Risk Reduction, Management, and Mitigation from Experience-Based Learning During Construction of Cross Passages, Seattle, Washington

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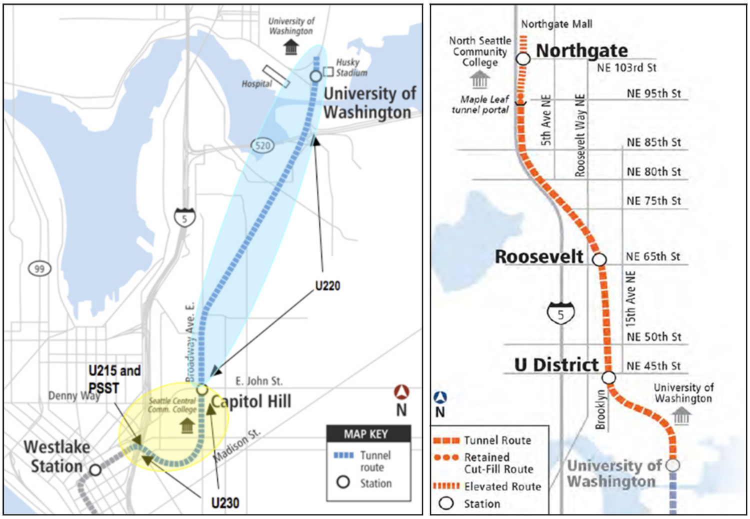
ABSTRACT

Cross passages are critical elements in transit and highway tunnels, providing a means of safe emergency egress between adjacent running tunnels. Although usually short in length, they are often technically challenging and can pose significant construction risks. Two recent projects in Seattle—Sound Transit's University Link Light Rail Contract U230 and Northgate Link Extension Contract N125—involved cross-passage construction between twin single-track Metrorail tunnels. This paper describes risk reduction, mitigation and management experience gained from the U230 and N125 contracts during construction of cross passages. Specific emphasis is given to challenges associated with excavation in glacial deposits under high ground water pressure and the ground improvement measures implemented, which included dewatering, grouting and ground freezing.

INTRODUCTION

Cross passages are critical safety elements in transit and highway tunnels, providing refuges or a means of egress between adjacent tunnels during emergencies such as fire in a tunnel or any incident which results in the closure of a section of a tunnel. For this reason, placement of cross passages along the tunnel alignment has important safety implications and must be carefully considered. National Fire Protection Association Standard "NFPA 130: Standard for fixed Guideway Transit and Passenger Rail Systems" requires cross passages to be constructed between the main tunnels for safety and evacuation. For twin bore tunnels, cross passages may be used in lieu of emergency exit stairways to the surface, at a maximum spacing of 244m (800ft.). They require minimum internal dimensions of 1120mm (44in.) in clear width and 2100mm (7ft.) in height.

Two recent projects—Sound Transit's University Link Light Rail Contract U230 and Northgate Link Extension Contract N125 involved construction of cross passages between twin single-track Metrorail tunnels in Seattle (Figure 1). This paper describes the challenges encountered during the construction and methods used to mitigate and minimize the construction risk and experience gained to manage risk during the cross passage construction. Specific emphasis is given to difficulties associated with excavation in glacial deposits under high ground water pressure, the methods used to control ground movement during excavation and implementation of the ground improvement program, which included dewatering, grouting and ground freezing. U230 and N125 are major tunnel construction contracts, forming part of Sound Transit's University Link and Northgate Link projects respectively. Both projects are



Courtesy: Sound Transit

Figure 1. Alignment Locations for U230 and N125

part of a large-scale expansion of the Seattle area's light rail system. U230 which was completed in 2013 included one mile long twin bore tunnels running between Downtown Seattle and the Capitol Hill neighborhood to the north with five cross passages between the TBM tunnels. N125 is expected to be completed in 2018 and includes approximately 3.4 miles of twin bore running tunnels and 23 cross passages running from University of Washington to the Maple Leaf Portal in north Seattle. The main running tunnels were bored using Earth Pressure Balance TBMs, and lined with a single pass, gasketed segmental lining, 10 inches thick. The finished internal diameter of each tunnel is 18ft 10in.

