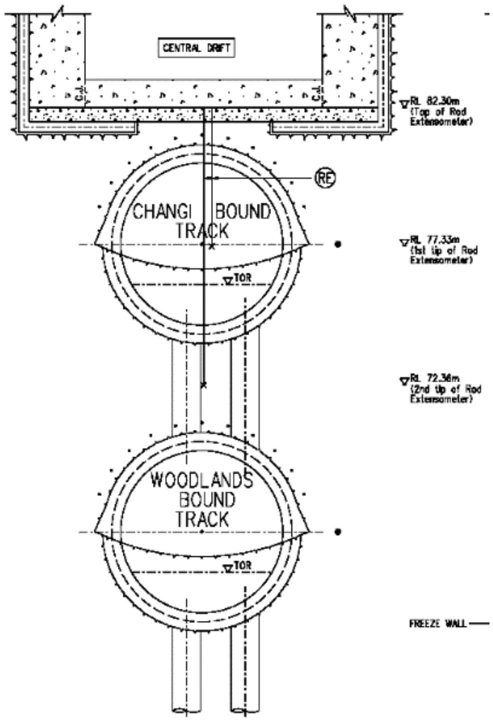

Figure 9. Rod Extensometer from Linkway

In efforts to mitigate any other risks during Ground Freezing works, with the live MRT tunnels being the topmost critical in our scope of monitoring, we had to ensure potential movements to the live tunnels due to frost heave and thaw settlement were totally addressed. Therefore, the frost heave, thaw settlement test and unconfined compression test results which were carried out in laboratory by using the soil samples from the construction site were carried out and submitted. Samples from the soil samples allowed the results to reflect the actual ground condition during Freezing works. Results shows achieved is as shown in Table 1.

	Frost heave constant C1(%)	Frost heave constant C2 (MN%/m2)	Frost heave constant C0(%)	effective stress σ1 (MN/m2)	coefficient of permeability k(m/sec)	Distance of the cooling surface and the water supply surface l(m)	final freezing surface L(m)	water intake ratio ξw(%)	frost heave ratio in site ξ'(%)
JGP Marine Clay	5.8	0.68	5.48	0.288	1×10^{-8}	4.6	1.45	2.38	8.074
JGP F2(上層)	4.2	0.59	3.88	0.263	1×10^{-8}	4.6	1.45	2.27	6.354
JGP F2(下層)	4.2	0.59	3.88	0.304	1×10^{-8}	3	1.45	2.04	6.104
Original OA(B,C,D)	0.45	0.14	1.76	0.34	1×10^{-7}	2.9	1.45	−0.82	0.866
Original OA(A)	0.62	0.11	2.42	0.413	1×10^{-8}	6.5	1.45	−1.4	0.894

Table 1. Test result submitted to LTA

With JGP layer showing a much higher frost heave ratio, thawing settlement value and laying directly under the live tunnels, contractor proposed for limitation pipes to be introduce in the Freezing pipe system.

3. GROUND FREEZING

3.1 *Concept of Ground Freezing in T226*

Ground Freezing was used in T226 to form up ice walls at both sides of tunnel excavation area in order to achieve water cut-off, without which, dangerous water ingress could happen at the weak ground and hard OA interfaces, causing any impending danger to existing structures or MRT tunnels. The design of the freezing system consists of Freezing pipes installed into the ground at a depth of around 28 meters and circulation of subfreezing temperature brine into the freezing pipes. When the moisture of soil was being to expose to the subfreezing temperature, it changes its state from liquid to solid. Frozen soil columns will then be formed around individual freezing pipes and as the ice columns grow over time, they will merge together to form a continuous frozen wall.

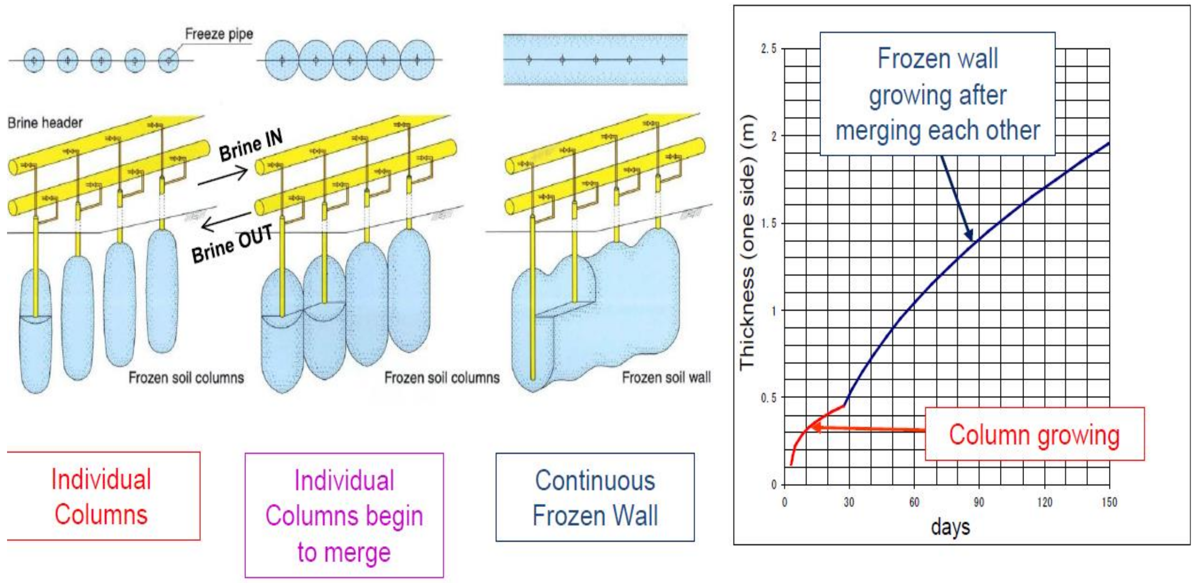

Figure 10. Ground Freezing Concept

Bine is a mixture of Calcium chloride with water. A 30% concentration can achieve a density of 1.26-1.28, allowing the brine temperature to reach -30 degrees C.

