McMILLEN JACOBS ASSOCIATES

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: DRAFT Geotechnical Exploration Level of Effort for the Line 5 Replacement Tunnel	

1.0 Introduction and Question

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 variable rock conditions. Depth to the tunnel below grade ranges from 60 feet near the south shoreline, to over 350 feet near the middle of the tunnel.

This document analyzes the geotechnical investigation completed, to date, for the Line 5 replacement tunnel and assesses the level of tunneling risk based on the current level of the geotechnical investigation. It addresses the following questions raised by the EGLE Representative on October 20, 2020 (received via email) as part of the review process:

"Provide comparison of geotechnical exploration and borings done for past projects under similar conditions, including boring spacing and total drill lengths. Soil and rock with difficult access conditions should be part of this response/discussion.

- *Does the Enbridge summary document fairly characterize the geotechnical data report?*
- *Do we expect the current proposed tunnel route be primarily within bedrock? If not, to the extent it is not in bedrock what challenges will that present?"*

As part of the discussion, case histories of projects in similar ground conditions were analyzed including a comparison between the level of effort of the geotechnical investigations and the conditions encountered during construction. Specifically, this paper has reviewed the level of geotechnical investigation in conjunction with the construction records of these similar projects in order to determine if the current level of geotechnical investigation for Line 5 is adequate to categorize the ground conditions on site based upon our collective experience.

It should be noted that the following discussion is based on the data provided in the Geotechnical Data Report and the tunnel geology summary and alignment provided in the Enbridge Summary Document, which we are assuming to be the document “EGLE-GLTPTunnelProfileSummary_701690_7.PDF”, available as part of the permitting process. Further information has been provided by Enbridge on overall geotechnical conditions, including more detailed information on the tunnel alignment, and excerpts from a draft of the Geotechnical Baseline Report (GBR).

2.0 Answer to Questions

The subsurface investigation for the Line 5 project was compared to investigations for tunnels excavated with similar ground and depth conditions. The projects selected for comparison are deeper tunnels either below water bodies, or with challenging access considerations due to depth and/or topography. To respond to the question, the comparison was based upon average boring spacing of the program, based on the spacing between the borings at ground surface, as well as the total drill length of the program. These two parameters can be used to compare the level of effort of two subsurface programs when all the drilled borings reach the tunnel depth and when the two crossings are of similar depth. Using this comparison, investigation data collected to date on Line 5 is within the range of past comparable projects with similar challenges for boring access, and overall tunnel depth. A detailed breakdown of the comparison is provided in Table 1 in Section 3.1 below.

However, since many of the Line 5 borings did not reach the proposed tunnel depth and since the comparable projects were excavated at various depths, total drill length and average boring spacing are not always ideal comparisons when evaluating a subsurface investigation, as the focus should be on conditions at the tunnel horizon. To better compare between projects, the percentage of the tunnel that is classified by borings can be quantified. This comparison was done by assuming a 50ft zone above and below the tunnel for each boring that is drilled to the tunnel depth. A similar comparison as above was made using the same projects and subsurface investigations, however it only includes the information from within the zone in proximity to the tunnel alignment. Based on this revised comparison, the percentage of the tunnel alignment classified by the subsurface investigation is less than the typical level of classification from subsurface investigations for similar deeper tunnels. However, there is a precedent for a tunnel designed with a less comprehensive geotechnical investigation. A detailed breakdown of the comparison is provided in Table 2 in Section 3.1 below.

