Port Mann Main Water Supply Tunnel – Ground Freezing the TBM face under the Fraser River

Joseph A. Sopko, Ph.D., P.E.
Moretrench
Behzad Khorshidi, Ph.D., P.Eng.
McNally Construction Inc.
Brian McInnes, EIT
McNally Construction Inc.

ABSTRACT: The Port Mann Main Water Supply Tunnel involves a 1km long tunnel beneath the Fraser River from Surrey to Coquitlam, BC. At depths of up to 60 m below ground, the earth pressure reached 6 bar. The tunnel is constructed using an EPB TBM and gasketed precast concrete segmental liner. The tunnel and two shafts were constructed in a variety of soil conditions ranging from soft to stiff clays and silts, to compact to very dense sands and gravels.
After approximately 800m of mining, a very dense and highly variable soil group consisting of cobbles and boulders halted the TBM. Several options were considered to stabilize the TBM face so an intervention could be conducted. Although de-watering was considered, there was risk of settlement to the Port Mann bridge piers, which was within 500m of the tunnel. Hyperbarics were also considered, however, the cost, schedule and uncertainty of the work that needed to be done, made it a risky option. Ground freezing by Liquid Nitrogen was chosen as the best solution, which would provide a frozen block around the face of the TBM. A temporary platform on the river was designed and constructed to enable drilling and installation of the freezing pipes and temperature monitoring equipment. The operation required close coordination among the tunnelling, marine and freezing sectors.

Following the intervention, the TBM successfully broke through the reception shaft, and the remaining project was completed. This paper describes the design, construction and operational approaches used for the freezing and serves as a basis for future projects requiring expedited ground freezing.

Background and Introduction

The Port Mann Main Water Supply was a one kilometer long tunnel to provide water to Surrey, BC and the surrounding area. The tunnel contributes to the water supply from the Capilano Reservoir and is part of the expansion and seismic upgrade of the Metro Water Main. The Tunnel Boring Machine (TBM) created a 3.5-m cut that enabled the installation of the segmental lining that measured 3.3 m outside diameter and 2.8 m inside diameter.

The tunnel originated in Surrey, approximately 500 m west of the Port Mann Bridge. Tunneling progressed towards the terminus in Coquitlam Park, with 11 interventions during mining. Some of these interventions were planned, others necessary due to problems with the TBM. Most of these interventions were in clayey, impermeable soils where the repairs could be completed without significant inflows of groundwater. A significant problem occurred 800 m into the alignment related to a jamming of the internal screw. This location was not only at the approximate middle of the Fraser River, but in a zone of highly permeable sand with cobbles and boulders.