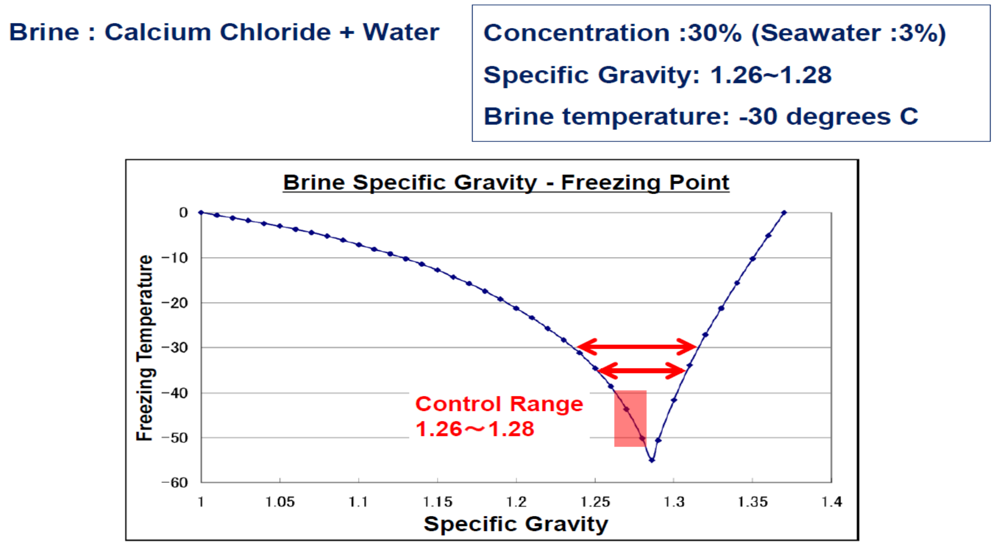

Figure 11. Brine Freezing Point

3.2 *Ground Freezing System in T226*

Ground freezing system in T226 consist of a freezing plant on the surface and pipelines runs from the plant and into the forming a close loop system. The layout of the freezing plant is as shown in Figure 12.

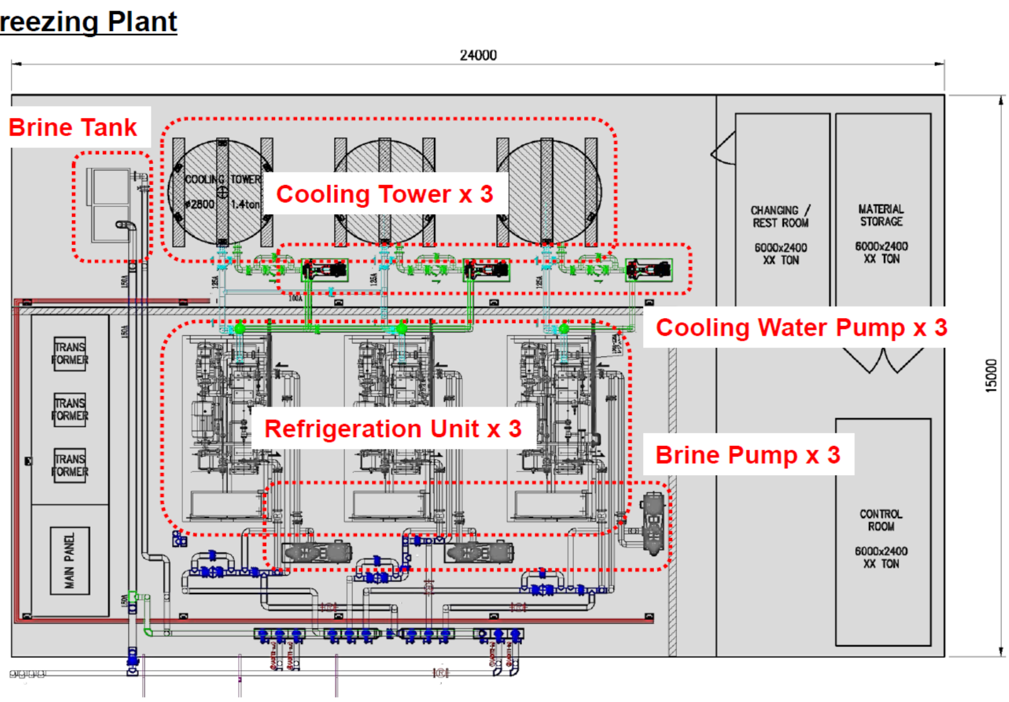

Figure 12. Freezing Plant Set up

Brine was being chilled to -30-degree C by brine cooler and pumped to central drift header pipes where it circulated into the individual freezing pipes. While being circulated, heat from the ground was transferred to the brine before they returned to the brine cooler. Figure 13 below shows the heat transfer concept in summary.