Geology and Ground Conditions

The geology of the area consists of soft ground deposits comprising both glacial and non-glacial deposits of the quaternary period overlying tertiary volcanic and sedimentary bedrock. The area was subjected to several glaciations and at the project area, thickness of the advancing ice sheets exceeded 3000ft. leading to the soil deposits being over-consolidated from very high overburden.

Both glacial and non-glacial deposits consist of clays, silts, sands and gravels in various proportions, combinations and densities. The distinction between the glacial and non-glacial deposits is made based on observation of sediment type, textures, sedimentary structures, amount of organics present, and identification of old soil horizons and other geologic indicators. Boulders are also present in both glacial and non-glacial deposits with higher amount in tills and diamicts of glacial deposits and along erosional contacts between different soil units. The groundwater system mostly comprises of aquifers and aquitards and there are changes in hydrologic heads when transitioning from one hydrologic regime to another.

Due to the considerable variability in the soil units, the ground conditions were described in terms of soil groups (SG) that exhibit similar behavior and characteristics. Each soil group was comprised of several geologic units which were based on soil index properties, particle size, Atterberg limits along with strength and deformation

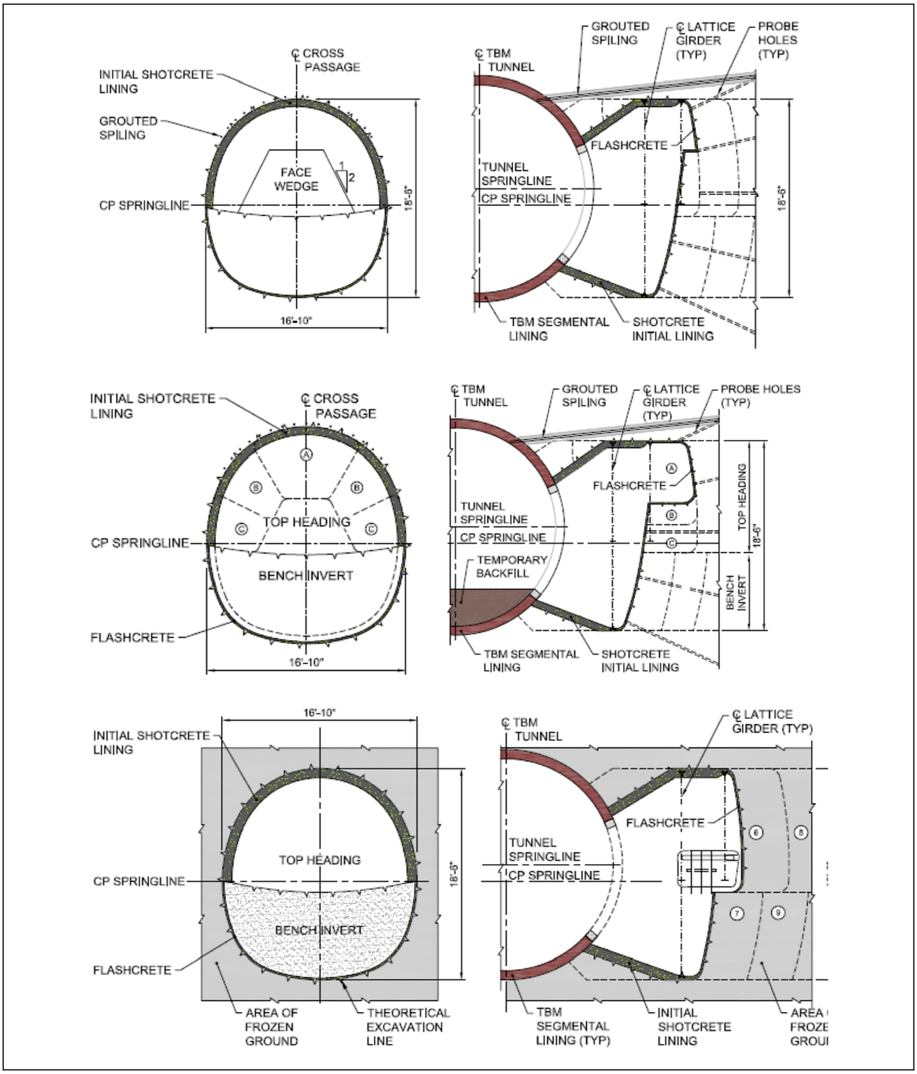


Figure 2. Ground Support Categories 1, 2 and 3 (from top to bottom)

properties. Most of the cross passages were excavated entirely below the groundwater table in the glacial deposits which were grouped into Engineering Soils Units comprising of Till and Till-Like deposits (TLD), Cohesionless Sand and Gravel (CSG), Cohesionless Silt and Fine Sand (CSF) and Cohesive Clays and Silts (CCS).

