GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Geotechnical investigations of a large landslide site at Quyon, Québec

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ABSTRACT
Geotechnical investigations were conducted at a large landslide site near Quyon, Québec. Previous studies concluded that the landslide was triggered by an earthquake about a thousand years ago. The current study continues the previous work to confirm the slope failure mechanism and the earthquake magnitude. This paper presents the results of the first year's study. Cone Penetrometer Tests (CPT), field Vane Shear Tests (VST) and laboratory tests were conducted. The CPT bearing factor N_{kt} is determined to be a constant 10.5. The CPT pore water bearing factor $N_{\Delta u}$ is dependent on the pore pressure parameter B_q. The soil undrained shear strength (S_u) ranged from 30 kPa to about 250 kPa. A clay layer of S_u lower than 100 kPa exists at all the undisturbed locations, but is either absent or dislocated within the landslide zone.

RÉSUMÉ
Une investigation géotechnique a été effectuée sur le site d'un grand glissement de terrain dans la région de Quyon au Québec. Selon des études antérieures, ce glissement de terrain a été déclenché par un séisme il y a environ 1000 ans. La présente étude vise à confirmer le mécanisme de la rupture et la magnitude du séisme en se basant sur les travaux précédents. Cet article présente les résultats de la première année de l'investigation. Des essais insitu (piézocône, scissomètre de chantier) ainsi que des essais de laboratoire ont été réalisés. Le facteur de capacité portante N_{kt} du piézocône est constant et a une valeur de 10.5 tandis que le facteur $N_{\Delta u}$ dépend du paramètre de pression interstitielle B_q. La résistance au cisaillement non drainé des sols (Cu) varie de 30 à 250 kPa. Un horizon argileux avec un Cu inférieur à 100 kPa se retrouve sur l'ensemble des sites intacts, mais est soit absent soit déformé à l'intérieur de la zone du glissement de terrain.

1 INTRODUCTION

An enormous landslide zone associated with the prehistoric failure of the sensitive Champlain Sea glaciomarine deposits is present along the lower Quyon River valley, near Quyon, Québec, that appears on many published soil, landslide and surficial geology maps (Figure 1; Wilson, 1924; Lajoie, 1962; Richard, 1976; Fransham et al., 1976; Aylsworth et al., 1997; St.-Onge, 2009). A recent study by Brooks (2013) interpreted that the Quyon Valley landslide zone is primarily the product of a massive failure that occurred between 980 and 1060 cal BP, based on the geomorphology and stratigraphy of the landslide deposits and radiocarbon ages of wood samples collected from the deposits. He further hypothesized that the failure was triggered by a prehistoric earthquake, based on the common radiocarbon ages of the Quyon Valley landslide with nine other landslides in the Quyon-Ottawa area (Brooks et al, 2013). Brooks (2013) estimated that the magnitude of the triggering earthquake was at least Mw 6.1, using the empirical landslide area – earthquake magnitude relationship of Keefer (1984) and Rodriguez et al. (1999).

A geotechnical investigation was initiated in 2014 at the Quyon Valley landslide site to improve the estimation of the magnitude of the paleoearthquake. This research requires investigating more completely the landslide triggering mechanisms and the seismic loading required for triggering the slope failures. We conducted surveys of the thickness of the glaciolacustrine deposits, cone penetrometer tests (CPT), vane shear tests (VST), soil sampling, and laboratory tests. This paper presents the geotechnical data collected from the first year of investigation.

2 STUDY AREA

The lower Quyon Valley is located in southwestern Quebec, about 44 km WNW of Ottawa. The landslide area developed within Champlain Sea deposits (St.-Onge, 2009) that were deposited between 13.9 and 11.5 cal ka BP (Dyke and Prest, 1987). Locally, the deposits are composed of 3~4 m of sand capping glaciomarine clay and silty clay of varying thickness that overlies bedrock (Gadd, 1986). The Champlain Sea deposits were incised by the postglacial stream network in the early Holocene as the Champlain Sea receded from the area because of regional postglacial uplift.

No published geotechnical data have been found on the Champlain Sea deposits within the Quyon Valley. Gadd (1986), however, reports "very sensitive" clay between 13.7 m and 17.7 m depth from a geological borehole located on the Champlain Sea plain, 2~3 km north of the village of Quyon. In a second borehole located nearby, but within the landslide area, "distorted" and/or "tilted" deposits were recovered to 14.4 m depth. The landslide area is primarily agricultural, consisting of cultivated fields, pasture, and woodlands. The village of Quyon is located in the southern part of the area along the Ottawa River (Figure 1).

