Packer permeability testing in deep inclined boreholes – feasibility study for Subsea Tunnel, Nalcor Energy Strait of Belle Isle Program, Newfoundland and Labrador

Sterling Parsons & Lorne Boone
Stantec Consulting Ltd., St. John's, Newfoundland and Labrador, Canada
Mark Peddle
Nalcor Energy, St. John's, Newfoundland and Labrador, Canada
Ágúst Guðmundsson
Jarðfræðistofan GEOICE Geological Services, Reykjavik, Iceland

ABSTRACT
This paper presents the details and results of packer permeability testing performed in five deep inclined onshore boreholes. The field investigation was part of the Nalcor Energy's Lower Churchill Project to assess the feasibility of constructing a subsea tunnel for the transmission of power cables across the Strait of Belle Isle. Over 200 packer permeability tests were carried out using several different equipment arrangements to assess the in-situ permeability of the geological formations. As part of the permeability testing, moderately high test pressures were used during packer testing in an attempt to initiate hydrojacking. This paper provides an overview of the test methodology, packer test equipment and results of packer testing. Interpretation of the data is discussed with consideration of the test methods and equipment used.

RÉSUMÉ
Cet article présente les détails et les résultats d'essais de perméabilité exécutés avec un packer dans cinq trous de forage obliques profonds sure le rivage. Les observations sur le terrain ont été exécutées dans le cadre du projet de la partie inférieure du fleuve Churchill de Nalcor Energy pour évaluer la faisabilité de la construction d'un tunnel sous-marins pour la transmission de lignes de transport d'interconnexion qui traverseront le Détroit de Belle Isle. Au-dessus de 200 essais de perméabilité ont été réalisés avec un packer utilisant plusieurs aménagements de matériels différents pour évaluer la perméabilité de formations géologiques in situ. Dans le cadre des essais de perméabilité, des essais à haute pression ont été utilisés dans un effort d'initier l'hydrojacking. Cet article fournit une vue d'ensemble des méthodologies de l'essai, les matériels et les résultats d'essais de perméabilité exécutés avec un packer. L'interprétation des données en est discutée avec une considération de la méthodologie d'essai et les matériels utilisés.

1 INTRODUCTION

The Churchill River in Labrador is a significant source of renewable, clean electrical energy; however, the potential of this river has yet to be fully developed. The existing 5,428 MW Churchill Falls generating station, which began producing power in 1971, harnesses about 65 per cent of the potential generating capacity of the river. The remaining 35 per cent is located at two sites on the lower Churchill River, known as the Lower Churchill Project (LCP). The Lower Churchill Project, one of Nalcor Energy's five lines of business, is the most attractive undeveloped hydroelectric project in North America.

The Strait of Belle Isle (SOBI) (refer to Figure 1) which divides Labrador and Newfoundland must be crossed with subsea power cables to transmit the electricity to the island of Newfoundland. The SOBI is 17.5 km across at its narrowest point and has a combination of risk scenarios that necessitates further investigation prior to project commencement. The Strait is fraught with sea ice and icebergs for part of the year, high currents, difficult bathymetry, harsh weather conditions and significant geotechnical uncertainty.

Figure 1: Map of the Strait of Belle Isle Indicating Drilling Locations (SNC-Lavalin, 2010a)

To further develop this project, Nalcor conducted studies for two potential crossing scenarios with one being the seabed submarine installation option, and the other being the option to tunnel underneath the Strait of Belle Isle. This paper describes the packer permeability testing that was carried out as part of the feasibility assessment of the subsea tunnel option. Also the paper provides comments on the observed advantages of hydraulic versus mechanical packers based on the bedrock conditions encountered.

1.1 Field Investigations Program

In 2009 Nalcor Energy, Lower Churchill Project (NE-LCP) initiated geotechnical investigations of geological structures in the Strait of Belle Isle (SOBI) area, in the Province of Newfoundland and Labrador, Canada. The investigations consisted primarily of a land based, near-shore diamond core-drilling program, as summarized in Table 1: Borehole Details.

Table1: Borehole Details

Borehole No.	Borehole Location	Borehole Length (m)	Average Inclination (degrees from horiz.) [range]
NF-01	Savage Cove	71	~ 30
NF-01B	Savage Cove	890	31 [24-34]
NF-02	Shoal Cove	955	29 [23-32]
NF-03	Lower Cove	146	44 [42-45]
LAB-01	Fox Cove	540	32 [25-34]
LAB-02	Point Amour	170	76 [76-77]

The investigations work was part of an overall program of geophysical investigations in the SOBI area being carried out by NE-LCP. The information obtained from the investigations would be utilized in the ongoing engineering studies associated with the potential installation of power cables across the Strait.

