Technical Memorandum

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

1.0 Introduction 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 and poor rock conditions.

This document discusses conditions of "collapses" in terms of face control and the operation of a shielded slurry TBM erecting segmental lining under such conditions. It also discusses situations where interventions may occur in open mode. 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 information on the idea of "collapses," in terms of mostly loss of face control of the tunnel. Describe situations that could be defined as collapses, including in-rush of material hitting karstic features or weak rock/soil where face pressure cannot be maintained; or large uncontrolled inflows into the tunnel heading if TBM is not in pressurized mode. Discuss how the TBM shield and segmental lining limits the risk of collapse away from the TBM face, and any other background on potential risks behind the TBM face."

2.0 Answer to Questions

Loss of control of groundwater and ground conditions at the face of the tunnel can lead to a potential "collapse", which can consist of a large ground loss and/or inundation of the TBM. Behavior at the face is dependent on how the machine is operated. Using a slurry TBM under fully pressurized operational conditions, where the face pressure of the TBM matches external hydrostatic pressures, significantly decreases the risk of ground loss if the TBM can remain pressurized. If a highly permeable feature is encountered while operating under pressurized conditions and slurry pressure is not maintained, ground loss may occur in weak ground conditions. Inundation of water inflow of the TBM under fully pressurized operation is typically not considered a risk based on the configuration of the TBM. Operation of the TBM in non-pressurized (or open mode), or in pressurized mode with less than full face pressure, increases the risks associated with ground loss and creates a risk of water inundation. Based on the available geologic data, conditions exist in the proposed alignment which could severely impact the tunnel operations and safety if not handled by TBM operations. If an open mode intervention is planned, ground conditions should be identified before intercept, and may require pre-treatment of the ground and/or proper operation of the TBM.

The TBM shield will be required to be designed for anticipated ground and full groundwater loads, including the potential for squeezing ground conditions. Design of the TBM shield itself for these conditions should effectively eliminate risk of collapse for the shield itself. Potential for the TBM to get stuck is still a concern, but can be mitigated by use of an injection system around the shield, as well as providing a high enough thrust capacity that can overcome squeezing ground on the shield.

Once the segmental lining has been installed and grouted into place, the lining will be required to be designed to take anticipated loads both during TBM operations (from TBM thrust loads) and for long-term conditions, and to keep the tunnel mostly water-tight. The lining provides a long-term stable condition for the tunnel. However, if large inflows occur from behind the TBM towards the heading, especially if the TBM is in open or partial pressure mode, these inflows could wash out annular backfill grout that helps to secure or bed the lining. Loss of bedding can cause distortion and associated damage to the lining.

3.0 Discussion

A “collapse” can be categorized into the following two conditions:

- Inability to build pressure or maintain consistent face support in weak rock resulting in large losses of ground at the face and around the TBM. Ground loss can be exacerbated by various factors, including inflows of groundwater.
- In-rush of large *uncontrolled* water inflows if the TBM is in open mode or partial pressure mode.

Mitigating risk of collapses is usually accomplished through TBM design and tunnel excavation procedures, as discussed in more detail in subsequent sections.

3.1 Fully Pressurized/Closed Mode

TBM design has advanced to the point where the current proposed alignment can be excavated in closed mode using a slurry (or Variable Density) TBM. Slurry TBMs were originally designed to excavate in granular material in a pressurized fashion thru conditioning of the spoils. Figure 1 shows a typical arrangement of a slurry TBM and the need to condition the spoils and create a slurry face pressure (D) to counter pore water pressure (A) and effective stress of the ground mass (B). Cutterhead pressure (C) is the direct pressure of the cutterhead (1) against the groundmass. Advancements in material admixtures and equipment design has allowed these machines to effectively excavate in a broader range of ground conditions (from their inception) from glacial till's populated with coarse material of cobbles and boulders, sandy clays and more recently fractured rock.

