Geotechnical and electrical properties of sensitive clay in Saint-François-de-la-Rivière-du-Sud, Québec, Canada

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ABSTRACT
Several flowslide scars are found in a deposit of clay along the banks of the du Sud River in the area of Saint-François-de-la-Rivière-du-Sud located near Montmagny, Québec, Canada. In collaboration with the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports du Québec and Université Laval, a geotechnical and geophysical investigation was undertaken to characterize the geotechnical and electrical properties of this clay deposit and assess the suitability of measuring electrical resistivity to map the areas prone to large retrogressive landslides. An electrical resistivity tomography was carried out along a survey line of 1435 m in length. A total of seven cone penetration tests with pore water pressure measurements and one electrical resistivity measurements were performed along this survey line. Basic geotechnical tests were also performed on samples obtained from three boreholes located close to three cone penetration tests. Based on the results, the studied clay deposit is made of four distinctive layers of clay and correlations have been found between their geotechnical properties, salinity and electrical resistivity.

RÉSUMÉ
Plusieurs cicatrices de coulée argileuse dans un dépôt d'argile ont été cartographiées le long des berges de la rivière du Sud dans la région de Saint-François-de-la-Rivière-du-Sud près de Montmagny, Québec, Canada. Dans le cadre d'une collaboration entre le Ministère des Transports, de la Mobilité durable et de l'Électrification des transports et l'Université Laval, des travaux d'investigation géotechnique et géophysique ont été réalisés pour caractériser les propriétés géotechniques et électriques de ce dépôt d'argile afin d'évaluer si la tomographie de résistivité électrique est une méthode géophysique adéquate de cartographie des zones potentiellement exposées aux glissements de terrain fortement rétrogressifs. Une tomographie de résistivité électrique a été réalisée sur une longueur de 1435 m. Au total, sept essais de pénétration au piézocône et un autre essai avec un module de résistivité électrique ainsi que trois forages ont été réalisés le long de cette ligne de levé. Des essais géotechniques de base ont aussi été effectués sur les échantillons du dépôt d'argile. Selon les résultats obtenus de cette investigation, quatre unités distinctes d'argile ont été identifiées dans le dépôt étudié et des corrélations entre leurs différentes propriétés géotechniques, leur salinité et leur résistivité électrique ont été déterminées.

1 INTRODUCTION

The Saint-Lawrence Lowlands area is mostly composed of clay deposited in marine water following the marine transgression of the Champlain Sea (Parent and Occhietti, 1988). The presence of salt ions dissolved in water allowed the clay particles to form ionic bonds with the salt and to flocculate during the deposition inducing very high water content in the clay. Following the isostatic uplift, the clay deposit emerged and was affected by freshwater infiltration. The flocculated structure of clay remained but the ionic bonds disappeared due to the leaching of dissolved salt. This causes the clay structure to collapse during remoulding and the resulting undrained shear strength is greatly reduced under such conditions. This structure collapse and decrease in shear strength in remoulded clay deposit can form large retrogressive landslides and represents a danger for the population and man-made infrastructures (Tavenas, 1984, Potvin et al., 2014). In Eastern Canada, for clay deposit prone to large retrogressive landslides (Tavenas, 1984), the undrained shear strength (S_{ur}) is less than 1 kPa while the liquidity index (LI) is higher than 1.2. The pore water salinity greatly influences the behavior of the clay when remoulded (Rosenqvist, 1966, Torrance, 1974, Long et al., 2012 and 2017).

The mapping of areas prone to landslides in the province of Quebec is among the mandates of the Ministère des Transports, de la Mobilité durable et de l'Électrification des transports (MTMDET) (Potvin et al., 2014). Undrained cone penetration tests (CPTU) and borehole sampling are the standard procedure to characterize the properties of clay deposits, but this is very expensive and time consuming to perform, and only provides local information. Following recent Scandinavian and Canadian studies (Solberg et al., 2012, Sandven and Solberg, 2014, Bélanger, 2017, Bélanger et al., 2017), geophysical investigations can complement standard geotechnical investigations to help delineating the leached clay areas. For finding a more effective way to map the areas prone to large retrogressive landslides, the MTMDET in collaboration with Université Laval and the Ministère de la Sécurité publique (MSP) has undertaken a geotechnical and geophysical investigation of a clay deposit in Saint-François-de-la-Rivière-du-Sud to assess the suitability of performing electrical resistivity tomography as a tool to delineate the areas of leached clay with higher electrical resistivity than saline clay. In this paper, the results of the geotechnical and geophysical investigation are presented and discussed. The correlations found between the geotechnical and electrical properties of the soil are also given and recommendations are formulated.

2 STUDY AREA DESCRIPTION

The study area is located in a valley crossed by the du Sud River near to Saint-François-de-la-Rivière-du-Sud, 50 km east of Quebec City (Figure 1). The clay deposit in this valley overlies the bedrock belonging to the Appalachian province (MERN, 2017). The river banks at this location are about 20 m high and many flowslide scars are visible along them (Figure 2).