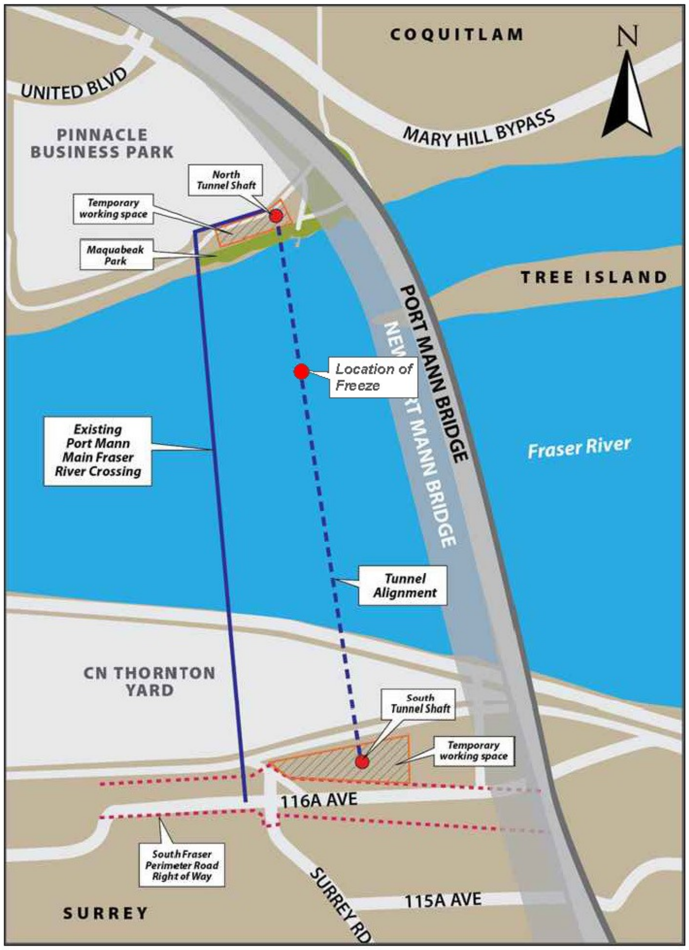


Figure 1. Site Location

This particular stratum contributed to significant groundwater infiltration making the required repairs impossible without some method of groundwater control. Dewatering was considered as the most expedient method to provided groundwater control, however due to the close proximity to the Port Mann Bridge, there were concerns that reduction in piezometric head could initiate settlement of the bridge foundations. For this reason, dewatering was ruled out as a technically appropriate technique. Another option was hyperbarics, operating under compressed air conditions. The cost, schedule and uncertainty of compressed air eliminated that approach from consideration. Permeation grouting was both uncertain and had the risk of release and contamination to the river.

After substantial evaluation and consultation with a ground freezing subcontractor that was experienced with liquid nitrogen freezing and TBM interventions, the joint venture decided on a freezing approach. This would be the first time such a freeze would be attempted in the middle of a river.

Frozen Block Design

The design of the frozen mass to provide the water tight seal for entry into the cutter head was straight forward. The frozen section must not only seal the face of the machine but also along the sides a short distance to prevent the groundwater entering behind the frozen face as illustrated in Figure 2.

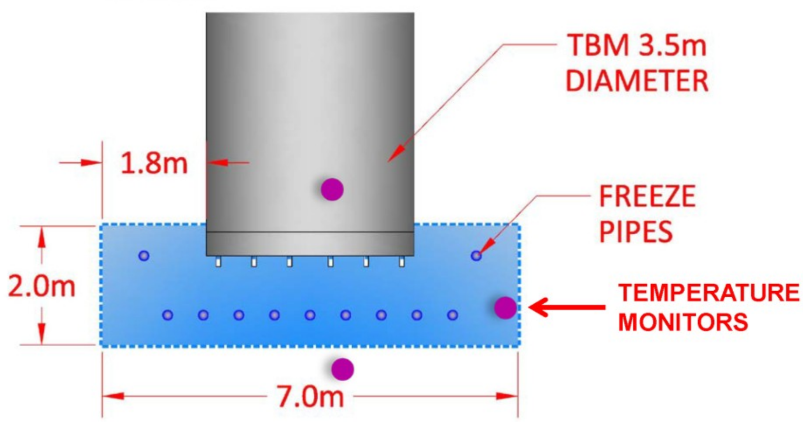


Figure 2. Frozen Mass Design

The freeze was proposed to be completed with the drilling and installation of 11 freeze pipes and two temperature monitoring pipes. Additionally there was one temperature monitoring location inside the TBM cutter head. The freeze pipes were 89mm outside diameter steel pipes with welded connections. Within each freeze pipe is a smaller diameter feed pipe that forces the liquid nitrogen to the bottom of the freeze pipe. As the liquid flows up the annulus it boils and changes phase to a gas where it was vented to the atmosphere. This is illustrated in Figure 3.