The successful ability of a slurry TBM to operate under changing conditions is a function of the rate of change in ground conditions. Rapidly changing permeability conditions can overwhelm operational conditions of the TBM if not prepared for. This is most relevant in open fracture/brecciated rock conditions where a rapid increase in hydraulic conductivity can result in loss of slurry face pressure (D) because the slurry mixture cannot be modified and/or increased quickly enough to maintain pressure. While pressures in the excavation chamber can be increased quickly due to the air bubble (3), if rapid reduction in slurry face pressure occurs due to slurry loss into the ground, the ground in the face can destabilize if the ground is weak and does not have the ability to self-support. Rapid and broad changes in hydraulic conductivity in soil conditions is not as pronounced as open fractures in rock, particularly in highly brecciated conditions. Voids/broken rock were identified in the drilling logs in both the St. Ignace and Pointe Aux Chenes formations as shown in Figure 2. The numerical values adjacent to the red X are length of zones in the boring logs either labeled as a void or no recovery of rock core. The transition into fractured rock from more intact rock, and the possible open fracture conditions in heavily brecciated ground within the rock mass, will be a challenge to maintain stable face conditions when operating the Slurry TBM in pressurized mode. Rapid transitions in behavior can be detected before interception by probing ahead of the TBM, as discussed in more detail below.

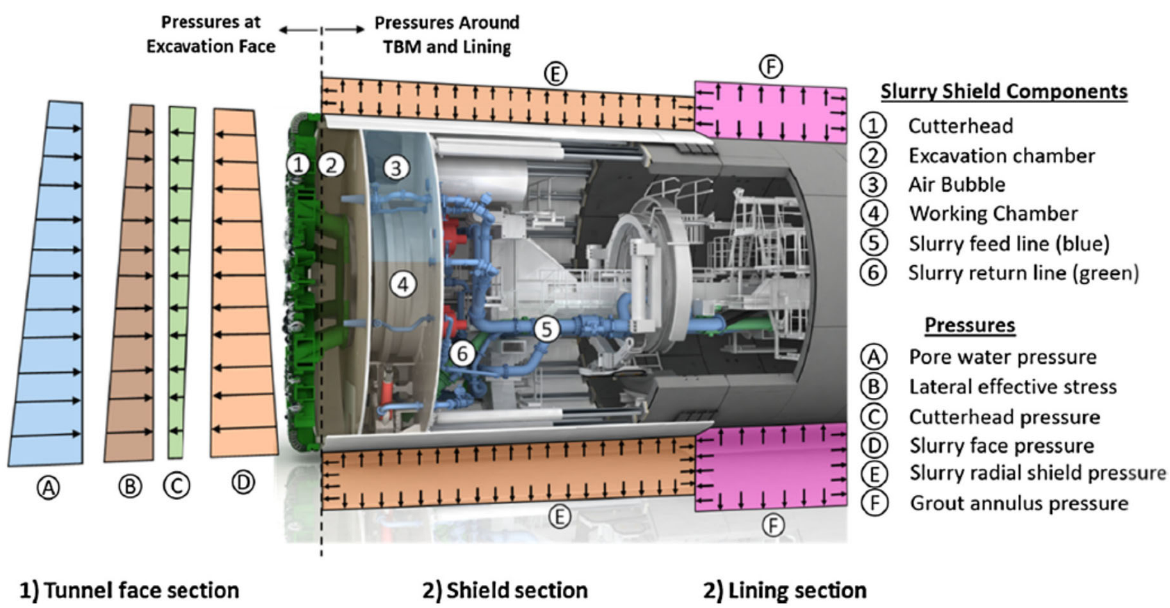

Figure 1 General Operational Configuration of a pressurized/closed mode Slurry TBM (from Herrenknecht)

