Geophysical and geotechnical characterization of a sensitive clay deposit in Brownsburg, Quebec

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Abstract: The results of a geophysical and geotechnical investigation in a sensitive clay deposit affected by numerous landslide scars in Vases Creek Valley near Brownsburg, Quebec, Canada are presented herein. The main objective of this investigation was to assess the suitability of electrical resistivity measurements in marine clay deposits for mapping out areas prone to flowslides. In addition to a 1.6 km-long electrical resistivity tomography (ERT) carried out perpendicular to the axis of the Vases Creek Valley, six piezocone penetration tests and five boreholes with sampling were also performed along the geophysical survey line. Moreover, standard geotechnical parameters and pore water salinity, as well as electrical resistivity of undisturbed clay samples were measured in the laboratory. According to the correlations found between the remoulded shear strength, the pore water salinity and the electrical resistivity, clay samples with salinity below 6.2 g/l are characterized by remoulded shear strength below 1 kPa and electrical resistivity above 2.8 and 10 Ωm measured respectively in the field and in the laboratory. In such conditions, sensitive clay deposits can be prone to flowslides if all other criteria are also met. Based on this resistivity limit value, only one small area of non-sensitive clay was identified in the interpretative stratigraphic cross-section assessed from the field investigation. Otherwise, the deposit is entirely composed of sensitive clay. The ERT is a promising geophysical tool for the delineation of areas prone to large landslides in eastern Canada.

1 Introduction

In the province of Quebec, Canada, approximately 90% of the population is settled within the limits of marine transgression of the Champlain, Laflamme and Goldthwait seas (Demers et al. 2014). The effects of leaching on geotechnical properties of such marine clays are well documented (Rosenqvist 1966). Leached clay deposits can be prone to flowslides, which is a great hazard for the population and for man-made infrastructures, justifying the need to develop tools to identify vulnerable areas. According to many recent Scandinavian studies, (Solberg et al. 2008; Lundström et al. 2009; Long et al. 2012; Dahlin et al. 2014; Pfaffhuber et al. 2014), areas of leached clay can be efficiently delineated using geophysical surveys along with standard geotechnical investigations. As a part of its mandate to map landslide-prone areas and assess the associated risk (Potvin et al. 2014), the Quebec government has recently undertaken, in collaboration with researchers at Université Laval, the characterization of a sensitive clay deposit affected by numerous large landslides in the Vases Creek Valley near Brownsburg, Quebec. The results of this investigation are presented herein.

2 Site description

The study area is located in the upstream part of Vases Creek Valley (Fig. 1). It is bordered to the north by the Canadian Shield's igneous and metamorphic rocks and to the south by a rise in the sedimentary bedrock of the St. Lawrence Lowlands. The center of the valley is buried under up to 60 m-thick clayey deposit of the Champlain Sea (Ross 2004). According to Carson (1981), up to 35 m of fluvioglacial sediments are present south of Vases Creek, between the marine clay deposit and the underlying till. Banks of 10 to 15 m high formed in the deposit along the creek. Following the study of landslides and geotechnical properties of the clay deposit in the valley numerous large landslide scars were mapped by Fortin-Rhéaume (2013) (Fig. 1).

3 Methodology

A 1.6 km-long induced polarization profiling was performed across the Vases creek valley using a Tx II transmitter and a GRx8-32 receiver from *Instrumentation GDD inc* (see location in Fig. 1). A dipole-dipole array with 20 m electrode spacing and a 10-m array displacement were used to perform the profiling. This configuration allows to investigate the entire clay deposit which reaches up to almost 50-m thick along the profiling. The polarity of the current was switched each 2 seconds with 2 seconds without electrical current flow in between to avoid the polarization of the electrodes. Inversion of the electrical resistivity data was performed with RES2DINV software using a smoothness-regularized least-square method.

Six piezocone penetration tests with pore pressure measurements (CPTU) were performed along the geophysical survey line (see location in Fig. 1). The cone has a 5 T capacity and was pushed at a constant rate of 1 cm/s in order to obtain a good resolution in clay. In addition to the CPTUs, clay samples were recovered with a stationary piston sampler and thin wall tube during drilling at five of the six CPTU sites. Some granular soil and bedrock samples were recovered by drilling.

