Effectiveness of RCPTU to detect improved properties in salt-treated highly sensitive clay

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Abstract

Salt wells filled with potassium chloride may be used as landslide mitigation in highly sensitive quick clays, as the changed pore-water composition permanently improves the remoulded shear strength. To verify improvements, resistivity cone penetration tests were conducted around salt wells installed at Dragvoll, Trondheim, Norway. The cone-test measurements for electric resistivity (or conductivity), tip resistance and pore pressure were combined with the results from laboratory tests on piston-core samples extracted around the wells. Salt content, soil and pore-water conductivity, pore-water composition and geotechnical properties were studied. Quick clay is defined as that having a remoulded shear strength of <0·5 kPa, and the soil conductivity is often <100 mS/m. Increased tip resistance was detected at soil conductivities exceeding 200 mS/m as a result of increased salt content, corresponding to a laboratory determined remoulded shear strength of 3·5 kPa. At Dragvoll, improved non-quick clay is detected by a normalised tip resistance of 3·5 and a pore-pressure parameter of 0·9. Improved geotechnical properties around salt wells may be verified by cone testing, but a site-specific interpretation model based on geotechnical properties from laboratory tests correlated to cone-test results may be needed.

Keywords: Field testing & monitoring; Geotechnical engineering; Site investigation;

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1 Introduction

Marine clays accumulated during and after the last ice age originally held a high salt content in their pore water of some 30-35 g/L (Rosenqvist, 1946; Moum et al., 1971). Leaching by meteoric groundwater flow has, however, decreased the salt content and thereby increased the repulsive forces between the clay particles so that they turn into a liquid when remoulded. Clays are characterised by a as quick clays at remoulded shear strengths of less than 0.5 kPa (Rosenqvist, 1946; NGF, 2011). Sodium (Na^+) is the dominant cation in the pore water in quick clays often having salt contents of less than 2 g/L (Torrance, 1979), and the clays may even behave as liquids at salt contents less than 1 g/L (Moum et al., 1971). Re-introducing high salt content in these clays decreases the repulsive forces and render the clays not quick (e.g. Rosenqvist, 1946; Bjerrum, 1955; Quigley, 1980; Torrance, 1983).

In January 2013, six salt wells filled with potassium chloride (KCl) were installed in a quick clay deposit at Dragvoll, Trondheim, Norway, in order to investigate the feasibility of KCl as ground improvement. In-situ tests are widely used to investigate the subsurface and to determine geotechnical properties effectively and relatively cheaply without the necessity of sampling. Resistivity cone penetration tests (RCPTU) were conducted around all the salt wells to investigate its applicability in detecting the improved geotechnical properties in the salt-treated clay, distinguishing when the clay ceases to be quick based on criteria for detecting highly sensitive quick clays developed the last decades (e.g. Solberg et al. 2012; Sandven et al. 2015). The electrical resistivity decreases with increasing salt content in the pore-water, and studies of the applicability of mapping quick-clay deposits by electrical resistivity measurements have been published by many researchers throughout the last decade (e.g. Dahlin et al., 2004; Lundström et al., 2009; Sauvin et al., 2011; Donohue et al., 2012; Solberg et al., 2012). Electrical resistivity tomography (ERT) allows a relatively quick and cheap mapping of large areas, and low-saline Norwegian quick clays may be indicated at electrical resistivity values in the range 10-100 Ωm (Solberg et al., 2012; Long et al., 2012), corresponding to conductivity values of 100-10 mS/m. Low-saline, clays with electrical resistivity values within the "quick range" do not necessarily imply quick clays, as the development of high sensitivity in leached low-saline, illitic-chloritic clays is governed by the composition of cations in the pore water (van Olphen, 1963; Penner, 1965; Moum et al., 1971; Rosenqvist, 1968; Torrance, 1983; Helle et al., 2016; Helle et al., 2017). Clays with low-saline pore-water compositions dominated by sodium (Na^+) may develop high sensitivity (Penner, 1965; Torrance, 1983; Mitchell and Soga, 2005), whereas low-saline clays with a ratio of the sum of the equivalents of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) over the sum of Na^+, K^+, Mg^{2+} and Ca^{2+} (major cations) exceeding 20% do not (Helle et al., 2017). Thus, low-saline clays may have electrical resistivity values within the "quick range" without being highly sensitive (Solberg et al., 2012).

