TBM Tunnelling Challenges and Managing High Groundwater Inflows on the Ashbridges Bay Treatment Plant Outfall Project

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ABSTRACT

Considered the largest outfall in Canada, the City of Toronto's Ashbridges Bay Treatment Plant (ABTP) Outfall project is building a new tunnelled outfall that will convey up to 3,923 Mega-Litres per day of treated effluent from the ABTP into Lake Ontario. Outfall construction components include an on-shore shaft approximately 85m deep with an internal finished diameter of 14 m; a 3,500 m long tunnel (7m internal diameter); and 50 risers constructed in line with the tunnel along the last 1,000 m of the tunnel extending from the top of the tunnel to the lakebed.

Tunnelling was performed with a single shielded Tunnel Boring Machine (TBM) mined entirely within the Georgian Bay Shale Formation (GBFS). The tunnel lining consisted of a one-pass Precast Concrete Tunnel Lining (PCTL) system. Following TBM assembly and on-site testing, mining commenced in March 2021. The first 2,500 m of tunnel was successfully completed with record setting advance rates reaching 46 m/day. However, the last 1,000 m of the tunnel proved to be extremely difficult as high groundwater inflows (up to 400 liters per minute) were encountered. Significant damages to the PCTL were observed and TBM mining was temporarily placed on standby.

During the high groundwater inflows, several measures were immediately implemented to stabilize the PCTL and allow TBM mining to resume safely and efficiently. These measures included implementation of additional PCTL support, pre-excavation probing and grouting, and implementation of systematic chemical and cementitious grout collar injection around the PCTL. The Engineer, Owner and Contractor met frequently and collaboratively to innovate and implement mitigation measures to overcome challenging groundwater inflow conditions and successfully completed the outfall tunnel.

1 INTRODUCTION & PROJECT OVERVIEW

The Ashbridges Bay Treatment Plant Outfall (ABTPO) project by the City of Toronto involves construction of a new tunnelled outfall to convey treated secondary effluent (water) from the ABTP into Lake Ontario. The ABTP is one of Canada's largest and oldest wastewater treatment plants. This new outfall will allow cessation of operations of the existing outfall which is reaching the end of its service life and has limited hydraulic capacity. With only 1 m of driving head available at peak design flow under high lake water conditions, the new ABTPO has been designed to minimize headloss and allow the outfall to operate by gravity with a design capacity of 3,923 Million Liters per Day (MLD).

Outfall components (as illustrated in Figure 1) consist of an 85 m deep, 14 m internal diameter onshore shaft constructed adjacent to the shoreline; a 3,500 m long, 7 m internal diameter tunnel constructed through rock beneath the lakebed; and, fifty 1,000 mm diameter risers with 830 mm diameter ports installed in line with the tunnel extending from the tunnel horizon to the lakebed at equal spacing along the diffuser. The project also includes the construction of a new effluent conduit that will convey treated and disinfected effluent from the ABTP to the new outfall for dispersion into Lake Ontario through the risers.

Construction of the ABTPO project commenced in 2019 and is anticipated to be completed by the end of 2024. The delivery of the construction contract followed a traditional design-bid-build procurement. Main team members on the project include:

- Owner: City of Toronto
- Consultant: Hatch with Jacobs/Baird
- Contractor: Southland Mole of Canada and Astaldi Canada Design & Construction Joint Venture

To date, the shaft and starter/tail tunnel have been excavated, the tunnel has been completed by TBM tunnelling and all 50 risers have been pre-installed from lakebed. Work remaining on the project includes completing all tunnel riser connections, shaft and starter tunnel final cast-in-place lining, and conduit connections with the treatment plant.

Figure 1. Summary of Major ABTPO Project Components

2 GEOTECHNICAL CONDITIONS

A geotechnical investigation program for both onshore and offshore portions of the project alignment were conducted during the detailed design phase. Following the investigations, a Geotechnical Data Report (GDR) and a Geotechnical Baseline Report (GBR) was prepared and included in the Contract. The interpreted geologic profile included in the GBR is shown in Figure 2.

Onshore at the shaft location, overburden materials up to 20 m in thickness were encountered consisting of sand, silt and clays overlain by landfill material associated with a historic reclamation area. Offshore at the riser locations, overburden material consisting of silts and sands overlain by recent sediments comprised of under-consolidated materials were encountered during construction.