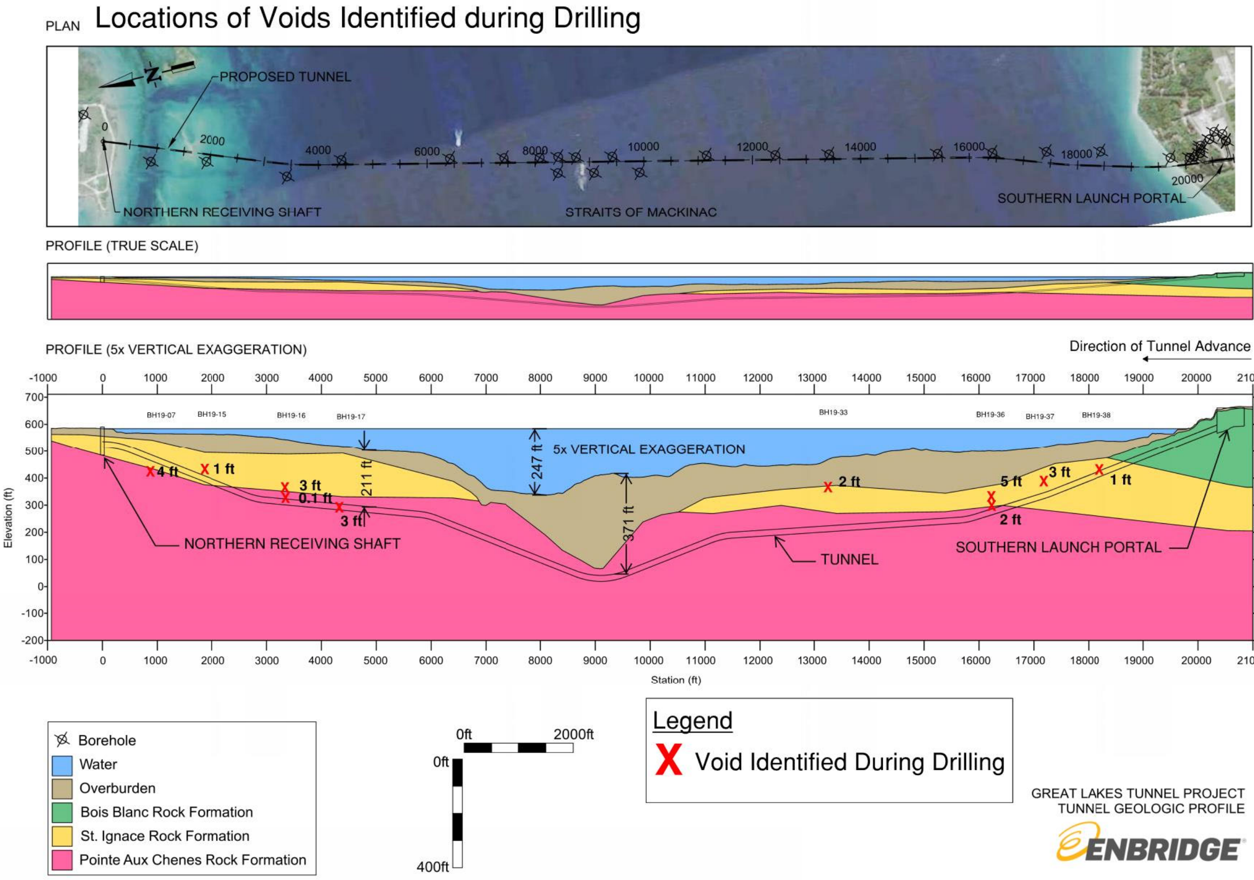

Figure 2 Location of Voids and Approximate Size Identified in Boring Logs

The rapid loss or reduction of slurry face pressure can result in a short term in-rush of loose or weak rock/soil, potentially created voids to develop ahead or above the TBM. Water in-rush while operating in pressurized/closed mode can be controlled by pressure monitoring, adjusting the air bubble pressure, and control in the pressurized slurry lines themselves. Therefore, the event of in-rush of water into a pressurized or closed TBM is typically mitigated by the closed TBM bulkhead and slurry handling system. Increases in ground mass permeability are monitored in the TBM slurry system as a reduction of slurry pressure and changes in cutterhead torque as the lateral effective stress on the cutterhead increases. These conditions typically are short term if carefully monitored and operational parameters are quickly and suitably modified while remaining in pressurized mode. The loss of face/slurry pressure (D) can also cause a loss of annular grout material by causing washout of the segment annular backfill (F). These conditions can be compensated by increasing the slurry density and pressure, and followed by additional annular grout pressure and material (F) to infill voids behind the segments.

