Technical Memorandum

To: James Clift (EGLE) and Ryan Mitchell (MDOT)	Project: Line 5 Pipeline
From: David Crouthamel, Sam Swartz, Jake Facey	cc: Marco Moccichino, Dan Adams
Date: January 13, 2021	Job No.: 6191.0
Subject: FINAL Risk Mitigation for the Line 5 Replacement Tunnel	

1.0 Introductions and Questions

The Enbridge Line 5 Tunnel Project is anticipated to utilize a slurry tunnel boring machine (TBM) to excavate an approximately 4 mile tunnel below the Straits of Mackinac that will house the new section of the Line 5 pipeline as replacement of the two existing pipelines on the lakebed of the Straits. The TBM is anticipated to excavate through bedrock with high hydrostatic pressure (up to 17 bars from available information) and with the potential for highly fractured rock conditions.

This document discusses methods to mitigate risk ahead of the advancing TBM. It addresses the following questions raised by the EGLE Representative on October 20, 2020 (received via email) as part of the permit review process:

"Provide more information on methods to mitigate risks ahead of the TBM, related to karstic conditions, potential for higher groundwater inflows and pressures, and softer ground conditions that could impact TBM performance.

- *Are the design borings sufficient for tunnel design? Are there any longitudinal gaps or insufficient vertical (or angular) borings based on the tunnel depth that might allow for unidentified fractured zones that could increase the amount of groundwater in the tunnel during construction?*
- *Because of zones that produce more infiltration, or ineffective grouting that might produce more infiltration, could flows exceed the flows specified in the NPDES permit application during construction? How would this situation be handled?*
- *There was a notable rock tunnel failure that occurred during construction in Southeast Michigan in 2003. Grouting was excessive, excessive infiltration occurred, and ability to dewater proved undersized. The 20-foot diameter tunnel flooded. Have techniques changed, or does the geology of the straits decrease or increase that possibility for this project was it to move forward?"*

2.0 Answer to Questions

Methods to mitigate risks ahead of the advancing face include configuring and operating the TBM to manage the variable ground and if necessary, investigating and modifying the ground ahead of the TBM as needed. The primary method to mitigate risks is to operate the TBM in closed mode, where the hydrostatic pressures along the alignment are balanced by pressures at the face of the TBM, anticipated to be done using a slurry TBM. Pressures can be maintained throughout the tunnel drive, including during interventions using saturation diving. However, if interventions occur using open mode, which allows for more efficient work, it is critical to have the ability to investigate ground conditions ahead of the face to determine the presence of adverse conditions, and to take the necessary actions to manage them. The most common technique is probing (with the capability to pre-excavation grout). Geophysical methods such as the BEAM system are also available, if larger voids are anticipated. Further discussion on operations of a slurry TBM is provided in the white paper *Collapse potential for the Line 5 Replacement Tunnel* (January 2021).

Based on the anticipated tunnel alignment, the existing geotechnical borings have data gaps which elevates the uncertainty of the presence of risks within the alignment. These data gaps are a result of drilling depths that stopped short of did not extend through the tunnel profile. There is also limited hydraulic conductivity testing near or within the tunnel profile. Operating the TBM in closed mode, or monitoring and mitigating conditions ahead of the TBM, will be crucial to preventing impacts to TBM performance and worker safety. If full pressures are not maintained at the face, adoption of TBM technology used in similar recent tunnel projects including probing techniques, well-planned pre-excavation grouting ahead of the face, and backfill grouting of the segments that limits wash-out potential will be crucial to mitigating potential impacts from groundwater inflows.

Exceeding the NPDES permit is not anticipated to occur for closed mode operations with fully pressures, as groundwater pressures are balanced and inflows are essentially zero. However, there is a risk if the TBM is not properly configured/designed to thoroughly investigate or treat the conditions to reduce inflows ahead of the advancing tunnel in open mode, or if partial pressure mode is implemented. Inflow potential can be effectively and efficiently controlled per discussion above on implementation of probing and grouting for open or partial pressure modes.