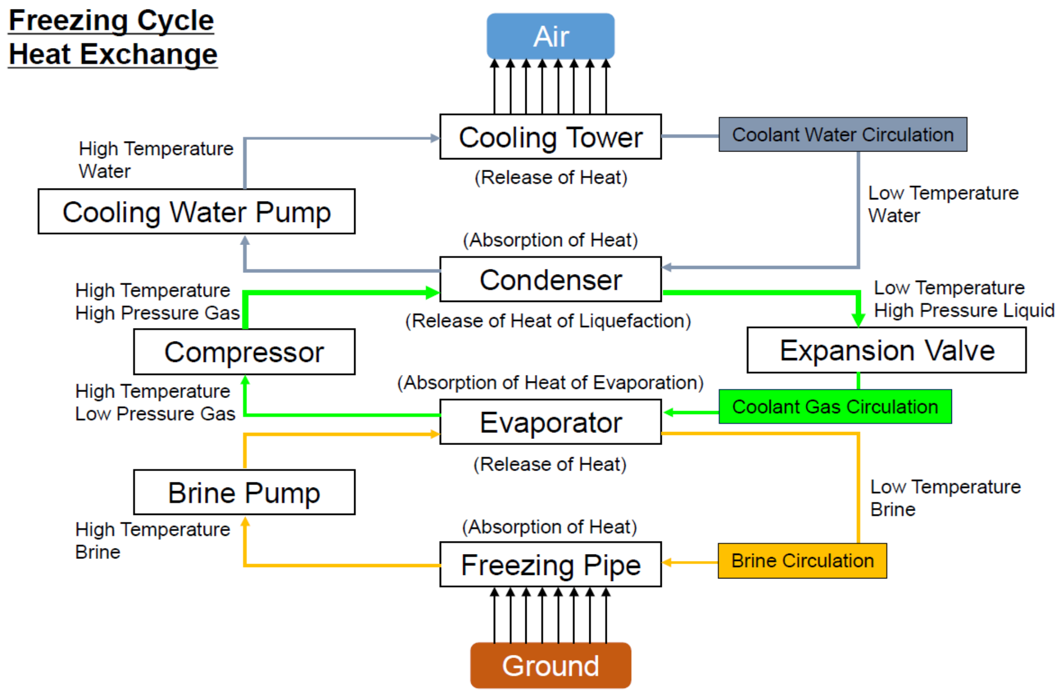

Figure 13. Heat Transfer Concept

The freezing pipes were designed to be installed at 1.2 meters apart from each other and the required thickness to ensure water tightness was 0.9 metres at single side from the freezing pipe.

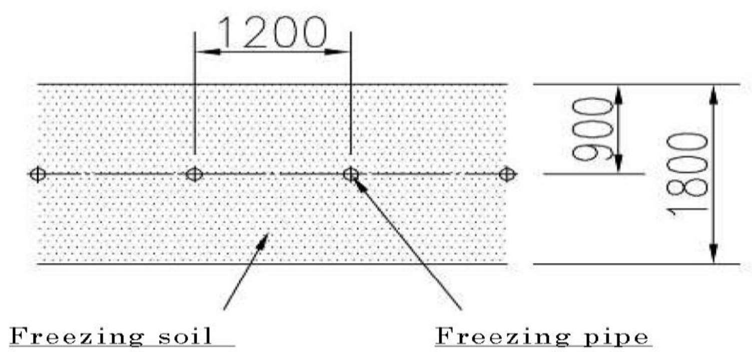

Figure 14. Freezing wall Thickness

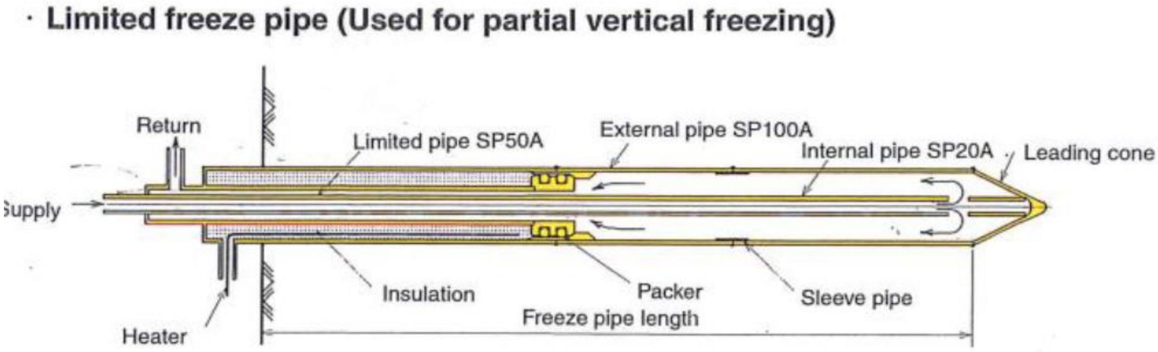

Figure 15. Cross Section of Freezing Pipe

Freezing pipes consist of 3 components, outer pipes, limitation pipes and inner pipes. Freezing pipes were installed from the central drift by first drilling to the require depth and then installing the pipes in sections of 2.75 meters where connections of the freezing pipes were fully welded together.

Limitation pipes were then installed within the outer pipes with the purpose of preventing brine circulation along the full length of freezing pipes to keep the frozen area at the minimum required level to prevent any unnecessary movements through the frost heave effect.

Figure 16. Limitation Pipes

Inner pipes were then installed to the toe level of the outer pipe to supply brine from the header pipes into the freezing pipes.