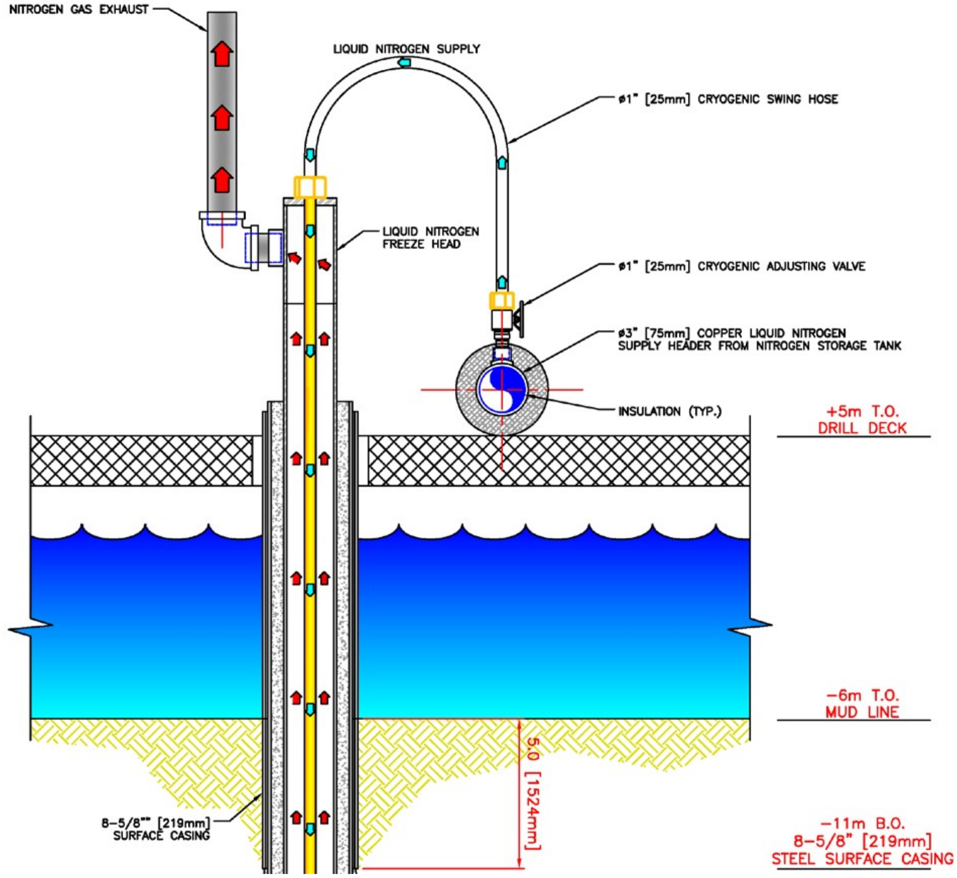


Figure 3. Freeze Pipe Detail

Effective heat transfer can only be achieved when the liquid nitrogen is actually in the liquid state. Once the liquid boils off and becomes gas heat transfer is very limited. On this project freezing was required only in the bottom nine meters of the pipe, as there was no point in freezing the ground above the TBM and wasting freeze energy. It was imperative that a liquid condition exist in these nine meters, however having a liquid level higher than this would result in waste. Maintaining this liquid level is achieved by a specialized inner pipe, temperature monitoring devices and flow control. The components and method of doing this are proprietary to the specialized ground freezing subcontractor.

The liquid nitrogen would be delivered in bulk to a storage tank and delivered to each individual pipe through an insulated copper distribution manifold as shown in Figure 4.

Figure 4. Distribution Manifold

Freeze System Construction

The fact that the location of this project was located in a river created the need to construct a platform for both the drilling and freezing operations. The contractor constructed a 31m x 7.32m platform from a barge in the middle of Frazer River. The platform was designed with a designed live load of 5 kN/m^2. Fourteen steel piles and two batter piles, 610mm in diameter, were vibrated into the riverbed to a minimum 12m depth. Each pile cap location and height was surveyed in place from land. Two layers of cross beams were welded to the piles and a timber deck was constructed on top. The structure served as a drill platform for the freeze pipes and later supported the LN setup including the two ballast tanks. Total construction took approximately 9 days.

The project configuration is illustrated in Figure 5 which also shows the relative depth of the frozen mass compared to the river surface level.

