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Published in:
Near Surface Geophysics

DOI:
10.3997/1873-0604.2013044

2013

Near Surface Geophysics, 2013, **11**, 659-670 doi:10.3997/1873-0604.2013044

Mapping of quick clay using geoelectrical imaging and CPTU-resistivity

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Received May 2012, revision accepted August 2013

ABSTRACT

Quick clay has a major impact on landslide risk and it is therefore of considerable interest to map its presence and extent. In Sweden, quick clay has been involved in most landslides in soft clay with serious consequences. The predominant method for detection of quick clay in Sweden has been to take undisturbed samples and to perform fall-cone tests on the clay in its undisturbed and remoulded state. Originally deposited in saltwater in a marine environment, the salt maintains the stability of the clay. When the salt is leached out, the clay can become quick. When salt is leached from clay of marine origin the resistivity increases. In this study the intention was to calibrate electrical imaging with cone penetration tests with resistivity measurements (CPTU-R) and measurement of the total penetration resistance, i.e. the total rod friction, together with both geotechnical and chemical analyses on specimens in the laboratory.

The results show that electrical imaging can be used for separation of leached soil volumes in marine clays that may form quick clay, from those where the salt content remains too high for this. In the dry crust and thin weathered zone at the top, the resistivity is high but the clay is non-quick. Also soils with less clay content will have higher resistivity without being quick. The technique may thus be used as a screening tool in order to delimit areas where further investigations are needed from areas that do not require more attention. This has a potential of saving significant resources if used in a relatively early stage of the survey process. It can also increase the overall quality and reliability of the survey results.

The induced polarization (IP) results are consistent and seem to be geologically realistic, and appear to contain additional information to the resistivity that is related to material or electrochemical properties, although it is not clear how due to lack of sufficiently detailed reference data.

The electrical imaging gives a general picture of the variation in resistivity along soil sections. The CPTU-R gives variations at depth with very high vertical resolution in one specific location. There is generally good agreement between the models based on electrical imaging and the CPTU-R. The CPTU-R results may be used to calibrate the electrical imaging results with quick clay estimations based on rod friction.

INTRODUCTION

The designation 'quick clay' refers to a clay whose structure collapses completely at remoulding and whose shear strength is thereby reduced almost to zero. Quick clay is formed through slow geological processes, mostly in sediments deposited in seawater at the last deglaciation. Research into the formation, properties and occurrences of quick clay has been carried out since the 1940s, mainly in Sweden, Norway and Canada (e.g., Rosenqvist 1946).

In these countries, quick clay has been involved in the major part of the landslides in soft clay with serious consequences. This led to the early development of criteria and methods for landslide hazard taking the occurrence of quick clay into account (Viberg 1981; Gregersen and Løken 1983; Lebuis, Robert and Rissman 1983). As quick clay has a major impact on landslide risk it is of considerable interest to map its presence and extent.

The relationship between the undisturbed and remoulded shear strength is designated sensitivity (St). In Sweden, quick clay is designated as a clay with sensitivity higher than 50 (St > 50) and a remoulded, undrained shear strength less than 0.4 kPa ($\tau_R < 0.4$). A highly sensitive clay is in Sweden defined as a clay with a sensitivity St > 30. Other countries have slightly different limits of sensitivity and remoulded undrained shear strength for the definition of quick clay.

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For a long time, the predominant method for detection of quick clay in Sweden has been to take undisturbed samples and to perform fall-cone tests on the clay in its undisturbed and remoulded state. This is reliable but rather costly and it only provides point information. The use of sounding methods to detect quick clay has been investigated earlier. Rygg (1978) found that the slope of penetration resistance versus depth could be linked to the sensitivity.

Based on his findings Möller and Bergdahl (1982) investigated the correlations between sounding resistance and sensitivity for the most commonly used sounding methods at that time: weight sounding and static pressure sounding. Correspondingly, the possibility of mapping quick clay using four different sounding methods and surface electrical imaging were investigated by Rankka *et al*. (2004) and Lundström, Larsson and Dahlin (2009). In Norway, there is an accepted method for establishing the presence of quick clay or highly sensitive clays in connection with slope stability assessment, which involves rotary pressure sounding. In Sweden, the use of sounding methods for mapping of quick clay only came into practical use in recent years. The potential for using electrical imaging for delineating areas with potential quick clay was demonstrated in the study presented by Rankka *et al*. (2004) and Lundström *et al*. (2009). These results are supported by results presented by Solberg *et al*. (2008) and Donohue *et al*. (2012). The above experiences have resulted in a Norwegian guideline for the use of electrical imaging for potential quick clay areas (Solberg *et al*. 2010).

This paper describes part of a study with an intention of finding possible ways to improve the common method in Sweden of mapping quick clay. The study was part of a large stability investigation (the Göta River Commission) covering both sides of the Göta River, from Lake Vänern to the city of Gothenburg, a total length of 186 km (Swedish Geotechnical Institute 2012). The work presented in this paper was carried out as a separate study within the Göta River Commission. The aim was to investigate whether electrical imaging based on surface electrode measurements together with geotechnical sounding and sampling can give a more complete picture of the presence of quick clay. The intention was to calibrate electrical imaging with cone penetration tests with resistivity measurements (CPTU-R) and measurement of the total penetration resistance, i.e. the total rod friction, together with both geotechnical and chemical analyses on specimens in the laboratory (Löfroth *et al*. 2011). The applicability of using the penetration force for detection of quick clay is supported by the results from the Göta River investigations (Löfroth 2011).

FORMATION OF QUICK CLAY

The geochemistry of the porewater is extremely important for the development of quick clay. This was observed in the 1920s (Holmsen 1929) and has been investigated in a great number of studies since then (e.g., Bjerrum 1954; Söderblom 1969; Torrance 1975 and a summary by Brenner *et al*. 1981). Originally deposited in saltwater, the salt maintains the stability of the clay. Due to, for example, infiltration of rainwater, groundwater flow or artesian pressure in underlying permeable soil or rock, the clay deposits can be subjected to leaching. When the salt is leached out, the clay can become quick. Other chemical substances (notably magnesium) seem to increase the stability again. Precipitation is freshwater, with a low salt content. When freshwater infiltrates salt clay, the ions in the porewater are easily carried away with the water. Thus sodium and chloride are rinsed downstream in the clay. The new porewater has too little sodium for equilibrium with the clay particle surfaces. Other ions from the infiltrating water replace sodium on the clay surfaces and the sodium from the surfaces comes into the porewater. After a certain amount of leaching, the salt content or ionic strength in the porewater of the clay is insufficient to maintain the stability. A number of studies have tried to estimate the salt content of the clays (Andersson-Sköld *et al*. 2005; Helle *et al*. 2009). Most are in the region of 2–5 g/l salt in the porewater. The exact salt content where instability occurs seems to depend on clay mineralogy, iron content and minerals, content of organic matter and calcium carbonates, etc.

Removal of ions with the porewater, exchange of ions on clay surfaces, and weathering of minerals to other minerals act together on the porewater composition. The net effect of leaching, ion exchange and weathering depends on local conditions, and these local conditions have led to quick, salt as well as stable clays in the Göta River valley.

QUICK CLAY, SENSITIVITY AND RESISTIVITY

Clay is defined as being quick based on its sensitivity, which is a mechanical parameter related to the shear strength of the soil. It has as such no obvious relation to the chemical properties of the soil.

The resistivity of clay is mainly linked to its salt content, but also to its grain size distribution. Research on resistivity ranges for leached and unleached clay has been investigated for several years in both Norway and Sweden. Based on vertical electrical soundings in Verdal, Norway, Berger (1983) proposed resistivity intervals of 1–20 Ωm for salt clay, 20–90 Ωm for leached clay and 70–300 Ωm for the dry crust of the clay. In previous investigations with electrical imaging in Buvika, Norway, Solberg *et al*. (2008) presented ranges of resistivity of salt/intact marine clay of 1–10 Ωm, and a range for leached clay that has a possibility to be quick of 10–80 Ωm. For dry crust, slide deposits and coarser sediments like sand and gravel, resistivity ranges above 80 Ωm are presented. In a guideline for the use of electrical imaging for potential quick clay areas (Solberg *et al*. 2010), resistivity limits recognized in other studies for leached clay with a potential to be quick have been summarized. In these studies the lower limit varies between 5 and 20 Ωm.