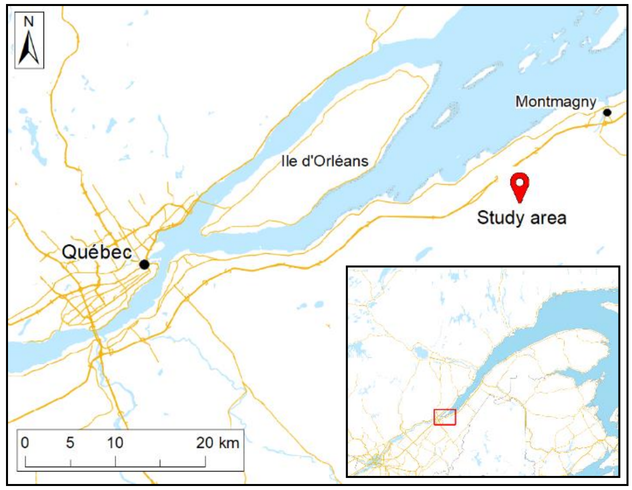

Figure 1. Location of the study area

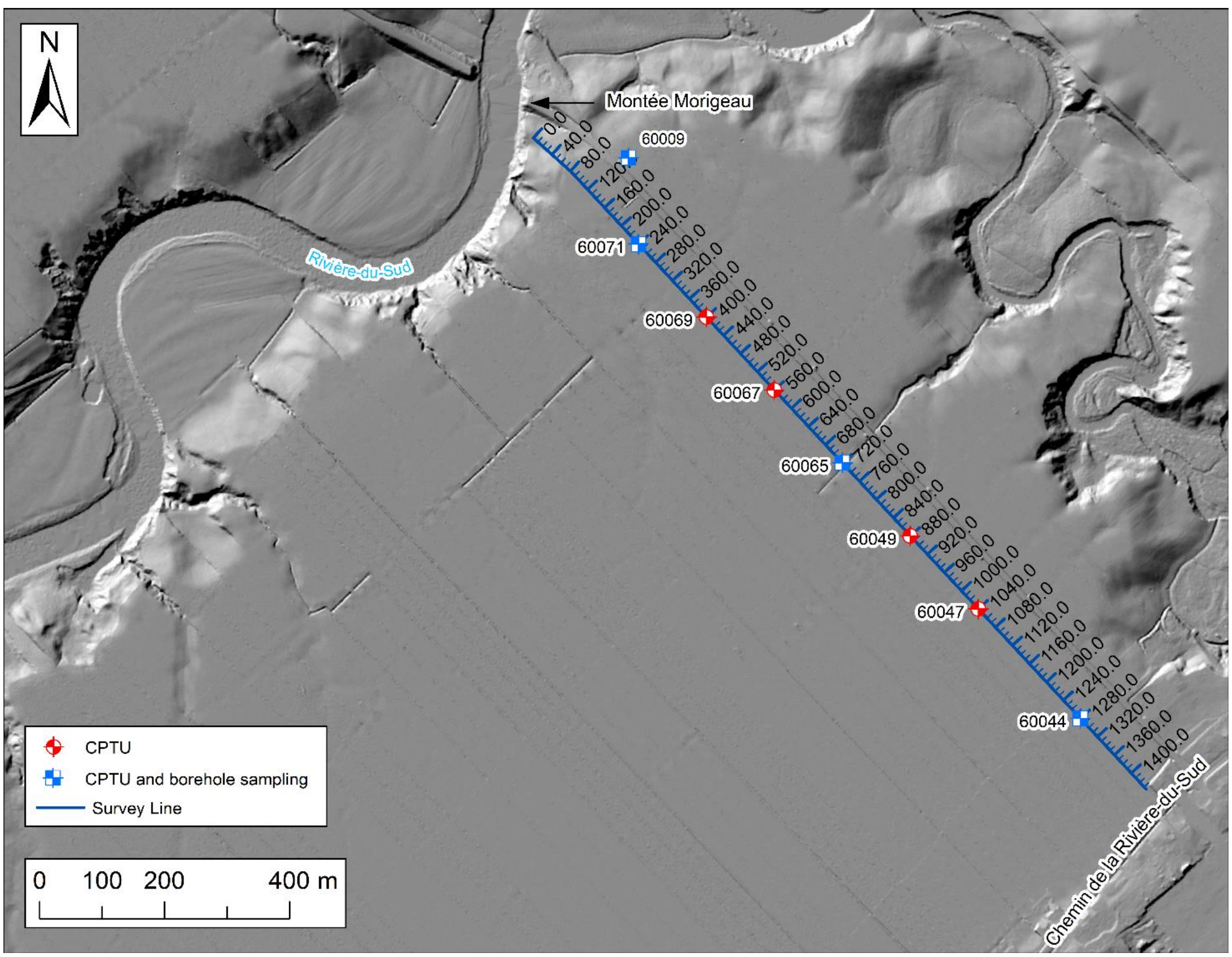

Figure 2. Study area in Saint-François-de-la-Rivière-du-Sud and location of the geotechnical and geophysical investigation. Flowslide scars are visible along the banks of the du Sud River.