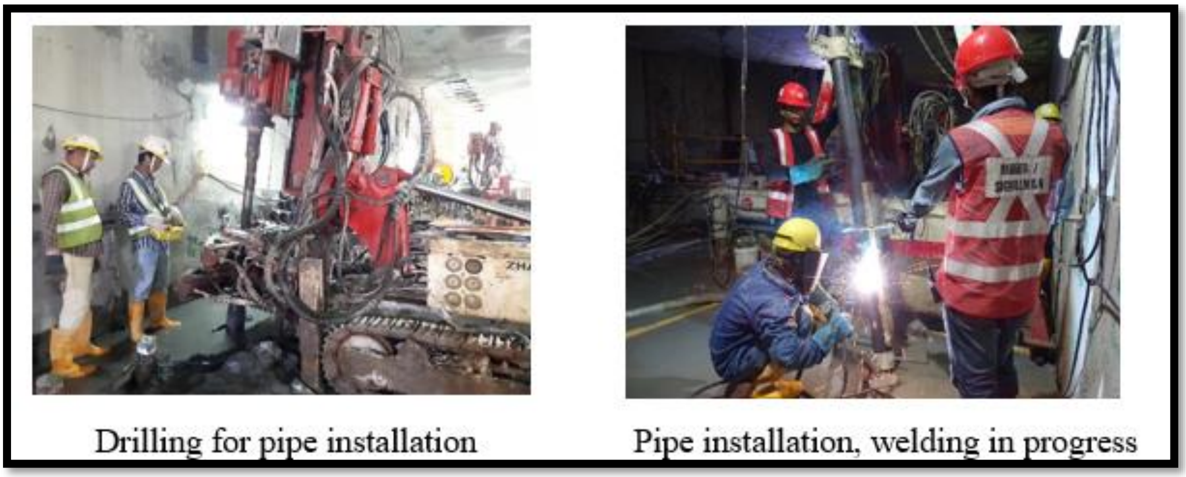

Figure 17. Freezing Pipes Installation

Figure 18. Freezing Pipes

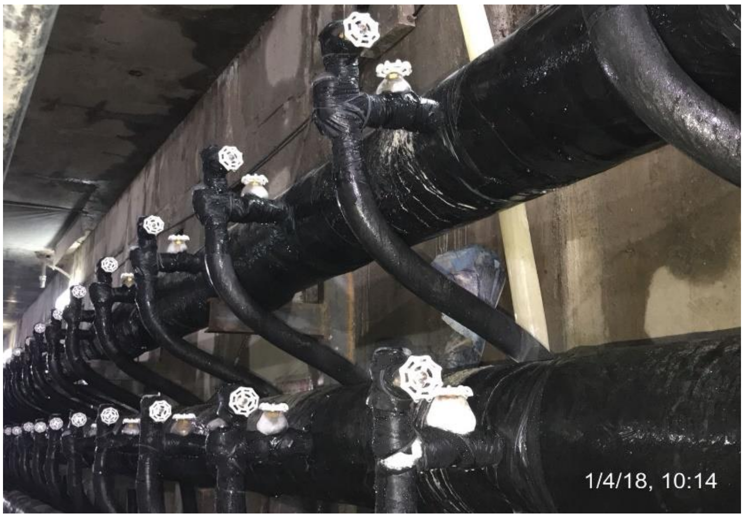

Figure 19. Values of individual Freezing pipes

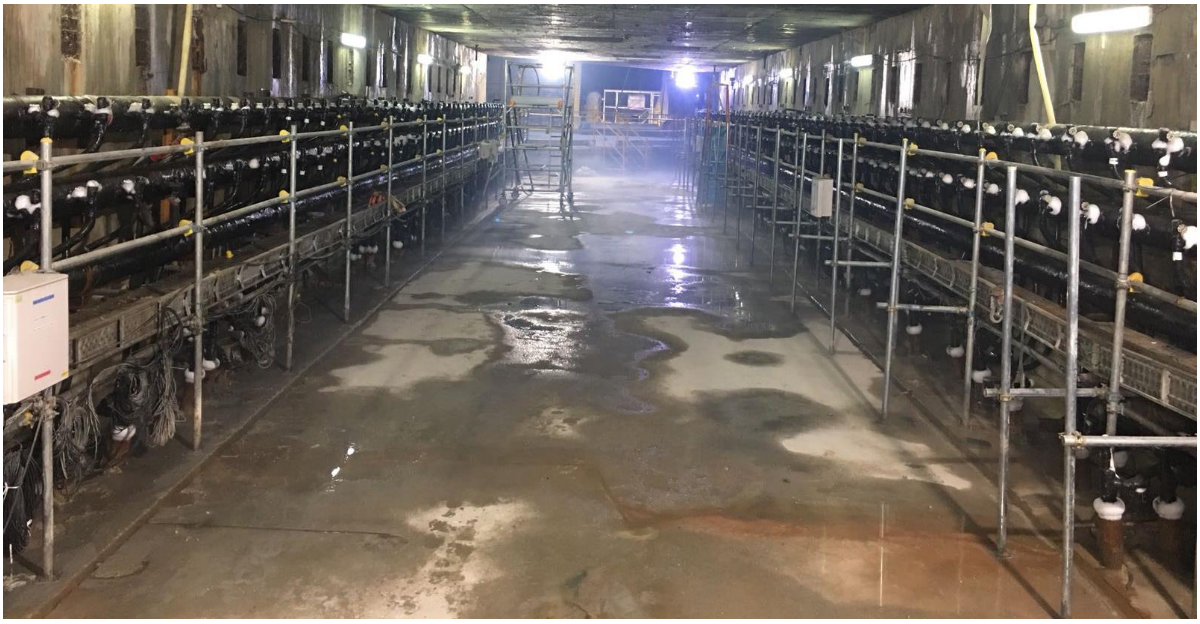

Figure 20. Completion of Pipe Installation

3.3 *Ensuring Quality of Freezing*

As Ground Freezing was a new implementation in the history of LTA rail construction, the team did not have experience and options of specialists to consider from. With Taisei Corporation having prior experience in Ground Freezing in Japan, their tender proposal of appointing Ground Freezing Specialist Seiken was much favourable to LTA's direction of zero accidents in our projects.

