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Geotechnical Assessment of the 1930s Jacques Cartier Bridge

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ABSTRACT

As part of the seismic performance assessment of the Jacques Cartier Bridge in the Montréal region in Québec, a detailed geotechnical investigation was carried out. The bridge represents a lifeline bridge as defined in CAN/CSA-S6-14 and is an important transportation link between the Island of Montreal and the South Shore of the St. Lawrence River with a total span of more than 3 km. The bridge is supported on a range of different foundation types, including large piers supported directly on bedrock, large piers supported on over 140 wood piles, small piers supported directly on soils and small piers supported directly on wood piles. The bridge is supported on 60 piers and 2 abutments covering range of spans from about 30 m to 332 m and includes île Sainte-Hélène Pavilion structure within its overall length. The ground conditions cover a wide range of bedrock types, from breccia intrusions to shale sedimentary rock, and soils ranging from silty clay to loose sands to dense glacial tills. Deep fills were also present in several locations, resulting from the original bridge pier work to the construction of the St. Lawrence Seaway. The field investigation included eight traditional boreholes with standard penetration tests (SPTs), six downhole geophysics shear wave velocity profiles, and four cone penetration tests (CPTs). A series of five test pits were also excavated on the Montreal shore to expose and assess some of the wood piles dating back to the 1930s. The results of the field investigation were used to assess site response relative to seismic loading, the potential for seismic liquefaction of certain loose soil horizons, and to model the dynamic axial and lateral load capacity and stiffness for the multitude of foundation types present. This case study reveals several interesting aspects relative to the seismic performance of the structure from the potential for seismic liquefaction, the dynamic response of specific sections of the bridge to seismic loads, the lateral dynamic stiffness and capacity of the existing foundation systems. Recommendations for additional field investigations as part of the next phase of bridge assessment were also provided.

RÉSUMÉ

Dans le cadre de l'évaluation de la performance sismique du pont Jacques-Cartier dans la région de Montréal au Québec, une étude géotechnique détaillée a été réalisée. Le pont représente un pont essentiel tel que défini dans la norme CAN / CSA-S6-14 et constitue une ligne de transport important entre l'île de Montréal et la Rive-Sud du fleuve Saint-Laurent avec une portée totale de 3 km. Le pont est supporté par différents types de fondations, y compris les grands piliers déposés directement sur le substratum rocheux, les grands piliers soutenus sur plus de 140 pieux en bois, les petits piliers appuyés directement sur les sols et les petits piliers soutenus directement sur les piles de bois. Le pont est soutenu par 60 piliers et 2 culées couvrant une plage de travées d'environ 30 à 332 m et comprend la structure du pavillon de l'île Sainte-Hélène dans la longueur totale du pont. Les conditions du sol couvrent un large éventail de types de substratum rocheux, des intrusions de brèche aux roches sédimentaires schisteuses, et des sols allant de l'argile limoneuse aux sables meubles aux tills glaciaires denses. Des remblais profonds étaient également présents à plusieurs endroits, résultant des travaux de jetée du pont d'origine à la construction de la Voie maritime du fleuve Saint-Laurent. L'enquête sur le terrain a inclus huit forages traditionnels avec des tests de pénétration standard (SPT), six profils de vitesse de cisaillement géophysique en fond de trou et quatre tests de pénétration de cône (CPT). Une série de cinq fosses d'essai ont également été creusée sur la rive de Montréal afin d'exposer et d'évaluer certaines des piles de bois datant des années 1930. Les résultats de l'enquête sur le terrain ont été utilisés pour évaluer la réponse du site par rapport à la charge sismique et le potentiel de liquéfaction sismique de certains horizons de sol meuble, de même que pour modéliser la capacité de charge et la rigidité dynamiques axiales et latérales pour la multitude de types de fondation présents. Cette étude de cas révèle plusieurs aspects intéressants relatifs aux performances sismiques de la structure du potentiel de liquéfaction sismique, la réponse dynamique de sections spécifiques du pont aux charges sismiques, la rigidité dynamique latérale et la capacité des systèmes de fondation existants. Des recommandations concernant des enquêtes supplémentaires sur le terrain, dans le cadre de la prochaine phase d'évaluation des ponts, ont également été fournies
.