In 2014, as part of its mandate to map the areas prone to large retrogressive landslides, the MTMDET performed a borehole and a CPTU (site no. 60009) close to the study area (Figure 2). Four distinctive clay units were sampled during this sounding down to a depth of 37 m. The first unit (unit A) from the surface to a depth of 17 m is composed of clay prone to large retrogressive landslides. The three underlying clay layers are not prone to large retrogressive landslides. The second layer (unit B) is 10 m thick and it is composed of very hard clay. The following layer (unit C) found between 27 and 32 m in depth is composed of normally consolidated clay and the deepest layer (unit D) is composed of normally consolidated clay interbedded with silt.

This site was chosen for its variability in soil properties which makes the site ideal to evaluate if the electrical resistivity tomography is suitable to delineate leached clay areas from saline clay areas.

3 METHODOLOGY

3.1 Geophysical investigation

The geophysical investigation was carried out in November 2017 along a survey line of 1435 m in length covering the south shore of the du Sud river (Figure 2). The electrical resistivity tomography (ERT) was performed perpendicular to the axis of the valley using a SYSCAL Pro SWITCH 96 made by IRIS Instruments. The Wenner configuration was chosen for its increased sensitivity to vertical variations in electrical resistivity (Loke, 2004) and a 5-m electrode spacing was used to maintain a good resolution while reaching a depth of investigation of the clay deposit in excess of 40 m. The electrodes were positioned using a GPS and the elevation of each electrode was determined using the data from a lidar survey performed in 2013 in the area.

A total of 17 microvibration measurements were done along the survey line at 80 m intervals with a TROMINO triaxial velocimeter made by MoHo Science and Technology. The depth of the contact between the clay layer and the bedrock or till layer can be estimated using this test (Perret, 2012, Chandler and Lively, 2014). For this study, it was assumed that the till layer overlying the bedrock is thin enough to ignore its effect.

The ERT data was inverted using the RES2DINV software. The robust method was chosen to better represent the sharp electrical resistivity contact between the clay deposit and the underlying bedrock (Geotomo Software, 2015). The estimated bedrock depth from the microvibration measurements was used as a sharp electrical resistivity boundary between the clay deposit and bedrock to constrain the inversion process. Besides the estimated depth of this boundary, no other information regarding the bedrock layer electrical resistivity was included in the inversion process. And, finally, the variation in surface elevation along the survey line was also corrected in the model of electrical resistivity found from the inversion.

3.2 Geotechnical field investigation

Seven piezocone penetration tests with pore water pressure measurements (CPTU) at the sites no. 60044, 60047, 60049, 60065, 60067, 60069, 60071 (Figure 2) were carried out along the survey line at the distances of 1280, 1040, 880, 720, 560, 400, and 240 m respectively from the beginning of the line (Figure 2). The maximum depth reached during these soundings is 48.83 m. Another piezocone penetration test with electrical resistivity measurement (RCPTU) was also performed at the site no. 60065. Clay samples were recovered from three boreholes at the sites no. 60044, 60065, and 60071 to perform geotechnical tests.

3.3 Geotechnical tests in laboratory

Basic geotechnical tests such as fall cone tests, and Atterberg limits along with grain size analysis and pore water salinity measurements were performed on each clay sample recovered in the boreholes.

Additional electrical resistivity measurements were obtained directly on the clay samples using a Sample-Core-Induced Polarization (SCIP) tester made by Instrumentation GDD Inc.

The pore water was extracted from the clay samples using an apparatus which apply air pressure to the surface of the sample creating a downward flow of pore water within the sample. The pore water was then collected, and the salinity of pore water was measured using a conductance meter. The calibration of the conductance meter was done using Na-Cl solutions of known salinity. The calibration and measurements were done in a temperature and humidity-controlled room.

4 RESULTS

The model of electrical resistivity obtained from the inversion of the ERT data is shown in figure 3. The electrical resistivity logs extracted at each of the sounding sites from the model of electrical resistivity are represented by the black lines while the orange line represents the electrical resistivity log obtained from the RCPTU at the site no. 60065. The depth to bedrock estimated from the microvibration measurements is also shown in figure 3.