In Sweden, in the study by Rankka *et al*. (2004), the geophysical investigations with electrical imaging confirmed an earlier rule (Söderblom 1969) that the resistivity should be ≥ 5 Ωm if the salt content is to be low enough to allow the clay

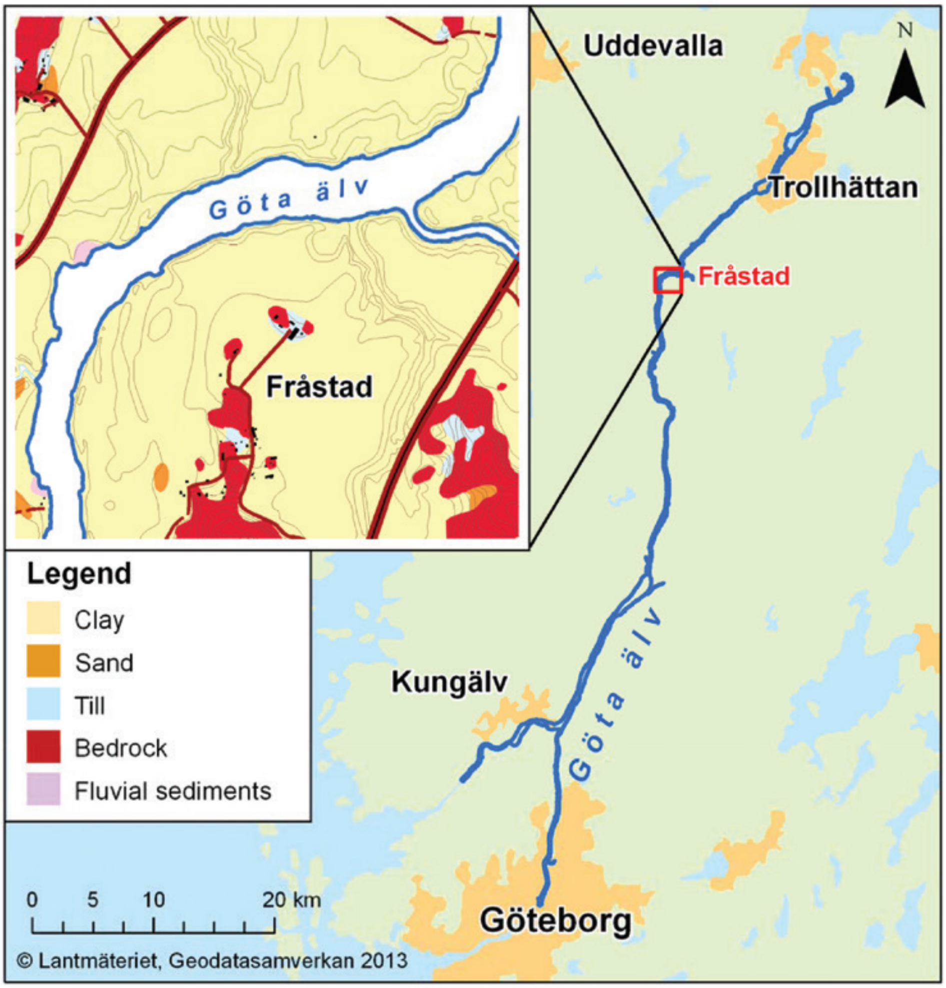

FIGURE 1
Location of test area Fråstad.

to be quick. In this study we have used this limit of 5 Ωm, found by the earlier Swedish studies, as the starting point in our comparisons.

TEST AREA FRÅSTAD

The test area Fråstad is situated on the east side of the Göta River, north of the municipality of Lilla Edet, 60 km north of Gothenburg (Fig. 1). Routine geotechnical investigations were carried out in three sections within the general investigation (Fig. 2).

In the eastern part, section E23/400, the soil profile under the dry crust consists of 20 m of soft clay and there under a coarser layer with a thickness of about 3 m. Underneath the coarser layer there is clay continuing to great depths. In the centre, section E23/540, the soft clay under the dry crust is about 24 m thick and the coarser layer is at least 15 m thick. The soundings have been stopped in the coarser layer. In between these two sections there is an old landslide scar from a typical quick clay landslide.

To the west, in section E23/910, under 3 to 6 m of fluvial deposits, the soft clay continues to more than 45 m depth. Quick clay was found in section E23/400 and E23/540, but not in section E23/910. The porewater pressures in the area are generally lower than hydrostatic pressure, indicating a downward groundwater flow. Especially above the coarser layer the porewater pressures are low.

The photograph in Fig. 3a shows a view along Line 1 towards the south, where the area with rock outcrops is visible in the background. Figure 3b shows a view towards the north-east over the slide scar from Line 1, with the Göta River in the background.

METHOD DESCRIPTION

Geoelectrical imaging

In the electrical imaging conducted within the study, resistivity and time-domain IP data were measured simultaneously as 2D geoelectrical imaging, also known as continuous vertical electrical sounding (CVES) and electrical resistance tomography (ERT) (e.g., Dahlin 2001). An ABEM Terrameter LS with 12 measuring channels was used for the measurements. The maximum transmitter output is 600 V or 2500 mA for a maximum power of 250 W. This instrument can also record the transmitted and received signals with 1 ms sampling interval. A measure-

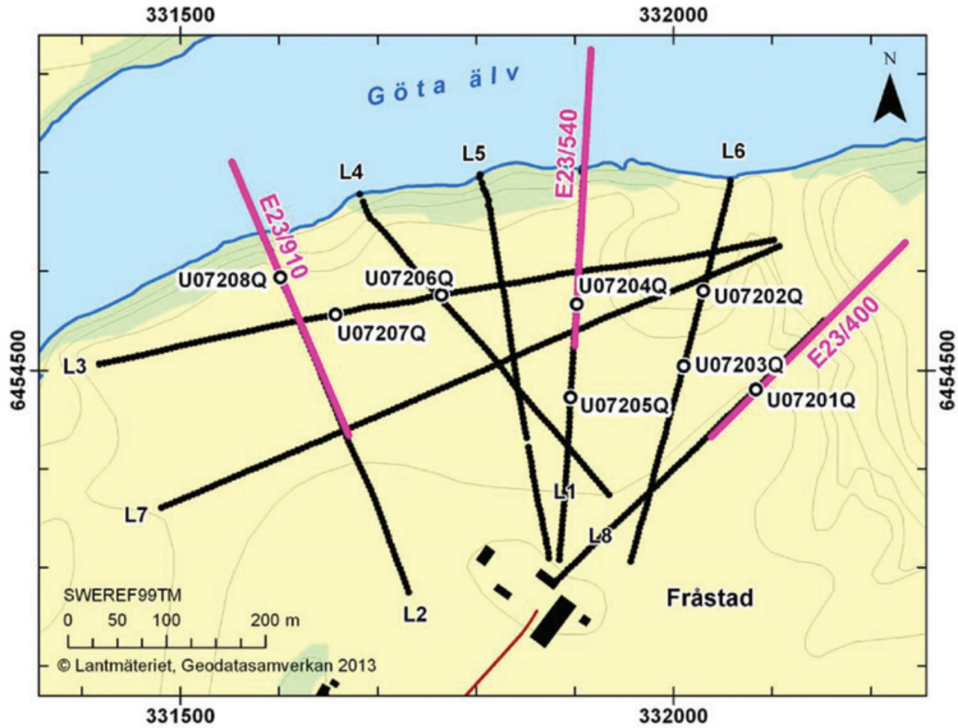

FIGURE 2
The location of the geotechnical reference sections, the geoelectrical investigation lines and CPTU-R measured at Fråstad. The location of a slide scar is also marked.