Identification of areas ahead of the machine with the possibility of very high hydraulic conductivity for highly brecciated/open fractures ahead of the TBM before intercepting them can aid in maintaining proper face pressure in fully pressurized/closed mode. Early warning information of significant ground changes while tunneling is advantageous to reducing hazardous risks of changes in ground conditions. Since it is anticipated that most of the conditions of rapidly changing permeability/ground behavior conditions will occur in the rock, systematic investigation ahead of the face while excavating could be considered. In rock, probe drilling ahead of the face is a prudent measure to consistently investigate the ground conditions and its transitions which could cause difficulties and risk in ground loss in operation of the Slurry TBM, both in pressurized, partial pressure and non-pressurized conditions. Additional measures that have been adopted by the industry is the use of geophysical tools to investigate ahead of the face, such as the BEAM system. While geophysical systems can detect significant voids, areas of highly fractured rock or change from rock to soil conditions, it cannot yield absolute information on inflow potential. This means it cannot replace the probe drilling in rock as the exclusive investigation tool, which can give more absolute information on inflow potential and need for possible treatment.

To limit risks during build of the segments, thorough annular backfill placement must be accomplished where backfill may be damaged due to the presence of flowing water towards the heading. See Section 3.4 below for further discussion on the lining system anticipated for the tunnel.

3.2 Open or Partial Pressure Mode

The selection of advancing the slurry TBM under open mode (non-pressurized) or partial pressure operational conditions will be based on the quality of the rock and the groundwater inflow potential. Another mode of operation is if the TBM is not advancing, and non-pressurized. This would typically be performed for maintenance of the TBM under atmospheric conditions. For stoppages, ground conditions and groundwater inflow potential would have to be favorable to provide safe working conditions.

Industry experience in operation and advancing the TBM under open mode in rock conditions is in the presence of limited groundwater inflows (well less than <200 gpm) and stable self-supporting rock conditions, ground that is not collapsing on the TBM cutterhead or shield. As mentioned in the discussion of closed mode conditions, washout of the annular backfill can negatively impact the segment build quality and result in washout of the cement backfill which will impact water treatment of the collected water prior to final discharge. In discussions with Enbridge, the Contractor must be prepared to operate the TBM (advancement) in *closed mode* conditions throughout the tunnel excavation. However, we understand that the Contractor does have the option to advance in less than full pressure mode, either in open mode or a partial pressure mode. If the Contractor is intending to operate the TBM in anything less than full pressure mode while excavating rock, the exposure to risk of unmanageable groundwater inflows and caving ground conditions in weak and highly permeable ground is significantly increased. We recommend that precautionary measures of continuous monitoring of the ground conditions ahead of the face and groundwater inflow potential would have to be done systematically if the TBM is not fully pressurized (closed mode). Unfavorable ground and groundwater conditions identified would require thorough ground modification procedures to prevent negative impacts on the TBM operation and segment build quality, or to return to closed mode. To limit risks of face instability and grout washout around the segments, it was indicated that a limit on inflows of 50 gpm would be set for allowable heading inflow. However, limiting inflows to this amount will not allow for significant groundwater pressure reduction in ground with higher hydraulic conductivity.