1 INTRODUCTION

The five-lane Jacques Cartier Bridge is one of the important bridges that connects the Montreal Island to its South Shore at the City of Longueuil. The bridge was opened to the traffic with only three lanes on May 14, 1930 under the name of the Harbour Bridge after the Harbour Commissioners of Montreal. Two more lanes were added afterwards between 1956 and 1959. The bridge has a total length abutment to abutment of 2,765 m and is divided into 9 sections: Section 1 to 6 make up the south approaches, Section 7 is the main span that crosses the St. Lawrence River and Section 8 to Section 9 form the north approaches. Although the bridge alignment is generally east to west, for the purposes of this paper, and to be consistent with local terminology, the western end will be referred to as the south end (south shore) and the eastern end will be referred to as the north end (Montreal shore).

The Jacques Cartier Bridge is a vital transportation link that was designed and constructed in 1920's. At that time, there were no seismic standards in force for the design of bridges. According to the definition in the Canadian Highway Bridge Design Code of 2014 (CSA group 2014), the bridge has been classified as a lifeline bridge which means that in the case of a seismic event, this bridge must allow for immediate service ensuring public safety. Furthermore, the bridge is located in a moderately-active seismic zone. Hence, to ensure the integrity of this crucial lifeline transportation link that will continue in service for many more years, The Jacques Cartier and Champlain Bridges Incorporated (JCCBI) deemed important to study the seismic performance of the bridge to better understand the seismic-related risks using a performance-based approach. As part of such studies, an analysis and evaluation of the seismic performance of the bridge was undertaken. This work also included the completion of geotechnical investigations to supplement the limited historic information and provide important input in assessing the bridge. Figure 1 shows an aerial view of the bridge as shown in Google Maps (2018).

Figure 1. Aerial view of the Jacques Cartier Bridge (Imagery captured from Google Maps 2018).

2 GEOLOGY AND SEISMIC ACTIVITY

2.1 Geology

The Jacques Cartier Bridge crosses three different rock formations (Énergie et Ressources naturelles Québec 2018):

1) The Nicolet Formation which consists of grey shale and mudstone interbedded with lithic sandstone, siltstone, calcarenite and dolarenite. This formation prevails the site occupied by the bridge.
2) Utica Shale which consists of dark brown to black calcareous shale, micritic clayey limestone; calcilutite interbeds scattered throughout the sequence. This formation is located towards the north approach of the bridge.
3) Monteregian Group which consists of alkaline rocks. This formation is found at two locations on Saint Helen's Island.

Figure 2 shows the regional geology at the site of the bridge as published on the interactive map by Le Système d'information géominière du Québec (http://sigeom.mines.gouv.qc.ca/). The three above-mentioned rock formations encountered at the site are shown on the Figure 2 below. On the same Figure 2, the dark line shows the Outremont Fault which crosses the site of the bridge near the north approaches.

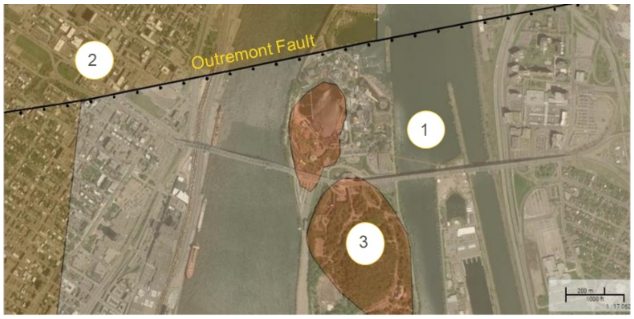

Figure 2. Regional Geology at the site of the bridge (modified after Énergie et Ressources naturelles Québec 2018).

It should be noted that the bridge crosses one of the most remarkable rocks in the vicinity of Montreal that is the breccia that underlies most of what is known nowadays as St. Helen's Island. Although breccias of many types occur in the Montreal area, the Breccia bedrock encountered beneath this island is by far the largest in area (Clark et al. 1967). It is noted that during the preparation for the 1967 Montreal World's Fair (Expo 67), the historical St. Helen's island was expanded to join another historical island, île Ronde, to form the current St. Helen's Island. The breccia occupying most of St. Helen's Island was originally considered to be sedimentary, later volcanic, and is now attributed to volcanic pipe (diatrem) action (Clark et al. 1967).