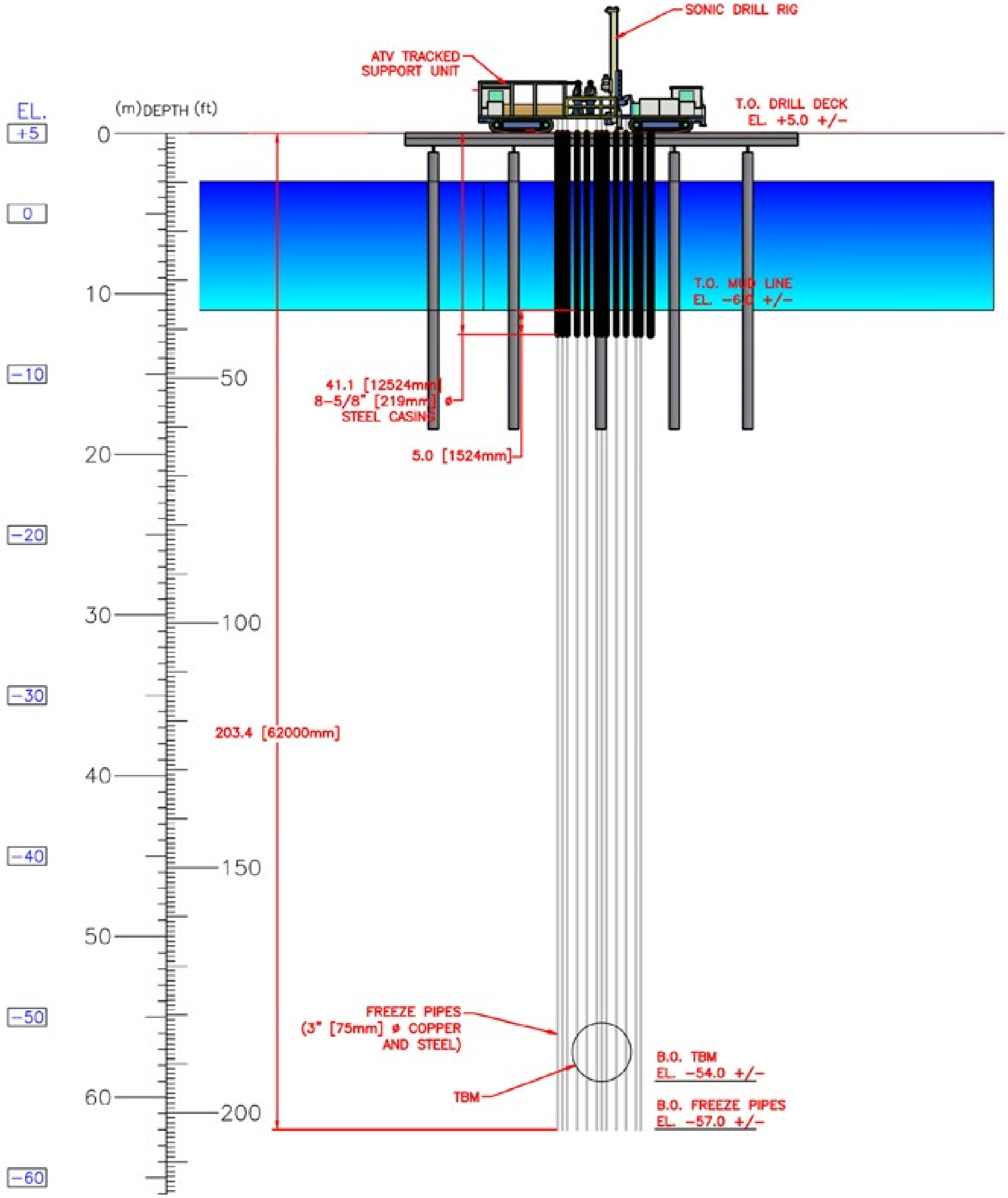


Figure 5. Platform Zone

The freeze pipe boreholes were drilled using the resonant sonic method was selected over conventional mud rotary systems specifically because it minimized any cuttings or waste that could potentially be released into the river. During the drilling operation it was necessary to control deviation, minimizing the distance between individual freeze pipes. Deviation was controlled by accurately setting up the drilling rig and using minimal down pressure, coupled with a slow penetration rate. Excessive spacing results in longer freeze times. Additionally, it was important that the pipes remained close enough to the face of the TBM to ensure the proper bond and also to make sure the pipes were close enough as to permit the propagation of the freeze under the cutter head.