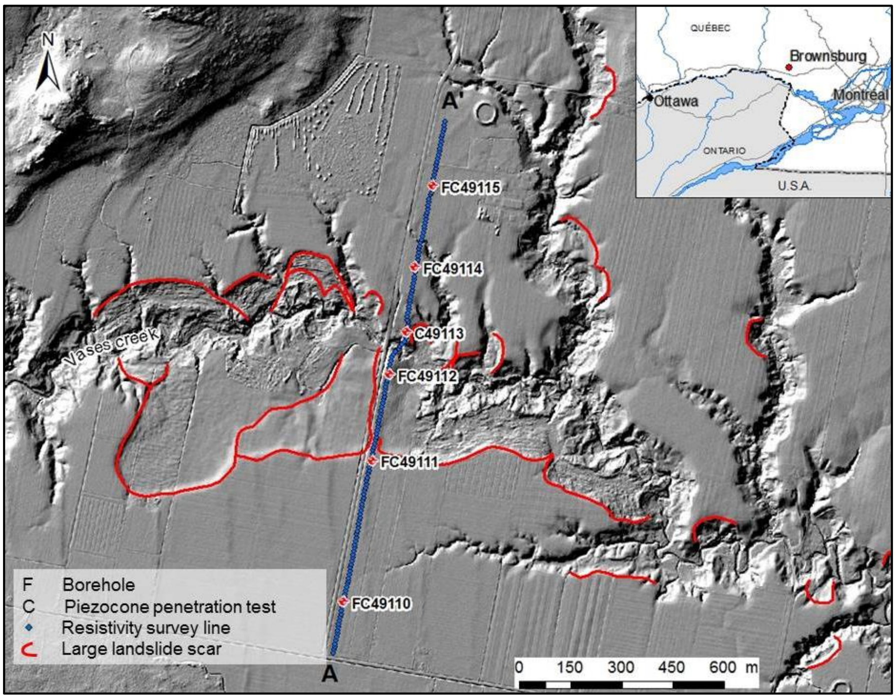

Fig. 1. Map of the Vases Creek Valley near Brownsburg, Quebec, showing the location of the geophysical and geotechnical investigation. Large landslide scars are delineated by red lines on a hillshade background.

Standard geotechnical tests, including grain size analysis, Atterberg limits and fall cone tests, were performed in the laboratory on each sample. Pore water salinity was determined with three methods: refractometry, electrical conductivity and X-ray fluorescence. Electrical resistivity was also measured on each samples with an apparatus made of two 85 mm copper electrodes called “SCIP” from *Instrumentation GDD inc*. The samples were 200 mm long, which is the same length that was used for standard geotechnical laboratory tests. Constant current of 500 µA was applied and a current cycle of 2 s was used as for induced polarization profiling.

4 Results

According to the geotechnical investigation, three different stratigraphic units called A, B and C were identified in the marine clay deposit. For instance, the geotechnical profiles of borehole F49114 is presented in Fig. 2 (see location in fig. 1). Location of the CPTUs with the identification of these three units is shown on a cross-section along the AA' geophysical survey line on Fig. 3a. Unit A corresponds to the surficial weathered clayey crust and is located from the surface to a depth of 2.5 to 3.0 m. Unit B is located between elevation 85 and 65 m.a.s.l. and is characterized with a linear increase of CPTU undrained shear strength. This unit is composed of pale grey clay with pink and blackish banding. The clay and silt content of this unit are between 70 and 86% and between 13 and 42% respectively. Its water content is generally higher than 75% and can reach up to 104%. The plasticity and liquidity limits in this unit vary between 24 and 30% and between 49 and 77% respectively. The intact and remoulded shear strength vary between 14 and 43 kPa and between 0.1 and 1.7 kPa respectively. The liquidity index varies between 1.2 and 2.5. Unit C is located from elevation 72 and 48 m.a.s.l. and it is composed of dark grey silt and clay with a mottled black pattern. This unit is composed of 33 to 56% of clay with 43 to 58% of silt. The water content of this unit varies between 35 and 64% and the plasticity and liquidity limits varies respectively between 20 and 26% and between 30 and 46%. The intact and remoulded shear strength vary between 35 and 71 kPa, and between 0.07 and 2.7 kPa respectively.