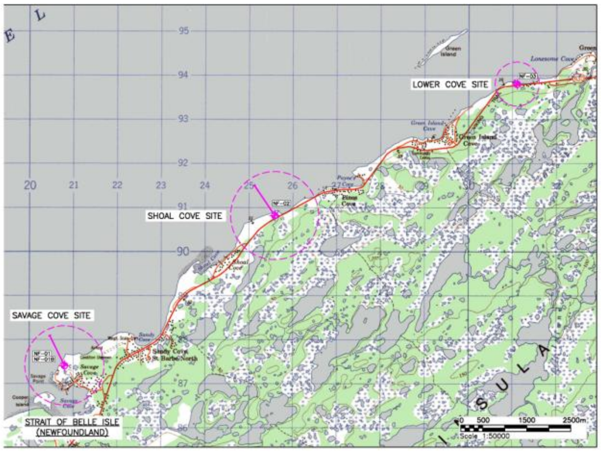

Figure 2: Borehole Locations on Newfoundland Side of Strait (SNC-Lavalin, 2010a)

The borehole program consisted of core retrieval, detailed core logging, packer testing, water sampling, downhole camera logging (visual and acoustical) and a limited program of field laboratory testing. Detailed borehole locations are shown in Figures 2 and 3.

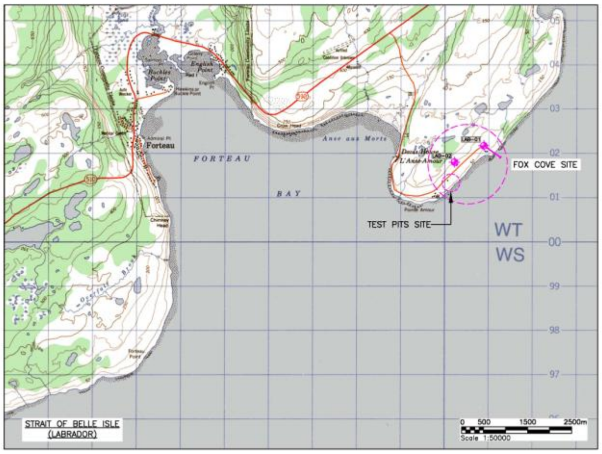

Figure 3: Borehole and Test Pit Locations on Labrador Side of Strait (Note: Test pits as shown were carried out as part of the drill rig location process) (SNC-Lavalin, 2010a)

The drilling program was intended to provide a description / understanding of the near shore lithology including permeability, composition, stratigraphy, identification/confirmation of potential near shore faults, the determination of the natural stresses within the local rock mass, as well as a determination of the global tectonic rock stress regime (compression vs. tension state).

The seabed option has since been chosen as the preferred method of crossing the Strait of Belle Isle.

1.2 Core Logging

The field program carried out consisted of detailed geotechnical core logging to collect data for the Q-method of rock mass classification. The Q–Method was used because it is a system for the classification of rock masses with regards to stability in tunnels and caverns (Barton et. al. 1974).

The Q-method is defined by 6 parameters, whereby a Q-value can be calculated for any rock mass according to the following formula:

$$Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF} \qquad [1]$$

The six parameters are:

- RQD = Rock Quality Designation
- J_n = Joint set number
- J_r = Joint roughness number
- J_a = Joint alteration number

- J_w = Joint water reduction factor
- *SRF* = Stress Reduction Factor

These parameters can be determined by engineering geological field mapping, mapping in tunnels or from drill cores. A high Q-value means good stability, whereas low values indicate poor stability.

A determination of the joint water reduction factor (J_w) is based on water leakage into the cavern. In general, the determination of J_w before a tunnel or cavern has been excavated can be difficult. However, permeability measurements in boreholes can provide useful information for design criteria. (NGI, 1997)