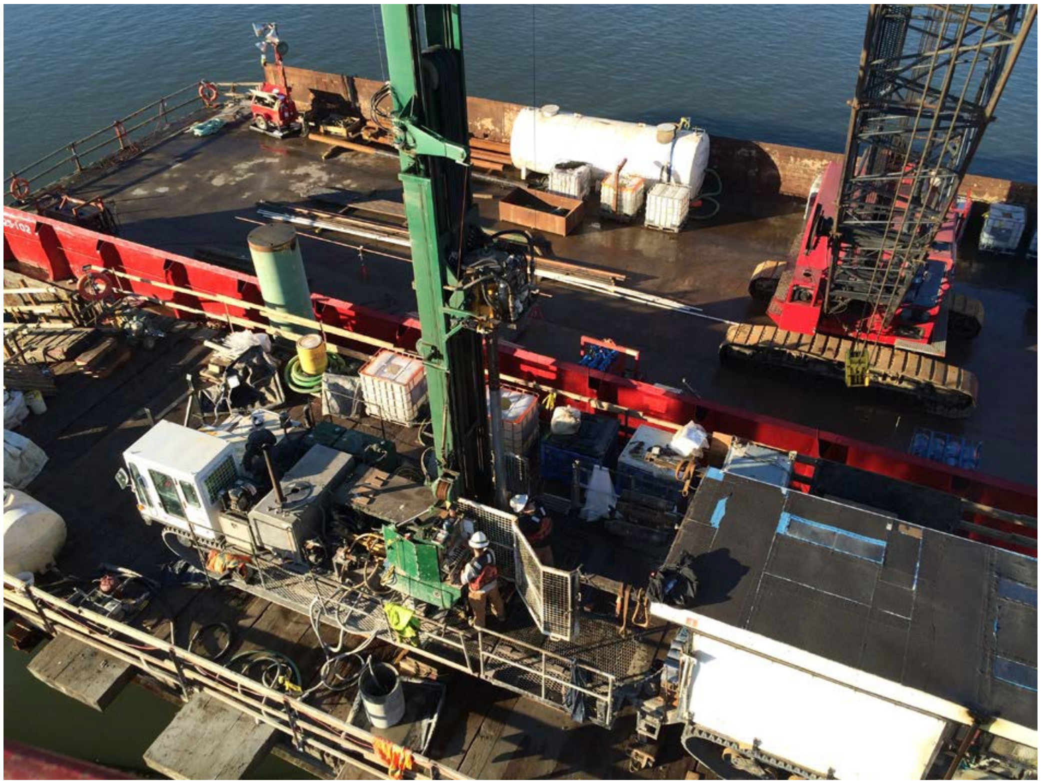


Figure 6. Freeze Pipe Drilling Operation

Following the completion of the drilling pipe installation, a verticality survey was completed using an orientable inclinometer. Results of the verticality survey were incorporated into a time dependent finite element method thermal model as shown in Figure 7.