Ground Support Categories. The initial design of the cross passages was based on data from borehole logging, pumping tests including permeability of the ground and interpretation from the geotechnical baseline report. Based on these findings, the cross passages were categorized into three different support categories (Figure 2) to reflect the soil and groundwater conditions and anticipated behavior for the corresponding ground classes.

Ground Support Category 1 comprised of systematic pre-support and within a competent ground that did not require any extra support measures.

Ground Support Category 2 comprised of systematic pre-support accompanied with pocket excavation and dewatering prior to excavation.

Ground Support Category 3 comprised of excavation in treated ground using jet grouting or ground freezing methods. However, during construction ground freezing was chosen as a preferred method along with elimination of spiles and pre-support.

Support Category 1 did not require any ground improvement due to the soil competency, Support Category 2 required dewatering of the CSG, CSF and TLD when ever encountered. The anticipated soil types in most of the Ground Support Category 2 cross passages had the inherent potential for fast raveling to flowing when under pressurized groundwater and exposed in a free face. The more cohesive clay and clayey materials were expected to display better stand-up properties in the tunnel face. For the Support Category 3 cross passages, which were constructed across or in close proximity to soil contacts between fine and coarse grained deposits or in large aquifers where significant drawdown was required relative to the saturated thickness, ground freezing was implemented to improve the ground around the cross passage. Support Category 3 required ground improvement through ground freezing because of a presumed inability to effectively dewater the soil due to the high flow rates and localized boundary conditions.

The U230 and N125 cross passages have similar structural support systems, comprising shotcrete and lattice girders as the initial lining and cast-in-place concrete final linings. However, their geometries differ slightly (Figure 3). The U230 cross passages have a “dog-bone” longitudinal profile, with larger cross-sections at each end, adjacent to the running tunnels and a smaller cross-section in the middle. The section varied in height from 13ft 2in to 15ft 6in and in width from 12ft 10in to 14ft 10in. The N125 cross passages had a uniform, slightly larger cross section, being 18ft 10in high and 17ft 2in wide. This larger cross-section is close in size to the running tunnels and makes the N125 cross passages some of the largest in North America, relative to the running tunnel size. The larger, uniform cross section provided more internal space for permanent equipment, and made the installation of waterproofing and reinforcement for final lining more straightforward.

The initial lining comprised of two inches of a steel fiber reinforced sealing shotcrete layer (flashcrete) and six inch sprayed fiber reinforced shotcrete with exception of four inches of flashcrete for the Support Category 3 cross passages. The additional two inch thickness accounts for sacrificial shotcrete near the contact with the frozen ground; which is unable to develop full strength due to the cold temperature from freezing. The final lining comprised of 10 inch thick cast in place concrete lining. A waterproofing membrane was used between the initial and final lining system. The excavation profile was maintained using pipe lasers and lattice girders.

Cross Passage Excavation and Support

Probe Drilling. Probe holes were drilled prior to installation of pre-support to verify geology before excavation of the cross passages (Figure 4). The probe holes were arranged in a systematic manner to cover the entire excavation face area and a zone around the excavation perimeter, and inclined to ensure that as many granular layers/ lenses as possible could be intercepted in one boring.