In the model of electrical resistivity, values of electrical resistivity from 10 to up to 58 ohm-m are found in the first 10 to 20 m from the surface (Figure 3). In the center of the model, a zone of electrical resistivity lower than 5 ohm-m is visible from 400 to 800 m in distance and at depth-elevation lower than 20 m. Toward the north, the resistivity values in this zone range from 5 to up to 10 ohm-m. Toward the south, the resistivity values gradually increase to reach those observed at the surface of the model. At greater depth, at the estimated depth to bedrock with the microvibration measurements, there is a sharp contrast in electrical resistivity between the clay deposit and bedrock. Although no information regarding the electrical resistivity value of the bedrock was provided

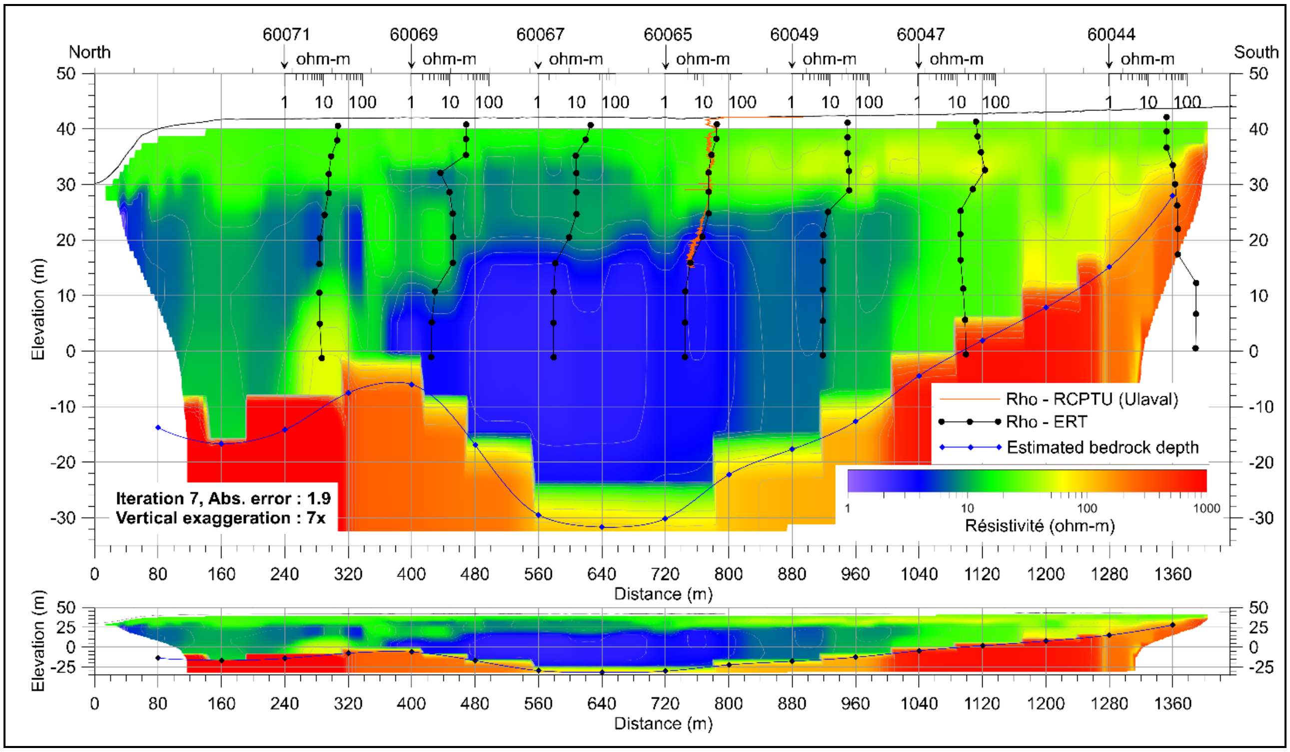

Figure 3. Models of electrical resistivity of du Sud River area (see figure 2 for location) with and without vertical exaggeration for clarity purpose. Electrical resistivity logs extracted from the model of electrical resistivity and RCPTU, and depth to bedrock estimated from microvibration measurements.