The tunnel alignment is situated entirely within the Georgian Bay Formation Shale (GBFS) which is described as a greenish to bluish grey non-calcareous shale. The shale is a fissile rock with widely spaced vertical or inclined jointing and closely spaced sub-horizontal bedding planes interbedded with limestone, siltstone and sandstone. As per the GBR, the average UCS values along the tunnel alignment baselined that the GBFS on average is ‘weak’, according to the ISRM Classification System. When discretized into certain reaches, the average rock quality was baselined as “excellent” between Station 0+000 and 3+200 and “good” between Station 3+200 and 3+500 based on the Deere Classification System. The lower rock quality baselines generally correlate with the reduced rock cover along the tunnel alignment as shown in Figure 2.

Based on historic tunnel projects in the project vicinity and by analyzing the hydrogeological tests completed during the geotechnical investigations, groundwater inflows during TBM tunnelling were anticipated and baselined in the GBR. Specific groundwater baselines during TBM tunnelling were stated in the GBR as follows 1) 100 L/min transient inflow and 2) 15 L/min steady state conditions measured after 48 hours from initial excavation.

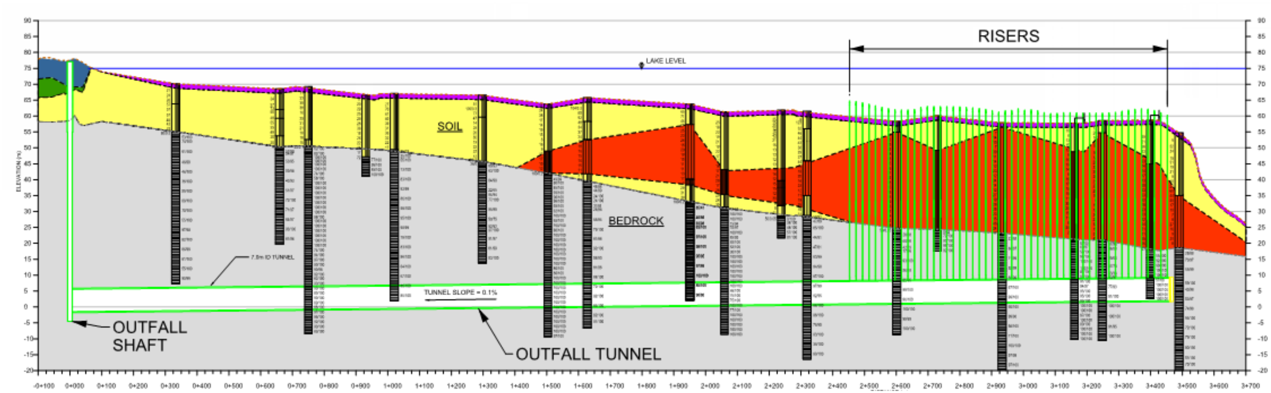


Figure 2. ABTPO Tunnel Geotechnical Profile

3 OVERALL PROJECT SEQUENCE

The outfall construction sequencing involved, among other elements, sinking a shaft adjacent to the shoreline and then mining a tunnel through rock beneath the lakebed below Lake Ontario. The most important construction sequencing constraint required all risers to be installed, grouted, and tested for leaks before tunnelling within 100m of any riser. The risers were to be installed and terminated at 0.5 to 1.0m from the top of the tunnel. This approach was implemented to mitigate risks of over-drilling a riser into a completed tunnel resulting in significant worker safety, property damage, schedule, and financial impacts to the Outfall project. Another constraint involved probing ahead of the TBM to assess the potential for water inflows. If flows were encountered during this probing, pre-excavation grouting would be performed to improve rock quality and limit water ingress into the tunnel. Following TBM mining, connections to the pre-installed risers would be made prior to outfall tunnel flooding.

4 TBM TUNNELLING

3.1 TBM Procurement, Testing

After comparing the benefits and challenges of a two-pass lining system with those of a single-pass system, a single-pass Precast Concrete Tunnel Lining (PCTL) was chosen for this project on the basis of lower out-turn cost due to shorter schedule, acceptable Time-Dependent Deformation (TDD) performance, superior durability and a safer working environment (control of gas inflow and fallout). The specification of the single-pass PCTL would therefore require the use a shielded TBM-type capable of erecting the PCTL during TBM tunnelling. Other minimum TBM & tunnel requirements including TBM advance probing, two-component PCTL annulus grouting injected from the TBM tail-shield, gas monitoring, refuge chamber and provisions for TBM pre-excavation grouting were also specified in design to manage the anticipated conditions and potential project risks.