For the Enbridge summary document, in short it alone does not adequately characterize the anticipated ground conditions on site. It provides an overview of the number of borings and amount of testing as well as generally describing the anticipated rock formations. It also provides a profile of the tunnel alignment relative to rock formations. However, the document does not summarize the detailed findings of the investigation. In order to fully understand the ground conditions, it is important to view the data in relation to the vertical alignment, as well as methods anticipated to excavate the tunnel, in order to identify any high risk areas. The main risk anticipated in this crossing is the potential for high water inflows if highly fractured and permeable rock is encountered and not properly mitigated by either TBM excavation methods, or by pre-treating the ground ahead of the TBM. The severity of this risk is compounded by the high hydrostatic head and low rock cover in the middle of the crossing. Additional risks are instability of the rock at the face of the TBM, or from squeezing ground around the shield in weaker rocks. These risks are manageable in most tunneling projects, however the lack of available data at tunnel depth for portions of the alignment adds uncertainty to ground classification. This uncertainty emphasizes the importance of either utilizing a TBM excavation method that can control the ground, such as fully pressurized face tunneling, and/or by probing ahead to evaluate ground conditions ahead of the face during excavation. Risks are discussed in more detail in responses to other questions, for the white papers *Collapse Potential for the Line 5 Replacement Tunnel* (January 2021), and *Risk Mitigation in the Line 5 Replacement Tunnel* (January 2021).

Based on the profile presented in the Enbridge Summary Document and subsequent verification by Enbridge of the vertical alignment, the proposed tunnel route will be excavated in bedrock for the entire alignment. A minimum cover of approximately 25 feet of bedrock occurs near the middle of the alignment. However, due to a significant number of borings terminating before the tunnel invert near the middle portion of the alignment, there are portions of the alignment where the rock quality and conditions within the tunnel have not been directly investigated. This lack of data spans the majority of the length of the middle half of the tunnel alignment.

3.0 Discussion

The following sections expand on the answers above and provide a more detailed comparison of the Line 5 Geotechnical investigation to historical projects. It also provides a more detailed breakdown of data from the Geotechnical Data Report, as it applies to the vertical alignment of the tunnel.

3.1 Comparison to Prior Projects

In recent history, several tunneling projects have been completed in similar ground conditions. The Rondout Bypass Tunnel (New York), Bay Tunnel and Arrowhead Tunnels (California), and Eagle Mountain and Second Narrows Tunnels (British Columbia) feature deep crossings in varied ground conditions under large bodies of water. These projects each have a varying level of geotechnical exploration resulting in varying levels of risk due to tunneling. Table 1 provides a summary of the geotechnical exploration programs for each of the projects mentioned above in addition to the geotechnical exploration completed to date for the Line 5 Project. It should be noted that Table 1 represents all available project borings, including, for some projects, several shaft borings that may not reach tunnel depth. Profiles for these crossings have been compiled, and are available upon request.

Table 1. Summary of Geotechnical Exploration in Similar Projects.

Tunnel Name	Tunnel Length (ft)	Maximum Tunnel Depth (ft)	Tunnel Ground Conditions	# of Borings	Average Boring Spacing (ft)	Total Drill Length	Drill Length/ Tunnel Length
Line 5	21,000	560	Soil, Mixed Face, and Rock	33	636	5,786	28%
Second Narrows	3,576	215	Soil, Mixed Face, and Rock	43	83	7318	205%
Arrowhead	50,350	2,000	Rock, faulted sections	53	950	21,872	43%
Rondout	13,500	900	Rock, faulted sections	53	255	18,255	135%
Bay Tunnel	26,000	110	Soil, Mixed Face, and Rock	29	897	5,011	19%
Eagle Mountain	18,914	1,476	Soil, Mixed Face, and Rock	5	3783	2,294	12%

The average boring spacing shown on the table above is based off the spacing of borings at surface and considers all project borings, including shallow borings within the shafts. Based strictly upon the comparison of boring spacing and total drill length, the data from Line 5 provides a roughly similar level of information as other comparable projects. As another quick check, dividing the total drill length by the tunnel length, Line 5 provides a factor of 28%. This value is generally lower than other comparable projects, which are on average closer to 80%, but ranges from 12% to 205%.