2.2 Seismic Conditions

The site of the bridge is located in the Western Quebec Seismic Zone (WQU), according to the Geological Survey of Canada (Natural Resources Canada 2019a). The WQU occupies an extremely large zone extending from Montreal to Timiskaming. Within the WQU, recent seismic activity has been concentrated in two subzones: one along the Ottawa River and another more active subzone along the Montreal-Maniwaki axis.

Historical seismicity inside the WQU includes three major events: (1) the 1732 earthquake that shook Montreal and caused significant damage. It had a maximum intensity on the Modified Mercalli Scale of IX (Natural Resources Canada 2019b); (2) the Temiscaming event of 1935 which had a magnitude, m_{bLg}, of 6.2-6.3 (M_w of 6.1) (Natural Resources Canada 2018a); and (3) the Cornwall-Massena event of 1944 which had a moment magnitude, M_W, of 5.8 (Natural Resources Canada 2018b).

3 BRIDGE FOUNDATIONS

The bridge is supported on 62 piers and abutments, numbered from 0 to 55 going from the south to north. The bridge foundations vary across the alignment as in type i.e. spread footings versus wooden pile foundations versus large gravity piers Table 1 provides a summary of the foundation types as can be deduced form the original construction drawings produced by the firm Monsarrat & Pratley and J. B. Strauss (1926 to 1930)

Table 1. Types of foundation along the bridge

Pier Number	Type of Foundation
0 to 14	Spread footing on rock (gravity piers)
15 to 16	Timber pile foundation
17 to 25	Spread footing on rock (gravity piers)
26 to 30	Spread footing on soil
31 to 36	Timber pile foundation
37 to 38	Spread footing on soil Timber pile foundation
39 to 43	Timber pile foundation
44	Spread footing on soil Timber pile foundation
45	Spread footing on soil
46 to 56	Timber pile foundation
57 to 58	Spread footing on soil Timber pile foundation
59 to 61	Spread footing on soil

Of note, the piers on timber pile foundations are also quite variable, with those on the Montreal shore (Piers 31 to 54), supported on typically less than 8 piles of less than 9 m in length (some are less than 2 m in length) supporting small shallow pile caps. Piers 15, 16 and 55 are large piers supported on about 124 to 144 wooden piles of about 6.7 to 11.3 metres in length. The large pile caps are at depths of over 14 m at piers 15 and 16.

4 SITE INVESTIGATION AND LAB TESTING

4.1 Site investigation

A geotechnical and geophysical investigation was carried out in order to fill certain gaps in the available geotechnical studies carried out between 1925 and 2016, for example (Monsarrat & Pratley et J. B. Strauss 1926, 1927, Labo SM Inc. 2015, SNC Lavalin 2016). The ground investigation program included drilling geotechnical boreholes, excavating test pits to inspect the timber piles, piezocone penetration profiles (CPT) and downhole seismic testing to plot vertical seismic profiles (VSP). Fieldwork was carried out between December 14, 2017 and March 6, 2018 in challenging seasonal conditions.

A total of eight (8) boreholes were drilled and cored into the soil and rock, five (5) test pits were excavated and four CPT profiles were completed.

Rock was cored for a total length varying between 3.0 m and 12.1 m.

Table 2 summarizes the field work carried out during current site investigation.

Table 2. Summary of Current Ground Investigation

Pier Number	Type	Total Depth (m)
9	Borehole & VSP	19.5
16	Borehole & VSP	41.1
	CPT	8.8
18	Borehole & VSP	15.5
22	Borehole & VSP	21.6
29	Borehole	23.9
33	Test Pit	3.5
	CPT	14.1
37	Test Pit	3.4
39	Borehole & VSP	33.2
43	Test Pit	3.5 &
	CPT	11.1
46	Borehole	18.0
48	Test Pit	3.1
49	CPT	10.6
55	Borehole & VSP	14.9
	Test Pit	1.90

4.2 Laboratory testing program

The laboratory testing program comprised carrying out grain size distribution (GSD) analysis by means of sieve and hydrometer analyses, determination of natural water content, Atterberg limits, organic matter content on soil samples, and unconfined compression strength (UCS) test on rock samples.

5 SUMMARY OF THE SUBSURFACE CONDITIONS

5.1 General

In all the eight boreholes, fill layers and native deposits were encountered, and the bedrock was cored to different depths.

In the sections below, a brief description of the encountered fill layer, native deposits and bedrock are discussed. Figures 3 and 4 show a simplified crosssections connecting boreholes drilled and cored during the current investigation and from previous studies at Longueuil and St. Helen's Island, and Montreal Island, respectively.