Pore water salinity of clay samples is also given in Fig. 2. Results from electrical conductivity and X-ray fluorescence are similar, with less than 0.3 g/l difference between the methods. However, for the samples with the highest salt content, gaps of up to 2 g/l are observed when comparing the salinity values from these two methods and the results from the refractometer. Apart from the previous results from refractometry, the pore water salinity varies between 0.3 and 7.6 g/l. Salinity values are below 1 g/l for samples collected in borehole F49111 and F49112, and below 2 g/l in boreholes F49110 and F49115. Only the samples from borehole F49114 have salinity values above 2 g/l.

The model of electrical resistivity obtained from the inversion of the induced polarization profiling is presented in Fig. 3b. Two areas having a resistivity below 10 Ωm, appearing in blue in the model, correspond to slightly leached marine clay. The first area is located south of the Vases Creek, while the second one is north of the creek. According to the different boreholes and CPTUs, leached clay has resistivity values between 10 and 80 Ωm and sand or gravel has resistivity values between 20 and up to 160 Ωm.

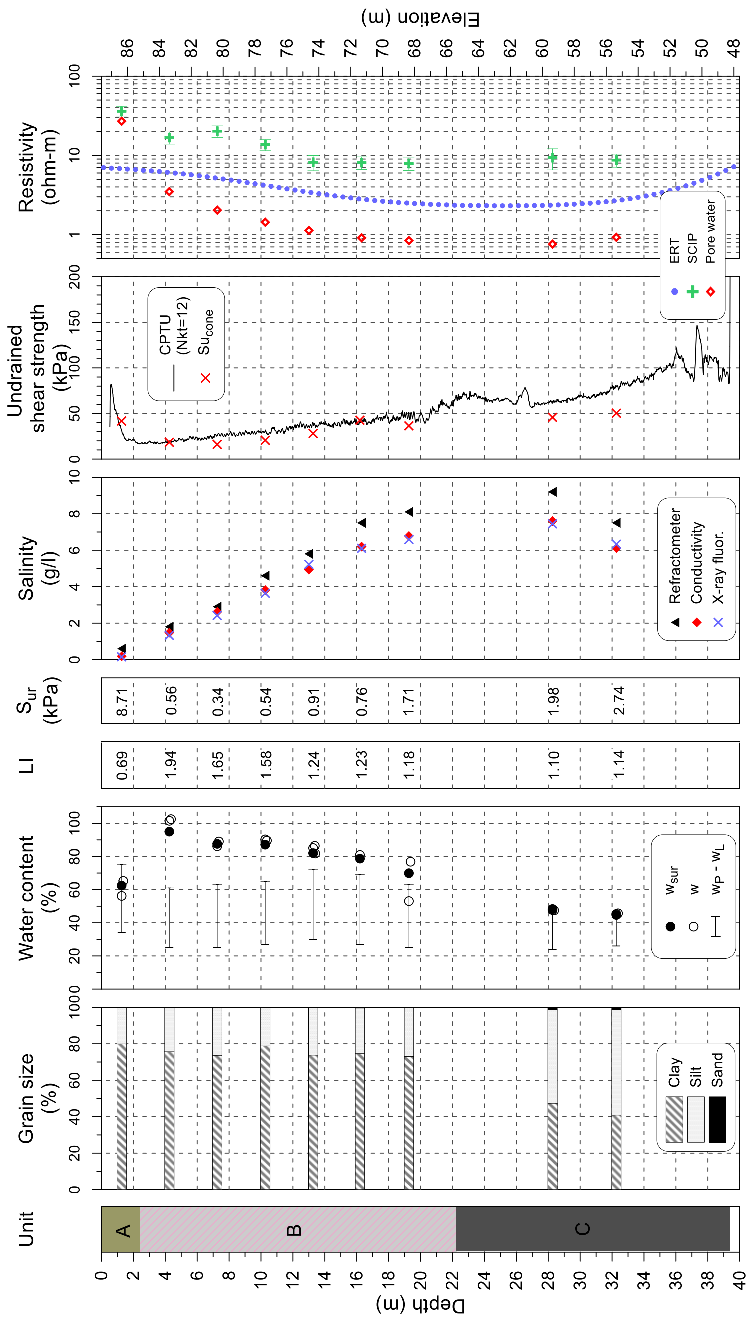

Fig. 2. Geotechnical and electrical resistivity profiles of borehole F49114 in the marine clay deposit of Brownsburg, Quebec.