In tunnels of similar depths, total drill length can be used to compare the level of effort of the subsurface investigations. However, when evaluating two crossings with an equal number of borings but significant differences in average depth, the deeper crossing will have a higher total drill length but the same level of coverage within the tunnel length itself. An example is to look at BH19-32 and BH19-33 in Figure 1. The two borings combined add approximately 450 ft to the total drill length yet offer no further information on the ground conditions in proximity to the tunnel elevation. As discussed in Section 3.1, taking boring spacing at the surface is not always an accurate representation of the spacing of borings within the tunnel alignment.

Focusing on only borings that reach the tunnel horizon provides a more practical approach to evaluating the level of completeness of a subsurface investigation for tunnel design purposes. Average spacing of borings drilled beyond the tunnel invert is a better comparison than average spacing of all borings drilled, and drill length within a predefined tunnel horizon is a better comparison than total drill length.

For the following comparison, the tunnel horizon is defined as 50ft above the tunnel crown and 50 ft below the tunnel invert, assuming approximately 20 ft tunnel diameter. The total drill length within this zone can be used as a more representative metric for the level of subsurface investigation for the tunnel. Using this definition, any shallow shaft borings or borings that do not reach the tunnel horizon are not counted towards the drill length. Table 2 provides a comparison of these projects based only on borings within the tunnel horizon.

For Table 2, the set of borings drilled beyond the tunnel invert was used to determine the “Boring Spacing” and “Longest Span without Boring” columns. Due to some borings terminating less than 50 feet above the tunnel crown, there are additional borings that do not count towards the average spacing but do contribute to the Cumulative Drill Length within Tunnel Horizon quantity.

Table 2. Summary of Geotechnical Exploration in Similar Projects – Altered Parameters

Tunnel Name	Tunnel Length (ft)	# of Borings Drilled Beyond Tunnel Invert	Boring Spacing (ft)	Longest Span without Boring (ft)	Cumulative Drill Length within Tunnel Horizon	Tunnel Horizon Boring Length/Tunnel Length
Line 5	21,000	9	2,333	8,000	1,200	6%
Second Narrows	3,576	12	298	700	1,440	40%
Arrowhead	50,350	47	1071	4,000	4,823	10%
Rondout	13,500	16	844	2,200	1,920	14%
Bay Tunnel	26,000	26	1,000	3,500	3,080	12%
Eagle Mountain	18,914	5	3,783	6,600	600	3%

Table 3 indicates that the level of coverage for subsurface investigation of the Line 5 Replacement Project is less than the typical level of coverage in projects with similar ground conditions, as borings drilled did not always provide information within the tunnel envelope. Based on the Tunnel Horizon Drilled Length per foot of tunnel metric, Line 5 (6%) is below the average (16%) for comparable projects. Also, at tunnel depth, there are some larger gaps without information (up to approximately 8000 feet), which is longer than the undocumented span in comparable projects.

The appropriate level of effort of a geotechnical investigation is a product of multiple factors including the length/depth of the tunnel, site ground conditions, accessibility of boring locations, as well as the acceptable level of risk in the design. While Line 5 generally is consistent with past projects for more common parameters (average boring spacing, total drill length), because a number of the borings were terminated above the planned vertical tunnel alignment, there are significant data gaps at tunnel depth.

3.2 Geotechnical Investigation

This section serves to summarize the geotechnical investigation completed to date for the Line 5 Replacement Project, how it was used for comparison purposes, and how the investigation compares to the Enbridge summary document. A brief discussion of the impacts the findings of the investigation will have on tunneling conditions and the assessment of risk will be discussed in Section 3.3, and further expanded upon in other white papers.

As of November 2020, a total of 33 borings have been drilled for the Line 5 Replacement Project. Note that this number considers all borings drilled for the project, including shallow borings at the south shaft site (BH19-11 through BH19-14). The borings considered herein vary in depth from 5 to 525 ft with an average spacing of approximately 636 ft. The borings show that, along the proposed alignment, the water depth varies from 0 to 240 ft and that depth to top of rock (from the water surface) varies from 50 to 520 ft. Prior geophysical surveys of the lake bathymetry indicated a valley in the middle of the straits which was confirmed by the geotechnical investigation.