With the incorporation of the Ground Freezing technique which was uniquely different from conventional tunnels construction, an additional appointment of the Ground Freezing Specialist as the Independent Reviewer was carried out. This is on top of the standard risk management strategies that LTA is adopting. Several candidates having vast experiences were considered and Professor Yue who has over 134 ground freezing project experiences was appointed as our independent reviewer.

As part of management direction, we set the intensity of the audits by our independent reviewer and incorporated their technical inputs for site implementation. Together with Taisei, Seiken and Kiso Jiban, the team ensured that the technical concerns were addressed duly. We brought the experts together on common ground in a meeting table and ensured all site measures were as tight as they should be. An example would be the incorporation of our specialist concern where a layer of reflective material should be wrapped around the insulation layer and we ensured the input was quickly followed up on site. Other technical concerns such as Freezing pipe alignment, freezing plant water supply adequacy, brine concentration and flow rate also helped us firm up Inspection and Test plans to be carried out on site.

Figure 21. Meeting with independent reviewer

Before implementation of reflective material

After implementation of reflective material

Figure 22. Reflection material implemented to reduce heat absorbing

For Ground Freezing works, the mechanical design and implementation were fully undertaken by Seiken. To close up any safety lapse in this aspect, we incorporated and involved internally our Electrical and Mechanical Project and Design specialists to review the implementation of the plant set up. All the comments were tabulated and addressed, strengthening our supervisory regime not just on the civil engineering aspect of the work, assuring good functionality, reliability of the Ground Freezing works. Freezing Plant inspection and acceptance test were carried out as it was critical to ensure the formation of ice wall and maintaining it during the lower bound tunnel excavation. A plant maintenance plan was requested and carried out daily, witness by our Qualified Personal.

Figure 23. Completion of Freezing Plant Inspection

Figure 24. Freezing plant daily inspection

Figure 25. Monitoring of Ground Freezing Plant Parameters

Misalignment during pipe installation may cause the spacing between freezing pipes to be wider resulting in discontinuities ice wall. As pipe leakages have adverse effects on the flow of brine and growth of ice, together with our independent reviewer, we crafted changes to tighten up the Inspections and Test Plans.

To prevent misalignment, laser marker and tilt meter were used to ensure that pipes were installed at the correct alignment and angle. Pen light test to verify the pipe alignment and angle. At our direction, all these works had to be witnessed by our Qualified Site Supervisor.

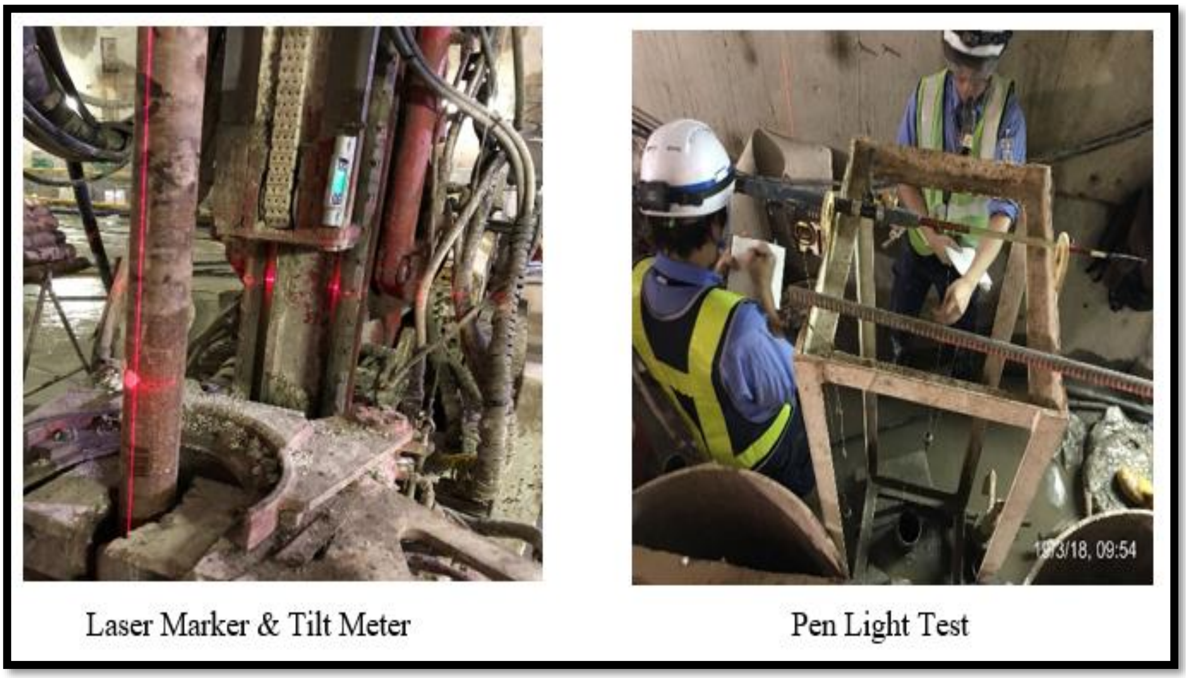

Figure 26. Ensuring alignment of Freezing pipes

All prefabricated outer & inner freezing pipes were delivered to site with standard length at 2.75m. During installation, every welded joints were to be tested by compressed air to ensure no leakage.