2 REGIONAL GEOLOGY

The boreholes completed for the Strait of Belle Isle investigation record the geological development of a continental margin from the basement Precambrian gneisses and granitic rocks of the North American Craton, to the younger Precambrian and Palaeozoic aged sedimentary rocks. The sedimentary rocks are dominated by sandstones of the Bradore Formation which unconformably overlie the basement rocks. This unit is believed to represent a deltaic to shallow marine environment. The Bradore Formation is overlain by a transgressive (advance of the sea over land areas) sequence of shale and limestone strata of the Forteau Formation which are indicative of quieter marine and near shore deposition. The Forteau Formation is in turn overlain by a regressive (contraction of the sea from land areas) sequence of primarily quartzitic marine sandstones of the Hawke Bay Formation. These sedimentary rocks are contained within the Labrador Group. Another sequence of sedimentary rocks comprising the Port au Port Group in turn overlies the Labrador Group. These rocks represent biogenic sedimentation in a shallow marine environment and are represented by dolomitic limestones of the March Point Formation. The upper most rocks exposed in the investigation area consist of primarily limestones and dolostones and shale of the Petit Jardin Formation. These overlie the March Point and represent shallow water marine to tidally influenced sedimentation (Knight, 1977). The stratigraphy beneath the Strait of Belle Isle is illustrated in Figure 9: Geological Cross-Section Beneath SOBI.

3 METHOD OF INVESTIGATION

3.1 Drilling Operations

A total of six boreholes were completed using three drill rigs during the field campaign. The summarized borehole details are presented in Table 1. Borehole NF-01 was abandoned at 71 m depth due to the drill string becoming stuck within a highly fractured zone. Borehole NF-01B was relocated approximately 44 metres west-southwest of NF-01. The total meterage drilled during the field program was 2772 m, including NF-01.

Each of the drill rigs included a fully-equipped unitized drill and large exterior water storage tank (approx. 5 m^3) used specifically for packer testing. Core drilling was completed using an NQ-3 core barrel fitted with a core orientation tool. NW size casing was advanced below grade into competent bedrock at depths between 3 and 9 m and was grouted in place.

Grouting of the borehole was carried out a number of times within the top 100 meters of bedrock in the boreholes. Grouting was carried out to maintain the integrity of the borehole walls through severely fractured zones, and to ensure an adequate volume of drill water return was maintained as the borehole was advanced. Drill water return was especially important for the inclined boreholes as the use of rod grease was restricted because of environmental concerns.

Single packer testing was completed as the boreholes were advanced. Straddle (double) packer testing was not completed during the field program. Measurements of borehole orientation (azimuth and inclination) were taken at regular intervals as drilling progressed and upon completion of the boreholes. Downhole geophysical logging was undertaken after drilling was completed.

As the field program progressed, a number of modifications were made to both the drill rig tooling as well as to the testing and sampling equipment.

3.2 Packer Testing Equipment

Two different types of packer systems were used for permeability testing, these included hydraulic packers and mechanical packers. The hydraulic packers consisted of an NQ size wireline packer assembly manufactured by Inflatable Packers International Limited (IPI). Hydraulic packers were selected over pneumatic packer systems because the hydraulic packer does not require the use of inflation lines or compressed gas at high pressures. A manufacturer supplied flowmeter was used which was capable of testing at pressures of 6890 kPa (1000 psi) and flows of 0.02 to 100 L/min.

Due to the inclination of the boreholes, it was at times challenging to properly install and retrieve the hydraulic packer. As a result, several techniques and equipment were utilized, this included the use of a specialized self-unlatching wireline overshot.

An NQ mechanical packer manufactured by Temiskaming Industrial Mining Equipment Limited (TIME) was used to carry out permeability testing primarily in zones of high permeability, but was also used in zones of low permeability. The packer consisted of a series of four to eight rubber sleeves that were expanded by the weight of the rods, or if necessary, by additional force from the drill. This packer was selected because of its simplicity and its ability to handle flows greater than 300 L/min. Two flow meters manufactured by Omega (700 series) were used as part of the mechanical packer flowmeter assembly, which included a 3.8 to 37.9 L/min flowmeter and a 38 to 380 L/min flowmeter. All flowmeters were calibrated prior to use.

Packer testing was completed utilizing two types of pumps. In zones of low to moderate leakage the drill rig's pump often provided sufficient water volume and pressure. Depending on the rig, the drill rig's pumps achieved maximum flows ranging from approximately 50 to 100 L/min. Two high capacity flow pumps were also available for testing in zones of high permeability. The pumps achieved maximum flows during testing of approximately 380 L/min at a pressure of 90 kPa (13 psi) to 230 L/min at a pressure of 3100 kPa (450 psi).

3.3 Equipment Calibrations

Prior to the start of drilling at each borehole location, a calibration test was carried out for each packer assembly to quantify the amount of friction pressure losses created through the flowmeter and the packer assembly. Results of a calibration test completed for the mechanical packer for borehole LAB-01 are illustrated on Figure 4.