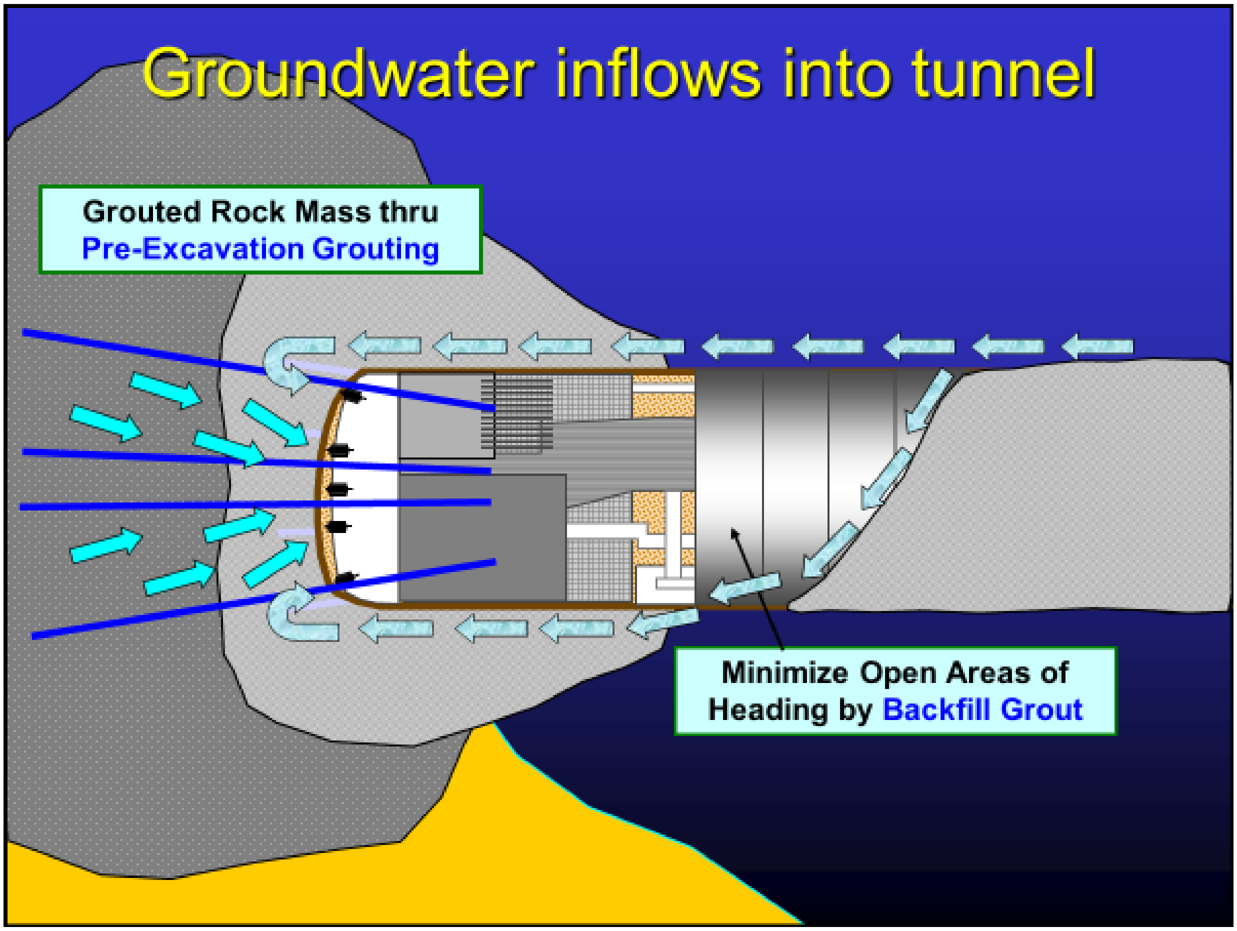

Figure 3 Open/Non-Pressurized or Partial Pressure TBM With Groundwater Inflows

Figure 3 shows the groundwater inflow sources from the groundmass around the TBM and segments (open or partial pressure mode either advancing or stationary). Under significant inflows within this area, when in open mode, backfill grout behind the segments can be compromised due to flowing water washing out the annular backfill. If this area around the TBM is non-pressurized, significant inflow of water around the shield towards the head will occur if the rock mass permeability is too high and the rock not treated. Typically, a slurry TBM of the size anticipated for Line 5 would have a shield length of 40 ft or more, with an additional inflow derived from around the segments which are not fully backfilled or backfill is partially washed out, say for an additional 50 ft (typical total length of tunnel inflow potential of approximately 100 ft). Based on the packer testing results of the investigation program in the rock along the proposed alignment and the anticipated depth, *untreated* and highly permeable rock can yield 2,000 to 3,000 gpm or *greater inflow* potential into the cutterhead depending on the rock mass permeability and depth (driving head) in the areas shown in Figure 3. If one uses hydraulic conductivities representative of open fracture conditions the inflow potential can be higher. These levels of inflow would have a significant impact on the segment annular backfill in addition to having to be pumped out of the cutterhead and out of the tunnel for treatment prior to disposal. Figure 4 shows an example of an inundation of a TBM cutterhead chamber creating unsafe working conditions in the cutterhead chamber due to high inflows.

Figure 4 Water discharge (approximately 1,500 gpm) thru a shielded TBM's open pressure bulkhead (cutter head beyond door opening) preventing maintenance/repair work within the TBM cutterhead chamber.