a) *b)*

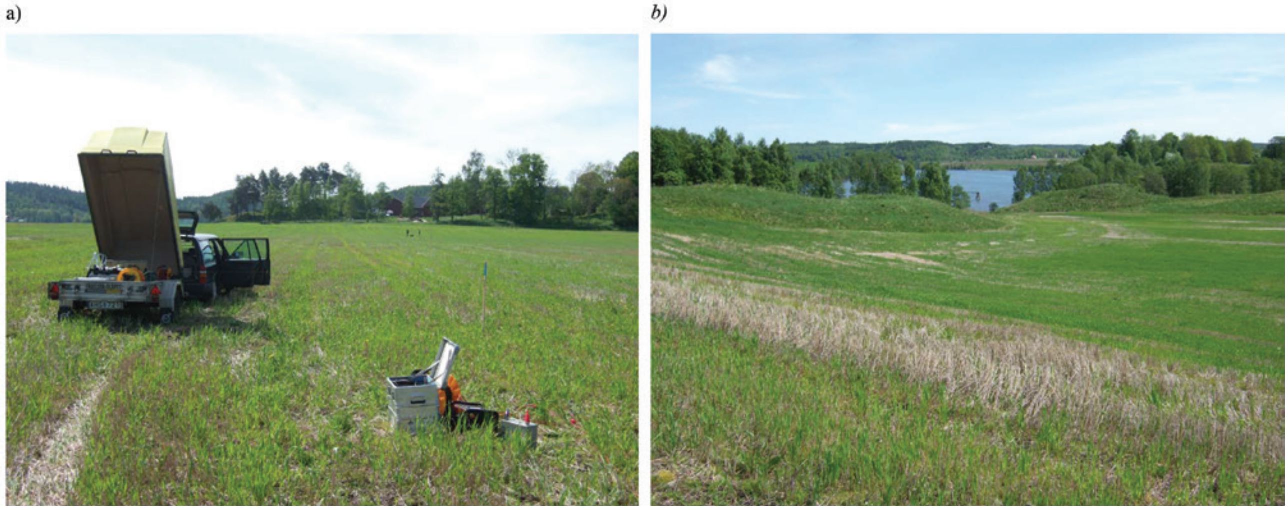

FIGURE 3
Photographs from the field site: a) view along Line 1 showing area with rock outcrops in the background, b) view over the slide scar from Line 1 with the Göta River in the background.

ment cycle with 1.1 s current transmission was used. After a delay of 400 ms the signal for the resistivity measurements was integrated over 600 ms. The IP data were measured in nine time-windows starting 10 ms after current turn-off. The first time window was 20 ms long, and the integration time increased with 20 ms for each time window.

An expanded multiple gradient electrode array was used, i.e. the regular multiple gradient array (Dahlin and Zhou 2006) measurements were supplemented by potential measurements outside the current transmission electrodes in order to enhance the resolution towards the ends of the measurement lines. Multiple gradient array is well suited to multi-channel measurement, speeding up the measurement process, while ensuring a good and informative data coverage, as theoretical (Dahlin and Zhou 2004) and other field comparisons have shown (Dahlin and Zhou 2006).

The software Res2dinv was used for inversion of the measured apparent resistivities and chargeabilities. Res2dinv optimizes a model of the resistivity distribution of the underground using 2D finite element modelling, so that the modelled potentials come as close as possible to the measured values. It is possible to minimize the root mean square error (L2-norm inversion) or the absolute errors between the measured and modelled values (L1-norm inversion). Both the L1-norm and L2-norm options were used for the inversion of the results of this field study (Loke, Acworth and Dahlin 2003). In the case of L1-norm inversion the software calculates the mean model residual as the arithmetic mean of the absolute value of the differences between the logarithm of the measured apparent resistivity and the logarithm of the computed value, whereas for the L2-norm inversion it calculates the root mean square instead. For the IP data, mean model residual is calculated between the measured and computed apparent chargeability.

The IP results are presented as normalized chargeability following the approach suggested by Slater and Lesmes (2002), which is expected to produce images of the variation in surface conductance of the materials.

Eight combined resistivity-IP lines (Line 1 to Line 8) with 5 m as minimum spacing between the electrodes were measured. The locations of the lines are shown in Fig. 2. Measurements were carried out in four sections perpendicular to the Göta River (Lines L1, L2, L5 and L6) which all start at the river. One section is perpendicular to the brook Brodalsbäcken (Line L8). In addition, geoelectrical measurements were carried out in two sections parallel to the Göta River and crossing Lines L1, L2, L5 and L6 (see Fig. 6). The northern parts of Lines L1 and L2 coincide with the onshore part of E23/540 and E23/910, respectively, in the previous investigation. Similarly the north-eastern part of Line L8 follows the south-western part of section E23/400. Lines L4 and L5 covered the area between section E23/540 and E23/910 and Line L6 covered the area between section E23/400 and E23/540 and passed through an existing landslide scar.

CPTU-R

A CPTU-R probe is a standard cone penetration test probe with an added module for measuring the in-situ resistivity placed immediately above the part that measures tip resistance, mantle friction and pore pressure. The module has four electrodes in the form of rings, where the outer ring sends a current through the soil, and the resistivity is measured continuously (Dahlin, Garin and Palm 2004; Helle *et al*. 2009; Rømoen *et al*. 2010). In this study, a resistivity CPTU (CPTU- R) from the Norwegian Geotechnical Institute was used, which has a resistivity module placed 1 m behind the cone. The distance between the outer rings is 20 cm, and the average depth of investigation into the formation consequently some cm. With this equipment the total penetration force was also measured.

The location of the CPTU-R points and the sampling was based on the results of the electrical imaging and the previous investigations. CPTU-R and sampling was carried out where

TABLE 1

Summary of measured resistivity-IP lines with respect to number of data points, length, quality indicators and relation to available geotechnical data. The variation coefficient, sometimes referred to as stacking error, was calculated from two stacks of the resistivity data. The mean residuals relate to the L1-norm (robust) inverted resistivity models.

Line no	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6	Line 7	Line 8
Orientation	N-S	~Ñ-S	~E-W	NW-SE	~N-S	N-S	~E-W	NE-SW
Date measured	2010-05-31	2010-05-31	6/1/2010	2010-06-02	2010-06-02	2010-06-02	2010-06-03	2010-06-04
Length [m]	400	400	700	400	400	400	700	350
No of data points	2550	2550	5444	2550	2550	2550	5437	2342
Var. coef. mean [%]	0.2	0.2	0.3	0.2	0.5	0.1	0.2	0.2
Var. coef. median [%]	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1
Var. coef. std. dev. [%]	0.4	0.5	0.4	0.5	3.7	0.2	0.3	0.4
Mean residual [%]	0.8	1.2	2.2	0.9	1.5	1.7	1.1	1.6
Geotechnical section	E23/540	E23/910						E23/400
Geotechnical soundings (position in metres from start of line)	07059 (5.4), 07060 (36.9), 07061 (105.6), 07062 (165.3)	07063 (4.2), 07064 (36.4), 07065 (99.7), 07066 (154.6), 07067 (219.6)	07065 (206.0), 07061 (495.3)				07067 (202.4) 07062 (456.9)	07056 (57.7), 07055 (127.2)

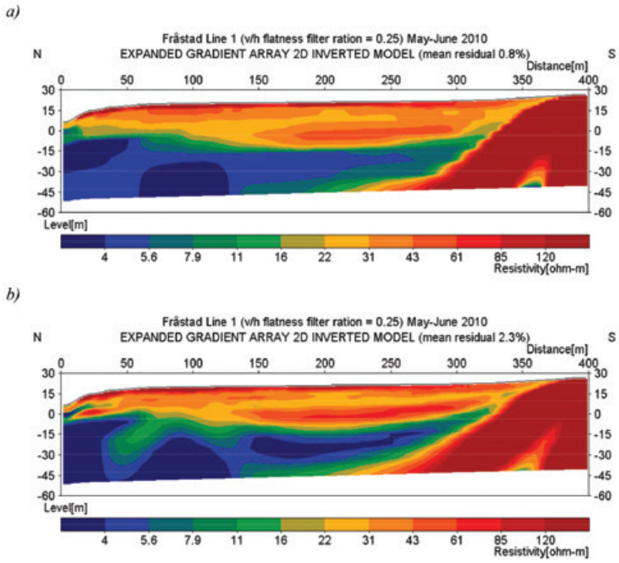

FIGURE 4

Resistivity section for Line 1 based on: a) L1-norm (robust) inversion, b) L2-norm (least-squares) inversion. No vertical exaggeration.