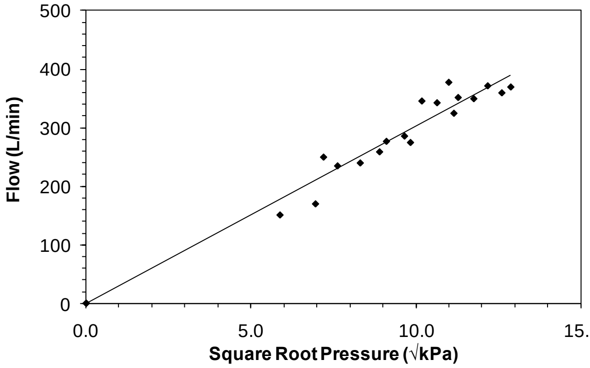

Figure 4: Mechanical Packer Calibration for LAB-01 (SNC-Lavalin, 2010b)

In addition, the calibration acted as a surface test to verify correct packer operation and to identify problems due to hydraulic packer inflation, water injection and/or any visible leaks. It was assumed that friction losses from the drill rods were negligible.

4 PACKER TESTING PROCEDURE

The packer testing program was completed in consultation with Nalcor's tunnelling consultant from Jarðfræðistofan GEOICE Geological Services. In preparation for testing drill water was circulated to flush the hole. The equipment type used for testing was selected based upon the test flows anticipated from the wash water return during drilling or partial constant head tests. In general, test section lengths varied from 3 to 70 m, depending on the anticipated bedrock permeability.

Following the expansion of either the hydraulic or mechanical packers, leakage was checked to ensure that water was not passing by the packer, between the expanded gland/rubber and the drillhole wall. No provision was made for monitoring test section pressures directly.

Water injection (packer testing) was carried out based on the following procedure:

- In general, "step pressure" testing was stepped up at 20%, 40%, 60%, 80% and 100% of the maximum test pressure which often caused widening of pre-existing fractures (hydrojacking) or the maximum pressure limit of the equipment.
- Following the 100% interval, the pressures were stepped down at 60% and 20% to assess for hysteresis. If the stepped down pressures did not follow the same path as the stepped up pressures then testing continued by stepping up at 60% and 100%. Depending on formation flow conditions the procedure varied between tests.
- In some cases where high flows and/or back pressures were anticipated, testing followed a cyclical methodology whereby the test pressures were stepped-up for example: 20%, 40%, 60%, 40%, 60%, 80%, 60%, 80% and 100% of the maximum pressures.

In addition to assessing the bedrock permeability and hydrojacking pressures, the testing procedure was intended to assess the storage capacity, the hysteresis sealing, and overall response of the rock mass.

Depending on the age or condition of the drill rods, water leakage can occur at the joints threads. An accounting of the amount of leakage is preferred for an accurate determination of bedrock formation permeability. In order to reduce the leakage at the drill rod connections, each connection was "wicked" using burlap materials. Drill rod leakage could not be estimated using the mechanical packer but could be roughly estimated by comparing the number rods and the measured leakage from the hydraulic packer. For a determination of leakage with depth and test pressure, a correction chart was plotted using the hydraulic packer. An illustration is presented in Figure 5.

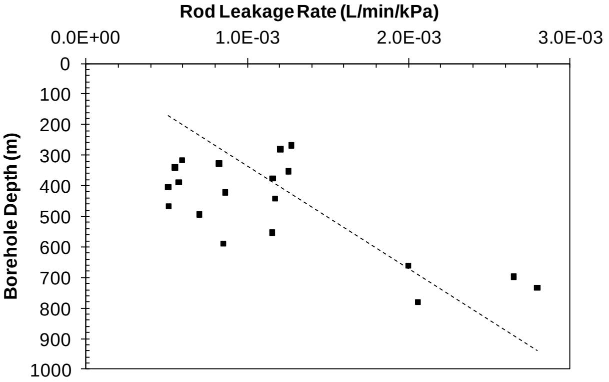

Figure 5: Estimated Rod Leakage from Hydraulic Packer (SNC-Lavalin, 2010b)

5 PACKER TESTING

5.1 Method of Analysis

Considering the type of equipment used, the length of the test sections and the approximation of the field data, a simple method of analysis was carried out. Based on Cedergren (1989), bedrock permeability can be calculated using the following formulas:

$$K = \frac{Q_{avg}\gamma_w}{2\pi L P_{net}} \ln\frac{L}{r_b}, L \geq 10r_b \qquad [2]$$

Where, K is the hydraulic conductivity, Q_{avg} is the geometric mean of the corrected measured flows, P_{net} is net pressure applied, L is the length of the test section, r_b is the radius of the borehole, and γ_w is the unit weight of water. P_{net} can be expressed as:

$$P_{net} = P_g + (H_g + D_w')\gamma_w - P_f \qquad [3]$$

In Eq. 3, P_g is the gauge pressure, H_g is the height of the pressure gauge above the ground surface, D_w' is the vertical depth to the groundwater level, and P_f is the frictional pressure loss. P_f can be expressed as the following:

$$P_f = (fQ_{avg})^2 \qquad [4]$$

Where f is a friction factor determined by calibration for each individual packer setup.