The average spacing mentioned above measures the average distance between adjacent borehole locations, at surface. However, several of the borings were terminated before reaching the tunnel invert, so 636 ft is not an accurate representation of the spacing of borings at tunnel depth. Only including the ten borings that reached the proposed tunnel depth results in an average spacing of approximately 2,100 ft. Figure 1 shows an overview of the boring program in relation to the profile, including the recorded elevations of top of soil, top of rock, and the bottom of boring. Note that for image clarity, shallow borings BH19-11 through BH19-14 were not included in the figure.

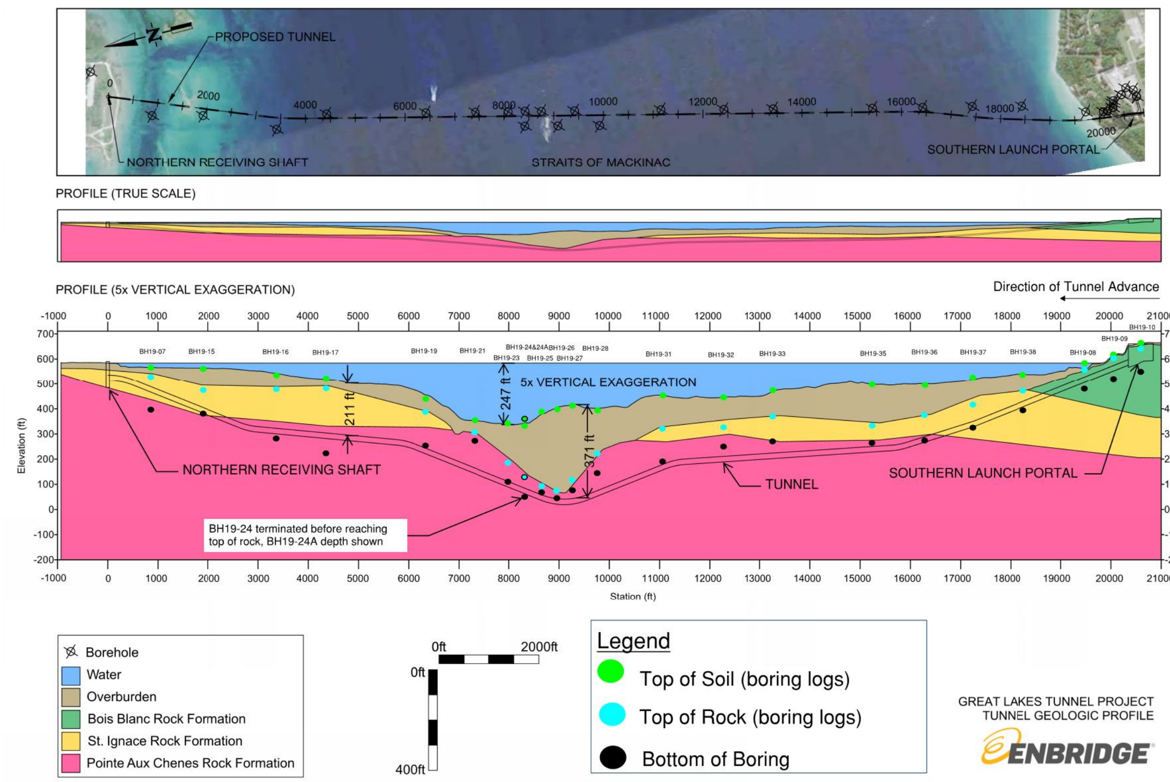

Figure 1: Comparison of Enbridge Summary Document to Top of Soil/Rock encountered during drilling

The figure reveals a large gap in borings that go to tunnel elevation between BH19-17 and BH19-36, which helps explain the difference in boring spacing when measured from the tunnel elevation vs the ground surface. See Section 3.2 for further discussion on comparison of this information to past comparable projects.