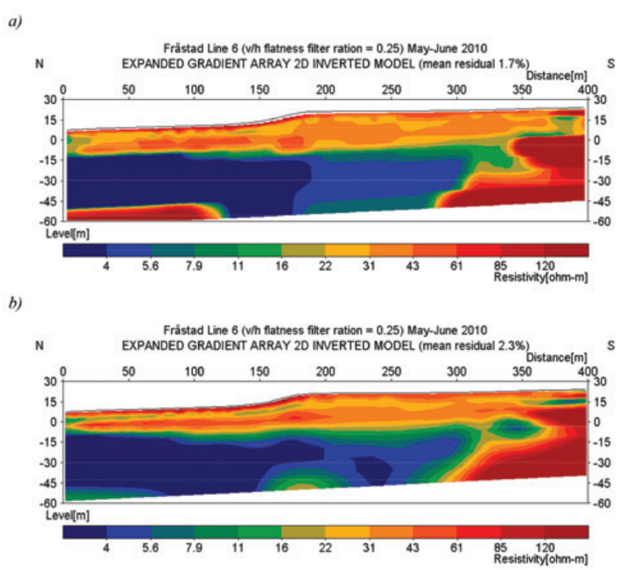

FIGURE 5

Resistivity section for Line 6 based on: a) L1-norm (robust) inversion, b) L2-norm (least-squares) inversion. No vertical exaggeration.

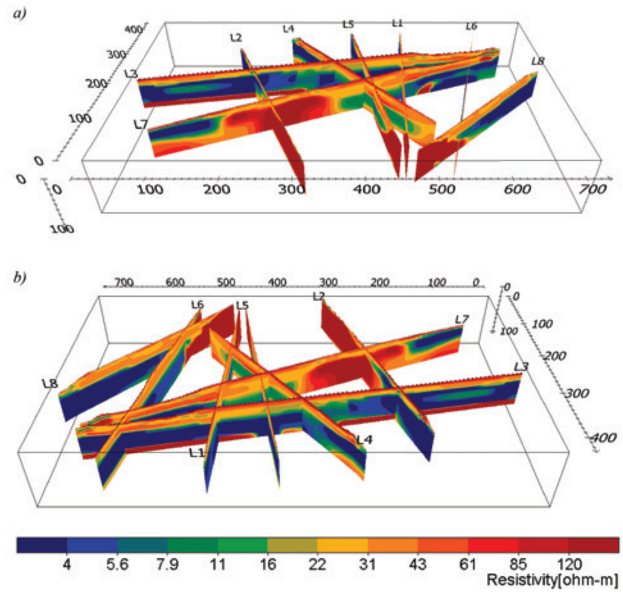

FIGURE 6

3D views over the inverted resistivity sections at Fråstad: a) from south, b) from north.

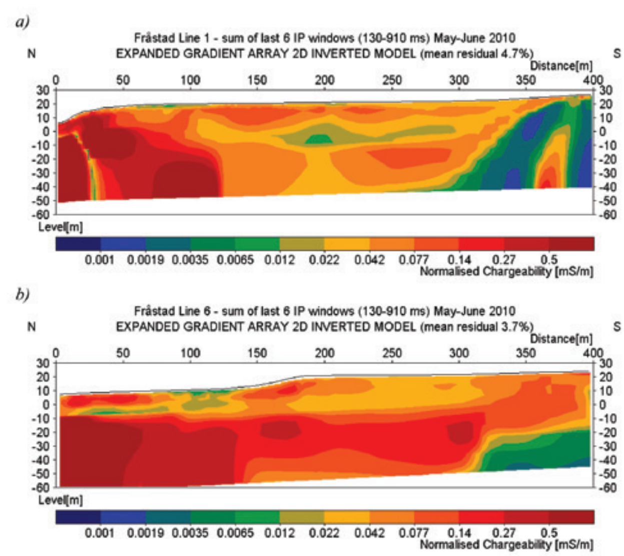

FIGURE 7

Normalized chargeability sections based on L1-norm (robust) inversion, for: a) Line 1, b) Line 6.

both high sensitivity clay (S_t > 30) and quick clay (S_t > 50, τ_{fu} > 0.4) had been found: point U07201Q and U07209Q. In Line L1, CPTU-R was also carried out at point U07205Q. In Line L6, CPTU-R and sampling were carried out at point U07202Q in the landslide scar and CPTU-R at point U07203Q behind the landslide scar. In Line L2, CPTU-R and sampling were carried out at point U07208Q where both clay with medium sensitivity (S_t = 8–30) and high sensitivity (S_t > 30) have been found, but no quick clay. In addition, CPTU-R was carried out at two points in Line L3, U07206Q and U07207Q, to try to verify the horizontal boundary between quick and non-quick clay indicated by the electrical imaging.

RESULTS AND DISCUSSION

Resistivity imaging

During the five field days, eight lines with a combined length of 3800 m and comprising over 26 000 resistivity-IP data points were measured. A measurement current ranging from 200 mA to 1 A was used. The overall data quality at this site is good and no culling of data was made before inversion. The median variation coefficient (stacking error) for the resistivity data is 0.1% or below for all lines, and the mean is 0.5% or less. The ERT lines are summarized in Table 1 together with information of how they are located in relation to the geotechnical surveys. Inversion gave consistent models with low mean residuals (1–2% for resistivity, 3–7% for IP). The results of the measured lines generally agree well. As examples of the results, we present the inverted resistivity section for Line 1 (Fig. 4) and Line 6 (Fig. 5). Figure 6 shows a 3D view summarizing the results of the resistivity investigations. The resistivity colour scale differs slightly from the inverted resistivity section in Fig. 4. The 2D sections are generally consistent with each other, as evidenced by the mostly good match at the intersections in the fence diagram 3D views (Fig. 6). The few intersections between inverted sections with significant mismatch can probably be explained by 3D effects or equivalence phenomena.

On the whole, the results of the resistivity imaging are consistent. Very low resistive (highly conductive) materials are mapped in the deeper sections in the part of the area close to the Göta River, which is a known location for salt clay. High resistivities (low conductivities) are evident in immediate connection with the outcropping crystalline rock in the southern part of the surveyed area. Evaluation of the results against geotechnical sounding data, as detailed below, shows that there is good agreement between the resistivity models. Thus, the lowest resistivities show non-quick saline clay, intermediate resistivity is possible in quick clay but may also be other soil types, and the highest resistivities are due to crystalline rock.

INDUCED POLARIZATION IMAGING

The quality of the IP-data suffers to some extent from small signal levels. The results are nevertheless mostly consistent and show a pattern of variation that is different from that of the resistivity but seems to be geologically realistic. This should contain information that is linked to the material or electrochemical properties of the clay, and it might thus be relevant for the behaviour of the clay. The inverted chargeability sections derived from the IP data have a consistent appearance in the shallow parts, whereas the deeper parts are probably unreliable due to data uncertainty.

The normalized chargeability sections are strongly influenced by the resistivity distribution, where low resistivity will enhance the chargeability. The low resistive saline clay will thus be characterized by high normalized chargeability (Fig. 7a). There are, however, structures in the IP results that have no apparent similarity with the resistivity structure, such as for example the area with low normalized chargeability at shallow depth in the interval 80–129 m on Line 6 (Fig. 7b). This variation in IP effect is expected to have a relation to variations in electrochemical properties of the ground, but the relation is not clear. We do not have sufficiently detailed and relevant reference data to draw any conclusions about the patterns of variation in chargeability, but the results suggest that it may be worthwhile to look further into this in future studies.

CPTU-R

Using the CPTU-R instead of conventional CPTU gives two ways of estimating the presence and layers of quick clay. First the prerequisites for leached and possibly quick clay can be estimated based on the resistivity (5 Ωm used as the limit in this study).