5.2 Overburden Soil

An overburden soil was encountered in all drilled boreholes. A fill layer of variable thickness is generally encountered as the top layer whose thickness varies from one pier to another, but it is between 1.4 m and 11.4 m. Below this top layer of fill, native soil, concrete or bedrock have been encountered.

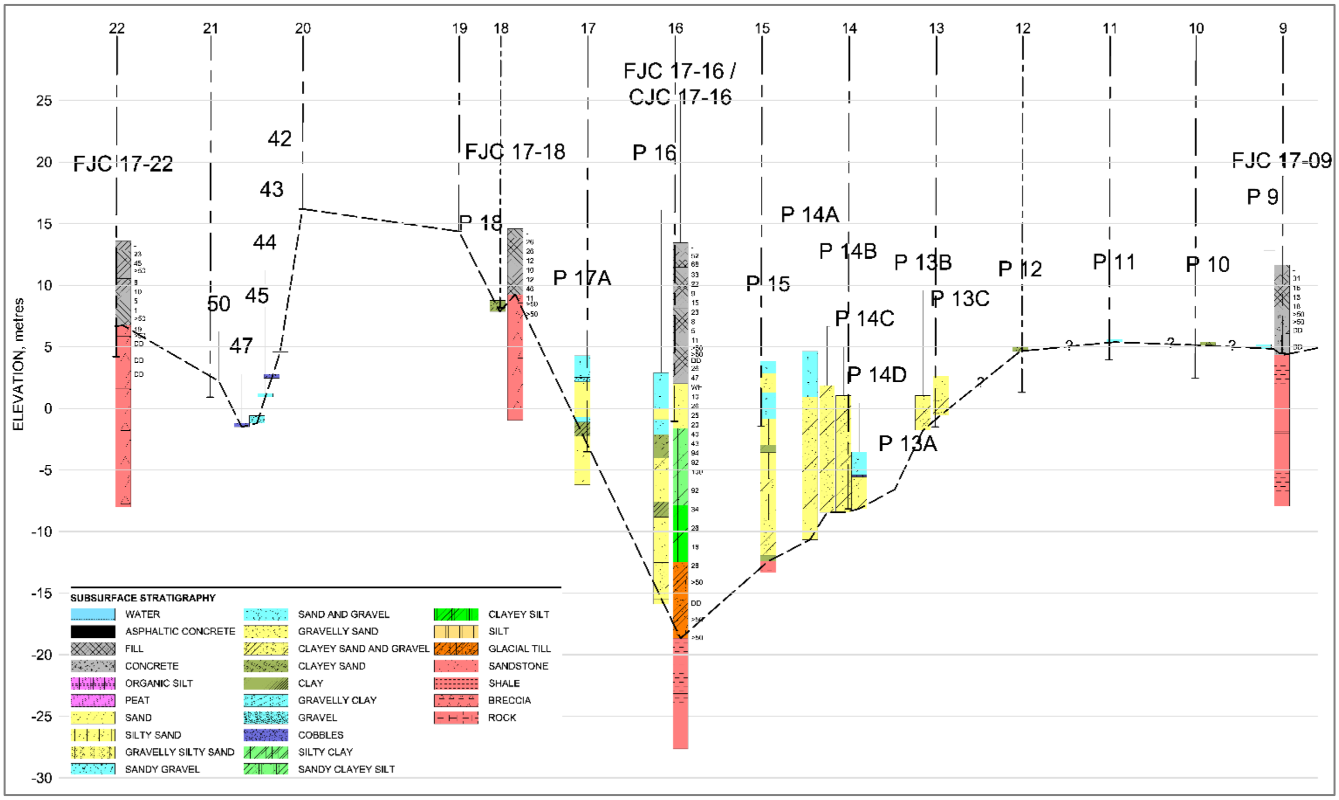

Figure 3. Cross-Section from piers 9 to 22 between Longueuil and St. Helen's island.