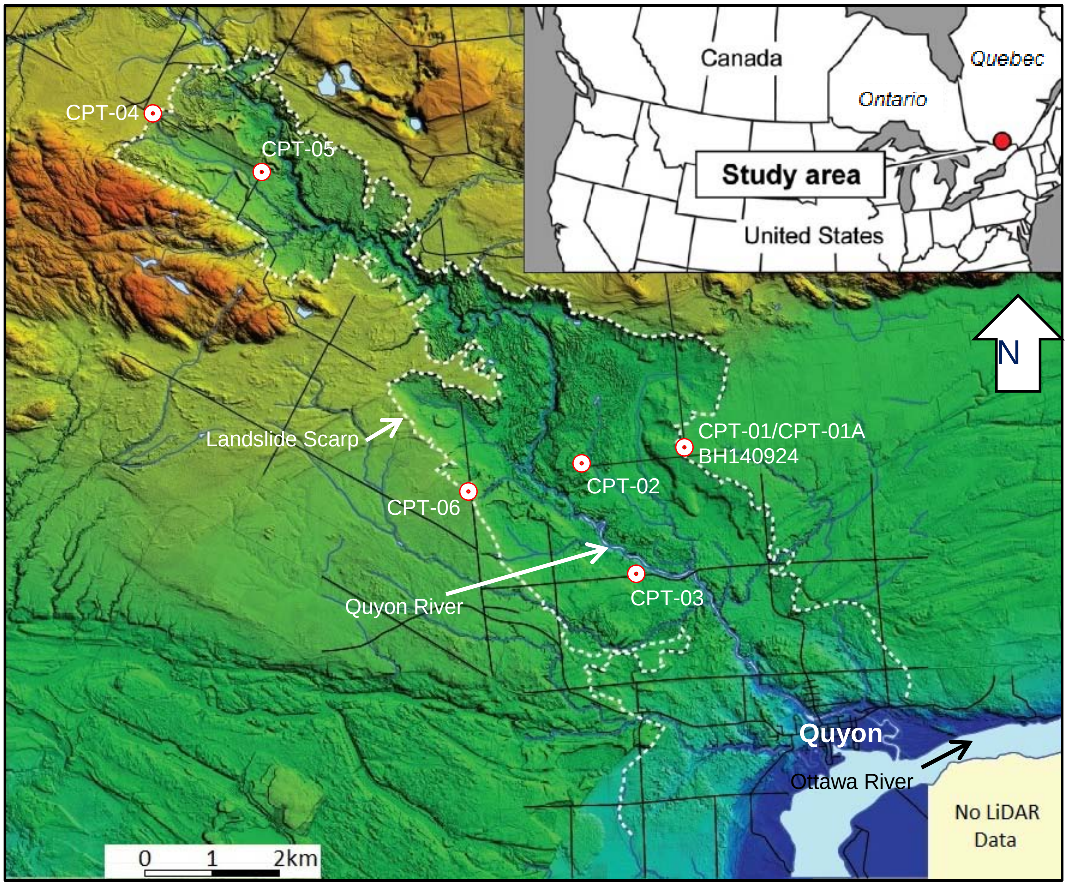

Figure 1. Location map of study area based on LiDAR image (LiDAR image © Government of Quebec)

The Quyon Valley is situated within the West Quebec Seismic Zone (WQSZ) which encompasses parts of western Quebec, eastern Ontario, and northern New York State (Basham et al., 1982). In Canada, most earthquakes in the WQSZ occur within two areas: a southeast-northwest oriented band extending from Montreal to the Baskatong Reservoir in the upper Gatineau River watershed and a less active, southern band trending just west of northwest along the Ottawa River from Ottawa to Lake Timiskaming (Adams and Basham, 1989; 1991). The Quyon Valley landslide area is located within the southern band. Seismicity along this portion of the WQSZ is associated with Paleozoic rift faults within the Ottawa-Bonnechere graben, while that of the northern band may relate to crustal fractures caused by the passage of the crust over a hot spot during the Cretaceous. Significant historic seismic events in the WQSZ include the 1732 Montreal (M 5.8), 1935 Temiscaming (M 6.1), and 1944 Cornwall (M 5.8) earthquakes; all of which occurred within the southern band (Lamontagne, 2010).

3 CHAMPLAIN SEA SEDIMENT THICKNESS

The thickness of the Champlain Sea clay deposit across the Quyon landslide zone was surveyed using a portable seismograph (Tromino). The instrument measures three-component ground motions and is designed for attaining the horizontal-to-vertical spectral ratio (HVSR) of ambient ground motion. In areas where the thickness of soft soil (with low shear wave velocities) exceeds about 10 m and overlies competent bedrock or firm soil (with high shear wave velocities), there is a possibility of ground resonance due to ambient seismic noise. In such areas, the HVSR indicates a peak period, T_0 (or frequency, F_0) equivalent to the resonant period of the ground, which is approximately related to the shear wave velocity and the thickness of the soil (NRC, 2010) as $T_0=4H/V_s$, where H is soil thickness; V_s is shear wave velocity.