Based on the lessons learned from the Detroit Outfall case history, over 17 years ago, the tunnel industry is significantly better prepared and equipped in managing the potential risks facing Line 5. Examples include the ability to excavate in closed mode under pressures anticipated for Line 5, including using saturation diving for interventions; improved probing and pre-excavation grouting understanding and techniques if open mode is anticipated (mostly for interventions); and improved lining and annular backfill technology, which provides a robust and mostly water-tight lining system concurrent with TBM advance. Also, based upon current investigations in the Straits and understanding of regional geology, we do not anticipate that the hazards of gassy conditions encountered in the Detroit Outfall will be encountered in Line 5.

3.0 Discussion

The following sections expand on answers above, providing more background information.

3.1 Sufficiency of Subsurface investigation

The subsurface investigation for the anticipated tunnel alignment has data gaps which increases uncertainty of the presence of risks which can impact the tunnel excavation. Typically, the industry recommends that investigational borings would be drilled through the tunnel alignment and beneath the tunnel profile (tunnel invert) to fully investigate the ground conditions surrounding the tunnel envelope. Figure 1 shows the profile of the anticipated alignment and depth of the subsurface investigation borings. Based on the boring logs, approximately 20 % of the borings terminate *more* than one tunnel diameter (assumed approximately 20 ft excavated) *above* the proposed alignment (Borings BH19-21, BH19-28, BH19-32 and BH19-33). Furthermore, based on the boring logs, half of the borings do not extend below the invert of the tunnel (BH19-19, BH19-21, BH19-23, BH19-25, BH19-26, BH19-27, BH19-28, BH19-31, BH19-32, BH19-33 and BH19-35). The limited depth of the investigational borings creates data gaps of the rock and hydrologic conditions near and within the tunnel profile, especially for the middle half of the tunnel alignment. This portion of the alignment has the highest hydrostatic heads on the project, and also appears to only have approximately a diameter of rock cover to the overlying soils within the middle of the Straits. Adequacy of the geotechnical data is discussed in the white paper *Geotechnical Exploration Level of Effort for the Line 5 Replacement Tunnel* (January 2021).