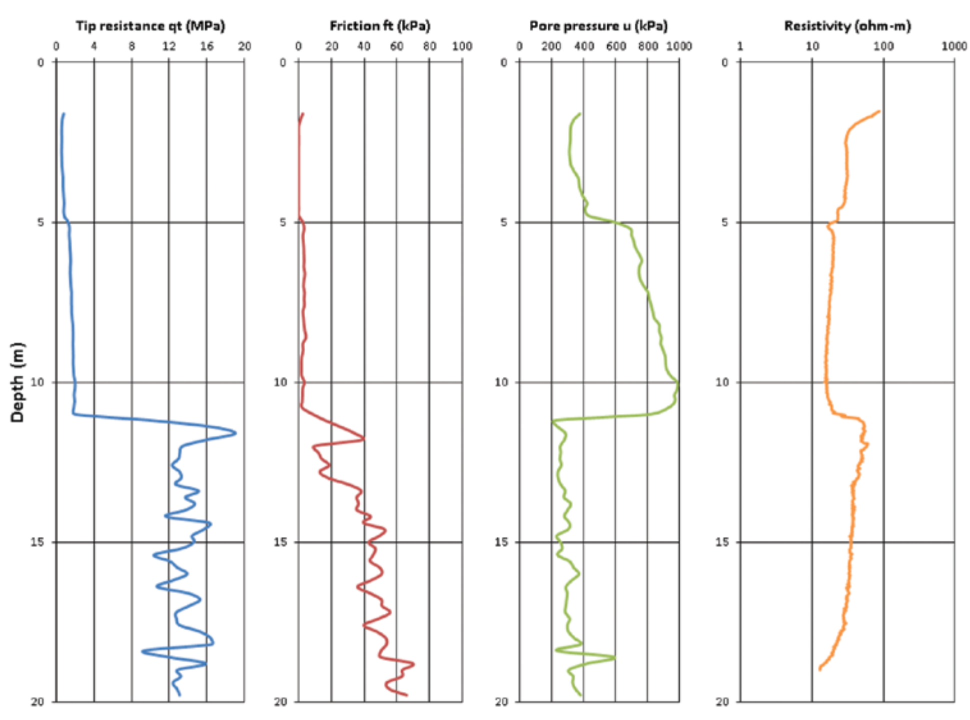

FIGURE 8
Example plot of all registered parameters from the CPTU-R U07202Q2: tip pressure, mantle friction, pore pressure and resistivity.

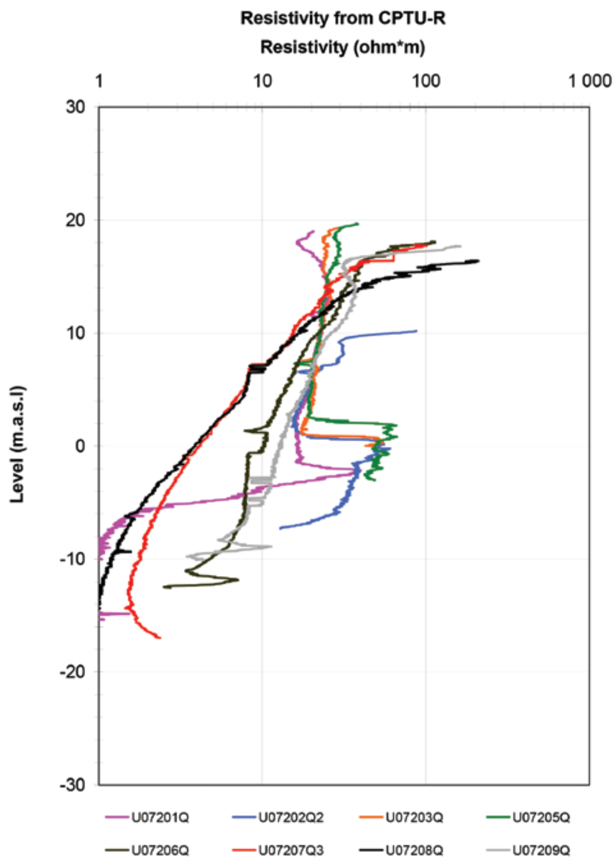

FIGURE 9
Resistivity from CPTU-R at all points.

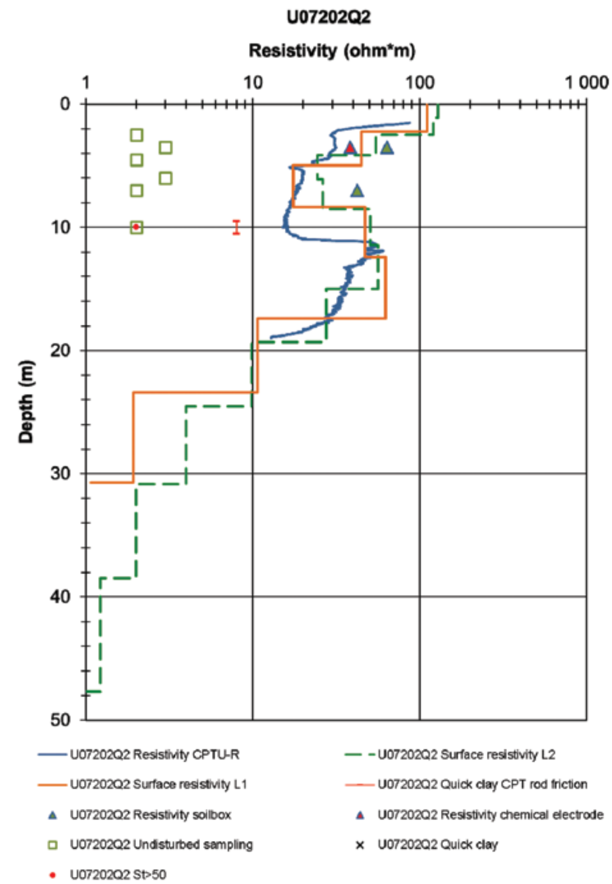

FIGURE 10
Results from CPTU-R U07202Q2 and corresponding inverted models from robust (L1-norm) and least-squares (L2-norm) inversion. Laboratory results from soil box and chemical electrode resistivity measurements on undisturbed samples also shown.

Thereafter, the presence of quick clay in the leached soil can be verified based on the total resistance against depression of the CPTU, i.e. skin friction along the rods (Löfroth *et al*. 2011, 2013). Figure 8 shows an example of a CPTU-R result (U07202Q2) with all the four registered parameters. Note the fine details in resistivity layering, and the correlation between increase in tip resistance, mantle friction along the friction sleeve, and resistivity (decrease in conductivity), and the associated negative correlation of the pore pressure. CPTU-R was made in eight points, and the resistivity results for all are summarized in Fig. 9. The results are here plotted against level in metres above mean sea level since the ground level varies between the sounding points.

Resistivities measured by the CPTU-R were compared with quick clay estimated from skin friction of the CPT-rods and with determinations of quick clay in the laboratory. In five of the eight CPTU-R soundings, resistivity indicates possible quick clay (> 5 Ωm) all the way from the surface down to the friction layer, i.e. U07201Q, U07203Q and U07205Q in the eastern part, U07202Q2 in the landslide scar and U07209Q in the central part of the test area. Also the other three CPTU-R soundings (U07206Q, U07207Q and U07208Q in the central and western part) have resistivities indicating possible quick clay (> 5 Ωm) in the upper 20–25 m, but there under lower resistivities.

In three of the soundings with high resistivity down to the friction layer, other measurements indicate no or less than 1 m of quick clay. In, for example, U07202Q2 (the landslide scar), laboratory tests show no quick clay, but at 10 m depth the clay has a sensitivity S_t = 157 and undrained shear strength cu = 0.43 kPa, i.e. very close to quick clay (Fig. 10).