In the general Ottawa area, the predominant seismic impedance boundary is the base of the soft Champlain Sea sediments overlying glacial sediments (ice-contact or glaciofluvial sediments) or, Paleozoic or Precambrian bedrock (if glacial sediments are absent). This stratigraphy typically exhibits a strong impedance contrast and yields a well-defined sharp peak period (resonant period) on the HVSR-F_0 (or T_0) plot. Dobry et al. (1976) has shown that a shear wave velocity gradient within young (Holocene age) unconsolidated sediments can alter the observed fundamental period and the estimated “effective depth” to the resonator. Hunter et al. (2010), using borehole and seismic reflection data developed an empirical relationship between the thickness of the soft sediment and the resonant period for the typical Champlain Sea deposits in the general Ottawa area $H = 56.7\ T_0^{1.48} \pm 6.1$. This correlation was used to interpret the soft sediment thickness from the HVSR measurements in the Quyon landslide area.

The HVSR measurements were conducted at 180 locations inside and outside the Quyon landslide zone. Rock outcrops in the area were also measured with a handheld GPS. The depths to seismic impedance, the outcrops, and the LiDAR surface elevation were used to interpret the depth of the Champlain Sea deposits. The result is shown in Figure 2. The impedance profile forms a valley in the subsurface that underlies the Quyon valley landslide scar. The maximum impedance depth measured was up to about 68 m. The data were used as a guide for the next level geotechnical site investigations.

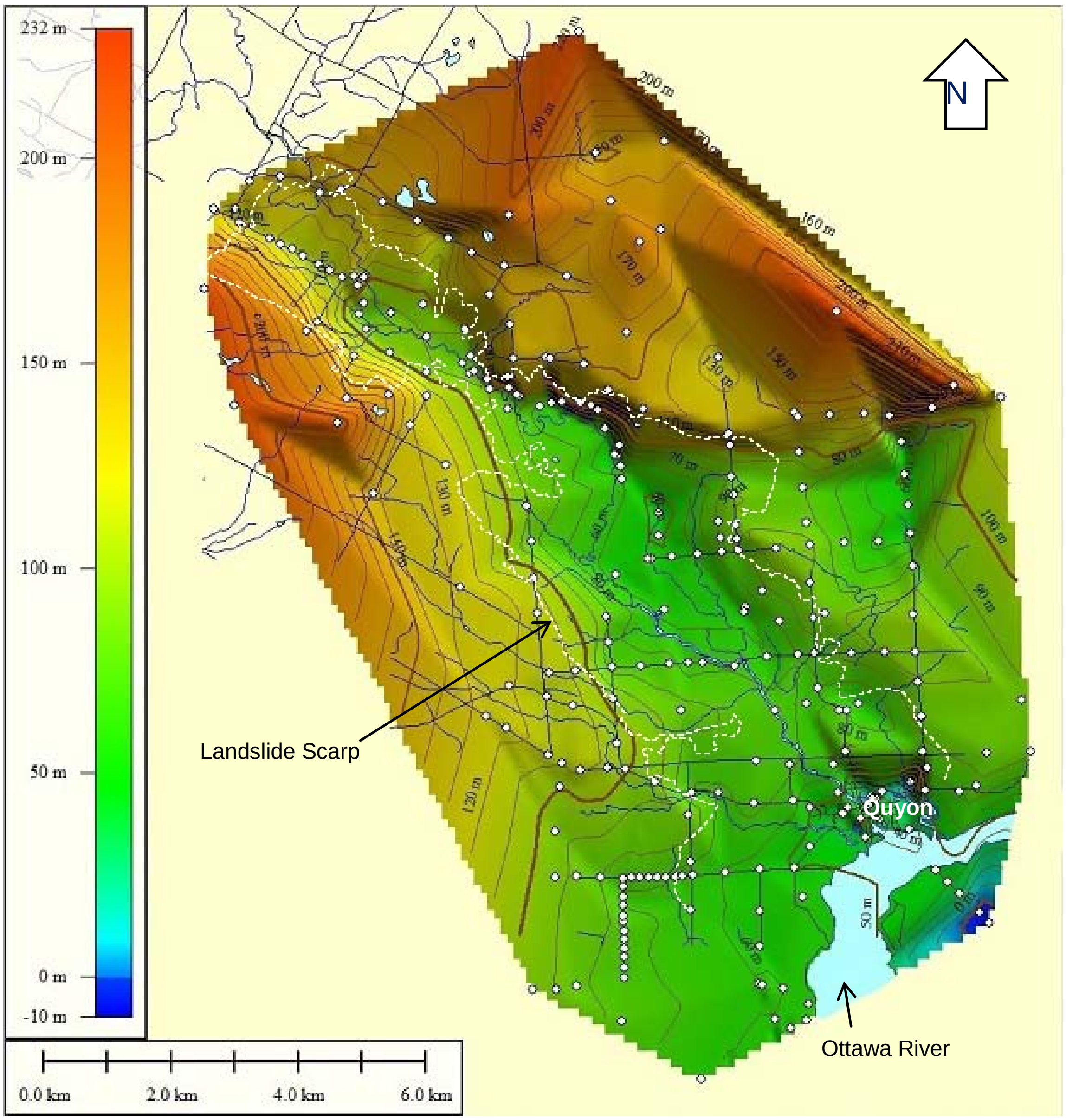

Figure 2. Map of the seismic impedance surface underlying Champlain See deposits in the general area of the lower Quyon valley, as interpreted from HVSR measurements. (Colour shading and contour values indicate impedance elevation asl). The locations of HVSR measurements are marked with white dots. Some surface features in Figure 1 are superimposed here for reference of locations.