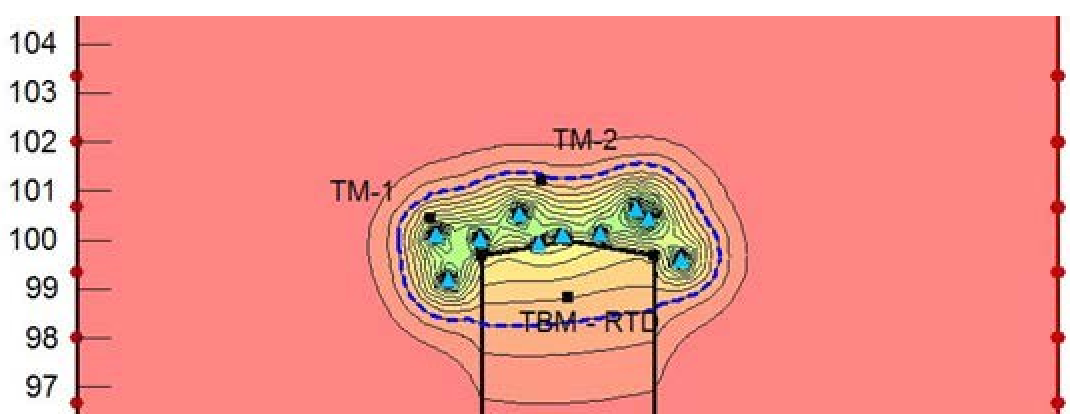
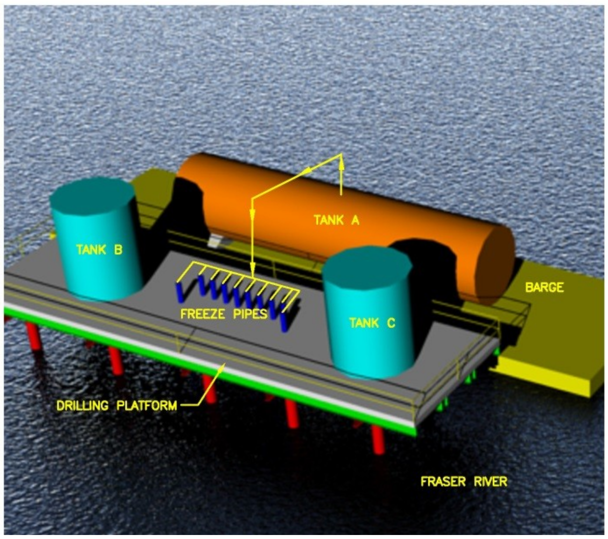


Figure 7. As-built Thermal Model

Results of the thermal model indicated that the drilling deviation resulted in a freeze time of approximately ten days, consistent with the design approach.

Due to the project location in the middle of the river, it was necessary to transport the liquid nitrogen via a large tank on a barge. Additionally two smaller tanks were installed on the platform deck to provide the required nitrogen while the large tank was taken back to shore for refilling. Figure 8 shows a schematic of the tank configuration.



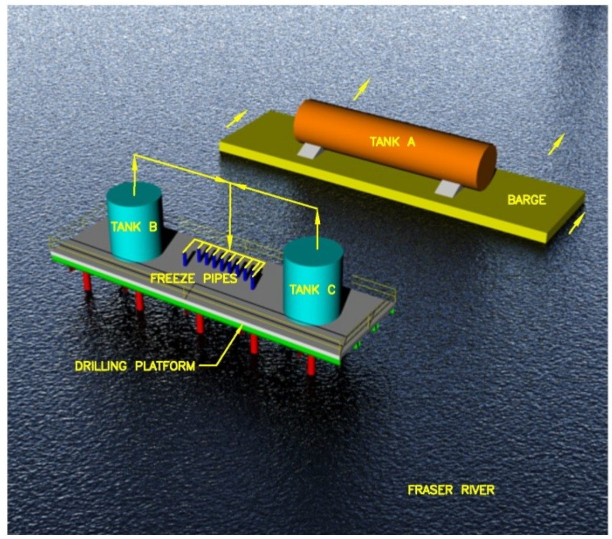


Figure 8. Liquid Nitrogen Tank Configuration

To ensure a constant supply the two smaller tanks were filled at the commencement of freezing. The freeze operation then began with nitrogen flowing directly from the large transport tank. As this tank was exhuasted, nitrogen was then transferred to the two smaller tanks. During this period the barge was taken back to the shore, refilled with tanker trailers and returned to the platform. The procedure was then repeated for the duration of the project.