Two soundings with high resistivity (> 5 Ωm) down to the friction layer do show quick clay with other measurements, e.g. U07209Q (Fig. 12). Laboratory tests in U07060, located less than 40 m from U07209Q, show quick clay from 12 m to the deepest sample at 26 m depth. Of the three soundings with low resistivities (< 5 Ωm) indicating unleached clay, under 20–25 m of high resistivity clay, two soundings were terminated in the clay at 38 m depth without reaching a friction layer. Only in one of the three soundings was a friction layer reached. The resistivity measurements indicate possible quick clay down to 30 m. In the two last metres, from 30 to 32 m, the measured resistivity is between 3 and 5 Ωm, i.e. unleached clay. No comparable sampling was carried out in this point.

In this study, at all levels where quick clay was determined in the laboratory, measured resistivity was above 8 Ωm, and at all levels where quick clay was estimated from skin friction of the CPTU rods the resistivity was above 6 Ωm. Thus, this study supports earlier studies stating that quick clay can be excluded on the basis of low resistivity. The limit of 5 Ωm as an upper limit for unleached clay, not able to form quick clay, is relevant also in this study. However, at this site, high resistivity (> 5 Ωm) indicating quick clay has been measured to more than 15 m depth without indication of quick clay by skin friction. In one of the points where sampling was also carried out, resistivity above 5 Ωm was measured down to 17 m without the clay being quick as determined by laboratory tests. However, samples with sensitivities higher than 50 have been found above 17 m in other points.

COMPARISON OF RESISTIVITY IMAGING AND CPTU-R

Investigation with a CPTU-R probe gives the resistivity profile with depth in a single point. The electrical imaging on the other hand gives the resistivity with depth along a line as estimated from a set of data where each data point integrates the resistivity over a large volume. To be able to compare the two methods with each other, the model from the inversion procedure can be plotted in the form of a step curve together with the CPTU-R data. The inversions in this project were performed with both L1 and L2 norms and both are presented in the resistivity plots.

The results from geotechnical investigations prior to the electrical imaging survey have shown that the area can be divided into three geological regions. In the eastern part under the dry crust there is an about 20 m thick clay layer, which is underlain by a 3 m thick friction soil layer. Beneath this friction soil layer there is again clay continuing to great depths. In the middle part the dry crust is followed by a 24 m thick clay layer and the thin friction soil layer is replaced by a friction layer with a thickness exceeding 15 m. In the western part there is a top layer with fluvial deposits with a thickness of 3 to 6 m. Underneath this layer there is clay continuing to more than 45 m depth. Geotechnical and resistivity information have in each of these regions been evaluated together to give a picture how the results

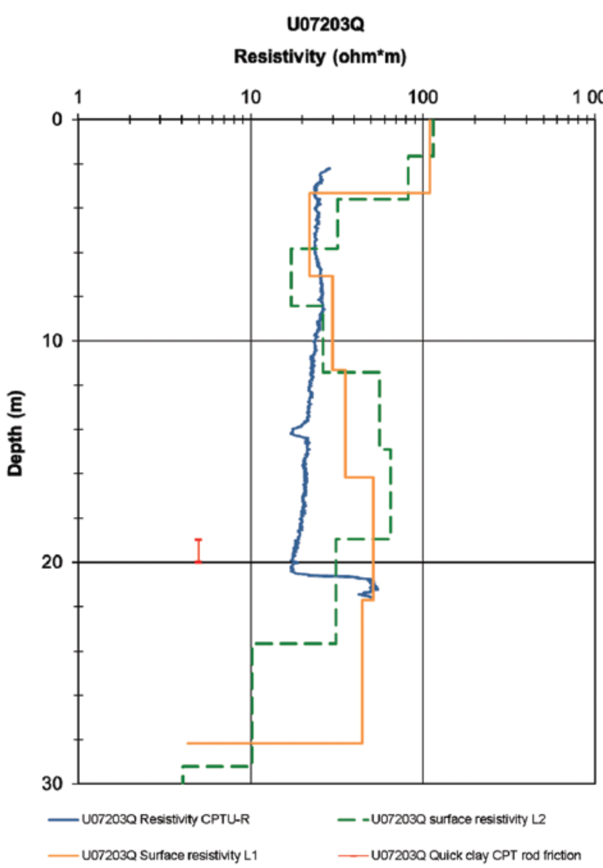

FIGURE 11
Results from CPTU-R U07203Q and corresponding inverted models from robust (L1-norm) and least-squares (L2-norm) inversion.

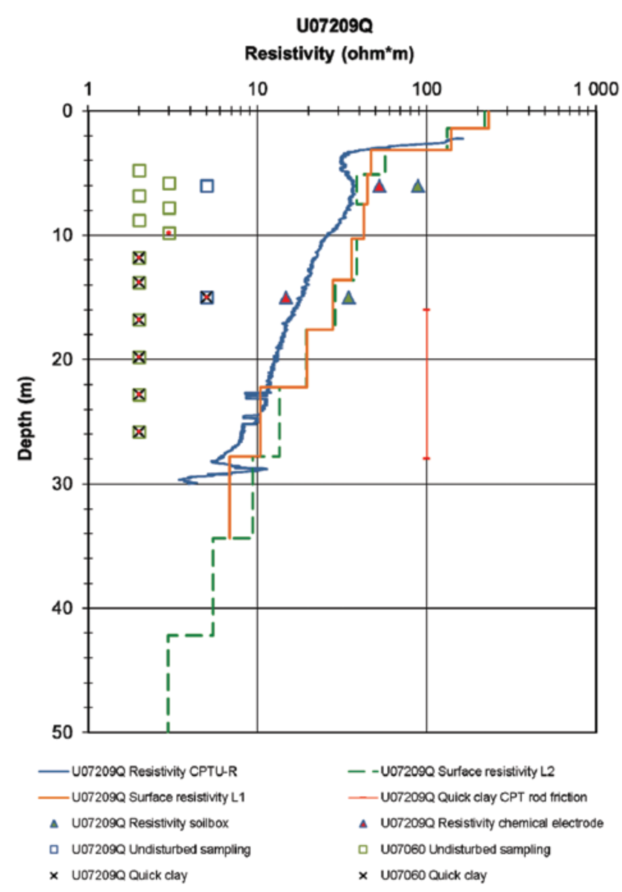

FIGURE 12
Results from CPTU-R U07209Q and corresponding inverted models from robust (L1-norm) and least-squares (L2-norm) inversion. Laboratory results from soil box and chemical electrode resistivity measurements on undisturbed samples also shown.

vary within that area. The soundings have been divided into four groups which show similar resistivity behaviour with depth.

Group one consists of soundings U07201Q and U07202Q (Fig. 10). Point U07202Q is located in an old landslide scar and the remoulded clay with higher resistivity at 11 m depth. This layer is accurately detected by the CPTU-R probe, which gives an immediate response when the resistivity changes. It is of course not as well resolved with the inverted models from ERT measurement for which the increase in resistivity comes at about 8 m depth; where the exact depth of change in resistivity comes is dependent on the discretization of the model grid used for the inversion. The different inversion settings give slightly different results at point 07202Q. Inversion models created with L2-norm fit the CPTU-R data slightly better than inversion results from L1-norm in this case.

Group two consists of soundings U07203Q (Fig. 11) and U07205Q. The results from CPTU-R in both points show that the resistivity deceases slowly from the surface down to a depth of 20 m. The ERT models agree down to 12 m depth, but indicate higher resistivity then CPTU-R below that. In the transition zone between the clay and the thick underlying friction material, CPTU-R shows a quick response in measured resistivity when the probe enters the friction material.