Upon contract award, the contractor procured a re-manufactured 7.95m bore diameter single-shield high performance hard rock single shield Tunnel Boring Machine (TBM) from The Robbins Company (Robbins). The original TBM was an 8.7m excavated tunnel diameter cross-over TBM utilized on the Túnel Emisor Poniente (TEP) II project located in Mexico City, Mexico.

3.2 TBM Mining & Productivity

Following TBM assembly and on-site testing, initial mining commenced in late March 2021 but was briefly halted to allow the initial PCTL installed within the starter tunnel to be fully grouted. Mining recommenced on April 19, 2021 and continued until completion of the total 3,353m tunnel drive on March 2, 2022. See Figure 3 which shows the cumulative tunnel progress over time as well as the weekly totals.

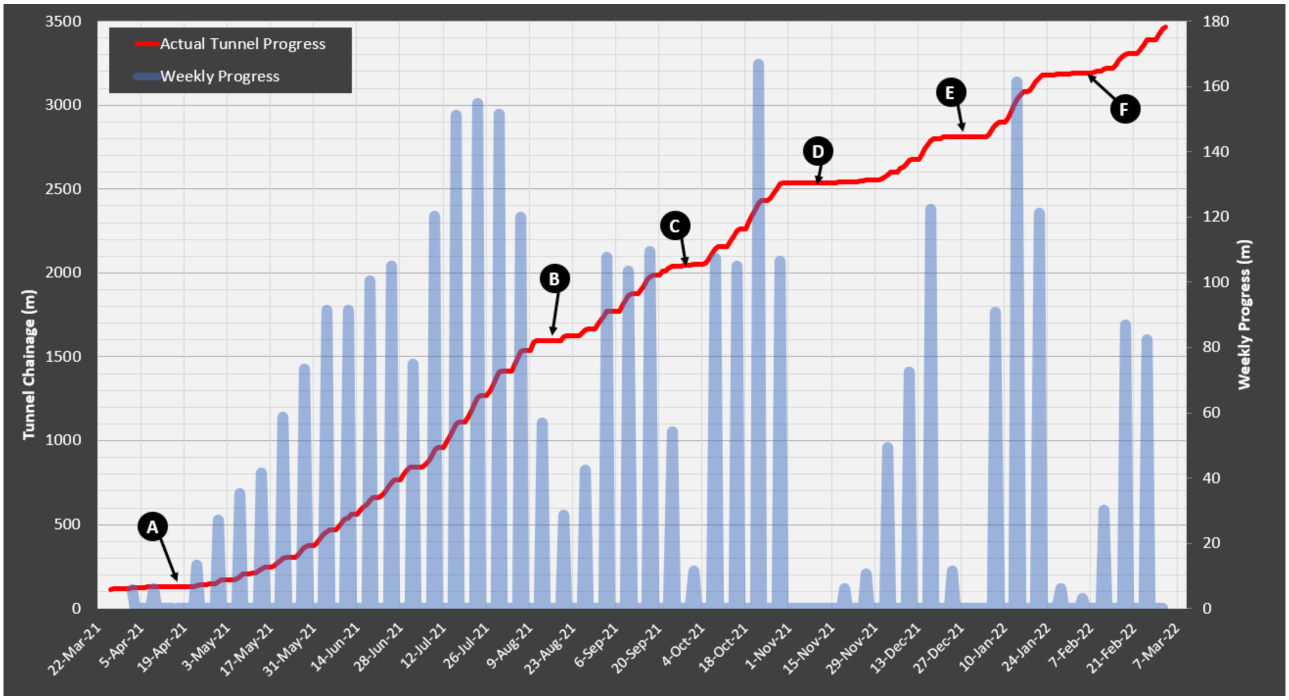


Figure 3. TBM Tunnelling Overall Productivity & Weekly Advance Rates

As shown in Figure 3, the total average advance rate (including all downtime) was approximately 14.9 m per working day. During TBM tunnelling, the working day consisted of two working shifts (12 hours each) per day, 5 days per week (2 x 12 hr shifts, 5 days per week).