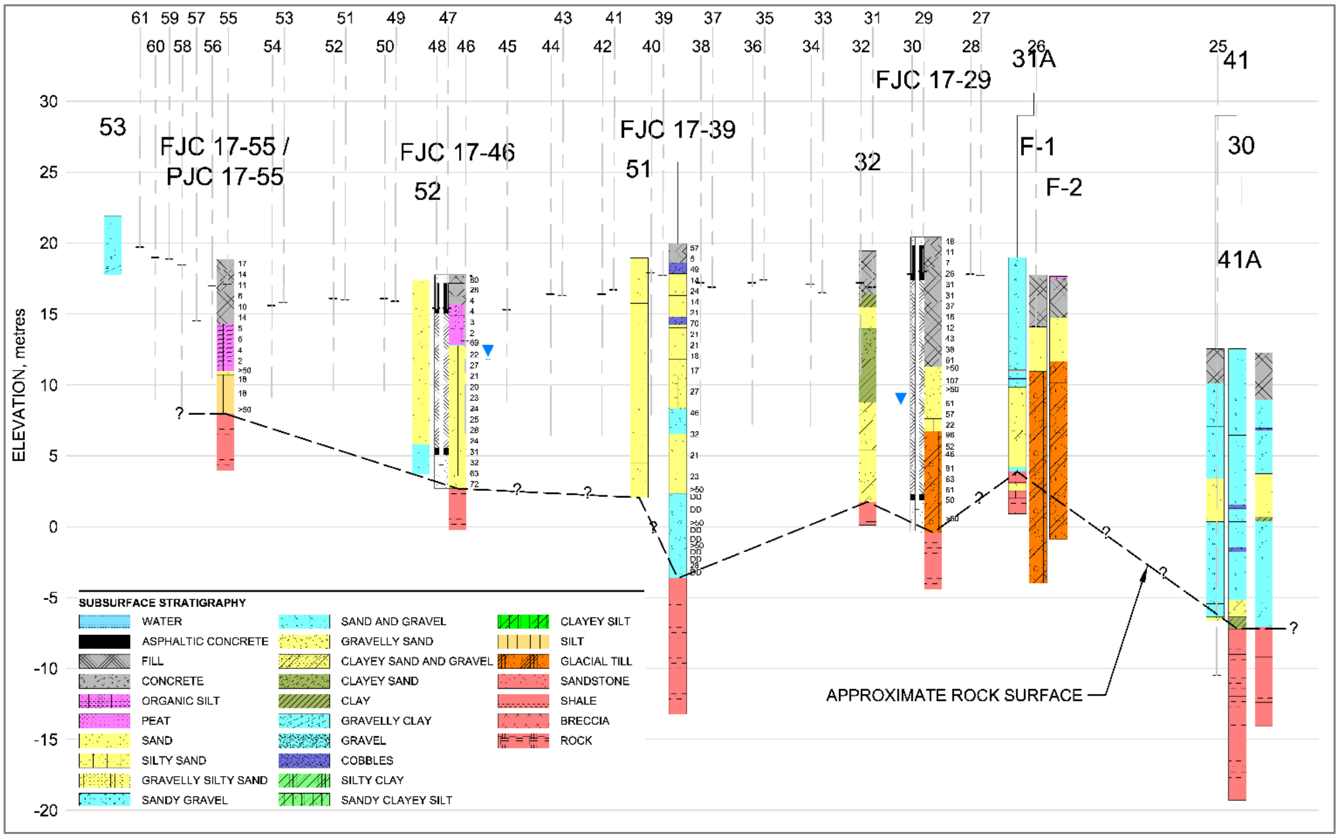

Figure 4. Cross-Section from piers 25 to 61 on Montreal island.

5.2.1 Fill

A surficial layer of fill was encountered at all drilled boreholes, thickness of which varies between 1.4 m (at pier 39) and 11.4 m (at pier 16). To welcome *L'Exposition universelle et internationale de Montréal de 1967* (Expo 67), St. Helen's Island was the subject of an extension (Bureau du patrimoine de la toponymie et de l'expertise - Ville de Montréal 2007) which connected it also to île Ronde. This is likely the source of the fill layers encountered next to piers 16 and 22.

It is composed of different proportions of gravel, sand and fine particles and sometimes fragments of bricks, topsoil and cobbles were encountered. Hence, the description of this fill layer is not constant either in depth or in location. For example, at pier 9, the fill is sandy silt on surface and changes with depth to sand and gravel, then it becomes silty, and at pier 55, it is mainly composed of sand on surface that changes with depth to silty clay then silty sand to silt (see Figures 3 and 4). This was confirmed by conducting five grain size distribution tests. The range of different tests is summarized in Table 3 along with the natural water content. The blow counts in granular fill layers varied between 1 and 80 indicating a compactness variation within the full range i.e. from very loose to very dense. Whereas the blow counts in generally cohesive fill horizons vary between 4 and 14 indicating a firm to stiff consistency.