Resistivity values higher than 160 Ωm in the southern area and higher than 500 Ωm in the center of the profile indicates the presence of bedrock, which was confirmed by the dolomite sample intercepted at depth in borehole F49110 and by the gneissic roc in borehole F49112.

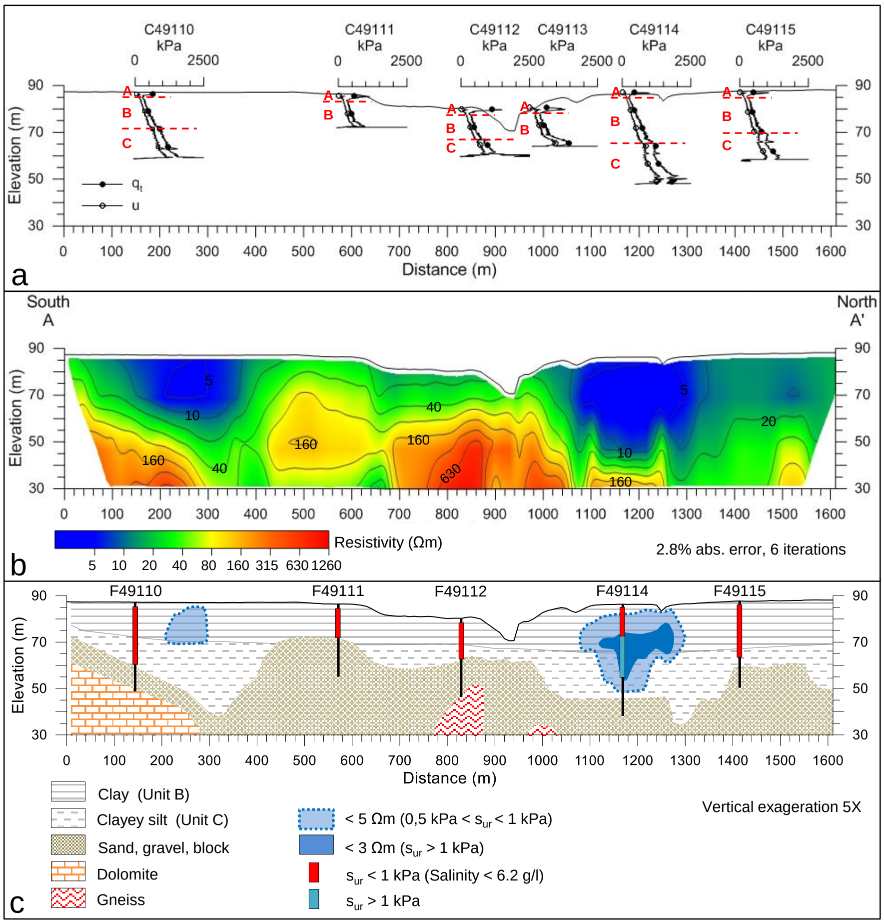

Fig. 3. a) Stratigraphy of the marine clay deposit in the Vases Creek Valley near Brownsburg, Quebec assessed from the CPTU profiles. b) Model of electrical resistivity obtained from the inversion of the induced polarization profiling. c) Stratigraphic cross-section of the marine clay deposit assessed from the combined interpretation of geotechnical and geophysical characterization. Most of the investigated clay deposit is prone to flowslides (s_{ur} < 1 kPa), except for the dark blue area with electrical resistivity below 3 Ωm and s_{ur} > 1 kPa.