Soil within the project area consists of sand, silt, clay and gravel. A higher percentage of sands is present on the northern portion of the crossing and a higher percentage of gravel is present on the southern portion of the crossing. The highest concentration of clay and silts were in the middle of the crossing, in the zone with the deepest top of rock levels. Overall, there is a significant proportion of soil containing fines, with 89% of samples having greater than 15% fines (passing #200 sieve), based on 97 total tests. Overall data for the soils are limited away from the shorelines.

Based on historical studies, bedrock within the project area consists of three geologic formations (listed from youngest to oldest): Bois Blanc, St Ignace, and Pointe Aux Chenes. The Bois Blanc formation consists of dolomite & limestone and is only present in the Southern end of the alignment, accounting for approximately 10% of the total alignment length. The St Ignace formation, accounting for approximately 20% of the tunnel length, consists of predominately dolomite and is present at both the northern and southern ends of the crossing, with an approximately 4,000 ft span in the middle where it is not present. The remaining 70% of the tunnel will be excavated through the Pointe Aux Chenes formation, which consists of predominately claystone with occasional dolomite, limestone, and gypsum interlayers. The Pointe Aux Chenes Formation is present throughout the entire alignment, and lies directly under the soil in the areas where the St Ignace is not present. The boring logs confirmed the general composition and distribution of the rock units.

Recovery percentage is recorded while drilling and is useful when examining overall rock quality and for identifying potential voids in the bedrock. Figure 2 shows a histogram of all recovery values recorded during drilling, separated by rock formation. The data shows a higher potential for low recovery, which is indicative of poor quality rock, and/or open voids or heavily brecciated rock, in the St Ignace and Bois Blanc formations compared to the Pointe Aux Chenes. The impact of poor quality rock conditions on tunneling methods is discussed further in the document titled - *Collapse Potential for the Line 5 Replacement Tunnel* (January 2021).

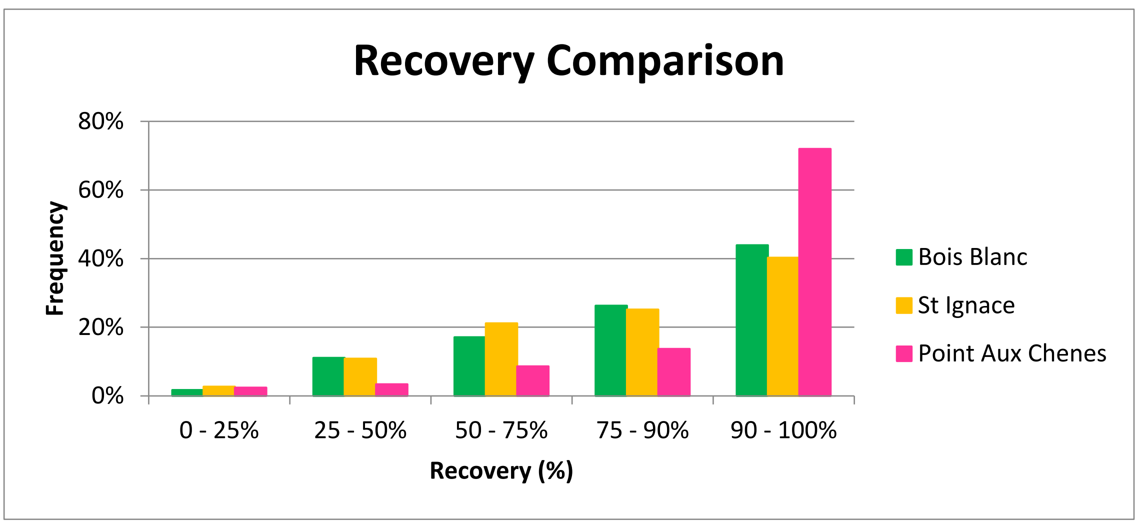

Figure 2: Comparison of Recovery – by Rock Formation

Rock Quality Designation (RQD) is a measure of the level of fracturing that helps describe rock with significant fracturing that is not identified when examining only recovery. RQD adds up the total length of all rock fragments, in a run, greater than 4 inches and divides by the total length of the run. Figure 3 shows a histogram of all RQD values, separated by rock type. The rock is typically highly fractured with approximately 50% of all rock cored having an RQD less than 25%, with the Bois Blanc and St Ignace exhibiting significantly lower RQD compared to Pointe Aux Chenes samples. See Table 3 below for a comparison of RQD versus Rock Quality, from Deere and Deere (1988).