5.2 Packer Test Results

Packer permeability tests completed for the SOBI project resulted in hydraulic conductivities in the range of practically zero (no measureable flow) to 5.1×10^{-5} m/s, as summarized in Table 2. Testing was carried out in deep inclined boreholes up to approximately 925 m length (452 m depth).

Table 2: Summary of Packer Testing Results (SNC-Lavalin, 2010a)

BH#	No. Tests	Depth Range of Testing (m)	Range of K (m/s)
NF-01	10	17.0 – 71.2	NMF - 6.1×10^{-6}
NF-01B	52	6.5 – 889.9	NMF – 6.4×10^{-6}
NF-02	64	10.3 – 925.4	NMF – 2.1×10^{-5}
NF-03	20	8.5 – 146.1	5.6×10^{-8} – 4.2×10^{-6}
LAB-01	38	10.3 – 540.1	5.5×10^{-9} – 5.1×10^{-5}
LAB-02	17	3.1 – 170.2	5.3×10^{-9} – 1.8×10^{-5}

Note: NMF indicates no measureable flow. Due to the equipment and apparatus used, formations with very low permeability's could not be accurately measured.

Due to the limitations of the equipment used and the method in which test pressures were estimated, the permeability was lower than was practically measurable at some test sections. In such instances, it was stated that no measureable flow was recorded.

Permeability test results are generally interpreted from a plot of flow against pressure (PQ plot). Figure 6 presents the results of permeability testing at LAB-01 from 242.5 m to 264.0 m.

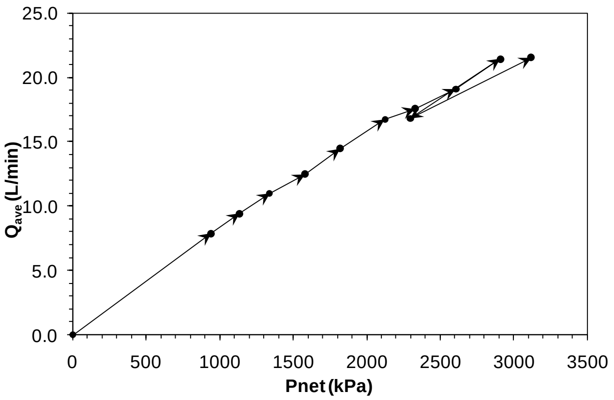

Figure 6: Test results from LAB-01 from 242.5 to 264.0 m. (SNC-Lavalin, 2010b)

The vertical depth to the center of the test interval is 134.3 m below the ground surface. All packer tests results were corrected for the varying inclination of the borehole. The curve in Figure 6 demonstrates linear relationship, where flow is laminar travelling probably through clean fractures.

From the shape of the curve, a determination of fracture behaviour may be gained where flow can become non-linear. This increase in permeability indicates fracture opening due to excess pressure. This increase opening of the fractures during testing may be an indication of the onset of hydrojacking. (Hartmaier et al., 1998).

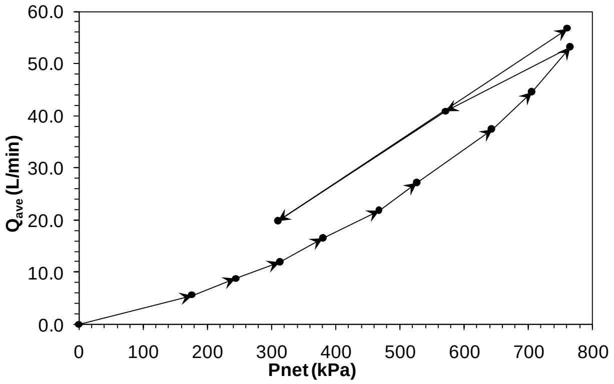

Figure 7: Test results from NF-03 from 26.1 to 32.5 m. (SNC-Lavalin, 2010b)

Figure 7 presents the results of permeability testing at NF-03 from 26.1 m to 32.5 m. The vertical depth to the center of the test interval is 20.3 m below the ground surface. The curve in Figure 7 demonstrates a slight increase in permeability with increased pressure, as the recovery curve shows a permanent increase permeability within the formation. (Evans and Meier, 1995).