Electrical resistivity log assessed from the model of electrical resistivity at the location of the borehole F49114 is also given in Fig. 2 along with the measurements of electrical resistivity on clay samples and pore water. The electrical resistivity data show the same trend. Minimum values of electrical resistivity are 0.8 Ωm for pore water, 2.4 Ωm in the log assessed from the resistivity model and 7.9 Ωm with the SCIP measurements on clay samples. The difference between the resistivity values obtained from ERT and SCIP measurements is most likely due to the current flow in the soil. On one hand, during ERT, the current flows parallel to the bedding principally in the most conductive layers which reduces somewhat the electrical resistivity. On the other hand, in the SCIP cell, the current flows perpendicular to the bedding in all the layers even the most resistive ones which increases the electrical resistivity.

5 Discussion

According to Tavenas (1984), one of the criteria for the assessment of sensitive clays prone to flowslides is a s_{ur} below 1 kPa, which also corresponds to a liquidity index above 1.2. For this reason, this criterion was used in this study in order to delimit areas prone to flowslides. Clay samples of units B and C have s_{ur} between 0.07 and 2.7 kPa while values of pore water salinity assessed from the X-ray fluorescence vary between 0.3 and 7.5 g/l. The correlation between remoulded shear strength and pore water salinity is shown in Fig. 4. Clay samples with s_{ur} below 1 kPa have salinity values below 6.2 g/l. A salinity value of 2.5 g/l was found in the Brownsburg clays for s_{ur} below 0.5 kPa, which is similar to the salinity value of 2 g/l proposed by Torrance (1975) for quick clays.

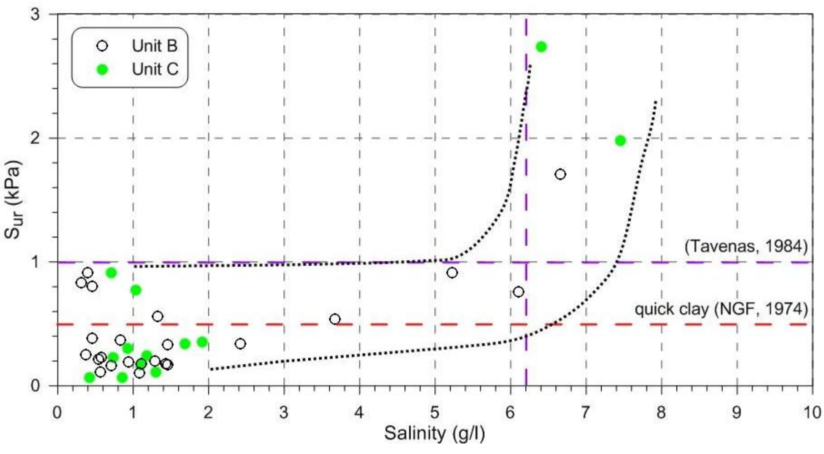

Fig. 4. Relationship between the remoulded shear strength and pore water salinity for units B and C of marine clays of Brownsburg, Quebec.

Values of electrical resistivity were taken from the model of induced polarisation at the location of each clay sample. In Fig. 5, values of electrical resistivity assessed from resistivity model and from SCIP measurements are related to the pore water salinity. For salinity values below 2.5 g/l, the resistivity assessed from ERT varies between 5 and 85 Ωm and forms a scatter plot with no evident trend, possibly caused by the large volume of soil involved. For salinity values above 2.5 g/l, the ERT resistivity values line up according to a semi-log law. Using the salinity limit value of 6.2 g/l which corresponds to a s_{ur} of 1 kPa (Fig. 4), a resistivity of 2.8 Ωm is found as a limit value to identify sensitive clays prone to flowslides in Brownsburg (see Fig. 5). This resistivity limit is found for a dipole-dipole array with electrode spacing of 20m. Using the same semi-log relation, a value of 5 Ωm is bound to a salinity of 2.5 g/l which also corresponds to a s_{ur} of 0.5 kPa. Resistivity values from laboratory measurements are higher and less scattered than ERT resistivity values. For salinities below 2.5 g/l, resistivity is above 17 Ωm and for salinities between 5 and 7.5 g/l the SCIP resistivity values are between 7 and 10 Ωm. According to Solberg et al. (2008), Long et al. (2012), and Donohue et al. (2012), a limit value of 10 Ωm is generally admitted for quick clay in Norway (s_{ur} < 0.5 kPa). However, a limit value of about 6 Ωm is presented in Swedish studies for s_{ur} < 0.4 kPa (Dahlin et al. 2014; Lundström et al. 2009).