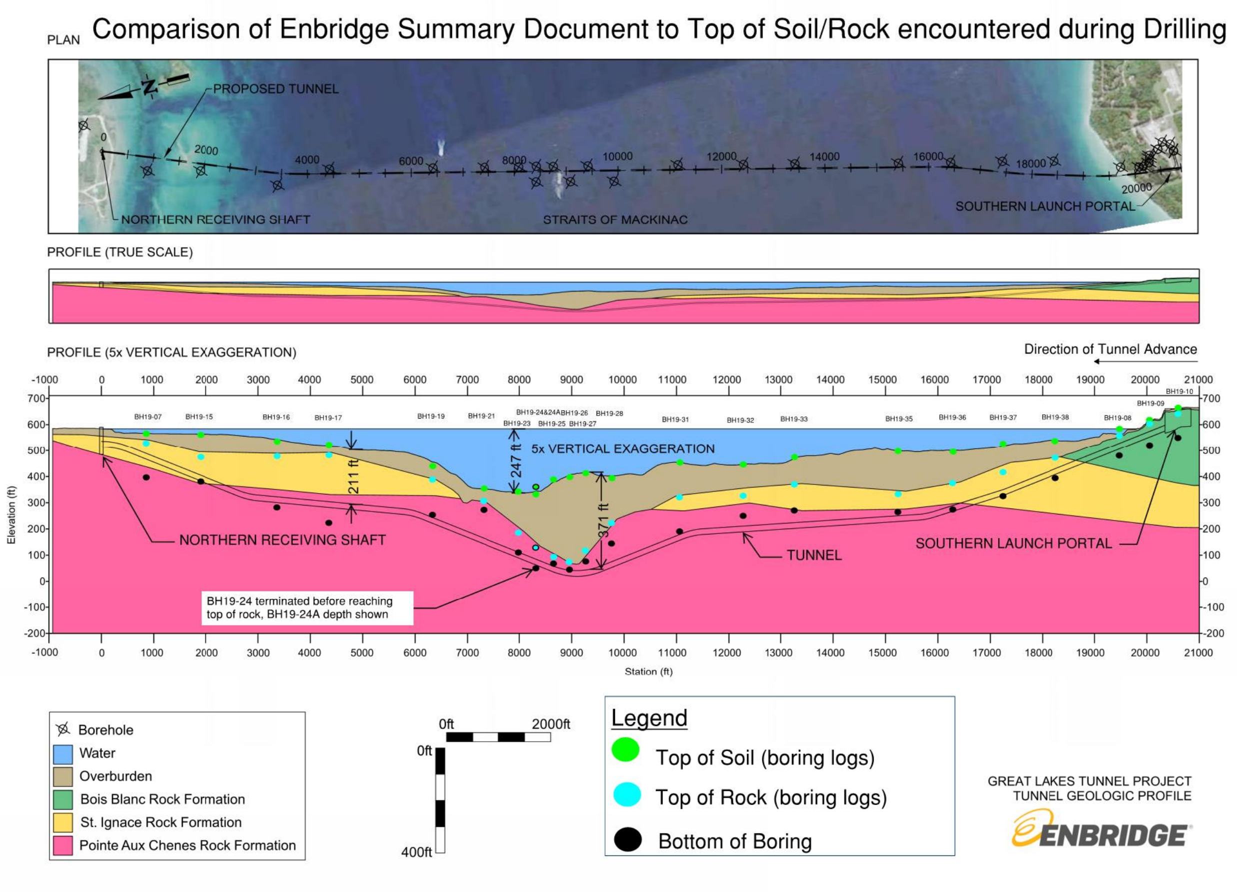

Figure 1 Boring Depth Relative to Tunnel Alignment

Figure 2 shows that hydraulic testing of the rock mass within borings B19-19 thru B19-37, the deepest section of the proposed alignment, does not investigate hydrologic conditions near or within the tunnel profile. The boring logs show that hydraulic tests are either absent, well above the tunnel or not below the tunnel. It is also not technically applicable to project the hydraulic conductivity of the rock well above the tunnel into the tunnel profile. Fracture zones or open seams generally are discrete features associated with faults, shear zones or overall rock mass conditions. The most meaningful measurement of the hydrological conditions is within 1 to 2 tunnel diameters above and below the tunnel alignment. Based on the anticipated vertical alignment of the tunnel, nearly half of the alignment length and a majority of the alignment with the highest driving head does not have hydraulic testing near the tunnel alignment. Rock mass features with hydraulic conductivity values of approximately 1 x 10^{-4} cm/s or higher can produce significant groundwater inflows into the tunnel and would be categorized as areas of significant risk impacting tunnel operations due to high groundwater inflows. These risks are discussed in the white paper *Collapse potential for the Line 5 Replacement Tunnel* (January 2021). Based on the proposed tunnel alignment, fully pressurized closed face mining is anticipated to deal with uncertainty in ground conditions, and potential for zone of higher hydraulic conductivity. If open mode or partial pressure excavation is anticipated, monitoring and investigation ahead of the advancing tunnel for hazards, associated with high hydraulic conductivity and weak ground, will be needed during excavation to prevent impacts to the tunnel excavation process.

The higher range hydraulic conductivity values associated with highly jointed, faulted and/or sheared rock, if not identified and treated prior to the tunnel intercepting the features, could potentially exceed NPDES discharge levels and overwhelm the water treatment facilities if the TBM is in open mode and cannot be quickly sealed. While these conditions would not be present if the TBM is able to advance in pressurized model using slurry face support, these conditions can occur if the TBM requires servicing which is either due to routine maintenance or emergency repairs.