As part of the packer testing program, hydrojacking or hydraulic jacking was carried out at various test interval locations up to 300 m vertical depth in the boreholes. This data was gathered for future consideration by others, but was not part of the geotechnical scope of work. This depth was considered a maximum depth for the construction of potential tunnels. Moderately high test pressures (based on limits of the equipment used) were applied in an attempt to open the existing joints of the formation or cause fracture widening.

The pressures applied during the permeability tests were mainly focused on applying pressures which could be expected in a tunnel (possible hydrostatic pressure near open water bearing joints). As the tunnel elevation (depth) was not decided, some test pressures may seem high.

When considering the design of a tunnel, the primary criterion when assessing the requirements for a tunnel liner is whether the hydrostatic head at the depth of the tunnel is less than the minimum principal stress in the rock mass surrounding the tunnel. Under this condition no liner is required. If the hydrostatic head is greater than the minimum principal stress, a steel liner is required to isolate the pressurized tunnel water from the surrounding rock. (Hartmaier et al., 1998)

Figure 8 below shows a PQ plot which demonstrates the pressure dependency. At low pressure, a linear trend is seen depending upon whether flow is laminar or turbulent. Hydrojacking occurs when the water pressure in the joint begins to exceed the normal stress across the joint, causing the joint to dilate. Figure 8 presents the results at NF-01B from 189.0 to 199.3 m depth in the borehole. The plot demonstrates the non-linear increase of flow with minimal increase of pressure. The vertical depth to the center of the test interval is 103.0 m below the ground surface. As a result, the effective overburden stress at the middle of the test section is approximately 1670 kPa, which is roughly corresponds at the point on non-linearity PQ response during the test.

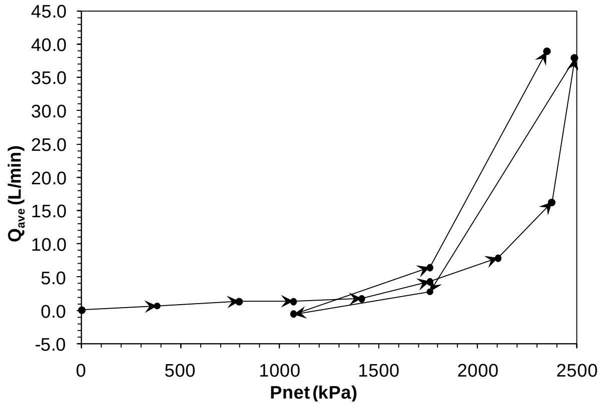

Table 3: Summary of Packer Permeability Results by Formation (SNC-Lavalin, 2010a)

Formation	RQD	Q-Value Range	Lugeons	K_{avg} (m/s)
Petit Jardin	Very poor to excellent	0 - 75	2.8 - 160.7 (avg 19.2)	3.5x10^{-7} - 2.1x10^{-5} (avg 2.6x10^{-6})
March Point	Very poor to excellent	0 - 150	0.9 - 179.8 (avg 25.1)	2.1x10^{-5} - 1.3x10^{-7} (avg 3.3x10^{-6})
Hawke Bay	Very poor to excellent	0 - 100	NMF - 26.7 (avg. <3.8)	NMF - 3.8x10^{-6} (avg. <5.6x10^{-7})
Forteau (NFLD coast)	Dolomite: good to excellent, Shale: Poor to fair	0 - 100	NMF - 0.1 (avg. <0.04)	NMF - 2.4x10^{-8} (avg. <7.7x10^{-9})
Forteau (LAB coast)	Very poor to excellent	0 - 40	0.04 - 65.4 (avg. 15.9)	5.6x10^{-9} – 9.0x10^{-6} (avg. 2.3x10^{-6})
Bradore (NFLD coast)	Fair to excellent	0 - 200	NMF - 1.9 (avg. <0.4)	NMF - 3.5x10^{-7} (avg. <7.2x10^{-8})
Bradore (LAB coast)	Very poor to excellent	0 -145	0.03 - 444.5 (avg. 33.2)	5.33x10^{-9} - 5.05x10^{-5} (avg. 3.98x10^{-6})
Basement (NFLD coast)	Fair to excellent	< 5 - 30	No Data	No Data
Basement (LAB coast)	Poor to excellent	0 - 200	0.03 - 1.5 (avg. 0.5)	5.48x10^{-9} - 2.63x10^{-7} (avg. 9.32x10^{-8})

Note:

- NMF indicates no measureable flow. Due to the equipment and apparatus used, formations with very low permeability's could not be accurately measured.
- Average lugeons and K_{avg} calculated using measured permeability's. Tests with NMF were not included in calculation.