4 CONE PENETROMETER TESTS

Seven Cone Penetrometer Tests (CPT) were conducted at six locations on August 19, 2014 and January 14~15, 2015. The CPT locations are shown in Figure 1. All CPT were carried out on shoulder of roads.

A commercial 25 ton tire truck mounted CPT rig was used to carry out the tests using an integrated electronic cone penetration testing and data acquisition system. The CPT soundings were completed in accordance with ASTM D5778. The cone and rods were pushed into the ground using the hydraulic ramset, located inside the rig, at a steady rate of two centimeters per second. The data acquisition frequency was every 5 cm.

The cone that was used at CPT-01 through CPT-03 had a maximum tip capacity of 100 MPa, a tip area (A_c) of 10 cm^2, a friction sleeve area (A_s) of 150 cm^2, and a pore pressure transducer capacity of 3.4 MPa (500 psi). The cone that was used at CPT-04 through CPT-06 had a maximum tip capacity of 150 MPa, a tip area (A_c) of 15 cm^2, a friction sleeve area (A_s) of 225 cm^2, and a pore pressure transducer capacity of 3.4 MPa (500 psi). A pore pressure filter of six millimeter thick located directly behind the cone tip was also used. The pore pressure filter was saturated in silicone fluid under vacuum pressure prior to testing and the pore pressure cavity within the cone was filled with silicone fluid.

CPT-01, CPT-04, and CPT-06 are located in undisturbed areas at the crest of the landslide scarp (Figure 1). A repeat test CPT-01A was done 10 m south of CPT-01 to double-check the depth to refusal. The other three tests, CPT-02, CPT-03 and CPT-05, were conducted within the landslide zone. All the CPT holes were pushed to refusal (bedrock). Soil sampling and field vane shear testing (VST) were carried out at CPT-01 and CPT-04, as discussed in the next section.

5 VANE SHEAR TESTS AT CPT-01 AND CPT-04

Field vane shear tests (borehole BH140924) were carried out at about 15 m east of CPT-01 on Sept. 24, 2014. It is in an undisturbed zone on the crest of the landslide scarp. A commercial tire truck mounted drill rig was used for the drilling and testing. The drilling was conducted with a hollow stem auger of ID 10.8 cm (4¼ inch). Shelby tubes were used for undisturbed soil sampling. The Shelby tubes are ID 7.0 cm (2¾ in), OD 7.3 cm (2⅞ in) and length 67.6 cm (26⅝ in). The vane shear tests were carried out in accordance with ASTM D2573 and Shelby sampling with ASTM D1587. A full Shelby core was retrieved from 4.6 m (15 ft) depth and another from 9.2 m (30 ft) depth. Only a half core was retrieved from the 13.7 m (45 ft) depth. The half core slipped from the top to the bottom of the tube when it was brought up to the surface. Attempts were made to collect samples at 18.3 m (60 ft), 22.9 m (75 ft) and 27.4 m (90 ft) depth. However, the cores were lost halfway in the drill hole during retrieval.

Another field vane shear test was conducted at 10 m south of CPT-04 on March 16~19, 2015. It is in an undisturbed zone on the crest of the northern scarp of the landslide. A commercial track mounted drill rig was used for this operation. The drilling was conducted with a hollow stem auger of ID 10.8 cm (4¼ inch). Shelby Tubes were used for undisturbed soil sampling. The Shelby tubes are ID 7.0 cm (2¾ in), OD 7.3 cm (2⅞ in) and length 67.6 cm (26⅝ in). Vane shear tests were carried out in accordance with ASTM D2573 and the Shelby sampling with ASTM D1587. The soil sampling and vane shear testing were done at: 12.2 m (40 ft), 16.8 m (55 ft), 24.4 m (80 ft), 32.0 m (105 ft), 39.6 m (130 ft), and 47.2 m (155 ft) depth with one Shelby sampling followed by two vane shear tests. A full Shelby core was retrieved from each of the above depths.

The soil samples were waxed at the two ends of the Shelby tubes and transported in accordance with ASTM D4220 to the Geological Survey of Canada's (GSC) sedimentology laboratory for geotechnical index property testing.