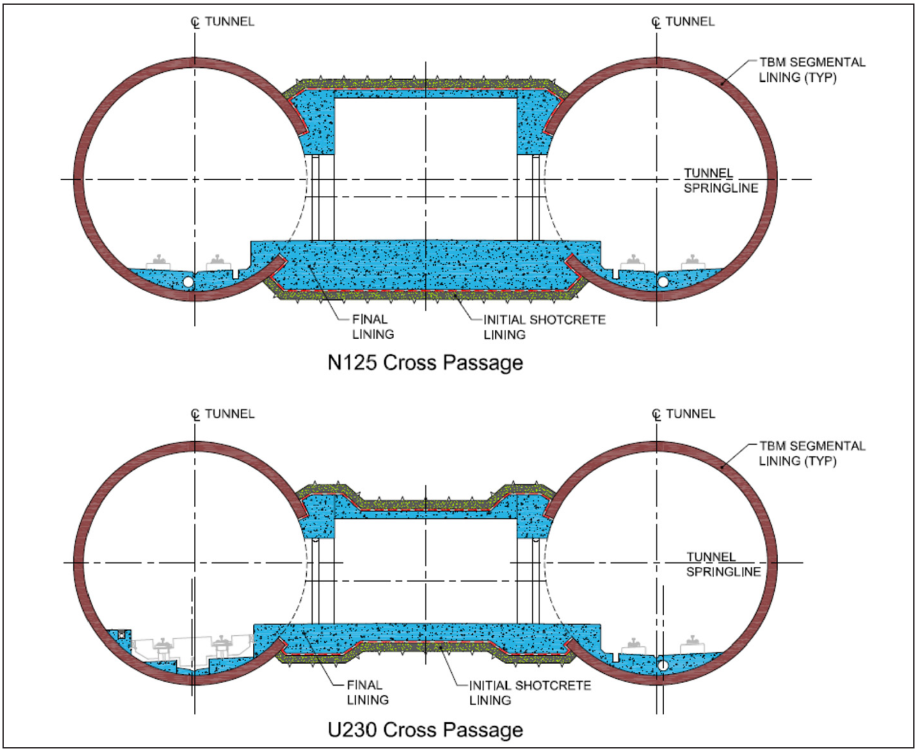


Figure 3. Typical longitudinal section along the cross passages

For Support Categories 1 and 2, a minimum of nine probe holes (6 in the top heading and 3 in the bench/invert) were drilled with the final number depending on the actual conditions found during probing. These probe holes were converted to drainage holes whenever groundwater inflow was encountered and used to dewater the soil. In some cases, they were attached to a vacuum system for dewatering.

For coarser materials with low flow rates gravity drainage was sufficient. For fine-grained material (silt, fine sand) or soils with more clay content, vacuum depressurization of the soil was used to extract groundwater from these pipes. During drilling, probe holes were continuously logged to assess the actual ground and groundwater conditions encountered. The logged data were used to assess the need for application of vacuum dewatering or the installation of screened pipes or additional probe/depressurization holes. These dewatering holes were used to depressurize a seven foot zone around the tunnel opening. In case of Support Category 3, only short, small diameter probe holes were drilled to verify the temperature of the frozen soil to ensure competency of the frozen ground.

Pre-Support. Prior to the commencement of break-out from the TBM tunnel into the cross passage, pre-support was installed using a drill rig and consisted of a steel self-drilling hollow bolt (IBO) grouted spiles to allow for grouting through the tube in a systematic manner. Systematic pre-support was installed only for the cross passages in Support Categories 1 and 2. For Support Category 3 cross passages, the extent of ground freezing was sufficient to stabilize the soil and provide pre-support and therefore grouted pipe spiling was not required. However, the effectiveness of ground freezing was carefully verified through thermal couplings and evaluated by the ground freezing engineer.

Cross Passage Breakout Support. Shear Bicone Dowels were installed between the running tunnel lining segments at cross passage breakout locations and the segments were propped using vertical steel propping. The Shear Bicones were used to transfer loads from cross passage opening to the running tunnel lining. The TBM lining segments were saw-cut to form the required opening (10'x10') for the break-out (Figure 5). Segments were broken with a hydraulic hammer and removed. The edges of the segmental lining were protected with temporary wooden protection blocks to avoid damaging the segments. Upon removal of the segments (or parts thereof), steel fiber reinforced shotcrete was immediately applied over the exposed ground surface to stabilize the face.

Excavation and Support. The cross passages were excavated with a staggered heading based on the Sequential Excavation Method (SEM). This method involved the development of a top heading with a face wedge, where required, and a bench / invert to ensure safe tunneling conditions and control the development of any instabilities. At the break-in a smaller temporary opening was excavated, which was enlarged to a full cross passage size after the first two