Below the fill at pier 9, a 3.7-metre-thick concrete layer was encountered, while at piers 18 and 22, the fill rests directly on the bedrock.

At pier 16 a CPT test was performed and reached a refusal in this layer of fill at a depth of 8.83 m below ground surface. The cone tip resistance ranges from 284 kPa to 39,178 kPa. This range indicates what was observed in the borehole of variation of fill composition: relatively low values indicate the presence of clay and silt mixtures while relatively high values indicate the presence of sand and gravel mixtures. From the CPT tests at piers 33, 43 and 49, the thickness of fill layer ranges between about 2.8 m and 4.0 m and the cone tip resistances varying from 205 kPa to 11,833 kPa confirming the presence of clay, silt and sand mixtures.

Table 3. Summary of all grain size distributions of fill and native layers.

Material	Gravel (%)	Sand (%)	Fines (%)	Water Content (%)
Fill	28-50	28-43	16-40	5.3-14.7
Sand to silty Sand Sandy	0-22	60-92	8-33	7.2-23.6
Gravel to gravelly silty sand	36-40	43-46	17-18	11.8
Glacial till	35	45	20	-
Silt, sandy silt or clayey silt	0	10-37	63-90	15.3-22.0

5.2.2 Native Deposits

Native soil deposits were generally encountered below fill layers. However, at the location of some piers, chiefly at piers 9, 18 and 22, no native deposits were encountered as the piers at these locations were directly founded on the bedrock.

At boreholes 16, 29, 39, 46 and 55, a layer of mainly sand to silty sand was encountered (see Figures 3 and 4). Its thickness ranges between 0.9 m and 9.2 m. The ranges of grain size distribution and water content are presented in Table 3. The blow counts in this layer varies between 0 and 32 indicating a compactness from very loose to compact. The cone tip resistance in this layer as interpreted from CPT tests at piers 33, 43 and 49 varies between 6,392 kPa to 68,407 KPa. Higher tip resistance indicates the presence of sandy matrix with the presence of gravel.

A layer of gravel to sandy gravel to gravelly silty sand was encountered at piers 29 39 where the blow counts were varying between 27 and 61 and refusal. This layer has a thickness of about 3.7 and 6.0 m. The cone tip resistance in this layer as interpreted from CPT tests at piers 33, 43 and 49 varies between 8,961 kPa to 25,139 KPa. Higher tip resistance indicates the presence of sandy matrix.

At piers 16 and 55, a layer of sandy silt to clayey silt was intercepted which a thickness of about 2.8 m to 10.8 m. the results of grain size distribution and water content are summarized in Table 3. The blow counts in this layer varies between 18 and 100 where lower values were encountered in the clayey silt and higher values in the sandy silt indicating a compactness degree of compact to very dense.

A layer of glacial till was encountered at piers 16, 29 of a thickness of about 6.2 m and 7.1 m. The glacial till is underlain by the bedrock. It is composed of silty sand to gravelly sandy silt to silty gravel with possible cobbles and blocks. The blow counts range from 26 to 98 to more than 50 counts per 150 mm (refusal). One grain size distribution test was conducted on sample taken from this layer and summarized in Table 3.

A layer of cobbles was intercepted at piers 39 and 46 (see Figure 4) of a thickness of about 0.6 m to 0.8 m.

At piers 46 and 55, layers of organic silt and peat were encountered. Pieces of wood and shells were also found in this layer. The thickness of the organic silt varies between about 0.76 m and 3.3 m while the fibrous peat has a thickness of about 0.76 m. The blow counts in these layers varies between 2 and 6. These layers were also recognised at pier 49 from the interpreted results of CPT of about 2.5 m thick and the cone tip resistance ranges between 446 kPa and 1298 kPa. A summary of the organic matter content, the water content and the consistency limits are shown in Table 4.

Table 4. Summary of results of different tests on organic soils.