6 RESULTS AT CPT-01 AND DATA CALIBRATION

A summary of the CPT, VST and laboratory test results of CPT-01 is provided in Figure 3. The results from the repeat test at CPT-01A (as shown later) are very similar to that of CPT-01. Based on the CPT soil behaviour type and the soil samples, the materials at CPT-01 from the surface down are inferred to as: 0 to 3 m - clay/silt; 3 to 21 m - sensitive clay; 21 to 31 m - silt of increased stiffness; 31 m to 33 m - sandy/clayey silt; and 33 m depth - refusal (bedrock). The CPT soil behaviour type indicated a silt unit at 31 m depth at CPT-01 and 32 m depth at CPT-01A. This unit is about 1.5 m thick above refusal (or bedrock). A seismic impedance depth of 37 m was interpolated for this location from the HVSR data collected 70 m and 340 m away. This is reasonably close to the findings from the CPT.

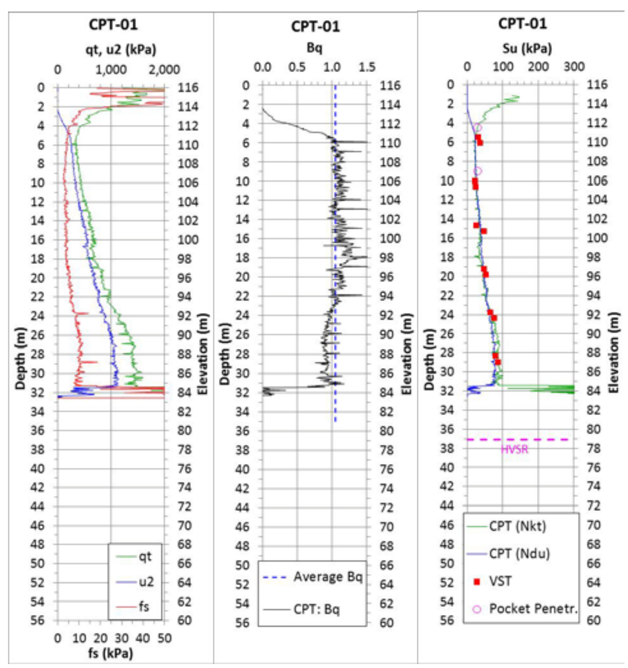

Figure 3. Results at CPT-01

Soil samples from BH140924 (at CPT-01) were tested for geotechnical index properties at the GSC Sedimentology Lab. Pocket penetrometer tests were also conducted on some samples to determine the undrained shear strength. A Pocket Penetrometer CL-700 by Soiltest was used for the tests. Repeated tests were done on samples from the same Shelby core to obtain an average value of the results, which is considered as a representative value for that depth. The laboratory test results are provided in Figures 3, 4 and 5.

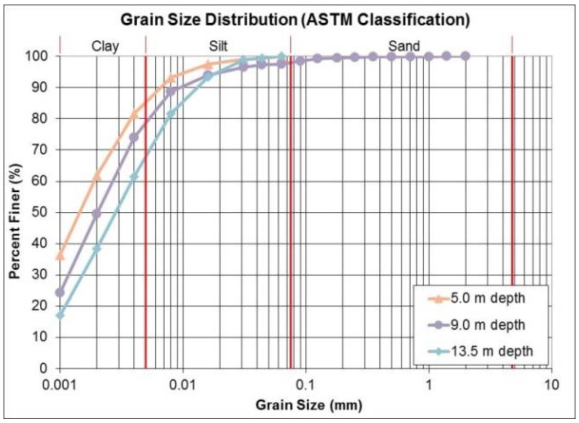

Figure 4. Gradation chart of soil samples from BH140924

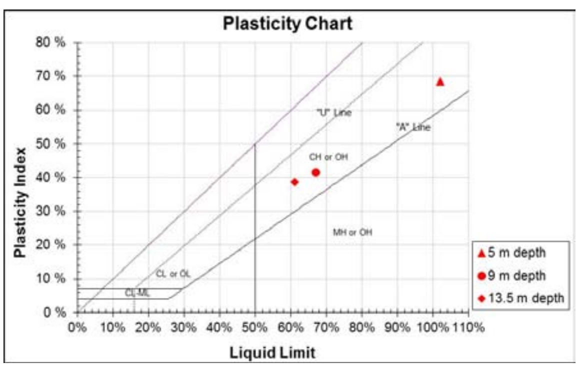

Figure 5. Plasticity chart of soil samples from BH140924

As seen from Figures 4 and 5, the samples tested are clay to silty clay of high to extremely high plasticity.

The field vane shear test results are used for CPT data calibration. The soil undrained shear strength (S_u) is conventionally calculated from the CPT tip resistance as $S_u=(q_t–\sigma_{vo})/N_{kt}$, where q_t is the total corrected cone tip resistance; σ_{vo} is the total vertical overburden stress; N_{kt} is a bearing factor (Konrad & Law, 1987 and Yu & Mitchell, 1998).