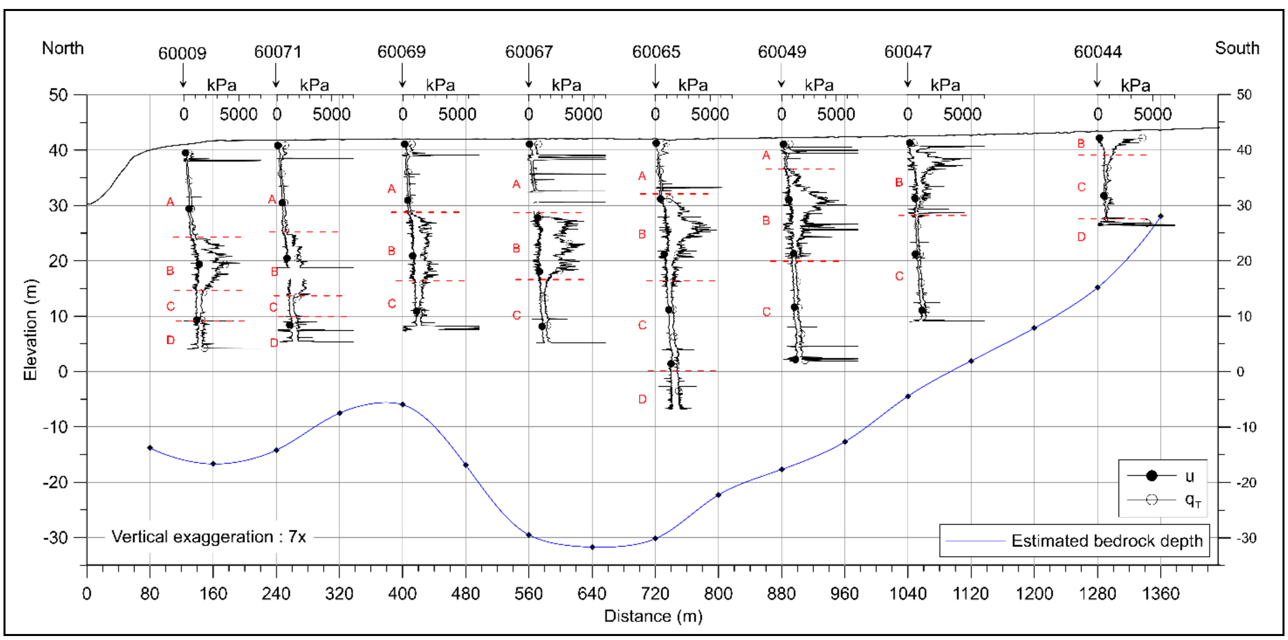

Figure 4. Stratigraphy determined from CPTU results (u: pore pressure and q_t: tip resistance in kPa) and depth to bedrock estimated from microvibration measurements of du Sud River area (see figure 2 for location).

for the inversion of the ERT data, the electrical resistivity found for the bedrock is higher than 100 ohm-m and can be in excess of 1000 ohm-m in given zones. These values are in accordance with what is expected for bedrock (Solberg et al, 2014). The log of electrical resistivity extracted from the model of electrical resistivity at the site no 60065 has resistivity values very close to the ones measured along the RCPTU.

The results of the seven CPTUs are shown in figure 4 according to their position along the survey line. The results from the CPTU performed in 2014 at the site no. 60009 are also provided at its approximate corresponding position along the survey line. The four units as observed at the site no. 60009 are visible along the entire survey line except for the unit A which was not probed in the CPTUs at the sites no. 60047 and 60044. The unit B with thickness from 10 to 15 m is clearly visible with a sharp increase in the tip resistance from 500 to over 2000 kPa. While the top of unit B is fairly flat, the elevation of its base varies along the survey line from 15 m at the north end up to 40 m at the south end. The unit C is also visible on all CPTUs with tip resistance between 700 and 2000 kPa and its thickness varies greatly along the survey line ranging from 3 to 20 m. The unit D can only be properly identified where a borehole with sampling has been performed as its CPTU response is similar to the one of unit C.

The results of the geotechnical tests performed on samples recovered in the site no. 60065 are given in figure 5. Similar profiles were also produced for the sites no. 60044 and 60071 but these results are not presented herein due to lack of available space.