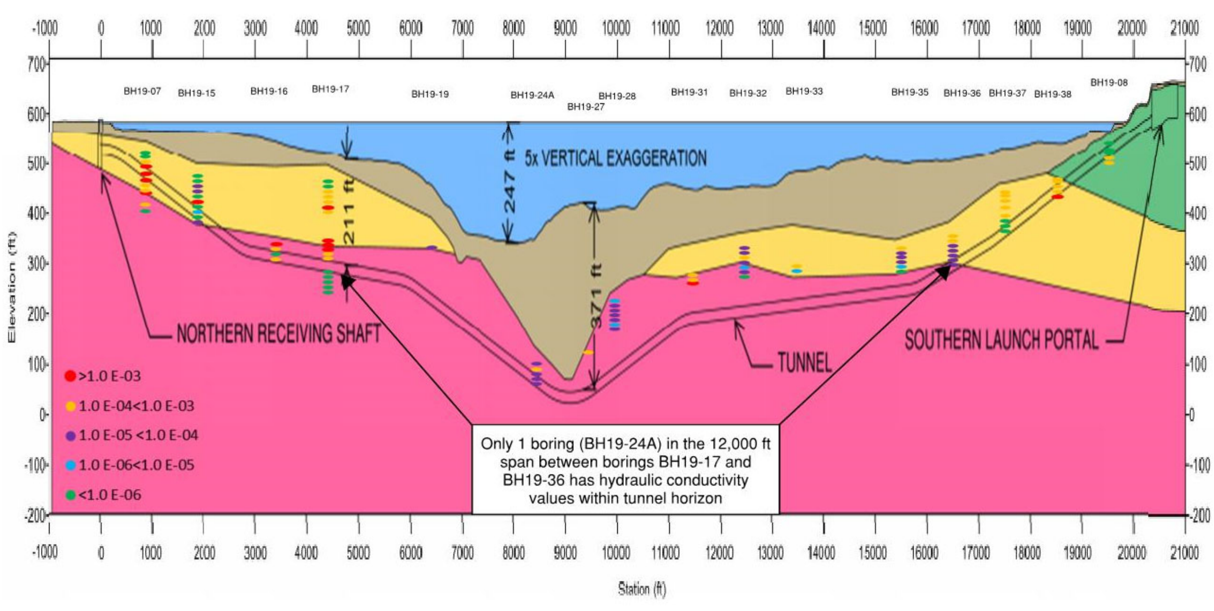

Figure 2 Hydraulic Conductivity Tests Along Proposed Tunnel Alignment

3.2 Risk Mitigation Methods

Overall risk mitigation methods are highlighted in the white paper *Collapse potential for the Line 5 Replacement Tunnel* (January 2021). The primary method of risk mitigation is mining in fully pressurized slurry mode. For potential areas for open mode interventions and/or partial pressure mode mining, the key to mitigation methods is identification of features ahead of the TBM and prior to intercepting hazardous features. Not treating features ahead of the TBM can have very significant risks and ramifications if encountered in open mode, as these features can cause significant delays to projects in trying to deal with them at and around the TBM heading. Investigation techniques include probe drilling and geophysical methods. While the geophysical techniques can identify cavities surrounding the tunnel excavation, additional information can be derived by probe drilling into the features. Probe drilling can confirm the location, geometry and most importantly, the hydraulic conductivity of the groundmass and its features ahead of the face. Logging of the probe drilling can yield information which relates to not only the hydrologic conditions ahead of the face but also relative rock strength. An example is shown in Figure 3 from the Arrowhead Tunnel project (Steve Duke et.al., 2003). Similar techniques have been used on tunnel projects in New York as well as drill and blast tunnels. Instrumentation of the hydraulic drills allows the collection of data on relative rock strength to be interpreted along with determination of water bearing features, cavities and their associated hydraulic conductivity conditions ahead of the face. This allows decisions to be made on how the TBM should be operated, how much further advancement of the TBM should be made or if measures for ground treatment, such as pre-excavation grouting, are necessary.