The undrained shear strength can also be independently calculated entirely from the excess pore water pressure measurements (Δu) as $S_u=\Delta u/N_{\Delta u}$, where Δu is commonly determined from $\Delta u=(u_2–u_{eq})$ with u_2 being the recorded dynamic pore pressure behind the tip of the cone (shoulder element); u_{eq} is the equilibrium pore pressure determined from water table depth; and $N_{\Delta u}$ is a pore pressure bearing factor (Tavenas & Leroueil, 1987). Note that N_{kt} and $N_{\Delta u}$ are linked as:

$$N_{\Delta u} = B_q\, N_{kt} \qquad [1]$$

where B_q is a pore pressure parameter calculated as $B_q=(u_2–u_{eq})/(q_t-\sigma_{vo})$.

By comparing the VST and CPT data at CPT-01, the bearing factors are determined to be N_{kt} = 10.5 and $N_{\Delta u}$ = 11.0 for this location. The average B_q is 1.05 at CPT-01. The S_u and B_q profiles for CPT-01 are shown in Figure 3.

Also shown in Figure 3 are the laboratory pocket penetrometer test results of the undrained shear strength. As seen from Figure 3, the pocket penetrometer results agree well with the field VST and CPT results at CPT-01 (and CPT-01A).

7 CALIBRATION FROM CPT-04 AND APPLICATION

The field vane shear test at CPT-04 allowed further calibration of the CPT data. By comparing the VST and CPT data at this location, it was found that the bearing factor N_{kt} remains the same as that determined from CPT-01, i.e., N_{kt} = 10.5, but $N_{\Delta u}$ changed to 7.4. Note that the $N_{\Delta u}$ value at CPT-04 is consistent with Eq. 1 for an average B_q (Figure 6) at this location. Based on these results, we applied the constant N_{kt} = 10.5 and the average B_q to interpret the S_u profiles for all other CPTs.

Figure 6 shows the B_q profiles with average values indicated for all the CPTs. The interpreted S_u profiles for the CPTs are given in Figure 7.

8 RESULTS AND DISCUSSIONS

Further to the results presented in the earlier section, this section discusses the general results from the field tests.

CPT-06 is across the Quyon River from CPT-01 (Figure 1). It is in an undisturbed area about 8 m above the crest of a shallow scarp of the landslide zone. The soil behaved similarly to that of CPT-01. The CPT soil behaviour types are, from surface down, 2 m sand, 16 m clay, 5 m silty sand and then refusal (bedrock). The undrained shear strength of the clay ranged from about 55 to 80 kPa. Based on the S_u profiles in Figure 7, the clay at CPT-06 is likely the same unit of the lower portion of CPT-01. The HVSR impedance depth is 20 m at CPT-06, which is very close to the CPT measurement of the bottom of the clay at 18 m depth where increased cone resistance was encountered (Figure 7).