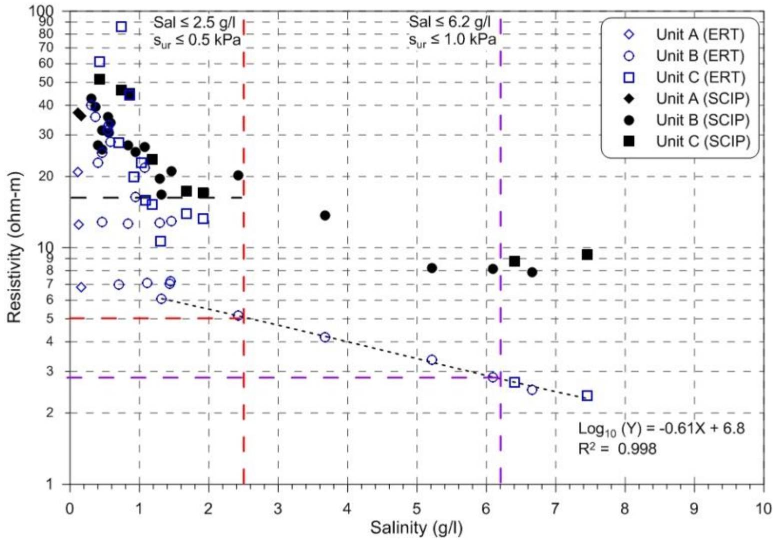

Fig. 5. Relationship between the electrical resistivity and pore water salinity of marine clays of Brownsburg, Quebec.

In Fig. 3c, the interpretation of the geotechnical and geophysical investigation is presented as a stratigraphic cross-section along the AA' geophysical survey line.

Sections of boreholes with clay samples that have s_{ur} values below 1 kPa are identified with red boxes while the section with s_{ur} above 1 kPa is identified with a blue box. Two light blue areas with resistivity below 5 Ωm are identified in Fig. 3c. These areas correspond to inferred salinity between 2.5 and 6.2 g/l and s_{ur} values between 0.5 and 1 kPa. Therefore, the clay in these areas is assumed to be sensitive but not quick. A dark blue area within the light blue area north of the Vases Creek, corresponding to resistivity below 3 Ωm, was also delineated. According to the relationship presented in Fig. 5, this area has pore water salinity above 6.2 g/l and s_{ur} above 1 kPa. Clay in dark blue area would therefore not be sufficiently leached to be prone to flowslides. Based on Tavenas' (1984) flowslide criteria of s_{ur} below 1 kPa and the criterion of resistivity above 3 Ωm proposed in this study, most of the investigated section of marine clay deposit in the Vases Creek Valley would be prone to flowslides, except for the dark blue area in the interpretative stratigraphic cross-section north of the Vases Creek in Fig. 3c. The results obtained in this study are similar to those obtained by Carson (1981).

6 Conclusions

A geophysical and geotechnical investigation of a marine clay deposit was performed in the Vases Creek Valley, near Brownsburg, Quebec to characterize the standard geotechnical properties, pore water salinity and electrical resistivity, and to assess the areas prone to flowslides. According to the results of this investigation, clay samples with pore water salinity below 6.2 g/l in Brownsburg are characterized by remoulded shear strength below 1 kPa and electrical resistivity above 2.8 and 10 Ωm measured respectively in the field and in the laboratory. In such conditions, sensitive clay deposits can be prone to flowslides if all other criteria are also met. Based on the limit of 2.8 Ωm, one area of clay was identified as not prone to flowslides (s_{ur} > 1 kPa) in the interpretative stratigraphic cross-section, but otherwise, most of the investigated section is composed of sensitive clay prone to flowslides (s_{ur} < 1 kPa). The ERT is a promising geophysical tool for the delineation of areas prone to large landslides in sensitive clay deposits. The achievement of future studies in other sensitive clay deposits is needed to improve the relationships between the geotechnical and geophysical properties given herein and to refine the limit values of pore water salinity, remoulded shear strength and electrical resistivity. Areas having different geological contexts in Quebec should be also studied in order to check if these relationships and limit values are applicable to all the sensitive clay deposits found in eastern Canada.

Acknowledgments

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