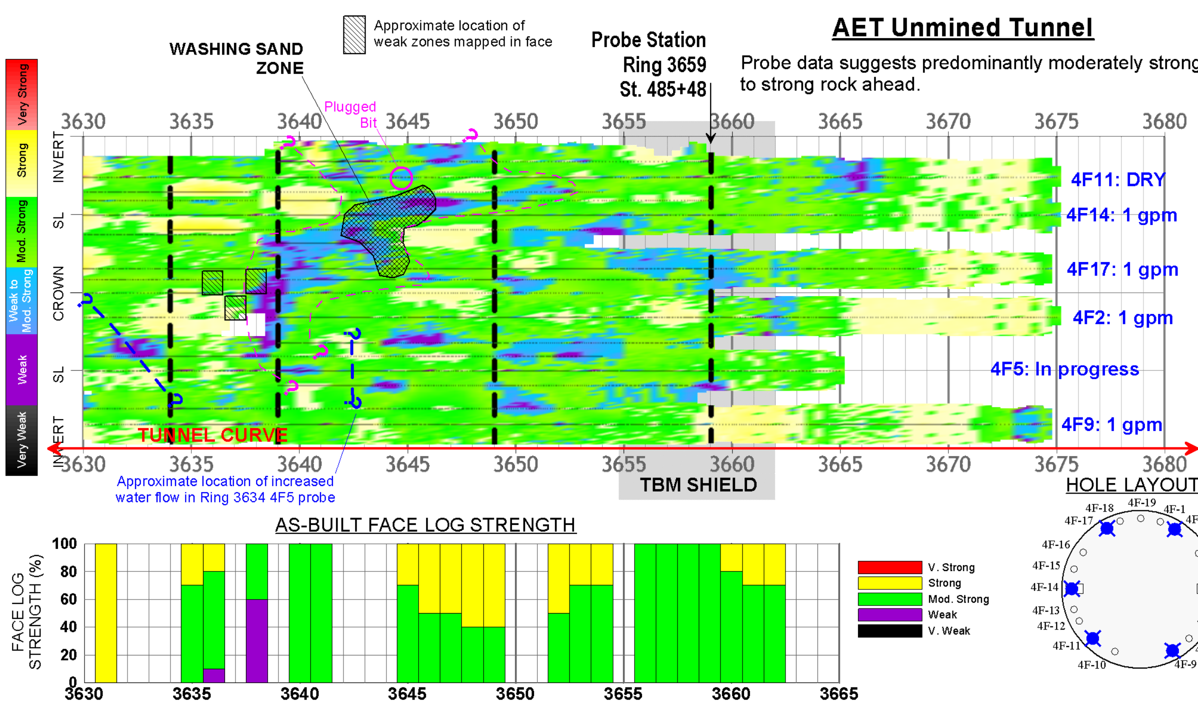

Figure 3 Probe Hole Recording and Interpretation (Arrowhead Tunnels)

The industry has also equipped the tunnel boring machines with multiple drill locations and drills to facilitate coverage outside the excavation limits of the tunnel and ahead of the face. For a tunnel excavation size of 20 ft, up to 45 drill locations have been provided on past projects, as a combination between drilling thru the face near the tunnel wall or directly thru the TBM shield. This allows thorough coverage around the full circumference of the excavation to investigate the ground conditions. Figure 4 shows the typical arrangement of 45 drill penetrations through a TBM similar in diameter to what is anticipated for Line 5. The intent of this hole arrangement is to drill into the rock mass enveloping the tunnel periphery and extending beyond the tunnel wall typically no more than one tunnel diameter. Investigation and if necessary, treatment of the rock mass at and immediately outside the limits of the tunnel excavation is the goal of this drilling pattern. Water inflows which can impact the tunnel operations are derived along the tunnel wall and investigation and treatment is critical in this area. Drill positions should be as uniform as possible within this treatment area. TBM's of this size can often accommodate two drills for drilling thru the face and two drills for drilling thru the TBM shield with two drills operating simultaneously.

In addition to having suitable drilling equipment, the TBM is typically equipped with grouting equipment which allows grouting at high volumes and pressures, with multiple grout plants to allow efficient and rapid treatment. Rock with high hydraulic conductivity typically has open seams in the rock mass that require high volume pumps to be able to place large volumes of grout quickly. Grout typically used for this application can be either standard Portland cement, microfine, or ultrafine cement, depending upon the level of inflows and type of features to be treated. To create a zone of grouting around the tunnel, it is recommended to limit grout quantities per hole, typically set at approximately 40,000 pounds of cement per 100 foot long hole. Projects faced with high permeability conditions often can overwhelm the grout plants and result in inadequate treatment or large delays. Typically, grout plants for this work are permanently fixed to the TBM trailing gear, automated and use bulk cement bins for continuous operation of the high production grout plants. In addition, large and open seams should be filled with thick grouts which require high pressure pumps which will have to pump against up to 17 bars of water pressure.