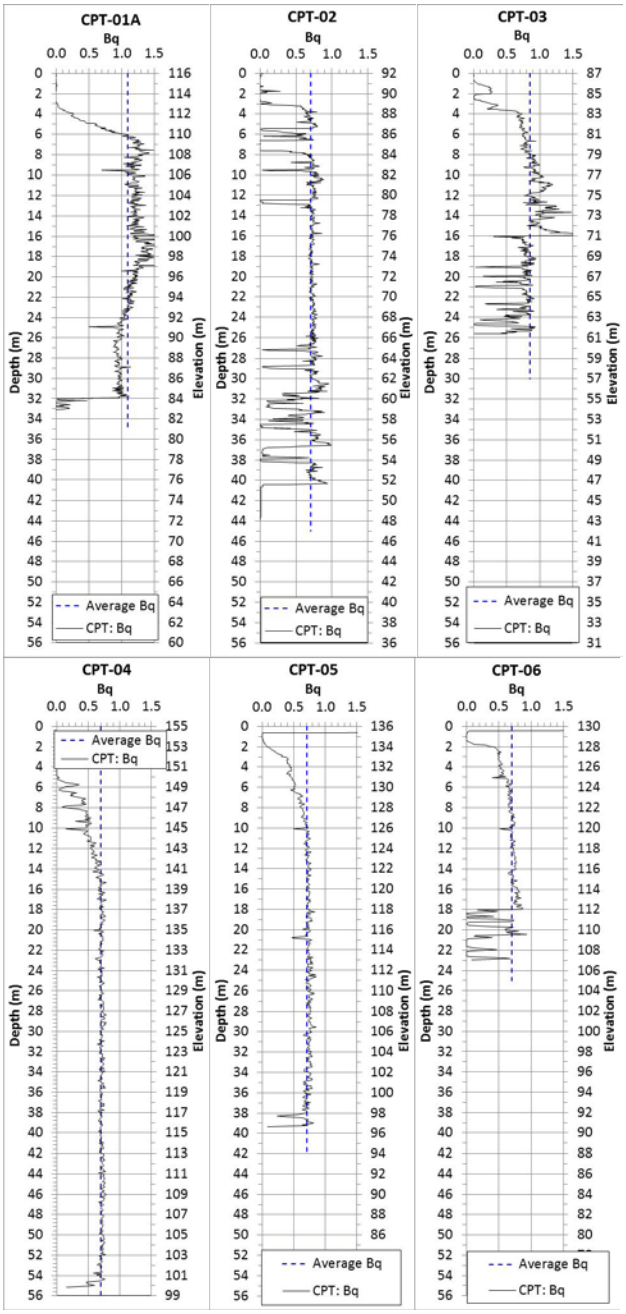

Figure 6. Profiles of pore water pressure parameter B_q at CPT-01A to CPT-06

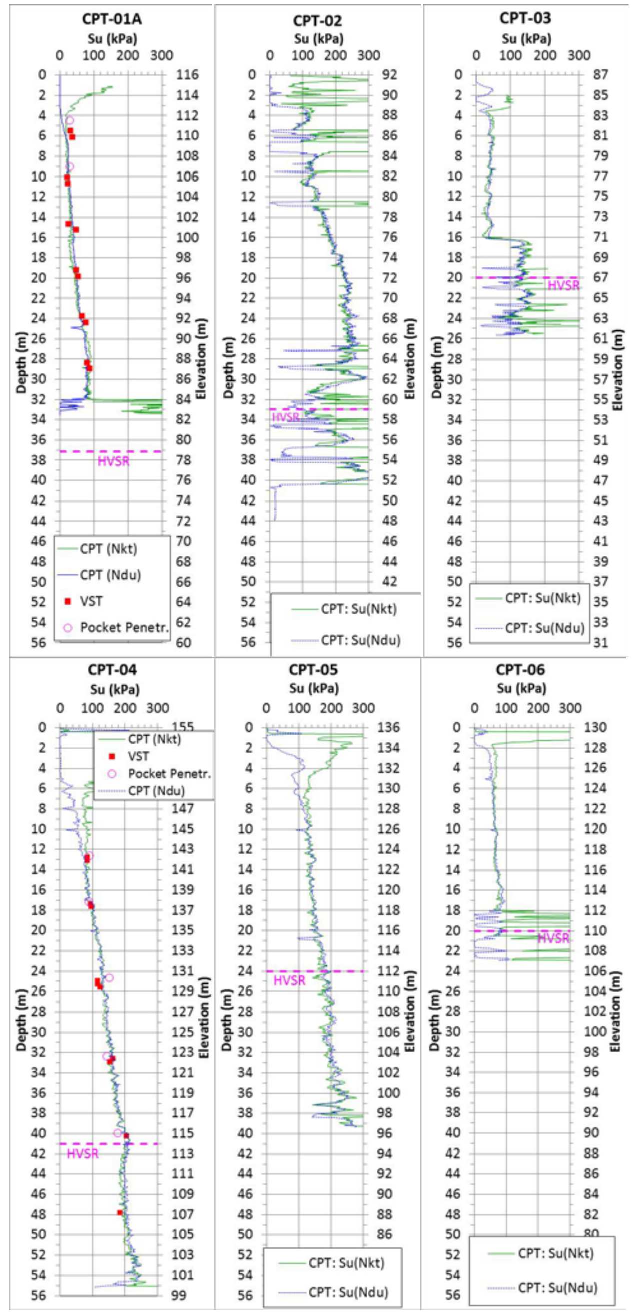

Figure 7. Undrained shear strength at CPT-01A to CPT-06

CPT-02 is located inside the landslide disturbed area about half way between CPT-01 and CPT-06 (Figure 1). It is near the centre (or bottom) of the Quyon River valley. The undrained shear strength ranged from about 100 to 250 kPa. The low strength clay unit observed at CPT-01 and CPT-06 is absent at CPT-02. This is perhaps the result of the landslide where the sensitive clay was likely displaced. The upper 8 to 12 m of materials are likely disturbed based on the discontinuity of the S_u profile of CPT-02. Such discontinuity of the S_u profile is not observed from the undisturbed locations (CPT-01, CPT-04 and CPT-06). The disturbance at CPT-02 is consistent with the observations along the nearby Quyon River where the exposed clays exhibit tilted and noticeably displaced beds at about the same elevation. The stronger materials of S_u greater than 100 kPa are probably undisturbed based on the continuous CPT-02 S_u profile shown in Figure 7. The landslide slip surface is therefore likely at around 10 m (±3 m) depth at CPT-02, which is about the same elevation of the bottom of the nearby Quyon River

The HVSR impedance depth measured at CPT-02 is 33 m. This is consistent with the change of the S_u profile at about 28 m to 30 m depth at CPT-02.

CPT-03 is also in the landslide disturbed zone near the centre of the Quyon River valley and located at about 1.8 km downstream of CPT-02 (Figure 1). The CPT detected a firm clay unit of S_u ranging from 30 kPa to 50 kPa between 4 m and 16 m depth (Figure 7). There is a strength change at 16 m depth. The shear strength increased abruptly by about 100 kPa from 30~50 kPa to 130~160 kPa at this depth. Refusal (bedrock) was encountered at 26 m depth. By comparing with CPT-01 and CPT-06, the abrupt soil profile change at CPT-03 indicates that the landslide slip surface might be located at 16 m depth at this location.