RQD (Rock Quality Designation)	Description of Rock Quality
0 - 25 %	Very Poor
25 - 50 %	Poor
50 - 75 %	Fair
75 - 90 %	Good
90 - 100 %	Excellent

Table 3: Rock Quality Description Based on RQD (Deere & Deere 1988)

In general, the Bois Blanc rock is generally Very Poor; St. Ignace is Very Poor to Poor; and the Pointe Aux Chenes is quite variable, with most rock Fair to Excellent, but approximately 20 to 30% Very Poor to Poor as well.

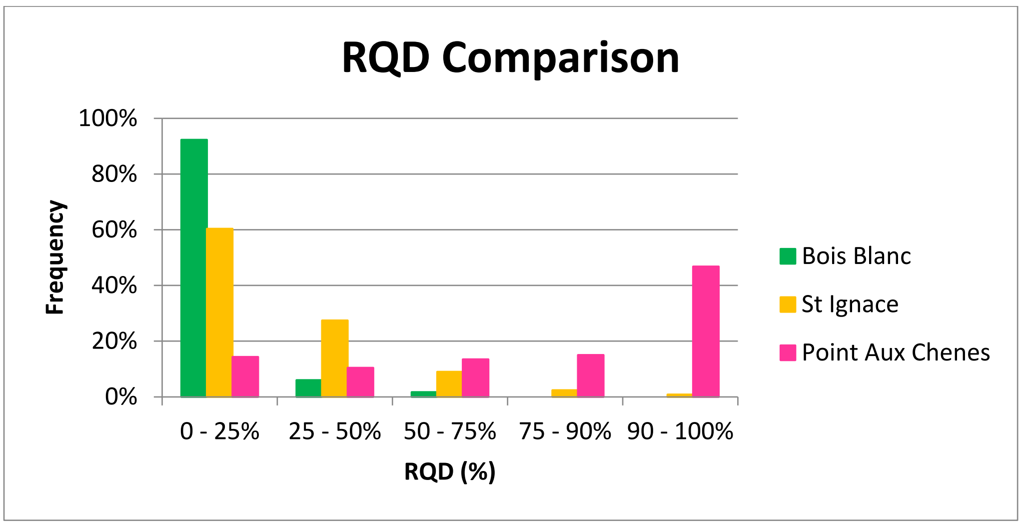

Figure 3: Comparison of RQD by Rock Formation

Hydraulic Conductivity is a measure of the ability of water to travel through a rock or soil medium. When analyzed alongside other parameters, such as hydrostatic head and fracturing, hydraulic conductivity values can be used to help quantify expected inflows during tunneling. Hydraulic conductivity tests were completed on 16 borings along the Line 5 Replacement Tunnel Alignment, which is summarized in figure 4 below.