Figure 27. Air Leak Test

3.4 *Monitoring during Ground Freezing*

The formation of ice wall was monitored by Temperature monitoring pipes. During the freezing operation, temperature data obtained by detector were transmitted by the Data Logger to the Control Room computer software. Where it was able to produce the different diagrams of the ground temperature in terms of time, position and distance. 20 temperature monitoring pipes were installed along both sides of the freezing pipes at an interval of 4 metres and within each temperature monitoring pipes, 4 thermo-couplers were located at different levels.

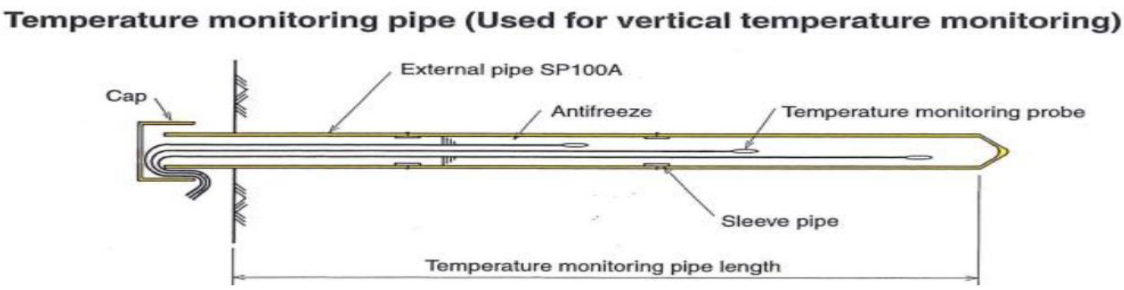

Figure 28. Temperature Monitoring Pipe

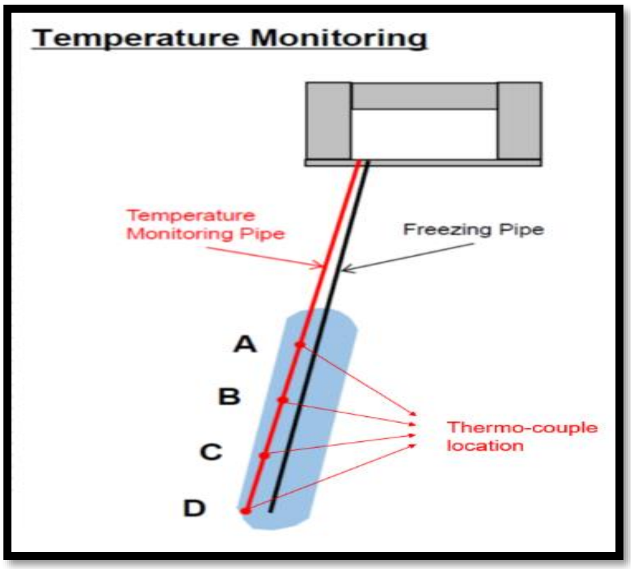

Figure 29. Thermo-Couple Locations along temperature monitoring pipe

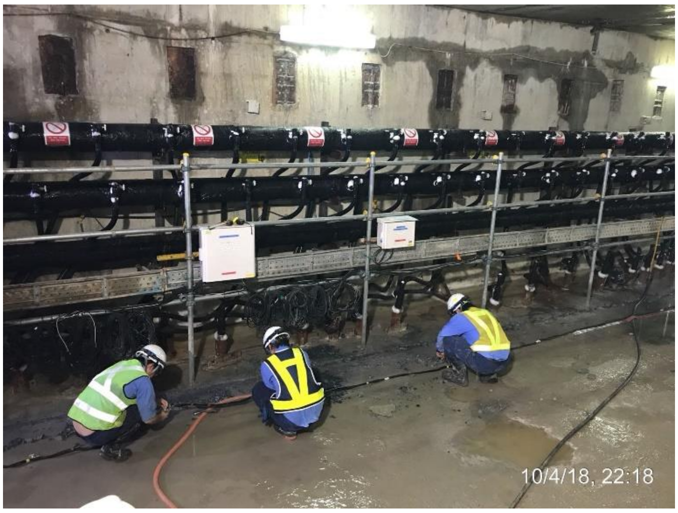

Figure 30. Weekly Thermo-Couple maintenance

As we require the temperature monitoring to be readily interpreted and understood, the 3D BIM model was developed daily, translating numerical temperatures into figures which enabled us to have a clearer picture on how the temperature reflects in terms of thickness. This was crucial as we were able to monitor based on the ice thickness of individual pipes on a daily basis and check for any discontinuity in the walls before excavation works could proceed. Mitigation actions can be taken where we feel the ice is not growing as planned.