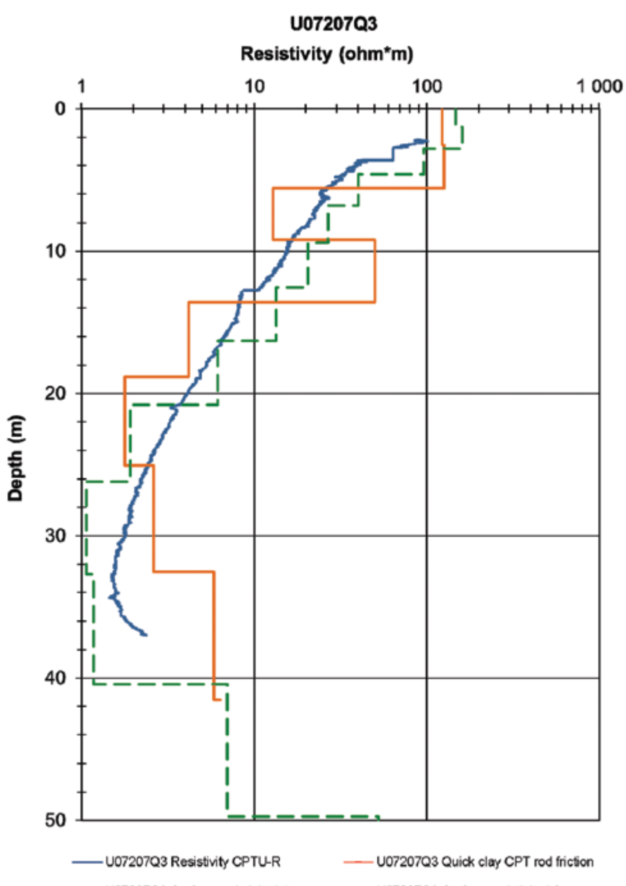

FIGURE 13
Results from CPTU-R U07207Q and corresponding inverted models from robust (L1-norm) and least-squares (L2-norm) inversion.

Group three consists of soundings U07206Q and U07209Q (Fig. 12). The inversion result with both L1- and L2-norm shows a gradual decrease in resistivity with depth. In both soundings the CPTU-R data show a good resemblance with both inversion results and all the data and models have the same inclination with depth.

Group four consists of soundings U07207Q (Fig. 13) and U07208Q. At both these points the results from geotechnical investigations show that the soil profile down to a depth of 38 m consists of clay, meaning that the friction layer is located even deeper in this area.

Overall there is a good resemblance between the CPTU-R and ERT results in all the survey points except for the deeper parts of point U07203Q. In some of the comparisons, inversion models based on L2-norm give a slightly better image of the resistivity variations in the subsurface (e.g., Fig. 13), but in some cases the L1-norm model is closer (e.g., Fig. 11).

Since the changes in resistivity in leached quick clay are very gradual, L2-norm (least-squares) inversion of the electrical imaging works well, as it gives gradual transitions in the resistivities. In many other cases L1-norm inversion is preferable as it is less sensitive to noise in the data and gives sharper transitions between the layers, which is often the case in the geological structures (e.g., Loke *et al*. 2003; Dahlin *et al*. 2004). Here L1-norm can be expected to be better at defining the transition from soil to bedrock, and maybe also the transition from the top soil with higher resistivity to the underlying more conductive soil, but for variation within the clay sequences there is in some cases better agreement between the CPTU-R and the L2-norm models. Using L2-norm inversion combined with sharp boundaries for, for example, the dry crust and bedrock interfaces could be an attractive option, but we were not able to prove the concept in our test due to lack of continuous bedrock information. Such information could be achieved from a seismic survey.

COMPARISON OF LABORATORY ANALYSES AND CPTU-R

A comparison was made between resistivity measured in the field by CPTU-R and resistivity measured in the laboratory. Resistivity measurements in the laboratory were carried out using two different methods: soil box (size 45 mm × 45 mm × 100 mm), in which the resistivity of the whole sample is measured, and chemical electrode, in which the resistivity of the porewater is measured.

The resistivity measured with both laboratory methods generally follows the resistivity from the CPTU-R with depth (in a logarithmic diagram) (see Figs 10 and 12). However, the resistivity measured with soil box is throughout higher than the CPTU-R in all points. The resistivity measured with chemical electrode is in better agreement with the CPTU-R, although these measurements were only carried out on the porewater. It has not been possible to find a reason for the discrepancy between soil box resistivity and CPTU-R, but lateral variation may be an explanation as the samples and CPTU-R readings were not taken in identical positions. Normal checks such as calibration of the soil box equipment were carried out. Samples from two other locations along the Göta River, one with normal sensitive clay and one with quick clay, agreed within 8–13% (Löfroth *et al*. 2011). The low resistivity of the less leached clay was mainly due to sodium and chloride in the porewater. Resistivity was analysed with greater spatial resolution in one sampling point and the analyses showed a linear relationship between sensitivity and salt content in non-quick clay (Löfroth *et al*. 2011; Löfroth *et al*. 2013). Measurement of sodium or electrical conductivity measured by electrode can separate leached clay (potentially quick) from less leached clay, similarly to other resistivity measurements. This could be of interest for monitoring over time, since porewater conductivity may be measured without much disturbance of the soil.

The quick clay's higher resistivity was accompanied by porewater containing sodium and carbonates, typical of a freshening situation. Chloride in the porewater of the quick clays has leached out of the soil, while sodium is still supplied by the sodium sorbed on the quick clay particles.

The grain size distribution curve was determined for all the samples that were tested. It was noted that in each point the measured resistivity and the clay content follow each other, i.e. at a depth with lower clay content the resistivity is higher than at a depth with higher clay content. This holds for all sampling points.

CONCLUSIONS

Resistivity models from electrical imaging can be used for separation of leached soil volumes in marine clays that may form quick clay, from those where the salt content remains too high for this. In the dry crust and thin weathered zone at the top, the resistivity is high but the clay is non-quick. Also soils with less clay content will have higher resistivity without being quick.

The technique may thus be used as a screening tool in order to delimit areas where further investigations are needed from areas that do not require more attention. This has the potential to save significant resources if used in a relatively early stage of the survey process. It can also increase the overall quality and reliability of the survey results.

Results of electrical imaging have to be supplemented by geotechnical investigations, but these might be reduced in relation to a traditional geotechnical investigation. Resistivity imaging is an excellent basis for designing a geotechnical investigation programme, and should thus be carried out early in an investigation programme as a base for optimized detailed in-situ investigations and sampling.

There is generally good agreement between the models derived from resistivity imaging and CPTU-R. Small-scale variations at depths detected by CPTU-R can obviously not be resolved by the electrical imaging, but given the difference in scale of resolution the deviations are limited. Because the agreement is quite good for the examples shown, there is limited potential for improving the inverted models by using the CPTU-R as *a priori* data to constrain the inversion in this particular case.

The IP results are consistent and show patterns of variation that are different from that of the resistivity but seem to be geologically realistic. They can be expected to contain information that is linked to the material or electrochemical properties of the clay, and might thus be relevant to the behaviour of the clay. There are, however, not sufficiently detailed and relevant reference data to draw any conclusions about this, but it suggests that it may be worthwhile to look further into this in future studies.

CPTU with measurement of the penetration resistance corresponding to the skin friction along the rods for estimation of quick clay is suitable as a complement to laboratory tests. As the CPTU is often used in clayey soils for stratification and estimation of the undrained shear strength of the clay, estimation of quick clay by skin friction gives additional information about the clay at the locations where CPTU is carried out primarily for other purposes (Löfroth *et al*. 2013).

As mentioned above, resistivity can only be used to distinguish between marine clay sufficiently leached to form quick clay and marine clay with a salt content too high for this. In this study, clay classified as quick, by CPTU skin friction and/or laboratory tests, has a resistivity higher than 6 Ωm, which is in agreement with earlier studies in Sweden. The combination of CPTU with measurement of the penetration resistance and resistivity, using a CPTU-R, gives the possibility to link quick clay at a specific location and depth to the measured resistivity at the same location and depth. As there is generally a good agreement between the electrical imaging and the CPTU-R, the CPTU-R may be used to calibrate the electrical imaging models with quick clay estimations by rod friction using the approach suggested by Löfroth *et al*. (2013). Thus, by combining electrical imaging along a section with the resistivity at one point measured by the CPTU-R together with quick clay estimations by skin friction, a better judgement of the extension of the quick clay is feasible.