Figure 4. Ground probing from inside of the TBM tunnel

Removing rebar and bicone dowels

Breaking upper left segment

Exposed grout behind segment

Excavating after removal of segments

Figure 5. Break-in to the cross passage

Figure 6. Lattice girder and shotcrete installation at the top heading

rounds of excavation and support. The full ground support comprising of lattice girders and steel fiber reinforced shotcrete was installed immediately after completion of each excavation round. A two inch thick flashcrete layer was installed at the face and covered all other exposed ground surface immediately after completion of each excavation round. Following the flashcrete application, a pre-fabricated lattice girder was installed, followed by application of an additional six inch fiber reinforced shotcrete layer (Figure 6). The flashcrete was an integral part of the eight inch thick shotcrete initial lining. All cross passages were over-excavated by three inches to account for construction tolerances and anticipated deformations. The general excavation and support sequence is:

1. Installation of temporary support for TBM tunnel at break-out location
2. Ground treatment (ground freezing or dewatering), if required
3. Probe drilling with in tunnel dewatering installation
4. Installation of systematic pre-support (grouted pipe spiling) from within the TBM tunnel at the break-out location
5. Removal of TBM tunnel lining segments
6. Excavation and support of the cross passage in a sequential manner including enlargement

Risks and Challenges Identified During Construction

Both U230 and N125 were constructed in highly over consolidated glacial deposits consisting of clays, silts, sands and gravels in various proportions, combinations, and densities and very high water head. Such heterogeneity and variability in ground conditions resulted in considerable and frequent changes in the soil behavior. One of the biggest challenges was uncertainty in the ground conditions. Geology changes are very frequent and can occur over very short distances. For example, at a given cross passage elevation, the boring at one end showed the soil type as gravel while other end showed sand. This leads to a very complex and non-uniform geology along the cross passage alignment (Figure 7). Sometimes face stability would also be a problem due to short standup time during excavation, again due to the varying soil behavior. In some cases, running or flowing ground was experienced in the cohesionless soils or raveling in more cohesive soils.

To mitigate risks associated with uncertain ground conditions, a thorough ground probing program was conducted to identify geology ahead of the tunneling face. Ground probing comprised of both horizontal and inclined probe holes. The probe holes were installed outside of excavation profile of the tunnel to reduce the risk of encountering

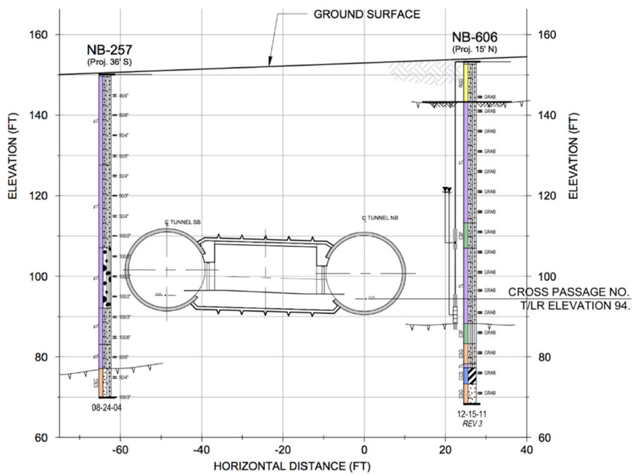


Figure 7. Cross-passage showing variability in geology between two tunnels

unanticipated soil or groundwater conditions. Probing was designed to investigate the soil conditions a minimum of five feet above the crown of the cross passages.

Hydrogeological conditions were also an important factor, posing challenges during excavation. The excavation area showed a varied hydrogeological regime, including a number of aquifers, aquitards and hydraulic connections. The heterogeneity in soil composition led to variations in the ground permeability which was compounded by high ground water pressure. Groundwater heads have been identified up to 74ft above the tunnel. One area may show ground as dry while another, nearby area has very high flow. The presence of groundwater at the face compounds the unstable conditions during excavation. Therefore, managing groundwater flow was a significant challenge.

The risk associated with instability from groundwater inflow was minimized using systematic dewatering. Surface dewatering was used to dewater ground associated with coarser soil deposits particularly in areas where larger flows were expected. In the case of fine grained soil deposits, dewatering was implemented from inside the TBM tunnels using well points with gravity drainage. If the gravity drainage was not sufficient, the drainage system was connected to a vacuum pump to suck the water from narrow pores of the fine grained soil. Water encountered during excavation was collected using drain mats and pipes. Typically, nine well points were drilled from the tunnel and additional well points were installed as needed, based on the results of the probe drilling and observed water inflow. The ground was depressurized over a minimum of seven feet zone outside the cross passage excavation boundary prior to starting open face excavation. Dewatering was successfully achieved using this combination of surface wells, gravity drainage and a vacuum dewatering system. It was important to run the dewatering system until completion of the final lining.