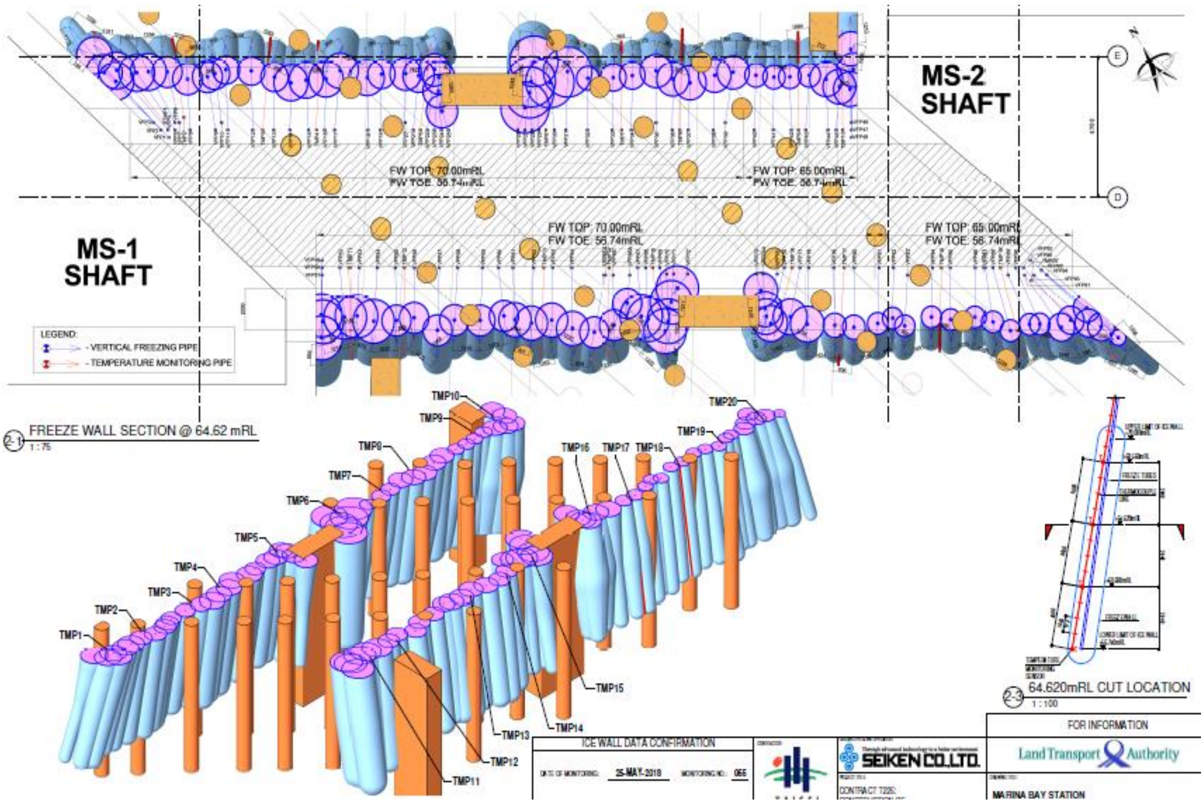

Figure 31. BIM Model of Ice Thickness for Daily Monitoring

For heat transfer to take place at a constant rate, flow rate of individual pipes was monitored daily and with the temperature of the supply and return brine of individual pipes, it enables the performance of each freezing pipes to be monitored.

Form number	FK-1015-01
Date of enactment	2016.09.21

DATE (04／07)

Brine management record Temperature difference check	Singapore T226work place

	field representative	attendant
Loh YUNIE	Shiota shiota	esaka esaka

Freezing pipe No.	date of implement	send (℃)	return (℃)	ΔT	judgment	the person in charge	remarks
VFP1	04/07/2018	−29.4℃	−27.8℃	1.6℃	good	esaka	esa
VFP2	04/07/2018	−29.4℃	−27.6℃	1.8℃	good	esaka	
VFP3	04/07/2018	−29.4℃	−27.7℃	1.7℃	good	esaka	
VFP4	04/07/2018						stop by thinning out
VFP5	04/07/2018	−29.4℃	−28.0℃	1.4℃	good	esaka	
VFP6	04/07/2018						stop by thinning out
VFP7'	04/07/2018	−29.4℃	−28.0℃	1.4℃	good	esaka	
VFP8	04/07/2018						stop by thinning out
VFP9	04/07/2018	−29.4℃	−28.1℃	1.3℃	good	esaka	
VFP10	04/07/2018						stop by thinning out
VFP11	04/07/2018	−29.3℃	−28.2℃	1.1℃	good	esaka	
VFP12	04/07/2018	−29.3℃	−28.2℃	1.1℃	good	esaka	
VFP13	04/07/2018	−29.3℃	−28.1℃	1.2℃	good	esaka	
VFP14	04/07/2018						stop by thinning out
VFP15	04/07/2018	−29.3℃	−28.0℃	1.3℃	good	esaka	

Figure 32. Flow Rate Checklist

Figure 33. Monitoring of Freezing pipe

4. CONFIRMATION OF ICE WALL FORMATION

After 59 days of freezing and monitoring, meeting with all parties concluded the readiness of the ice walls before the lower tunnel excavation commenced. Taking proactive stance against the unknowns in a new implementation of Ground Freezing works, the LTA team worked seamlessly with many parties, internally and externally, to ensure that the ice walls have been formed continuously.

Not only taking reference from the temperature monitoring pipes, additional thermo-couplers were installed along the D-walls to ensure that the ice encroaches into the D-walls. This was to prevent water slippages between the excavated area and D-wall. As shown in figure 34.