To prevent these conditions of inundation of the TBM in open mode or excessive inflows during partial pressure operation, the Contractor must have the ability to monitor ground conditions ahead of the tunnel face (drill probe, geophysical or both) to allow such conditions to not be intercepted if it can impact TBM operation. The Contractor should also have the means to treat the ground mass through geotechnical techniques such as pre-excavation grouting of the rock and drainage of discrete fractures. For partial pressure operation, the ability to regulate groundwater inflow to no more than 50 gpm can be challenging if conditions rapidly change or if the ground is unstable. It is therefore recommended that similar methods of investigation and treatment ahead of the face also be reserved for sections of the tunnel anticipated to be excavated under partial pressure conditions. Figure 3 shows areas ahead of the tunnel face and surrounding the tunnel excavation which should be targeted for treatment (gray shaded areas). Typically, given the size of the tunnel for Line 5, targeted grouting should be made of the ground mass surrounding the tunnel excavation periphery. This requires drilling access thru the TBM cutterhead and thru the TBM shield to effectively treat the rock mass prior to operating or performing work with the TBM in open or partial pressure mode.

Drilling through the TBM shield and through the pressure bulkhead and face can be done in either pressurized or non-pressurized conditions. Typically, it is more efficient to perform the work with the TBM in non-pressurized conditions. Figure 5 shows an example of equipment positioned thru the pressure bulkhead to facilitate probing and grouting ahead of the face with the TBM closed. Drill thru valves called blow off preventors are used to allow drilling under pressure and tools to be advanced ahead of the face. These devices can be mounted to facilitate drilling thru the TBM shield and pressure bulkhead giving the ability to have enough positions to treat the rock mass ahead of the face and a significant portion of the ground surrounding the TBM shield.

Figure 5 Drill port thru TBM pressure bulk to allow drilling ahead of the face. Note valve above worker is another drill position for drilling under pressurized conditions.

Maintenance interventions for the TBM will be necessary to provide inspection and repair of the TBM excavation tools when working in rock. The contractor must plan to either perform inspections and repairs under pressurized conditions (most likely using saturation diving), or to determine locations ahead of the TBM using probing and grouting to perform the maintenance work under safe conditions.

Typically pre-excavation grouting can reduce the rock mass permeability levels which can reduce inflows a tenth or less, i.e. hundreds versus the thousands of gallons described above, if the TBM is properly configured with probe and drilling positions and the Contractor is using suitable grout equipment and techniques to treat the rock mass. In addition to rock mass treatment, drainage thru the segments can be employed to divert water from entering the TBM and ensure worker safety is maintained. These drains can be sealed and the segment secured after they are no longer needed.

3.3 Water Management

Water management in the tunnel will be important to keep accumulating water from impacting tunnel work, particularly in the downward slope of the tunnel. This will require that the TBM to be equipped with sufficient dewatering pumps and water management systems when the TBM is in open, partial pressure or closed mode. Based on the size of Line 5 tunnel, dewatering pumps of sufficient capacity should be reserved to ensure the tunnel heading remains pumped out under all anticipated conditions. Figure 6 shows a single 2,500 gpm dewatering pump on a TBM trailing gear on standby to dewater a down sloped heading like Line 5. The pump can be connected to both a backup generator and the main power source. In discussions with Enbridge and their consultants, we understand that inflows of up to 3,000 gpm will be capable of being pumped out of the TBM, and treated at the surface.