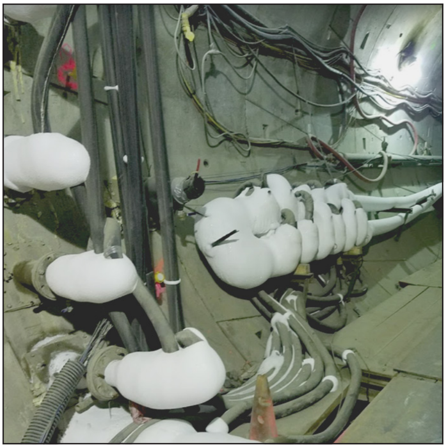
Although, dewatering works well in areas with lower permeability, it becomes expensive and risky to operate in soils with high permeability that have hydraulic connections with high groundwater recharge zones. In such scenarios, dewatering requires very long pumping times and will produce large quantities of pumped water which needs to be disposed of properly. Managing and removing such a high volume of water becomes a costly operation, adding to the project cost since there are high discharge fees to the local combined sewer system.

As a means to minimize risk, pumping tests were conducted before each cross passage excavation to assess the ground permeability and possible water inflow. If the pumping test results showed groundwater flow to be very high, making dewatering impractical; ground freezing was implemented in lieu of dewatering. This change reduced risks associated with managing a high volume of groundwater and eliminated costs for its treatment and disposal.

Therefore, as a mitigation measure, thorough testing and a detailed study of hydrogeological nature of the associated ground water including flow rate, permeability and transmissivity has to be conducted. Detailed investigation and planning is required if high permeability is suspected in certain areas to assess the viability of dewatering and the recharge rate of the pumped aquifer. For example, the top of the permeable layer during a U230 excavation was encountered above the bottom of the excavation contrary to the anticipated 15 ft. to 20 ft. below the bottom of excavation. This led to installation of more dewatering wells. Such scenarios were expected also during N125 and to avoid this, probe drilling and pumping tests were carried out to assess the ground for further ground treatment in terms of dewatering or ground freezing. A backup power systems were also arranged to provide an uninterrupted power supply in case of power outage or failure, to ensure continuous operation of the dewatering pumps.

Ground Freezing. Ground freezing is a method of ground treatment where the ground is frozen to provide stability during excavation. Freezing converts the in-situ pore water into ice which binds the soil particles together and makes the ground stronger and impermeable. Freezing increases both strength and stiffness of the ground. Ground freezing is a proven technology which was originally developed and used in Germany in 1883 for a shaft sinking project in a coal mining application (Schultz, 2008).

Ground freezing was used for N125 cross passages where pumping test results indicated very high flow rates and where layered geology made dewatering impractical. Ground freezing was implemented at eleven locations using two different methods: ground freezing from the surface and ground freezing from inside the TBM tunnel. Ground freezing from the surface was performed by installing vertical zone freeze pipes from the ground surface and short angled haunch freeze pipes through the tunnel liners. The short pipes were to maintain the freeze adjacent to the tunnel during excavation where the freezing is most susceptible to the warmth from the TBM tunnels. Temperature monitoring pipes were installed to actively monitor the frozen zone. The chilled brine for the vertical zone freeze pipes was supplied by chillers located on the ground surface whereas chilled brine for the haunch freeze pipes inside the tunnel was supplied by small chillers located in each tunnel. The annulus around the freeze pipes was grouted over the freeze depth range to create effective contact with the surrounding soil. Such method is particularly useful if cross passage construction is in critical path, however it has challenges with logistics and surface restoration. The surface installation had to remain in place for the duration of the freeze, requiring temporary road closures and other traffic restrictions. Other third party considerations which complicated this method included the need to obtain power drops from the local utility provider, community concerns and the extensive street restoration required at each location once the freeze was decommissioned. Five cross passages on the N125 contract utilized ground freezing from the surface as a primary means of temporary ground stabilization. The freeze design was intended to freeze the soil between the



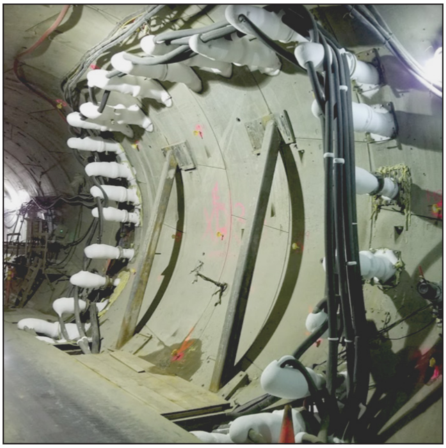


Figure 8. Ground freezing from inside the TBM tunnel

two running tunnels to 20ft above and below the tunnel springline at a minimum distance of 13.5 feet either side from the cross passage center line.