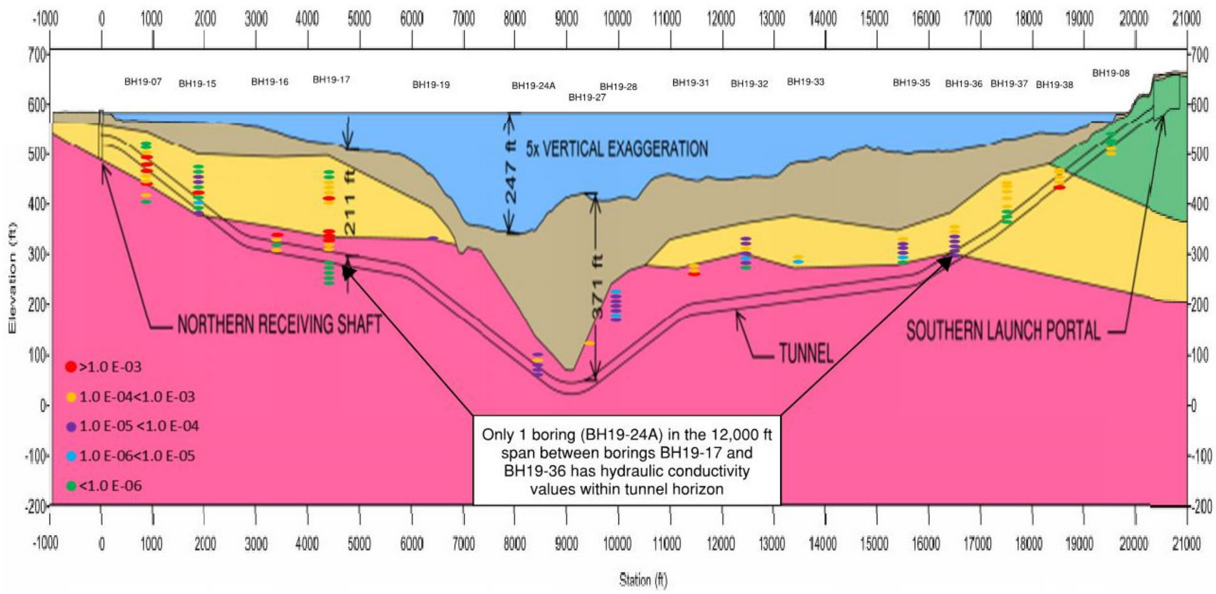

Figure 4: Hydraulic Conductivity along proposed alignment

Much like the top of soil/rock plot, Figure 4 reveals significant absence of available data from within the tunnel alignment as BH19-24A is the only data point within the alignment over a span of approximately 11,000 ft. This lack of data corresponds to an inherent risk in tunneling, and has the potential to be exacerbated by the high hydrostatic head within this span. It should be noted that, due to the limits of the testing apparatus, packer testing has an upper limit of 10^{-3} cm/s so it is possible that higher hydraulic conductivity values are present along the alignment. A further discussion of this risk, including impacts and potential mitigation techniques, are discussed in the white paper titled *Risk Mitigation for the Line 5 Replacement Tunnel*. (January 2021).

3.3 Design Challenges from Ground Conditions

Based on the Enbridge Summary Document and supplemented by the subsurface investigation, the Line 5 Replacement Tunnel alignment is anticipated to be excavated entirely within bedrock. However, due to the highly fractured and poorly cemented brecciated nature of the rock based upon core recovery and RQD data, it is possible that the ground behavior will be very poor, especially in the zone of lowest rock cover. However, as discussed above, there is a lack of boring information at tunnel depth within the roughly middle half of the project.

There is a historic precedent of highly fractured rock conditions in the limestone of the region, which was further confirmed by the presence of brecciated rock in the boring logs. Figure 5 projects the location of voids due to poor core recovery, identified on borehole logs, onto the anticipated tunnel alignment. The numerical values next to the red X represent the length of the zones in the boring logs either labeled as a void or with 0% recovery.