Figure 3 also shows major downtime events during TBM tunnelling (symbols A through F). The following summarizes these major event points:

A. TBM mining learning curve and planned stopped for grouting the initial PCTL rings installed within the starter tunnel.
B. Repair to TBM segment feeder cylinder, oil contamination purge, and installation of the tunnel conveyor booster station. Total downtime: 9 working days.
C. Methane gas infiltration standby and pre-excavation grouting due to observed groundwater inflows during advance TBM probing. Total downtime: 3 days.
D. Groundwater inflows and PCTL damages (Groundwater Inflow Zone 1). Total days impacted: 25 working days.
E. Conveyor drive motor replacement and year-end holiday site shut down.
F. Groundwater inflows and PCTL damages (Groundwater Inflow Zone 2). Total days impacted: 15 working days.

Section 4 describes the water inflows and PCTL damages (items D & F) in greater detail. When excluding these two specific events (which together contributed up to 40 working days), the average tunnel advance rate for the entire tunnel drive was 17.7 m per working day. Figure 3 also demonstrates that the rolling weekly advance rate was drastically impacted with encountering the high groundwater inflows during tunnelling.

The maximum weekly TBM advance rate was achieved the week of October 15, 2021 with a total excavated distance of 167 m (111 PCTL Rings) which translates to a sustained daily rate of 33.4 m per working day. The project also recorded several days of exceptional daily productivity. The best day was recorded as 46.4 m (31 PCTL Rings) which translates to an average PCTL ring installed and excavated every 46 minutes. This productivity rate is understood to be a record setting advance rate for this type of TBM, size and ground conditions. Overall, there were 78 working days when the daily productivity rate exceeded 20m/day, which equates to approximately 40% of the entire mining duration excluding the two major water inflow downtime events (see items D & F).

4 ENCOUNTERING HIGH GROUNDWATER INFLOW

During TBM tunnelling, unexpected ground conditions and high groundwater infiltration were encountered in two locations along the tunnel alignment which impacted TBM tunnel advancement and significantly damaged the PCTL. These two locations are shown as items D & F in Figure 3 and were initially encountered after 2,500m of successful mining. The following section summarizes the conditions encountered, the impacts it caused during TBM mining, and the innovation methods implemented to successfully mine through these challenging zones.

4.1 Encountered Ground Conditions

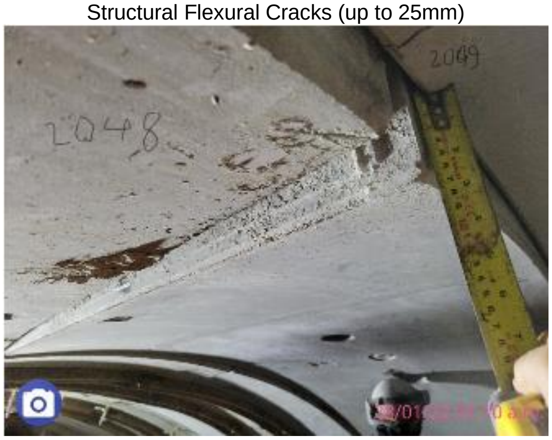
During mining in these two zones, high groundwater inflows (>400 lpm) were observed flowing through the TBM cutterhead and through the rock mass behind the PCTL lining. Refer to Figure 4 which shows the high groundwater inflows through various relief holes drilled through the PCTL. A sustained water inflow in excess of 100 lpm was measured per hole. The holes were left to drain and there was no evidence of reduced flow over a period of time. It was therefore contemplated that water inflows could have a direct connection to the lake above the tunnel alignment. At these locations, the ground conditions consistent of approximately 15m of GBSF rock cover above the tunnel and 35m of overburden deposits. The distance from tunnel springline to lake level was approximately 70m. In some holes, packers were installed to confirm groundwater pressures ranging between 25 to 45 PSI (1.7 to 3.1 Bar).

Figure 4. Significant Groundwater Inflow from the Rock Formation above the Tunnel Crown

When these conditions were first encountered, damage to the PCTL lining occurred in the crown of the tunnel consisting of structure cracks (>25mm in thickness) and movement to the rings (steps & lips) as shown in Figure 5. Upon investigation it was concluded that the high groundwater inflows washed away the specified two-component PCTL annulus grout, creating a void in the PCTL annular gap. It was concluded that the lack of lateral support around the ring due to the grout wash-out resulted is a loss of lateral confinement and support to the PCTL. Due to an annular gap (approximately 150mm) between the PCTL O.D. and the TBM excavated diameter, the PCTL ring squatted until the lateral deformation reached the rock surface (nominally at tunnel springline). Due to the squatting of the ring, the PCTL now acted as an arch and the additional bending and tensile forces in the ring caused the PCTL to crack. Refer to Figure 6 for illustration of the conditions which led to the noted damages.