Ground freezing from inside the TBM tunnel is implemented by installing horizontal freeze pipes around the periphery of the cross passages (Figure 8). This process employs primary refrigeration plants to chill a secondary coolant which is continuously circulated through a closed-loop distribution manifold and refrigeration pipes installed within the tunnels. The entire system is a closed circuit with no materials injected into the ground. Horizontal freeze pipes were drilled from the southbound tunnel and short inclined pipes drilled from the northbound tunnel for each cross passage. Ground freezing from inside the tunnel is particularly useful when cross-passage construction schedule is not on the critical path, and it also eliminates significant third party tasks and surface restoration at the ground surface. This method also simplifies excavation since freeze pipes are outside the excavation profile and do not interfere during excavation as in the case for the surface ground freeze method. Six cross passages on the N125 contract utilized in-tunnel freezing as a primary means of temporary ground stabilization.

As of December 2016, eight of the 11 cross passages have been excavated using ground freezing method, with three remaining to be excavated. Even though ground freezing provides stable ground for excavation, there are challenges and risks associated with the ground freezing operation.

The biggest challenge with the ground freezing operation is the coordination between the ground freeze contractor and SEM crew to prevent damages to the freeze pipes. The freeze pipes could easily be damaged by the excavator releasing the brine inside the pipe. This brine could thaw the neighboring frozen soil mass triggering tunnel instability. Care should be also given while reconnecting freeze pipes from the top heading to the invert during excavations that utilize the surface freezing method.

Such risks can be managed with proper coordination between the SEM crew and ground freeze contractor. Using hand excavation around the vicinity of the pipes and careful supervision with the SEM engineers on site helps to prevent damage to the pipes. Possible damage to the freeze pipes and leaking of the freeze brine can also be avoided by conducting an as-built survey of the freeze pipe installation prior to excavation. Experience showed this was critical especially at locations where only two to three feet of frozen ground remained.

Additionally, ground heave from the soil freezing induced deformation in the TBM tunnel lining. In one instance, the TBM tunnel lining underwent a maximum movement of 2.75 inches. In an effort to minimize tunnel deformation horizontal struts were installed at this location in the TBM tunnel to restrain tunnel movement. Further, thawing of the frozen ground may led to additional movement but these impacts are unknown at this time. Ground heaving from the surface freeze also posed a significant challenges since the heaving had potential to damage sensitive surface installations, particularly utilities. At surface freeze locations, near-surface frost heave of 0.5 to 2.0 inches was observed during the freeze down process. The heave was observed via surface and near-surface settlement monitoring, and utility settlement points. It was also observed as an apparent trend in extensometer readings; the surface monument of the extensometer moved upwards causing an apparent downward movement in all of the subsurface extensometers. The rate and amount of heave showed correlation to the brine temperature at any given time. Generally, the lower the brine temperature, the more rapid the trend in heave.

To manage risk associated with ground freezing to control ground movement, sufficient monitoring mechanisms have to be in place with pre-defined trigger levels. The trigger levels dictate further action to be taken once set levels are exceeded such as adjusting the temperature of the brine and selectively turning off parts of the freeze temporarily or permanently, as allowed by the ongoing cross passage construction. Attempts to mitigate the heave were also made by installing heat trace tape and circulating warm air into the annulus of freeze pipes, but these measures showed no significant beneficial effect.

Monitoring development of the frozen soil around the vicinity of the cross passage are necessary to ensure ground achieves the required stability. A drainage test from inside the tunnel has to be conducted to ensure sufficient tightness of the frozen ground mass. Attention should also be given to the groundwater flow velocity since high groundwater velocity retards the rate of ground freeze. In such circumstances grouting could be adopted in addition to the ground freezing but this was not required on N125.