HVSR impedance measurements in the area around CPT-03 consistently indicate an interface depth of 20 m. This is reasonably close to the CPT-03 measurement of the sharp strength contrast at 16 m depth.

CPT-04 is above the northern head scarp of the landslide zone. The drill hole is in an undisturbed area and located at about 85 m north of the crest of the scarp. The auger hole drilled at this location indicates fine sand from surface to about 11 m depth that is underlain by clay or silty clay to 48 m depth (with the lower elevation being siltier). The CPT data indicated a continuously increasing S_u profile in the clay zone (Figure 7). The S_u values of the clay at depth shallower than 18 m are less than 100 kPa. It increased up to 200 kPa at 41 m depth and the gradient dropped at the depth below 41 m. Note that the ground surface is more elevated from the east (CPT-01) to the west (CPT-06). It is further elevated from the south (CPT-06) to the north (CPT-04). By comparing the S_u profiles at the undisturbed locations (CPT-01, CPT-04 and CPT-06), it appears that the fine sediments become stiffer towards the northwest where the surface is more elevated.

The S_u profile change and the excess pore pressure profile change (not shown here due to space limit) at 41 m depth at CPT-04 indicates that the fine material becomes siltier below this depth. This was observed from the soil samples during drilling although sample testing is yet to be conducted in the laboratory. Coincidentally, the estimated depth to impedance based on the HVSR data is 41 m. Refusal (or bedrock) was encountered at 55 m depth at CPT-04. Shear wave velocities were also tested along CPT-04. The seismic data and soil sample test results will be reported in future publications.

CPT-05 is inside the landslide disturbed area (Figure 1). It is about 1.8 km downstream of CPT-04. The surface elevation at CPT-05 dropped by 19 m from CPT-04. As seen in Figure 7, a continuous S_u profile was detected at CPT-05. This is similar to that of CPT-04. However, the softer unit of S_u less than 100 kPa is absent from CPT 05. The $S_u(N_{kt})$ values at CPT-05 ranged from 120 kPa to 250 kPa. By comparing with CPT-04, the continuous S_u profile below 7 m depth at CPT-05 indicates that the materials below this depth might not have been disturbed by the landslide. The absence of the softer unit above is an indication that the material might have flowed away. The HVSR impedance depth is 24 m at CPT-05. Note that the S_u profile in Figure 7 does not show any strength profile change around this depth. However, the CPT-05 soil behaviour types (not shown due to space limit) do indicate a material transition from silt to sandy silt at around 20 m depth.

9 CONCLUSIONS

The soil shear strength calibration indicated a constant CPT bearing factor of N_{kt} = 10.5. The pore pressure bearing factor $N_{\Delta u}$ varies with the pore pressure parameter B_q. An average B_q value at each CPT location with the constant N_{kt} could be used to determine $N_{\Delta u}$ at that location.

The laboratory tests identified the materials from borehole BH140924 as clay to silty clay of high to extremely high plasticity. The results of the pocket penetrometer test in the laboratory agree well with the field VST and CPT results.

A clay unit with a nearly linear increase of S_u with depth was detected from all the CPT holes at the undisturbed locations next to the landslide scarp (CPT-01, CPT-04 and CPT-06). The materials become stiffer towards the northwest where the ground is more elevated (generally increased S_u from CPT-01 to CPT-06 to CPT-04). Materials of S_u less than 100 kPa exist at all the undisturbed locations tested.

Three test holes were drilled inside the landslide disturbed zone (CPT-02, CPT-03 and CPT-05). The clay unit with S_u less than 100 kPa was absent from CPT-02 and CPT-05, which indicates that this layer might have been displaced by the landslide. The continuous and nearly linear S_u profiles at the lower elevations in these test holes indicate that the materials at such elevations were likely undisturbed by the landslide. Although an upper softer clay unit was detected at CPT-03, an abrupt S_u profile change is inconsistent with those found from the undisturbed locations. It is therefore an indication that the softer material was likely moved to this location by the landslide.

The HVSR impedance depths are in general agreement with the depth of S_u profile changes at 5 out of

6 CPT locations. The HVSR depths were generally greater than the CPT measurements by about 2 to 5 m, which is considered reasonable. The overall data indicate that HVSR measurements can be used to locate the depth of material change reasonably well in the Champlain Sea region along the Ottawa Valley. HVSR measurements thus are useful for reconnaissance level mapping of the thickness of the Champlain Sea sediments in this region.

ACKNOWLEDGEMENTS

The authors would like to thank Alain Grenier, Matthew DeGeer, Andrea Reman, and Aldo Katrigjini for their assistance on the field works. Kind support from Heather Crow has been critical on obtaining funds and access to summer students for the field works. The authors would also like to thank Didier Perret for his detailed review and comments that significantly improved the quality of the paper. This research is supported by the Public Safety Geoscience Program, Earth Sciences Sector (ESS), Natural Resources Canada. This paper represents ESS Contribution # 20150093.

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