Instrumentation

Ground temperatures were monitored using a series of RTDs (resistance temperature devices) installed in the temperature monitoring pipes. The RTDs were installed within the pipes at various intervals as illustrated in Figure 9.

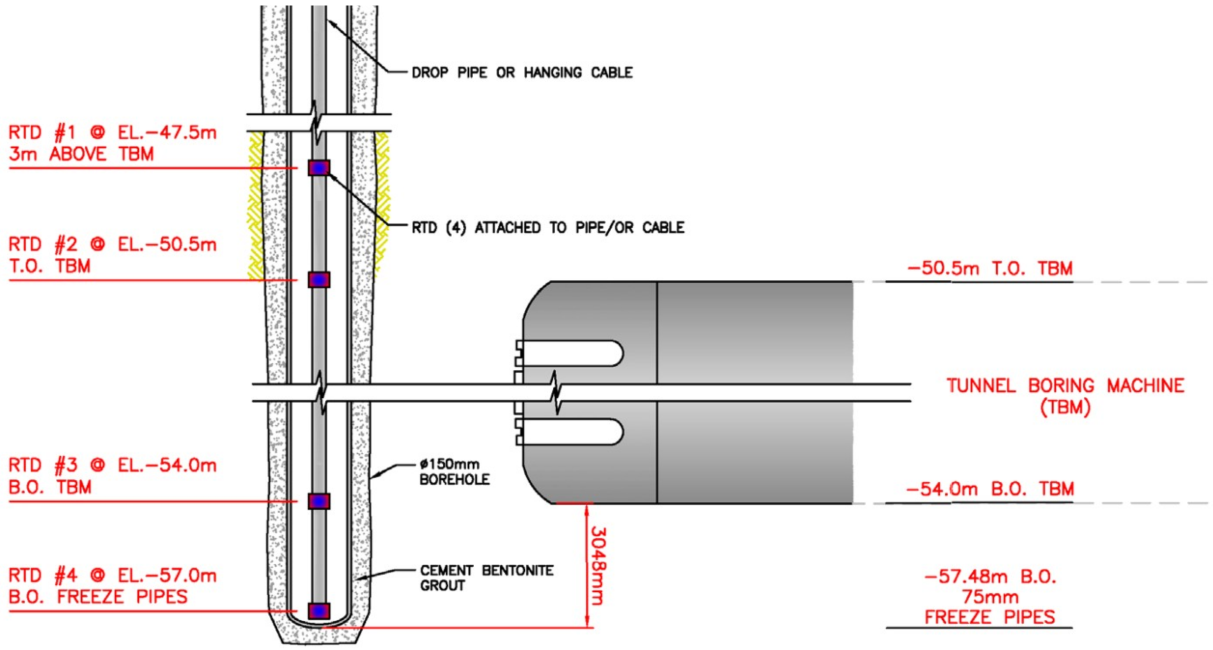


Figure 9. Temperature Monitoring Pipes

The temperatures were manually recorded and plotted as shown in Figure 10.