Material	Organic matter content (%)	Water content (%)	Liquid Limit (%)	Plastic Limit (%)
Organic layer	6-8.2	67-124	100-111	31.6-64.9

5.3 Bedrock

The bedrock at almost all piers is composed of Utica Shale intercalated with veins of calcite and limestone in places except on St. Helen’s Island where volcanic breccia is partially topping the Shale bedrock, which is consistent with what was published for regional geology in this area (see Figure 2). The geology of St. Helen’s Island is unique where more than half of the surrounding rock is composed of breccia whereas less than half is composed of Utica Shale (Bureau du patrimoine de la toponymie et de l’expertise - Ville de Montréal 2007). This was revealed in the extracted rock core from the boreholes next to piers 18 and 22. The bedrock is made up of “concrete-like” very fine-grained to coarse-grained breccia with limestone intrusions in places (see Figures 3 and 4). No evidence of the Outremont Fault was encountered on the Montreal shore.

The measured rock quality designation (RQD) for the Utica Shale cores is quite variable and ranges from 0% to 99% which means a very poor to excellent quality. At piers 16, 46 and 55, the RQD is generally of fair to excellent for all cores. However, at piers 9, 29 and 39, some cores have a RQD of very bad to bad i.e. RQD < 50 (Canadian Geotechnical Society 2006). The thickness of the latter varies between 0.43 m and 4.66 m. The unconfined compressive strength (UCS) of Utica Shale samples varied between 3.1 MPa and 11.2 MPa for cores retrieved from Longueuil and St. Helen’s Island, and between 60.1 and 97.7 MPa for cores retrieved from Montreal Island, except for one core whose strength is 15.7 MPa. The Young’s modulus and Poisson’s ratio varying between 3.7 and 56.4 GPa, and between 0.1 and 0.37, respectively.

For the breccia bedrock encountered at piers 18 and 22, the RQD is poor only for a thickness of about 2.2 m at pier 22 and elsewhere the RQD classification varies from fair to excellent (> 50%). The UCS varies between 135.2 and 342.6 MPa, the Young’s modulus varies between 60.5 and 99.9 GPa, and Poisson’s ratio varies between 0.19 and 0.26.

Figure 5 shows a sample of Utica Shale core from the bedrock cored next to pier 16, while Figure 6 shows a sample of breccia core from the bedrock cored next to pier 18.

5.4 Groundwater table

For most of the bridge alignment, groundwater levels are controlled by water levels in the adjacent waterways. At piers 29 and 46 on the Montreal shore two standpipe piezometers were installed. The screen at pier 29 was installed in the glacial till deposit at a depth of about 20.7

m while the screen at pier 46 was installed in the silty sand to sandy silt layer at a depth of about 14.9 m.

Figure 3. A sample of Shale rock core before being tested. Core extracted from borehole next to pier 16.

Figure 4. A sample of volcanic Breccia rock core before being tested. Core extracted from borehole next to pier 18.

The groundwater level was measured in February/May 2018. Both measurements are presented in Table 5. From the CPTs at piers 16, 33, 43 and 49 the groundwater levels were also estimated. Measured and estimated groundwater levels are presented in Table 5.

Table 5. Summary of groundwater levels as measured in the standpipe piezometers and as estimated from CPT.

Pier Number	Measurement	Groundwater depth (m)
16	CPT	2.5
29	Piezometer	11.8/11.6
33	CPT	6.7
43	CPT	7.2
46	Piezometer	5.8/5.7
49	CPT	6.7

6 DOWNHOLE TEST (VERTICAL SEISMIC PROFILES)

After completion of drilling the boreholes next to piers 9, 16, 18, 22, 39 and 55, solid PVC tubes (schedule 40) of a diameter of 2 inches (50.8 mm) were installed in each hole and a cement-bentonite grout was then poured to fill the annular space between the borehole walls and the tubes. These tubes were then used in performing the downhole shear wave velocity testing in general accordance with ASTM D 7400. Figure 7 shows the shear wave velocity profiles measured next to the above-mentioned piers. Table 6 shows the estimated range of measured shear wave velocity within the fill and the native soils. It is noted that measured shear wave velocities in the first metre are higher than expected for this type of fill materials, but this can be due to frozen ground when the tests were performed.

The shear wave velocity in the native inorganic soil ranges from 225 m/s to 1200 m/s. Higher values are recorded near the bedrock surface in gravelly and glacial till deposits. In the organic soils, the measured values range between 80 m/s and 160 m/s. In general, the shear wave velocity in the Utica Shale, which is the predominant bedrock at the site of the bridge, varies between 750 m/s to 1,850 m/s, while the shear wave velocity in the breccia bedrock ranges between 1,240 m/s and 1,900 m/s.