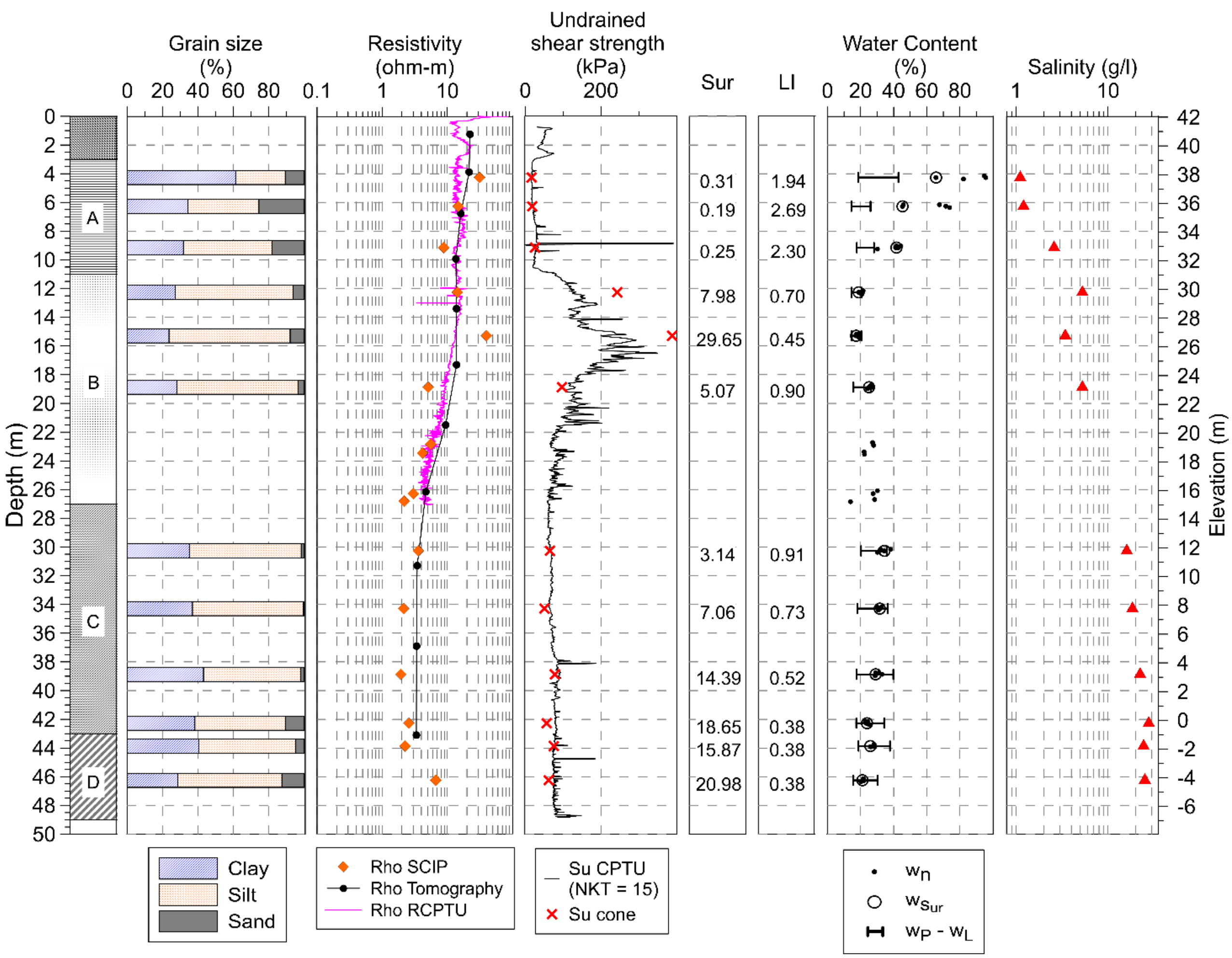

Figure 5. Geotechnical profiles (S_u: shear strength, S_{ur}: remoulded shear strength, LI: liquidity index, w_n: natural water content, w_{Sur}: water content from remoulded shear strength test sample, w_P: plastic limit and w_L: liquid limit) of the site no. 60065 of du Sud River area (see figure 2 for location).

The clay content in unit A is 61% at a depth of 4.3 m and decreases in depth down to 31% at 9.2 m whereas the silt content increases with depth from 28% in the upper sample up to 50% in the lower sample. The sand content ranges from 10 to 25% throughout the unit. The water content decreases from 66% close to the surface to 41% at 9.2 m depth. The unit A is characterized by undrained shear strength (S_u) values ranging from 16 to 25 kPa and remoulded shear strength (S_{ur}) values ranging from 0.19 to 0.31 kPa. The plastic limit (w_P) and liquid limit (w_L) range from 14 to 18% and from 26 to 42% respectively. All samples from unit A have a liquidity index (LI) near or above 1.2 while the pore water salinity does not exceed 2.5 g/l. The electrical resistivity values obtained from the SCIP vary from 8.8 to 31 ohm-m and the mean electrical resistivity measured during the RCPTU is 13.9 ohm-m. The values of electrical resistivity extracted from the model of electrical resistivity at each sample depth range from 14.0 to 20.5 ohm-m.

Unit B is composed of around 25% of clay, 67% of silt and 5% of sand. The water content varies from 18 to 25%. The S_u values range from 96 to 388 kPa and the S_{ur} values range from 5 to 29 kPa. The w_P has a value of about 15% and the w_L ranges from 20 to 26%. The LI varies from 0.4 to 0.9 and the pore water salinity is about 5 g/l. The SCIP values vary from 2 ohm-m in the deepest sample to 40 ohm-m where q_t is maximal along the CPTU logs (Figure 4). The values of electrical resistivity in the RCPTU and model of electrical resistivity decrease in depth. At a depth of 12 m, both methods give a value of 13.6 ohm-m which gradually decreases to 5.3 and 7 ohm-m respectively at a depth of 22 m.

Unit C is composed of 35 to 43% of clay, 51 to 63% of silt and 0.3 to 10% of sand. The water content varies from 23 to 34%. The S_u and S_{ur} values range from 50 to 78 kPa and from 3 to 18 kPa respectively. The w_P and w_L values are around 18 and 36% respectively and the LI varies from 0.3 to 0.9. The pore water salinity increases with depth from 16 to 27 g/l. The SCIP values vary between 1.9 to 3.5 ohm-m. The RCPTU reached only the first few meters in unit C. The electrical resistivity values obtained in this unit are 4.5 ohm-m in average. Values of electrical resistivity extracted from the model of electrical resistivity at each sample depth range from 4.8 to 3.3 ohm-m.