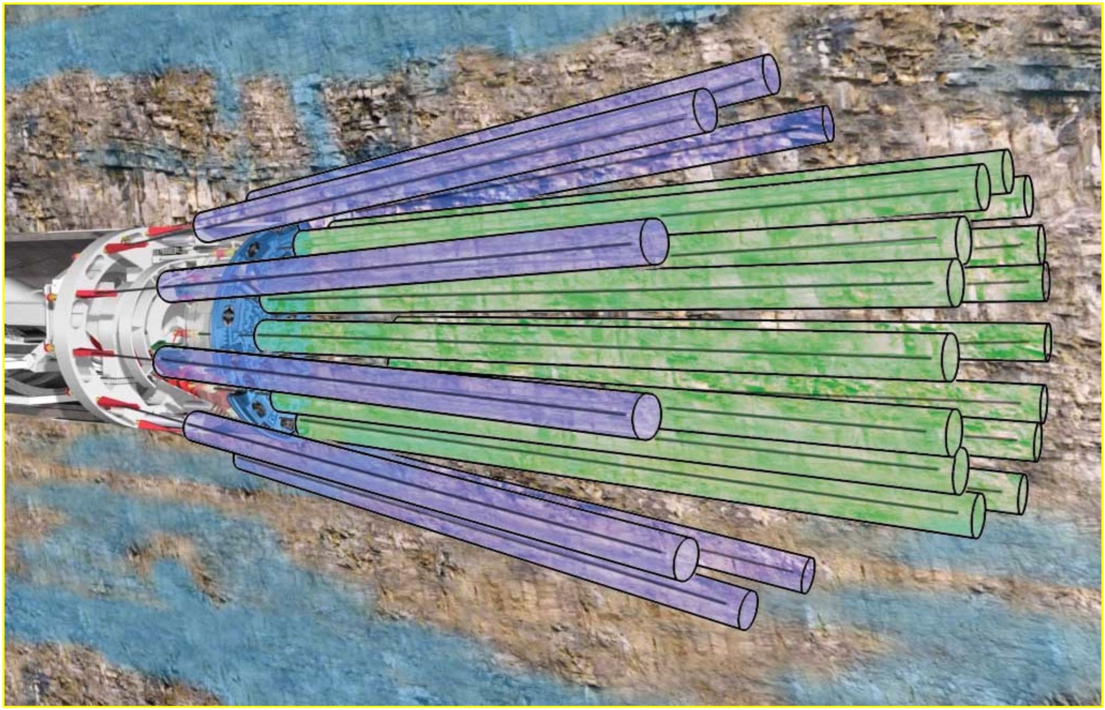

Figure 4 Typical Drill hole Geometry Ahead of Tunnel Face and Into Tunnel Periphery

3.3 Anticipated Infiltration Rates

In general, if the TBM is being advanced in fully pressurized mode, inflows are essentially zero. However, as indicated in the white paper *Collapse potential for the Line 5 Replacement Tunnel* (January 2021), it is possible to have inflows into the TBM cutterhead and shield area of *greater* than 3,000 gpm if the TBM is in open mode. This is based on the upper range of measured hydraulic conductivity values that could be measured in the investigation program (maximum $1x10^{-3}$ cm/s). Highly fractured rock and large open seams were not effectively tested, and would yield higher hydraulic conductivities than measured in the investigation program. These levels of inflows, if intercepted by the TBM in open mode would exceed the NPDES permit. If the TBM has to be serviced in open mode, either for emergency repair or routine service, safe havens have to be developed to ensure worker safety and water management can be maintained within NPDES permit limits. For partial pressure mode, inflows would depend upon differential pressures at the face and hydraulic conductivity. For limiting inflows to 50 gpm cited by Enbridge and their consultants as the upper limit for this mode, hydraulic conductivities in excess of $1x10^{-4}$ cm/s would not allow for significant reductions in pressure to meet this limit.