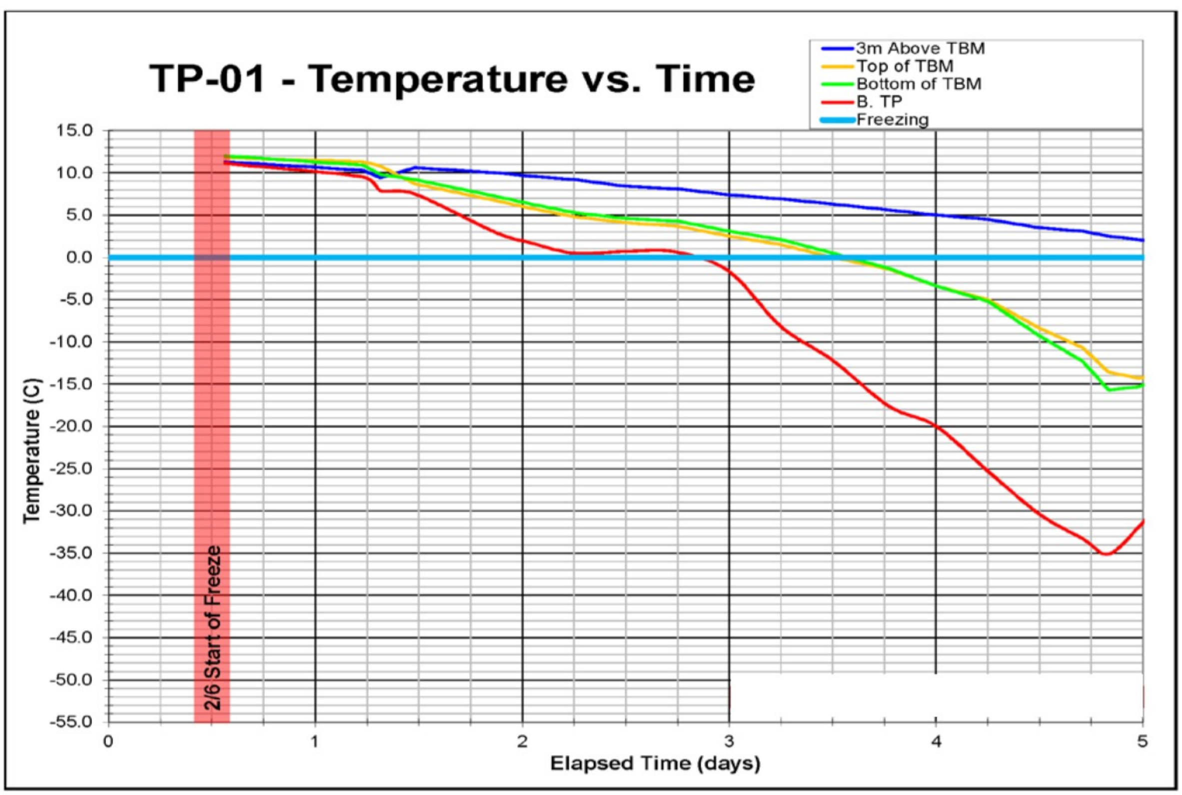


Figure 10. Time Versus Temperature Plot

After 12 days, as the temperature data indicated formation of a sufficiently frozen zone, entry into the TBM was permitted. The ground freezing was successful as the interior of the cutter head was dry and frozen.

Figure 11. Frozen Interior of Cutter Head

On most ground freezing projects the energy required to form the freeze is typically twice the amount needed to maintain the freeze. This applies to liquid nitrogen freezing jobs; once the frozen block is formed, the liquid nitrogen flow is reduced. This conventional “rule of thumb” did not apply to this project. Two issues resulted in the need to maintain the initial high rates of liquid nitrogen flow rates:

1. It was necessary to maintain a very strong bond between the frozen earth and the skin of the TBM. The colder the temperatures, the stronger the bond.
2. Repair operations from within the cutter head generated substantially more heat than anticipated. Higher liquid nitrogen flows were needed to compensate for the heat.

After 3 weeks of repair operations, liquid nitrogen flow was terminated. The TBM mined through the copper freezing pipes and the rest of the pipes were grouted and cut from 3m below the river bed. Tunneling operations resumed, a total of **8 weeks** after the initial construction of the platform.

Conclusions

This project was an extremely successful application of ground freezing executed under some of the most difficult logistics requirements in tunneling. There were also lessons learned that could be beneficial on future frozen ground TBM recovery operations. Specifically:

1. The cold bond required to form the soil/steel freeze can only be accomplished with liquid nitrogen. In cases where lower temperature brine methods are used, the brine system must be augmented with liquid nitrogen adjacent to the TBM.
2. Contrary to popular belief, frozen ground does not exert high, potentially damaging stresses on the exterior of the TBM. On the contrary, the heat generated from the TBM requires the low temperatures yielded by liquid nitrogen.
3. This application of freezing requires extensive expertise and experience and should not be attempted without adult supervison.