The clay content in unit D varies from 28 to 40%. The silt content ranges from 51 to 59% and the sand proportion is between 4 and 12%. The water content varies from 21 to 26%. The S_u values range from 61 to 75 kPa and the S_{ur} values range between 16 to 21 kPa. The w_P varies between 15 and 18% and the w_L varies from 30 to 37%. The LI has a value of 0.38. The pore water salinity is of 25 g/l in average. The SCIP values vary from 2 to 7 ohm-m and the ERT values extracted from the model at each sample depth average 3 ohm-m.

Units A and B have similar characteristics throughout the study area. Based on the results, unit A is entirely composed of sensitive clay prone to large retrogressive landslides with S_{ur} values below 1 kPa while unit B is not prone to such instability with S_{ur} values well above 1 kPa. As for units C and D, it is interesting to note that the geotechnical properties of the samples associated with these units in the site no. 60044, where the clay layer is thinner, are very different than those of the samples from the sites no. 60065 and 60071. For instance, the S_{ur} values for unit C and D in the samples from the site no. 60044 range between 0.27 to 0.69 kPa. The LI values vary from 1.5 to 1.9, the pore water salinity is about 0.45 g/L and the SCIP resistivity is around 20 ohm-m. Values of electrical resistivity extracted from the model of electrical resistivity at each sample depth are all above 30 ohm-m. One possible explanation is that a thinner deposit is more vulnerable to leaching of dissolved salts than a thicker one. This is consistent with the measurements of pore water salinity in the site no. 60044 which are significantly lower than the salinity measured in the sites no. 60065 and 60071 where the deposit thickness is greater.

5 DISCUSSION

The relationship between S_{ur} and pore water salinity is provided in figure 6. The remoulded shear strength increases with the increase in salinity. For clay samples characterized by S_{ur} above 1 kPa, the pore water salinity is higher than 2.8 g/l. Torrance (1974) suggested similar values for leached clays.

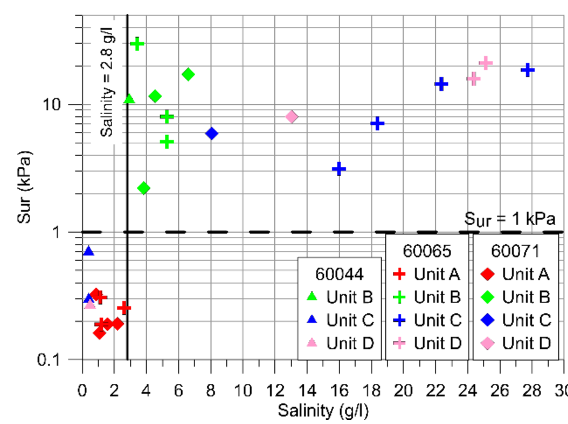

Figure 6. Relationship between remoulded shear strength (S_{ur}) and pore water salinity of clay samples of du Sud River area.

The relationship between S_{ur} and electrical resistivity values extracted from the model of electrical resistivity (ERT) and the SCIP tests is shown in figure 7. A value of electrical resistivity of 10 ohm-m from ERT can delineate leached clay samples with S_{ur} lower than 1 kPa. For the SCIP tests, a limit of 8.8 ohm-m looks more appropriate.

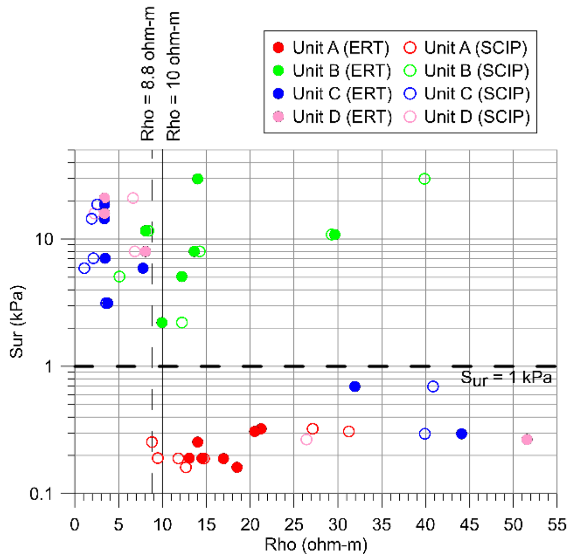

Figure 7. Relationship between remoulded shear strength (S_{ur}) and electrical resistivity obtained from ERT and SCIP methods of clay samples of du Sud River area.