Structural Flexural Cracks (up to 25mm)

Structural Compressive Cracks



Steps & Lips between Rings/Segments

Steps & Lips between Rings/Segments

Figure 5. Representative Example of PCTL Damages During Encounter High Water Inflow Events

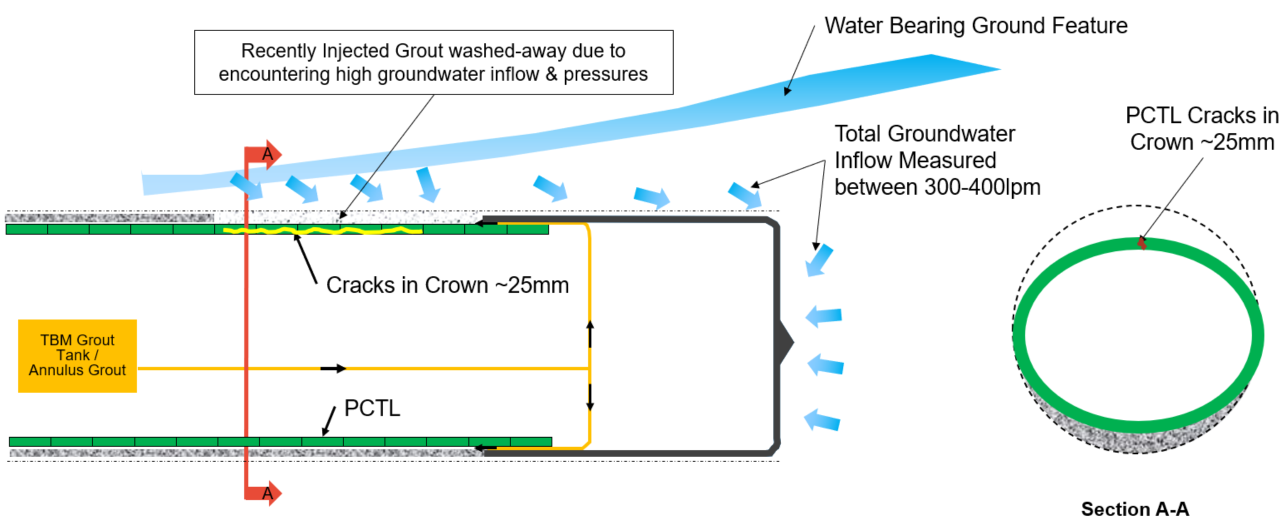


Figure 6. Overview of Encountered Conditions which Led to PCTL Damages

4.2 Site Investigations

The project team promptly mobilized additional resources to investigate the conditions and to develop a plan forward to repair the immediate area in the tunnel and to allow the remainder of the tunnel to be completed.

Due to the proximity of the pre-installed risers pipes located 1m above the tunnel crown (as described in Section 3), the project team was concerned that the water inflows observed was originating through the riser pipe annulus with direct conduit connectivity to Lake Ontario. To investigate this possible theory, a review of the previous riser installation records including annular grout test results and annulus pressure test records were completed along with in-lake diving inspections to ascertain if any leaks existed at risers along the lakebed. With the additional investigations completed, there was no direct evidence that the water inflows resulted from the pre-installed riser pipes. Investigations were therefore directed to concentrate around the tunnel and the surrounding rock mass. These investigations consisted of performing numerous pre-excavation probe holes and various 1 to 3 m length probe holes drilled through the PCTL lining.

The results of the TBM pre-excavation probing revealed general dry to damp conditions, with a few instances of some water inflows around the 25 lpm range. Pre-excavation probing was completed both directly horizontally ahead to the TBM as well as inclined above the TBM shield. Rock conditions were noted to be generally competent with a few zones of soft rock noted. In some instances, pre-excavation grouting through the probe hole was completed with insignificant grout volume uptake. No voids, fractures, shear or fault zones were intercepted during the pre-excavation probing.

A potential explanation for the conditions encountered is that a water bearing (or mud seam) feature within the GBSF was intercepted during tunnelling as illustrated in Figure 7. This water bearing feature when undisturbed is believed to be a tight formation which does not produce a significant amount of water inflow when intercepted with a small (2”) pre-excavation probe hole. However, when the TBM approaches this feature (7.95m excavated diameter), the ground around the TBM excavation is disturbed by the mining process and redistribution of in-situ stress. As a result, the water bearing features changes from a tight formation to a highly permeable feature. Once the tunnel intersects this feature, high water inflows flow into the excavation and around the PCTL.