6 DISCUSSION OF RESULTS

The near surface bedrock consisting of limestones, dolostones and shales of the Petit Jardin Formation, and dolomitic limestones of the March Point Formation on the NL side of SOBI and the shale and limestones units of the Forteau Formation on the Labrador side of SOBI, generally exhibit the highest degree of fracturing and measured permeability's. The shallowest portions of the Bradore Formation sandstones also displayed this general correlation. In general, the highest permeability's and fracturing was limited to the upper 25 m to 50 m depth.

The degree of fracturing represented by both the RQD and Q-values (which includes RQD as one of its terms) generally confirmed that higher Q-values, which corresponds to better quality bedrock, typically demonstrated lower permeability values. On the other hand, lower Q-values, which correspond to lower quality bedrock, typically demonstrated higher permeability values. A broad overview of the results is presented in Table 3 above.

7 CONCLUSIONS

Packer testing was carried out as part of the Nalcor Energy's Lower Churchill Project to assess the feasibility of constructing a subsea tunnel for the transmission of power cables across the Strait of Belle Isle. The information obtained from the investigation will be used for ongoing engineering studies associated with the potential installation of power cables across the Strait and will assist Nalcor Energy in selecting the preferred option for crossing the Strait of Belle Isle. At this point in time, the seabed option has been chosen as the preferred method for crossing the Strait of Belle Isle. Some key conclusions during this investigation are stated below.

The use of hydraulic and mechanical packer systems has resulted in the determination of hydraulic conductivities within rock formations by way of deep inclined boreholes. In general, the permeability of the deeper bedrock units were several orders of magnitude smaller than the near surface bedrock units. The hydraulic conductivities recorded generally show good correlation to the degree of fracturing or rock mass quality as obtained using the Q-method. More specifically, the bedrock formation strata at shallow depths generally yielded a higher degree of fracturing (lower Q-values) and higher permeability values. The bedrock formation strata at deeper depths generally yielded a lower degree of fracturing (higher Q-values) and lower permeability values.

The investigation confirmed that the use of both types of testing systems, presented individual advantages for an effective packer testing program. Some of the advantages include:

- In formations where permeability was high, use of the mechanical packer allowed the measurement of permeability without significant frictional losses. In general, the pumps were the limiting factor during high flow testing.
- The mechanical packer was simple to use.
- At shallow depths, the mechanical packer was relatively efficient with respect to installation time.
- In zones of low to moderate flow, the hydraulic packer proved to be a time efficient tool,
- At deep depths, the hydraulic packer was more efficient.

Some observed challenges of using the hydraulic and mechanical packers included:

- Due to borehole inclination, it was at times challenging to install/retrieve the hydraulic packer.
- The rubber sleeves of the mechanical packer were occasionally damaged from the exposed borehole wall.
- At deep depths, the use of the mechanical packer becomes time and cost prohibitive.

Based on field observations, the following improvements may be considered for future work:

- The use of H-size hydraulic packer may have helped reduce difficulties of packer installation and retrieval.
- The use of a downhole pressure transducer would have assisted installation troubleshooting.
- The drill rigs should be fitted with tower stands to remove drill rods for more efficient handling.
- The constraints of the equipment limited the maximum pressures that could be used, which limited the ability to achieve hydrojacking at deeper depths.

ACKNOWLEDGEMENTS

The writers would like to express thanks to Nalcor Energy for permission to publish this paper. Stantec also thanks SNC Lavalin for the opportunity to work together. The following individuals are also acknowledged for their input during the work and in preparation of this paper: Ian Knight, Geological Survey of NL; Mike Wawrzkow, SNC Lavalin; Dr. Arun Valsangkar, Stantec Consulting Ltd.

REFERENCES

Barton, N.R., Lien, R. and Lunde, J. 1974. Engineering Classification of Rock Masses for the Design of Tunnel Support. *Rock Mechanics*, 6: 189-239.

Cedergren, H.R. 1989. *Seepage, Drainage, and Flow Nets*. 3rd Ed. John Wiley & Sons, New York, NY, USA

Evans, K. and Meier, P. 1995. Hydrojacking and Hydrofracturing Tests in a Fissile Schist in South-West Switzerland: In-situ Stress Characterisation in Difficult Rock. *Proceedings from the 2nd International Conference on the Mechanics of Jointed and Faulted Rock*. Ed, H.P. Rossmanith, Vienna, April, 1995.