The relationship between the electrical resistivity values extracted from the model of electrical resistivity (ERT) and pore water salinity is provided in figure 8. An exponential function with a coefficient of correlation of 0.89 fits very well this relationship. A pore water salinity of 2.8 g/l which is the limit to identify leached clays in the current study corresponds to an electrical resistivity of 13.23 ohm-m which is relatively close to the limit of 10 ohm-m value as suggested by Solberg et al. (2014) for delineating leached clays.

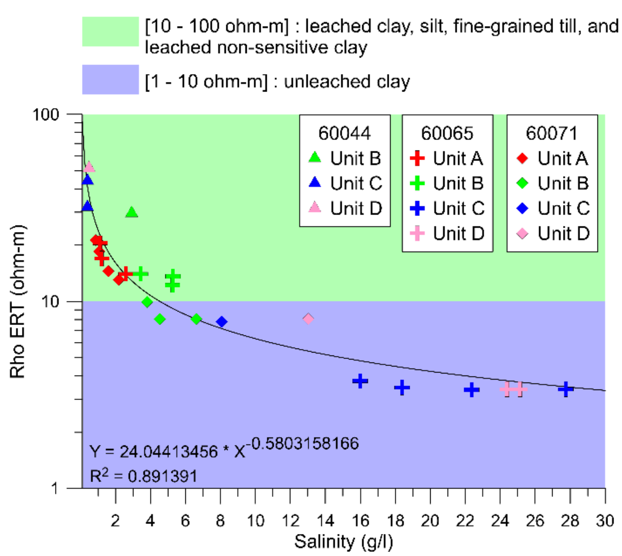

Figure 8. Relationship between electrical resistivity assessed from ERT and pore water salinity of clay samples of du Sud River area.

The geotechnical and geophysical limits to delineate leached clay according to the results of the present study are given in table 1.

Table 1. Geotechnical and geophysical limits used to delineate leached clay of du Sud River area.

	Sur ≤ 1 kPa (prone to large retrogressive landslides)	Sur > 1 kPa
LI	≥ 1.2	< 1.2
SCIP	≥ 8.8 ohm-m	< 8.8 ohm-m
ERT	≥ 10 ohm-m	< 10 ohm-m
Pore water salinity	≤ 2.8 g/l	> 2.8 g/l

Nevertheless, it is necessary to consider the type of soil prior to delineate leached clay for values of electrical resistivity above 10 ohm-m. Other types of soil such as silt and fined-grained till which are not sensitive can be characterized by electrical resistivity between 10 and 100 ohm-m (Solberg et al. 2014).

A few data points associated with unit B are located in the leached clay side of the relationship between the electrical resistivity and salinity even though unit B is not characterized by geotechnical properties of a clay prone to large retrogressive landslides. Since some data points also fall into the leached clay category even with a pore water salinity above 2.8 g/l, other factors are influencing the electrical resistivity value in this unit.

Based on the CPTU response in unit B, there is a large increase in the tip resistance in this unit in comparison to the three other units (Figure 4). The clay content and water content of the samples in unit B are slightly lower than the ones in the other units. However, the variability of electrical resistivity as observed in unit B (Figure 7) is not explained by the variations in clay content and water content alone. More geotechnical tests are needed on samples of this unit to assess its geotechnical behavior and geophysical response.

Although some samples of unleached clay are associated with leached clay, no leached clay sample is identified as unleached clay with the ERT method. From the results presented herein, clay samples from the area of du Sud River with electrical resistivity values below 10 ohm-m are not prone to large retrogressive landslide.

6 CONCLUSION

The study area of du Sud River near Saint-François-de-la-Rivière-du-Sud, Québec, Canada, is composed of a superficial 15 to 20 m thick layer of clay prone to large retrogressive landslides. Where the clay deposit is thick enough, the underlying layers are not composed of leached clay. Based on the results presented herein, the pore water salinity is a major factor influencing the values of electrical resistivity of clay deposit, but other factors are also to be considered in order to properly identify leached clay and other non-sensitive soil with high electrical resistivity values.

In this study, the clay samples prone to large retrogressive landslides with remoulded shear strength (S_{ur}) lower than 1 kPa and liquidity index (LI) in excess of 1.2 are characterized by values of electrical resistivity above 10 ohm-m and pore water salinity below 2.8 g/l. Moreover, all the samples with values of electrical resistivity below 10 ohm-m are not prone to large retrogressive landslides as assessed from the geotechnical properties measured on these samples.

Based on the results from the geotechnical and geophysical investigation performed in Saint-François-de-la-Rivière-du-Sud, the electrical resistivity tomography can is an efficient geophysical method to delineate unleached clay zones in clay deposit but with some limitations regarding soils with similar electrical resistivity. However, other studies are needed to improve the relationship between the electrical resistivity and the geotechnical properties of saline and leached clay deposit in Quebec post-glacial marine deposit.

7 ACKNOWLEDGEMENTS

The research funding for this study was provided by the *Plan d'action 2013-2020 sur les changements climatiques* (PACC 2013-2020) and by the *Fonds vert* of the government of Québec.

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