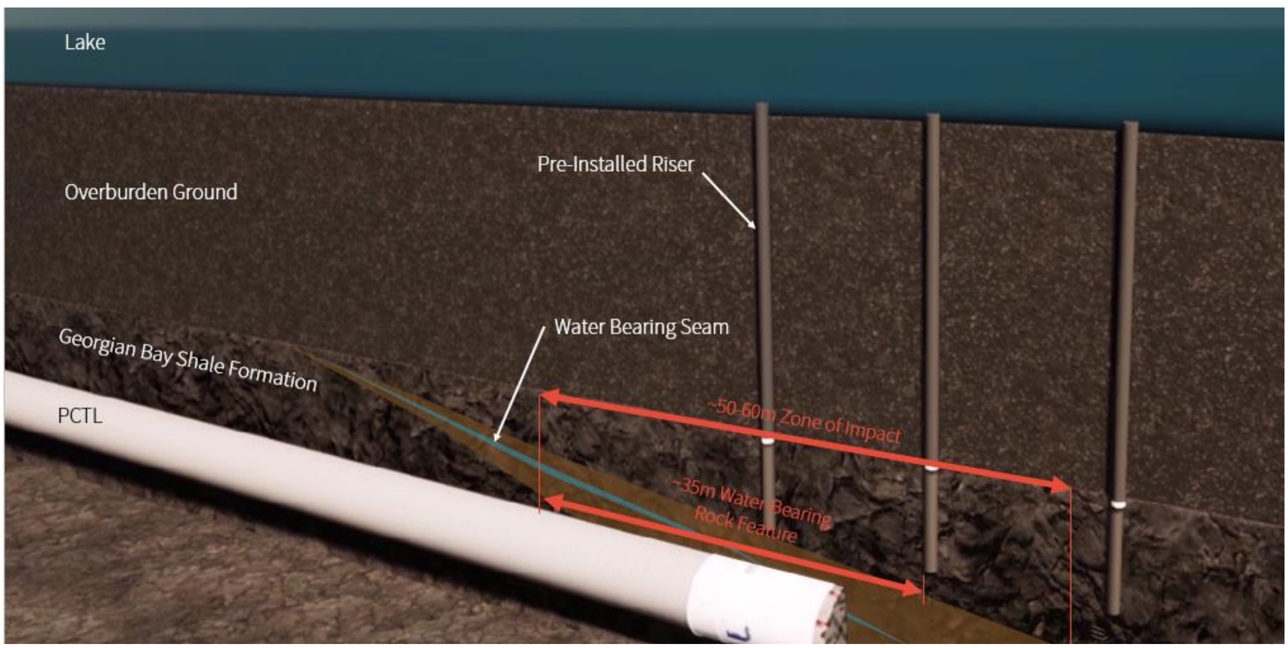


Figure 7. Assessment of Encountering Water Bearing Rock Feature

The theory regarding the potential feature “opening up” following TBM mining is supported by additional observations when mining through the second groundwater inflow zone whereby rock was found to converge and fall directly on top of the TBM shield. Ports were installed through the shield to monitor the annular gap within area and in some instances, no annular gap was found indicating complete convergence of ground onto the shield lining. Due to the additional rock loads onto the TBM, it was also found that the TBM shield had deformed which caused the support structure for the erector to deform resulting in the inability to rotate the erector arm. Erector support arm modifications (such as shimming and torching) were necessary to free the erector and restore functionality. While mining in this section, high propulsion forces were necessary (as high as 32,000 kN) to break out of the rock. Bentonite was also injected around the shield to reduce some of the shield skin friction to continue advancing the TBM.

5 REMEDIATION & RE-MINING PLAN

Once the conditions were encountered and investigations were completed to ascertain the likely cause of the PCTL damages and source of groundwater infiltrations, a remediation plan was developed by the project team. The plan was focused on three specific areas 1) remedial work necessary to restore the structural stability of the tunnel, 2) implementation of new work methods to allow mining to resume, and 3) completion of additional investigations.