3.4 Detroit Outfall Case History

In March 2003, members of this team did an on-site visit of the Detroit Outfall No. 2, a few months prior to the inundation event which overwhelmed the project. The purpose of this visit was to investigate measures being used to manage water inflows and their impacts to the tunnel operations. Design was underway for the Arrowhead Tunnel Project that we were working on, and the Detroit Outfall No.2 project was being studied for both similarities anticipated to be encountered using similar construction techniques, as well as key differences. These key differences are mainly attributed to the hydrogeology, the TBM design and the pre-cast concrete segment design. There are also key differences between the Detroit Outfall No. 2 and Line 5, as discussed in more detail below. The primary limitations and differences of the Detroit Outfall No.2 from both the Arrowhead and Line 5 Projects are as follows:

- Groundwater for the Detroit Outfall No.2 had high concentrations of H_2S (Hydrogen Sulfide). This greatly reduced the tolerance for water inflows as ventilation could easily be overwhelmed.

- The driving head for the Detroit Outfall No. 2 was approximately 300 ft, where Line 5 is anticipated to be 580 ft (Arrowhead was 900 ft).

- The TBM design for Detroit Outfall No.2 could not be closed or pressurized. TBM operations were fully exposed to the gas laden inflows. All inflows encountered had to be collected and pumped out around the clock.

- The TBM drilling capability was restricted through the TBM shield, had less than 10 penetration points and used a single drill. Because of the configuration of the drill assembly, the lower 30 degrees of the circumference could not be drilled.

- The TBM did not use large volume grout plants and used a single plant on a rail car and no bulk cement facilities. The Contractor informed us that the typical cycle for tunnel work operations was drill and grout for four days and advance the tunnel on the fifth day and resume drilling.

- Treatment of the rock mass was not only prolonged due to undersized grouting equipment but the grout placed was thin and incompatible (washout and dilution) with open highly permeable features.

- The Detroit Outfall No. 2 segments were both tapered and beveled, and used bitumen packing on the radial joints allowing the segments to easily experience offsets and therefore were not well interlocked. The resulting offsets ruptured the concrete within the segments around the longitudinal dowels in the segments, resulting in leakage, if significant offsets were experienced. The vulnerability of the segments resulted in the inability to perform additional phases of backfill grouting without risk of damage. The segments on the Detroit Outfall No. 2 were intended to be the final lining.

The site visit of the Detroit Outfall No.2 was hosted by the Contractor. We were informed that investigational holes had been drilled in the invert and presence of an open and highly permeable seam beneath the TBM was present. The Contractor had attempted treatment, but limited drill access prevented successful infilling of the feature. Interception of the seam a few months after the site visit resulted in an inundation event of approximately 4,000 gpm of inflow laden with hydrogen sulfide gas, which overwhelmed the ventilation system and the ability to safely work in the tunnel.

As discussed in this memo and in discussion in the white paper *Collapse potential for the Line 5 Replacement Tunnel* (January 2021), it is anticipated that a slurry mode TBM would be used for Line 5.

This should allow the ability for the TBM to be closed during both excavation and while stationary. We have been briefed on general design requirements for the TBM, but have not seen the detailed specification, nor in-depth design requirements. In discussions with Enbridge and their consultants, the tunnel lining for Line 5 will be a high quality gasketed precast concrete segmental lining with connectors, avoiding use of bitumen packers on radial joints. This system should significantly reduce issues encountered on the Detroit Outfall No. 2 for the lining system. The presence of gas for the Detroit Outfall No. 2 and vulnerabilities of its TBM, segment design and limitations of drilling and grouting were cumulative factors weighing against the project to be successful. However as discussed, the Tunnel Industry has employed design choices and investigation and treatment measures ahead of the face, after the Detroit Outfall No. 2, as well as significant advances in pressurized face tunneling, which can mitigate the possible risks facing Line 5.

4.0 References and Additional Information

Steve Duke, et. al, "Arrowhead Tunnels: Assessing Groundwater Control Measures in a Fractured Hard Rock Medium," Rapid Excavation Tunnel Conference, Chapter 27, 2003.