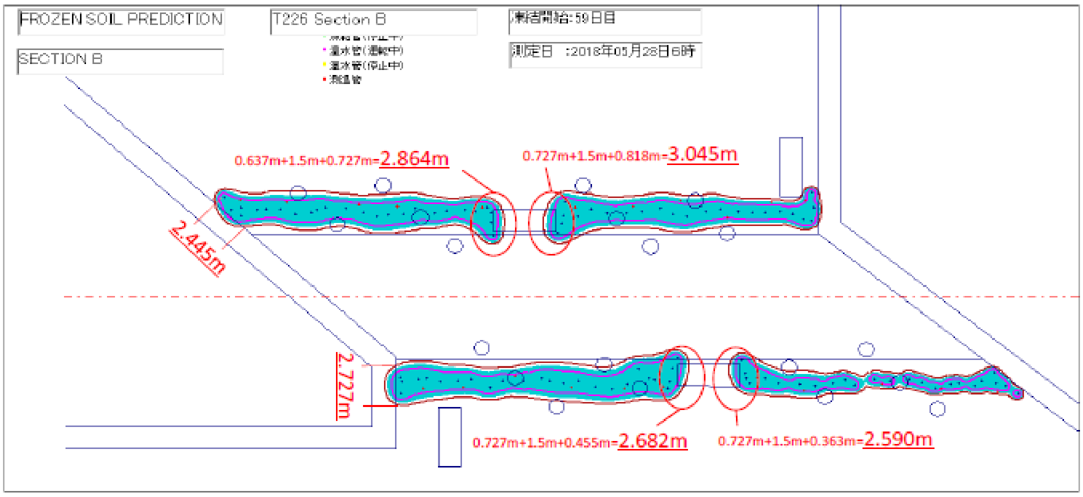

Figure 34. Confirmation diagram of Ice Wall Formation

Figure 35. Installation of Thermo-Couple on D-wall

Besides monitoring of temperature, water ingress from within the excavated area also raise our confidence in the ice wall formation as amount of water ingress and its temperature can reflect if the ice walls were fully formed. Actual temperature records of the water ingress were at around 30°C which was about the same as ground temperature taken initially shows that the water ingress comes from trapped water within the confinement of the D-wall and frozen wall.

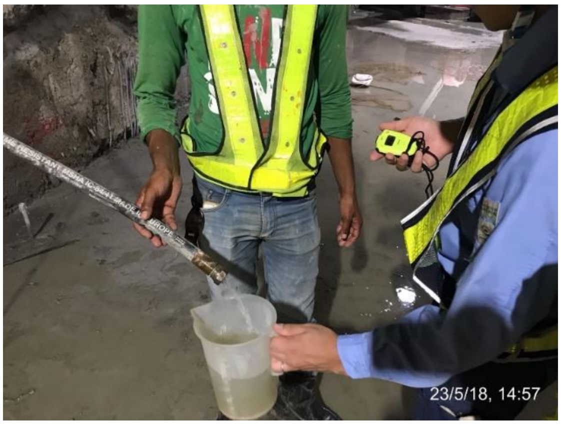

Figure 36. Water Ingress Check

Water ingress recorded shows minimal amount of water ingress from the top heading with treated JGP layer and Old Alluvium layer.

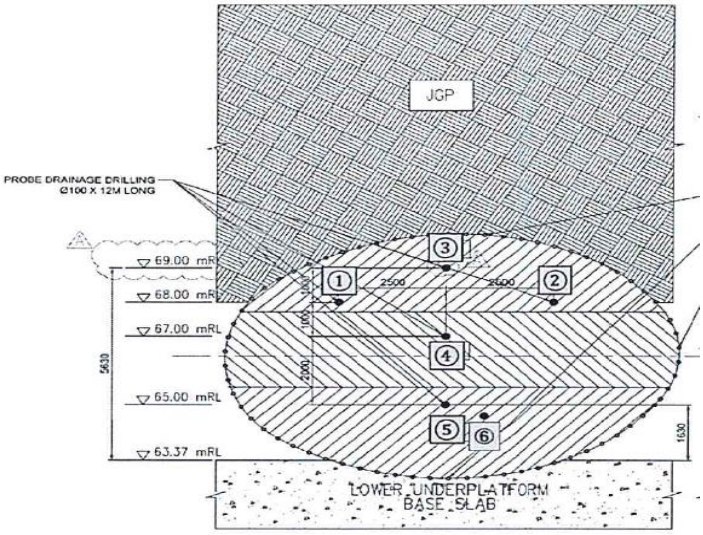

Figure 37. Probe Drilling Location

4.1 *Actual site condition*

After the breakout, top heading had a well-treated JGP block and for the Old Alluvium layer which was govern by the ice walls had a dry condition with minimum water ingress. The lower bound tunnel completed excavation with no soil collapse and any extensive water ingress.

Figure 38. JGP Condition

Figure 39. Old Alluvium Condition

Figure 40. Completion of Lower Bound Excavation

5. CONCLUSION

Being the first rail project to adopt Ground Freezing in Singapore enabled us to learn the concept of how this methodology worked in relation to the Geological and Climatic condition in Singapore. Taking no chance to risk, particularly under Live MRT tunnels, the adoption of the independent reviewer to tighten up work procedures together with the assistance of our LTA Electrical and Mechanical team, ensured that the system can function safely and according to our specification standards. We tightened up the existing regime on the ground, enhancing the Inspection and Test plan remain critical in achieving the successful completion of project without any structural impact to the live lines. As we completed the lower bound tunnel without any ingress of water from the sides, we were proven right in the successful implementation of the Ground Freezing works.

Reference:

"Underpinning of NSL MRT tunnels by Rectangular Open Face Shield Machine and construction of new tunnel by Ground Freezing method at Marina Bay Station", SPMI, 2019

T.S. CHUA, Michelle LEW (Kiso-Jiban Singapore Pte Ltd), "Ground Freezing for the Design and Construction of SCL Tunnels underneath Marina Bay Station, Singapore", Underground Singapore, 2018.