5.1 Remediation Work

Once the high-water inflows and initial PCTL damages were first encountered, the contractor was directed to temporarily stop TBM mining to allow the designer to assess the conditions and integrity of the PCTL tunnel. It was determined that additional PCTL repair was necessary consisting of crack repairs, channel installation within the crown, and rock bolt installations. The rationale for this required repair was to stabilize the rings to ensure axial load transfer was restored in the ring. Two channels per segment (C150x12.2) nominally spanning between the 10o'clock to 2o'clock position were installed to temporarily stabilize the segments. Depending on the damage segment and the orientation of the installed ring, up to 6 bolts per segment (1.8m in length and 32mm OD injectable anchors using TPH TD Solid Seal TX Resin) were installed.

Once the segments were repaired, the focus was then shifted to ensure that the annular gap between the PCTL and excavated rock was fully filled. Various check holes completed and numerous gaps (voids) in the shoulders and crown of the tunnel were discovered. As noted in Section 4.1, without sufficient ground confinement around the PCTL, the segments would not be fully stable. The re-use of the two-component cement grout used during TBM mining was unlikely to be able to withstand the water inflows and pressure. Implementing an alternative PCTL annular grouting method was deemed necessary.

There are many types of specialty grout material available on the market which could be injected under the high water inflow conditions. However, the ABTPO PCTL was designed to accommodate TDD and a very specific grout strength range (1 to 3 MPa) was needed (Susetyo et al, 2018). Finding a grout that would meet this strength range requirement while being capable to inject under noted groundwater inflow conditions in a market with materials supply limitations was challenging.

After contemplating several products, a polyurethane chemical grout was selected as the preferred annular backfill grout. This chemical grout was a closed cell polyurethane foam used for filling voids, sealing larger volume of leaks, and stabilizing the ground. Field trials were performed to select the necessary dosage of accelerant. The chemical grout was injected at closely spaced ports (3/8" diameter holes) around the periphery of the PCTL to completely fill the annular gap behind the PCTL.

Throughout this remediation period, attempts at completing curtain grouting within the rock mass using both cementitious and chemical grout were made. Although evidence of reducing some water inflow was observed, it was not possible to fully cut off and stop water inflows given the extent of the water bearing rock feature and the location of the TBM relative to this feature.

5.2 New Work Methods & Resuming Mining

Once PCTL repairs and annular gap filling to stabilize the tunnel lining were complete, TBM mining resumed. As mentioned before, cutting off all water inflows was not possible around the TBM. Therefore, without adopting alternate work methods, the site team fully expected that future PCTL rings installed in the TBM within this rock feature would continue to be damaged as of result of grout washing away the annular gap. To mitigate further damage to PCTL rings, the following sequence was ultimately adopted:

1. Install a chemical grout collar around the first ring immediate outside the TBM shield. In total approximately 50-70 drill holes were installed around the complete ring, with approximately 2 to 4 L of chemical grout injected per hole. See Figure 8.
2. Mine and build next ring while carefully examining movements and damages to nearby rings. During TBM mining, continue with injecting two-component annulus grout through the TBM shield while increasing the B-component accelerant.

3. Pre-install channel supports on the ring built within the TBM shield. It was determined that the pre-installation of channel supports prior to the ring leaving the TBM mitigates segments damages, lips and steps in the event that PCTL moves further due to lack of annulus confinement.
4. Monitor PCTL damages and have material and equipment available to repair segments as needed (crack repairs, rock bolts, additional channels, etc.).
5. Perform additional check holes and proof grouting using both the two-component grout and chemical grout. Ensure all segments are stable and the annular gap is full prior to mining the next ring set.
6. Repeat the pattern until the TBM successfully mines through the encounter ground feature.

Figure 8. Chemical Grout Collar Radial Injection Ports to Stabilize Ring along with Steel Channels