Before break-in, the extent of the frozen zone was evaluated and discussed with the ground freezing contractor, the Designer of Record and the CM Team to ensure the frozen ground had achieved its design requirements. Additionally, a second redundant power supply system for ground freezing is needed to ensure uninterrupted operations of the chiller plant and freezing system. There were a few instances of power outages and backup systems were utilized to run the ground freezing smoothly which could otherwise comprise the integrity and structural support of the frozen ground mass.

The size of the N125 cross passages in relation to the main TBM also posed construction challenges during installation of the pre-support, since the sizes of the cross passage and TBM tunnel were very similar. The original design employed horizontal spiles as a pre support measure which was impossible to install near the cross passage crown during break-out since drill rig could not be positioned at such high levels within the tunnel. As a solution, those spiles were installed at an angle going slightly upward from the cross passage crown. Spiles were also designed to be installed at each heading through the lattice girders. Due to the geometry of the cross passage opening, this installation is basically impossible. In this instance it was decided to install full length spiles from the running tunnel, to ensure a complete canopy across the entire length of the cross passage.

One important aspect of addressing challenges and risk mitigation during cross passage construction is communication and coordination between various stake holders including contractor, SEM crew and owner's representative. Daily site meetings were held between SEM crew, contractor, design teams and owner's representative to ensure efficient communications and planning for each day of operation including discussion of construction progress, encountered difficulties during construction and remedial measures. These meetings greatly helped to allow different crew members working synchronously during construction to avoid conflicts in schedule and efficiently utilize logistics.

CONCLUSIONS AND LESSONS LEARNED

Cross passages can be constructed safely in very challenging ground, provided the construction is commenced with careful planning and implemented after proper knowledge of the ground is obtained from ground probing and test results that supplement the geotechnical baseline information. Experience gained from the U230 showed a planned approach needs to be implemented before proceeding with excavation, especially in terms of ground probing and ground treatment. Several challenges were encountered during excavation which were successfully addressed with modification of the ground support systems and ground treatment. Overall, the cross passages at U230 (5) and most of the cross passages at N125 (23) have been successfully constructed without any major delays or issues despite significant construction challenges posed by difficult ground conditions. The following list summarizes important lessons learned during construction of the cross passages.

- Daily site meetings between the SEM crew, contractor, design teams and owner's representative are considered to be very important to ensure efficient communications and planning for each day of operation including discussion of construction progress, encountered difficulties during construction and their remedial measures.
- Probe drilling is very important to verify ground conditions ahead of the face, especially where ground conditions can vary significantly between nearby locations. Probing aided to confirm the ground support type for particular cross passages. Further, probe drilling becomes most valuable if done as early as possible, to give time to react if anything unexpected is found.
- Pocket excavation is recommended to limit over-breaks in difficult ground. As many as 23 pockets were excavated in one cross passage to ensure stable excavation face.
- In cohesionless glacial deposits, such as the CSG, the ground has to be completely depressurized or frozen to achieve stable excavation.
- If dewatering is planned, a pumping test should be carried to verify groundwater flow as it will confirm the risks and likely success of dewatering. At certain cross passage locations, results from pumping tests showed very high ground water flow which led to reclassification of five cross passages from Ground Support Category 2 to Category 3.
- Excavation of frozen cross passages requires close coordination between the Ground Freeze Contractor, SEM Superintendent and Excavation Crew.
- Before opening of the segments, probing at the center of the frozen ground is recommended to verify the frozen ground conditions. There were instances

where the frozen ground mass was very solid around the periphery of the tunnel but was relatively soft at the center of the face. This shows that even though temperature monitoring showed frozen ground, the center core was not completely frozen which resulted in flow of water requiring additional depressurization. A probe hole at the center of the frozen mass, about a week in advance before the breaking of the segments helps to avoid such situations.

- Backup power system—A second redundant system is required. There were multiple instances of power outages and the backup system had to be used which is critical for both dewatering and ground freezing operation.
- The potential for heaving or bulk expansion of the frozen ground shall not be underestimated since it may exert significant pressures on the lining. In one case the frozen ground moved the lining as much as 2.75 inches and deformed the circular TBM lining into an oval shape.
- Experienced SEM Consultants, Superintendents and Contractors are required for safe, high quality and on time completion of large and complicated projects, such as U230 and N125.

REFERENCE

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