Hartmaier, H.H., Doe, T.W. and Dixon, G. 1998. Evaluation of Hydrojacking Tests for an Unlined Pressure Tunnel. *Tunneling and Underground Space Technology*, 13 (4): 393-401.

Jarðfræðistofan GEOICE Geological Services. 2010. Strait of Belle Isle Cable Crossing. Report prepared for Nalcor Energy. Report Document No. JFS - 80.

Knight, I. 1977. *The Cambrian-Ordovician Platformal Rocks of the Northern Peninsula*. Newfoundland Department of Mines and Energy Mineral Development Division. Report 77-6.

Norwegian Geotechnical Institute. 1997. *Engineering Geology, Practical Use of the Q-Method*.

SNC-Lavalin Ltd. 2010a. Strait of Belle Isle 2009 Geotechnical Program: Volume 1 – General Report and Drawings. Report prepared for Nalcor Energy. Report Document No. 723174-0000-30AG-0001-00.

SNC-Lavalin Ltd. 2010b. Strait of Belle Isle 2009 Geotechnical Program: Volume 2 – Borehole Data. Report prepared for Nalcor Energy. Report Document No. 723174-0000-30AG-0001-00.

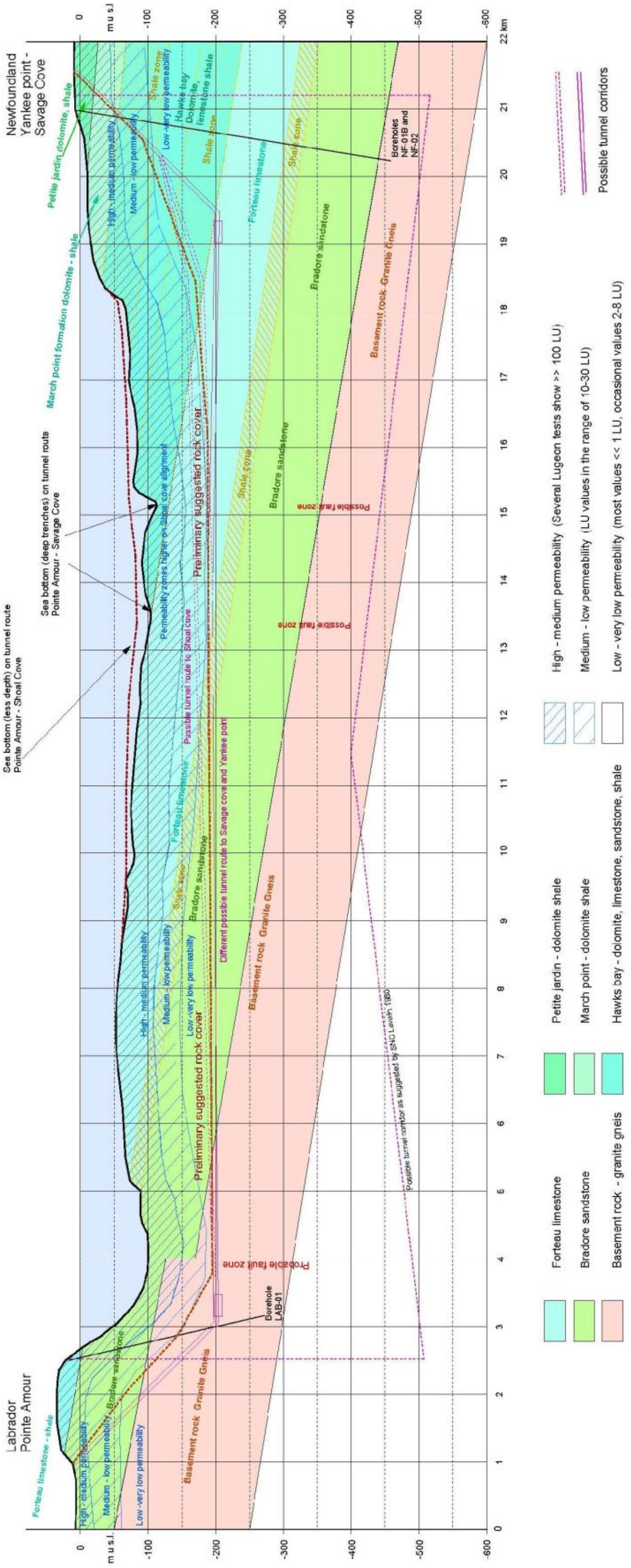

Figure 9: Geological Cross-Section Beneath SOBI (Jarðfræðistofan GEOICE, 2010)