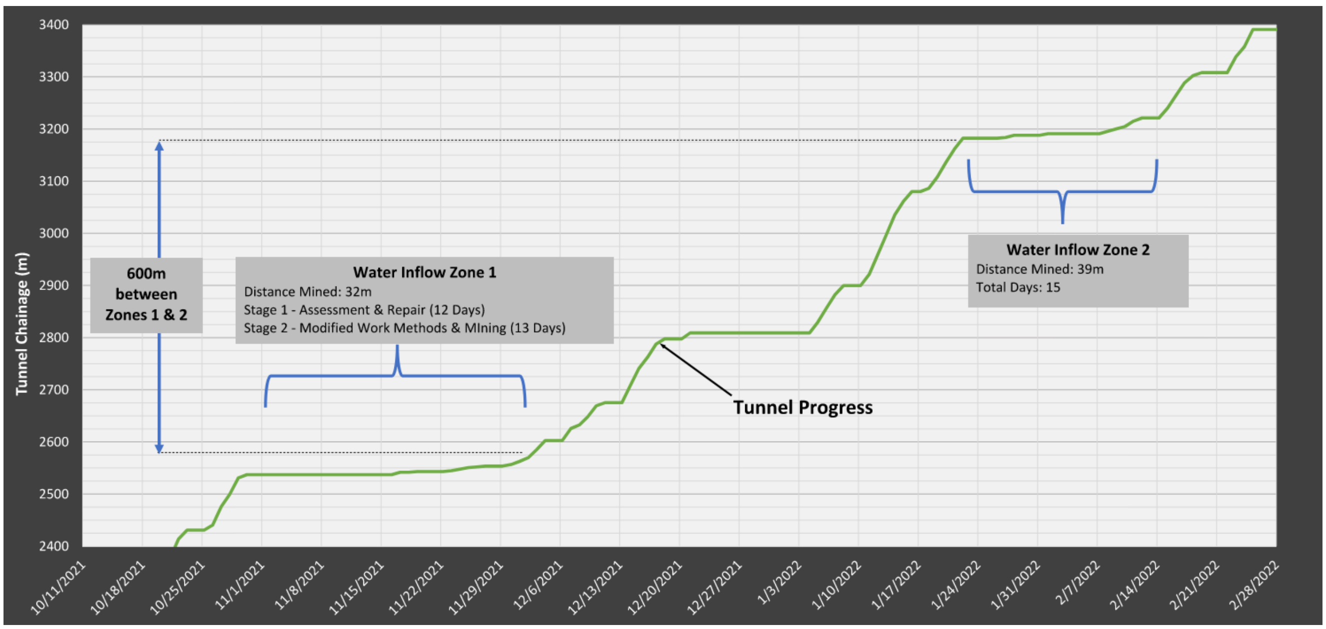


Figure 9. Time-Chainage Plot during TBM Mining Through Water Inflow Zone 1 & 2

The alternative work methods were collaboratively developed while considering diverse concepts and ideas brought forward by the entire project team including site supervisors, foremen, engineers, from all Contract parties (Contractor, Consultant, and Owner). Although the alternative work methods reduced daily tunnel advance rates, the plan did allow TBM to safely resume through the challenging ground conditions. Figure 9 demonstrates the overall TBM advancement during this challenging period.

As shown in Figure 9, the initial water inflows resulted in 12 working day standby as the site team investigated the condition, remediated the tunnel lining, developed alternative work method and procured new materials and equipment. The first zone was found to be approximately 35 m in length and mining through this zone progressed at a rate of 1.3 m/day. The second zone was approximately 39 m in length and the average productivity to mine through this zone was 2.6 m/day which is twice as fast as the first zone. The increase in productivity is attributed to the learning curve and readiness to implement the alternative mining method developed in the first zone.

5.3 Contingency Methods for Future TBM Mining

After successfully mining through the first water inflow zone, the project team hoped that that the challenging water inflow conditions were over. However, the team was aware that a potential re-occurrence was possible given the rock cover generally decreases toward the end of the tunnel alignment. To mitigate the risk of additional impacts, the project team agreed to perform additional advance probing during TBM mining. Furthermore, due to overall supply chain issues, a contract change order was issued to pre-purchase additional chemical grout material as contingency.

While entering through the second water inflow zone, there was approximately 250m of tunnel remaining to be completed. At this time, the project team considered the potential risk that groundwater inflows may continue for the remainder of the tunnel drive. Therefore, additional mitigation measures were considered and through a risk-based decision, it was decided to pre-procure a pea gravel conveyance equipment and have it ready on site in the event that the grouting methodologies needed to switch to a pea-gravel annulus filling operation. Fortunately, when the pea gravel conveyance equipment arrived on-site, ground conditions improved allowing the tunnel to successfully be completed without having to implement the additional contingency measures.

6 CONCLUSION

During TBM tunnelling on the ABTPO project, challenging ground conditions consisting of significant groundwater inflows were encountered which unfortunately impacted TBM productivity and damaged sections of the Precast Concrete Tunnel Lining. The site team quickly reacted to the situation by working closely together to develop a remediation plan and revisions to the work methods to allow TBM mining to resume. The tireless effort and actions implemented by the entire project team were effective to address the unexpected conditions encountering during tunnelling. The successful implementation of the plans demonstrates that challenging and adverse conditions can be safely and efficiently overcome by working closely as one diverse team.

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