7 INSPECTION OF THE TIMBER PILES

Five test pits were excavated next to piers number 33, 37, 43, 48 and 55 in order to partially expose the timber piles supporting the piers, establish their approximate number and geometry, visually inspect and sound the pile integrity, and take samples of the wood to assess their species and establish some mechanical properties.

The visual inspection of the piles showed that the piles have been treated with tar or creosote and appear intact (Figure 8). The exposed piles were then assessed using a hammer to find out if they were solid or hollow. The sound of the hammer strikes showed that the shafts were solid which indicated a good condition of the timber piles.

Some piles were drilled with an auger wood bit and the wood samples were collected for laboratory examination.

The action of drilling the piles shows good resistance of the wood and the absence of cavities, and the drilled holes were filled with treated wood studs of the same diameter as the holes in question.

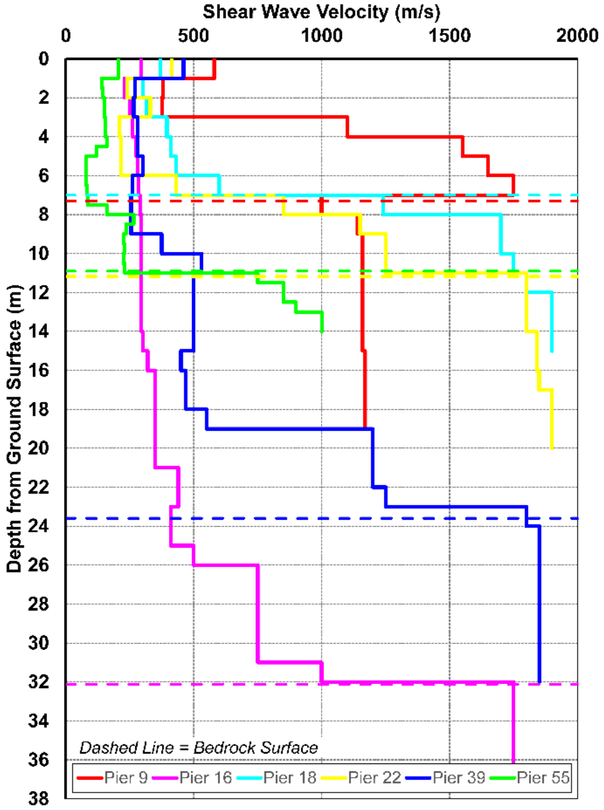

Figure 5. Measured shear wave velocity profiles at the six piers.

Table 6. Ranges of measured shear wave velocity in fill and native soil layers

Layer	Measured Vs Range (m/s)
Fill Materials	140 - 580
Native inorganic soils	225-1200
Native organic soils	80-160

The examined wood samples indicate that the type of wood used in the timber piles is red pine. No sign of pile deterioration was observed. According to Wilkinson (1968), the elastic modulus of red pine wood would be in the range of 7,860 and 11,030 MPa. Therefore, based on field observations, an average value of about 9,240 MPa was considered reasonable.

Figure 6. An exposed timber pile.

8 CONCLUSION

The Jacques Cartier bridge is considered a lifeline bridge and an architectural and historical emblem of Montreal. Designed and constructed in the 1920s, no seismic performance design at that time was performed. To better understand the durability of the bridge under major seismic event, The Jacques Cartier and Champlain Bridges Incorporated mandated a consortium to study, using a performance-based approach, the seismic performance of the bridge. In order to accomplish this goal, a geotechnical and geophysical site investigation and study were conducted by drilling boreholes, performing downhole tests, piezocone tests and test pits to inspect the timber piles status.

One of the special characteristics of the bridge is the diversity of the type of its foundations where some are shallow footing resting on soil or rock, some are massive gravity piers, and some are timber piles of variable numbers and length.

The current investigation that included drilling geotechnical boreholes and conducting piezocone penetration tests showed the variability of soil conditions below the bridge foundations. However, the granular matrix dominates the soil stratigraphy with few exceptions. Organic silts and peat were encountered near the north end of the bridge on Montreal Island, mainly between piers 46 and 55. On the other hand, the bedrock is mainly composed of Utica Shale with exception on St. Helen's Island, where breccia was intercepted. Fill materials were encountered as the top layer at all borehole locations.

9 ACKNOWLEDGMENT

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