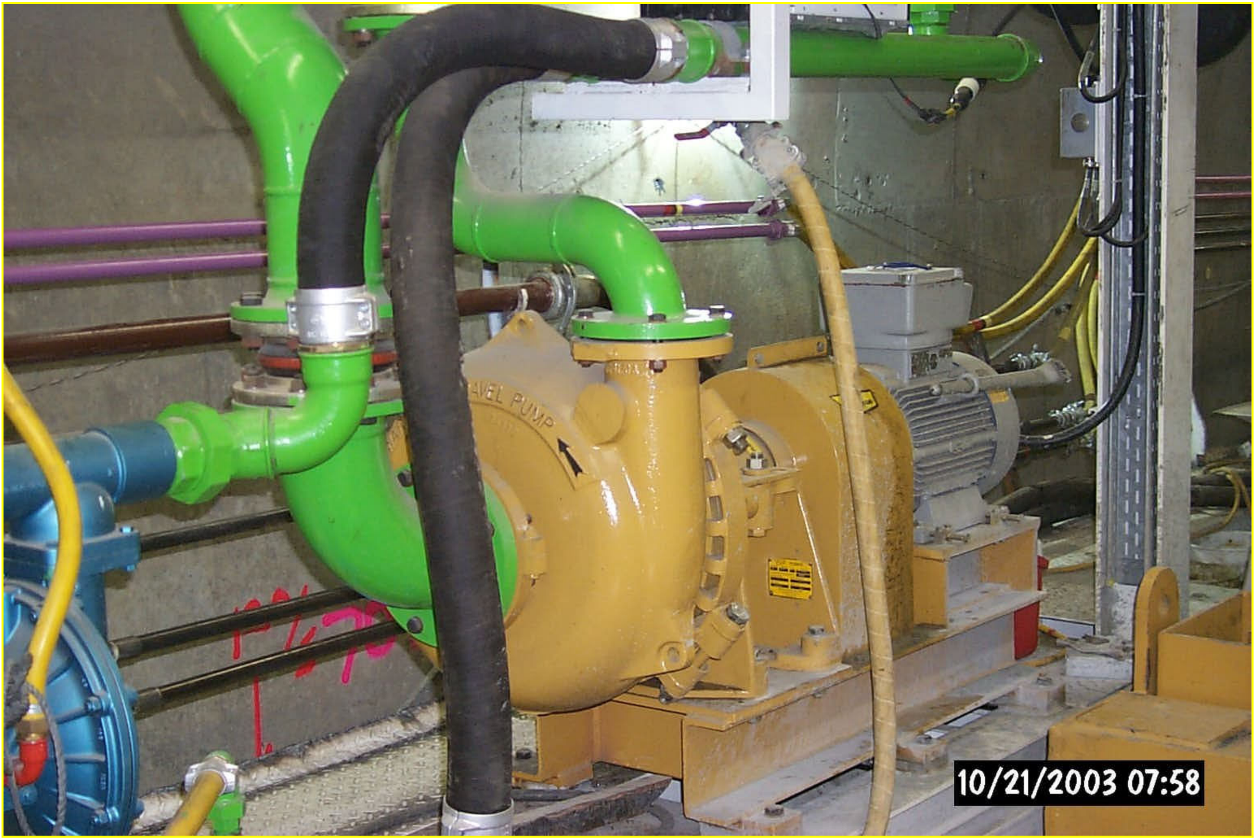

Figure 6 Standby Dewatering Pump on TBM trailing gear, 2,500 gpm

3.4 Conditions Behind TBM

It is anticipated that the TBM shield, to be used as initial support, will be designed for full hydrostatic head and maximum ground loads, including squeezing ground.

It is anticipated that a segmental lining will be the permanent support of the tunnel (final lining) and therefore carry the permanent ground loads. Once the segmental lining has been installed and grouted into place, the lining can be designed to take anticipated loads. Loads primarily include hydrostatic and ground loading, as well as seismic loads and other unusual loading conditions. Design life is usually set as at least 100 years, and the lining would be designed for long-term durability considerations. The lining system provides a long-term stable condition for the tunnel.

The segmental lining incorporates rubber gaskets along all joints to keep the tunnel mostly water-tight. These gaskets are designed for anticipated external hydrostatic pressures, with a factor of safety to account for long-term relaxation of the gasket, as well as ring build inconsistencies. For similar levels of hydrostatic pressures, gasketed linings have been successful on keeping inflows to well below 1 gallon per minute per 1000 feet of tunnel.

As part of installation of the lining system, annular grout is injected into the small void between the outside of the lining and the excavated ground. This void is typically about 4 to 6 inches on the radius. The grout sets up quickly, and holds the lining tight against the ground. As mentioned above, if face pressure is not controlled, ground loss can occur as well as washout or erosion of the annular backfill grout material. Additional grouting thru the segments (second stage backfill grout) to verify the adequacy of backfill is typically performed in areas of concern and is considered an industry approach when conditions of risk become recognized. In addition to reasons cited above, it is very important to cut off groundwater to the extent possible through pre-excavation grouting for locations where open mode conditions are anticipated to occur. If these conditions occur due to emergency situations, measures are available for trying to cut off water from behind the TBM, but are often a challenge to implement in the field.