Electrical imaging gives a general picture of the variation in resistivity along soil sections. The CPTU-R gives small-scale variations at depth in one specific location. In this study, the resistivity results from the CPTU-R results give a very good view of the small-scale variation of resistivity within the area. They clearly show the gradual change from the leached clay in the eastern part and unleached clay in the western part. The repeatability is also very good, showing very similar resistivity in the CPTU-R soundings located in the same part of the area. The sand layer present in the eastern part is also registered by all the CPTU-R soundings as an increase in resistivity. This layer was not detected by the electrical imaging, which could be expected due to resolution limitations. The CPTU-R in the landslide scar also registered an increase in resistivity of the slide masses, thus showing a sharp border between slide masses and undisturbed clay.

The resistivity measured with chemical electrode is in reasonably good agreement with the CPTU-R, although these measurements were only carried out on the porewater. The resistivity measured with the soil box was throughout higher than the resistivity measured with the other methods in this study, for reasons that have not been explained. The low resistivity of the less leached clay was mainly due to sodium and chloride in the porewater.

ACKNOWLEDGEMENTS

Virginie Leroux was instrumental in organizing and managing the field campaign, thereby making it very successful, and she also did substantial parts of the data processing. Apart from members of the author team, Hanna Tobiasson Blomén also contributed to the success of the data acquisition.

We wish to thank Jonathan Chambers, two anonymous reviewers and the associate editor for constructive criticism of the manuscript that helped us improve the quality of it.

REFERENCES

Andersson-Sköld Y., Torrance J.K., Lind B., Oden K., Stevens R. L. and Rankka K. 2005. Quick clay – A case study of chemical perspective in Southwest Sweden. *Engineering Geology* **82**, 107–118.

Berger B. 1983. *Geofysiske metoder anvendt i ingenjörgeologiske undersökelser, del 1–3*. Diss. Norges Tekniske Högskole. Petroleumsteknologi og Anvendt Geofysikk. Trondheim. (in Norwegian)

Bjerrum L. 1954. Geotechnical properties of Norwegian marine clays. *Geotechnique* **4**, 49–69.

Brenner R.P., Nutalaya P., Chilingarian G.V. and Robertson J.O. 1981. Engineering geology of soft clay. In: *Soft Clay Engineering*, (eds E.W. Brand and R.P. Brenner). Elsevier, 159–238

Dahlin T. 2001. The development of electrical imaging techniques. *Computers and Geosciences* **27**(9), 1019–1029.

Dahlin T and Zhou B. 2004. A Numerical Comparison of 2D Resistivity Imaging with Ten Electrode Arrays. *Geophysical Prospecting* **52**, 379–398.

Dahlin T. and Zhou B. 2006. Gradient array measurements for multichannel 2D resistivity imaging. *Near Surface Geophysics* **4**, 113–123.

Dahlin T., Garin H. and Palm M. 2004. Combined Resistivity Imaging and RCPT for Geotechnical Pre-investigation, *Procs. NGM 2004, Ystad, Sweden*, 18–20 May 2004, 9.

Donohue S., Long M., O'Connor P., Helle T.E., Pfaffhuber A. and Romoen M. 2012. Multi-method geophysical mapping of quick clay. *Near Surface Geophysics* **10**(3), 207–219.

Gregersen O and Løken T. 1983. Mapping of quick clay landslide hazard in Norway, Criteria and experiences. Symposium on slopes on soft clays, Linköping, March 8–10, 1982. Swedish Geotechnical Institute, SGI. Report 17, 161–174.

Helle T.E., Pfaffhuber A.A., Rømoen M. and Forsberg C.F. 2009. *SIP12 – Correlation between horizontal and vertical resistivity measurements. Internal report.* Norwegian Geotechnical Institute, Oslo.

Holmsen G. 1929. Lerfaldene ved Kokstad, Gretnes og Braa. Norges Geologiske undersøkelse, 151. (in Norwegian)

Lebuis J, Robert J.M. and Rissman P. 1983. Regional mapping of landslide hazard in Quebec, in Symposium on slopes on soft clays, Linköping, March 8–10, 1982. Swedish Geotechnical Institute, SGI. Linköping, Report 17, 205–262.

Loke M.H., Acworth I. and Dahlin T. 2003. A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. *Exploration Geophysics* **34**(3), 182–187.

Lundström K., Larsson R. and Dahlin T. 2009. Mapping of quick clay formations using geotechnical and geophysical methods. *Landslides* **6**(1), 1–15.

Löfroth H. 2011. Kartering av kvicklereförekomst för skred-riskanalyser inom Göta älvuppdraget – Utvärdering av föreslagen metod samt preliminära riktlinjer. Mapping of quick clay formations within the Göta River Commission – Evaluation of proposed method and preliminary guidelines. Göta River Commission, Sub report No 29. Swedish Geotechnical Institute, Linköping. www.swedgeo.se. (in Swedish)

Löfroth H., Suer P., Dahlin T., Leroux V. and Schälin D. 2011. Quick clay mapping by resistivity – Surface resistivity, CPTU-R and chemistry to complement other geotechnical sounding and sampling, GÄU - subreport 30, Swedish Geotechnical Institute, Linköping, 56 + appendices. www.swedgeo.se.

Löfroth H., Suer P., Schälin D., Dahlin T. and Leroux V. 2013. Mapping of quick clay using sounding methods and resistivity in the Göta River valley. In: *Geotechnical and Geophysical Site Characterization 4*, (eds Coutinho & Mayne). Taylor & Francis Group, London, 1001–1008. ISBN 978-0-415-62136-6

Möller B. and Bergdahl U. 1982. Estimation of the sensitivity of soft clays from static and weight sounding tests. *Procs. European symposium on penetration testing, 2, ESOPT, Amsterdam*, vol. 1, 291–295.

Rankka K., Andersson-Sköld Y., Hultén C., Larsson R., Leroux V. and Dahlin T. 2004. *Quick clay in Sweden*. Swedish Geotechnical Institute, SGI. Report 65. Linköping. www.swedgeo.se

Rosenqvist I.T. 1946. Om leirers kvikkagtighet. Statens Vegvesen. Veglaboratoriet. Meddelande No 4. Oslo. (in Norwegian)

Rygg N. 1978. Dreietrycksondering: Tolkning av sonderingsresultat. Vegdirektoratet, Veglaboratoriet, Intern Report No 816. Oslo. (in Norwegian)

Rømoen M., Pfaffhuber A.A., Karlsrud K. and Helle T.E. 2010. Resistivity on marine sediments retrieved from RCPTU-soundings: a Norwegian case study. *Procs. International symposium on cone penetration testing, 2, CPT'10, Huntington Beach, CA*. vol. 2, 289–296.

Slater L. and Lesmes D. 2002. IP interpretation in environmental investigations. *Geophysics* **67**, 77–88.

Solberg I.L., Rönning J.R., Dalsegg E., Hansen L., Rokoengen K. and Sandven R. 2008. Resistivity measurements as a tool for outlining quick-clay extent and valley-fill stratigraphy: a feasibility study from Buvika, central Norway. *Canadian Geotechnical Journal* **45**(2), 210–225.

Solberg I.L., Hansen L., Rönning J.S. and Dalsegg E. 2010. *Veileder for bruk av resistivitetsmålinger i potentsielle kvikkleireområder.* Versjon 1.0. Norges Geologiske Undersökelse, NGU. Rapport 2010.048. (in Norwegian)

Swedish Geotechnical Institute (SGI). 2012. Skredrisker i Göta älvdalen i ett förändrat klimat. Landslide risks in the Göta River valley in a changing climate (eds B. Lind, Y. Rogbeck and M. Tremblay). Swedish Geotechnical Institute, SGI. Göta River Commission, GÄU. Final Report. Part 1, Linköping. www.swedgeo.se. (in Swedish)

Söderblom R. 1969. Salt in Swedish clays and its importance for quick clay formation. Results from some field and laboratory studies. Swedish Geotechnical Institute. *Proceedings* **22**. Stockholm.

Torrance J.K. 1975. On the role of chemistry in the development and behaviour of the sensitive marine clays of Canada and Scandinavia. *Canadian Geotechnical Journal* **12**(3), 326–335.

Viberg, L. 1981. Mapping and classification of landslide conditions. *International Conference on Soil Mechanics and Foundation Engineering,* 10, Stockholm, June 1981. Procs, vol. 3, 549–554.