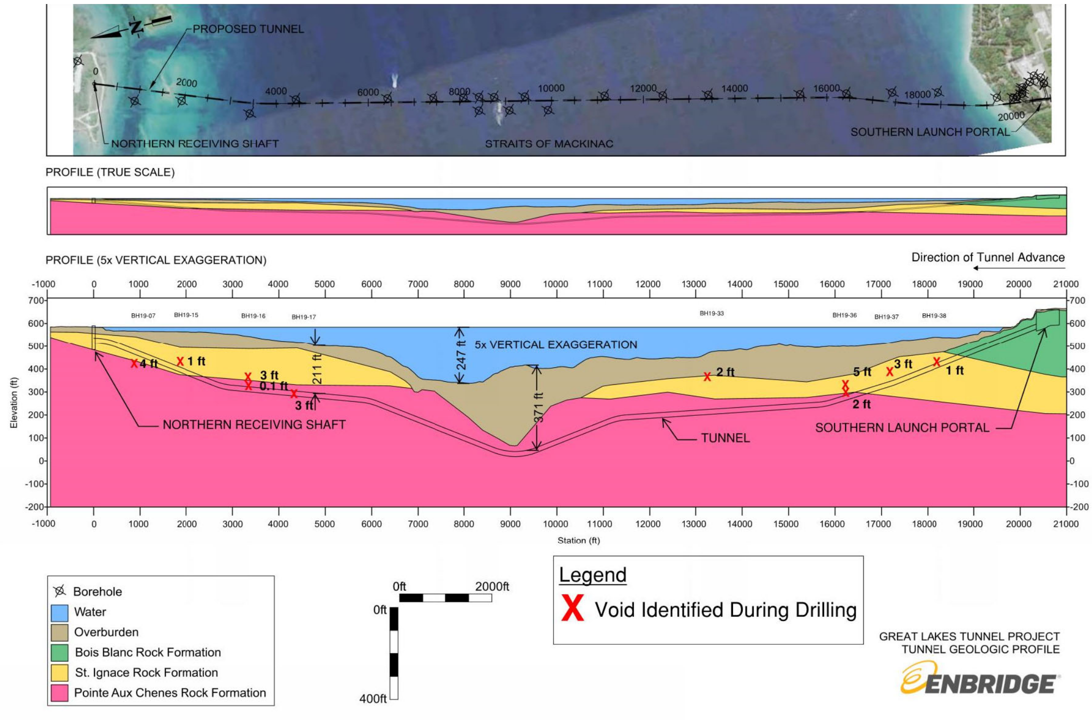

Figure 5: Hydraulic Conductivity along proposed alignment

Figure 5 above notes 10 instances of “voids” due to poor core recovery identified during drilling, however it is likely that more of these conditions exist in the spans between borings. Also, it should be noted that most of the brecciated rock exist within the St Ignace formation, however there were some zones discovered in strata identified as Pointe Aux Chenes. When tunneling, it is important to either mitigate conditions by use of a fully pressurized TBM, or to identify and mitigate these areas. Failure to control inflows during open interventions can result in unmanageable groundwater inflows, slower advance rates, and ground loss which, in the worst cases, can significantly impact progress and overall water inflows into the tunnel. The white paper titled: *Collapse Potential for the Line 5 Replacement Tunnel* (January 2021) offers a more detailed discussion of the design challenges associated with brecciated or open seam fractured rock conditions.

A second challenge is the lack of available borings to sufficiently characterize the ground conditions at tunnel depth. As described above, a significant span of the tunnel alignment does not have any borings that reach proposed tunnel depth. In the tunneling industry, subsurface investigation borings typically extend beyond the proposed invert elevation. While it is possible to excavate a tunnel at depths below the bottom of borings, significant emphasis must be placed on either excavation techniques that control ground and groundwater at the tunnel heading (such as pressurized face TBMs), and/or probing ahead of the TBM to assess the upcoming rock conditions before excavating. Conditions such as undetected sections of highly fractured and highly weathered rock can cause ground loss and groundwater inflows if not properly treated, resulting in delays in progress. The white paper titled *Risk Mitigation in the Line 5 Replacement Tunnel (January 2021)* offers a further discussion of the challenges associated with tunneling without a comprehensive investigation.

4.0 References and Additional Information

Deere,D. U. and Deere D.W, “The Rock Quality Designation (RQD) Index in Practice,” Rock Classification Systems for Engineering Purposes, ASTM STP 984, Louis Kirkaldie, Ed., American Society for testing and Materials, Philadelphia, 1988, pp 91 - 101

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