The RCPTU provides conventional cone penetration test (CPTU) data together with electrical resistivity, and the soundings are carried out in the same manner as conventional CPTUs. Therefore, it is considered an effective tool, and has been used for contaminant mapping over the last decades (e.g. Campanella and Weemees, 1990). Due to the nature of the pore water and its impact on the geotechnical properties in leached post-glacial marine clays, RCPTU may also be used in detecting highly sensitive quick clays (e.g. Rømoen et al., 2010; Löfroth et al., 2011; Sandven et al., 2015, 2016b). The RCPTU measures the electrical conductivity often inverted to electrical resistivity. Pore-fluid conductivity is directly correlated to the salt content, whereas the soil conductivity in clays is not due to the impact of the charged clay surfaces (Waxman and Smits, 1968; Glover et al., 2000). Nevertheless, the salt content also greatly influences the soil conductivity. The use of RCPTU in mapping highly sensitive quick clays is not extensively used due to the fact that conductivity measurements in clays does not necessarily distinguish highly sensitive, low-saline quick clay from non-quick low-saline clays. Combining the conventional CPTU data with the conductivity measurements facilitate the interpretation.

Very low tip resistances (q_c) measured by the CPTU may indicate soft clays, but it does not distinguish whether the clays are quick or not. Improved soil properties in the reclaimed soft clays at Changi airport, Singapore, were successfully detected by increased tip resistance (Bo et al. 2005). However, normalised parameters derived from the tip resistance may be more applicable to find a general interpretation model for improved properties and indication of quick clays (Sandven et al., 2015, 2016a). The measured tip resistance (q_c) is corrected by the area factor of the cone (α) and the measured pore pressure (u_2) behind the cone:

(1) $q_t = q_c + (1-\alpha)\cdot u_2$

A normalised tip-resistance (N_m) below 4 (Equation 2), and a pore-pressure parameter (B_q) exceeding 1 (Equation 3) may indicate highly sensitive, quick clays. The N_m is determined by the ratio of the net tip resistance ($q_n = q_t - \sigma_{v0}$) over the sum of effective overburden pressure (σ_{v0}') and attraction (a), which may be excluded at depths exceeding 5 m (Sandven et al., 2015).

(2) $N_m = q_n/(\sigma_{v0}' + a)$

(3) $B_q = (u_2 - u_0)/q_n$

Combining the soil conductivity with the normalised parameters N_m and B_q may simplify distinguishing highly sensitive, low saline, i.e. low conductive, clays from improved clays of low sensitivity. The in-situ measured soil conductivity at Dragvoll was correlated to the pore-water chemistry (ion composition and salt content) and geotechnical properties determined on clay samples extracted from nearby boreholes. Whereas previous studies on electrical resistivity and geotechnical properties include investigations and correlations from various sites with different geological history, the investigations presented herein is isolated to the Dragvoll research site with its specific geological history. The improved geotechnical properties is only due to changed chemistry in the pore water and in the adsorbed positions on the mineral surfaces. This paper presents the challenges in distinguishing improved clay properties from quick clays based on soil conductivity caused by the non-unique relationship between pore-water and clay-soil conductivity. Furthermore, the data show the effectiveness of using RCPTU to distinguish quick from non-quick clays combining soil conductivity and normalised parameters, at the same time as mapping the extent of the salt plume and improved geotechnical properties around salt wells. The correlations between salt contents, ion compositions, conductivity data, geotechnical parameters and CPTU results, which promote the use of RCPTU in detecting improved properties in salt-treated quick clays are presented.

2 Research site Dragvoll

2.1 Site description and soil properties

The Dragvoll research site is located at 156 m above current sea level, in close vicinity to the marine limit at around 175-180 m above current sea level (Kjemperud, 1981; Hafsten, 1983).

The groundwater table is fluctuating between the terrain surface and 1 m depth depending on the weather conditions and season, and the visible dry crust/weathered zone extends down to 1-2 m depth. Clay, gravel, shells and shell fragments are commonly found down to about 4 m depth and occasionally found at deeper levels. The investigated quick clay encountered from 3-4 m depth (Bryntesen 2013) is interbedded with millimetre thick silt and sand layers with a few centimetre spacing. Closely spaced 1-2 cm thick silt/sand layers are detected at 7.5-8.0 m depth (Helle et al., 2017). The clay content is 34-41%, with a bulk mineralogy consisting of quartz, albite, illite and chlorite (Bryntesen 2014). The clay mineralogy consists of 67% illite and 33% chlorite (Helle et al., 2017). The salt content in the original quick clay is low, in the order of 0.6-0.7 g/L (Figure 1), with Na^+ as the dominant cation. This cause high repulsion between the clay particles, and the clay therefore easily remoulds. The remoulded shear strength (c_{ur}) is of 0.5 kPa around 4 m depth, decreasing below 0.1 kPa from 5 m depth downwards. Due to the low salt content, the conductivity in the quick clay is in the order of 20 mS/m, corresponding to an electrical resistivity of around 50 Ωm, within the “quick range”. The natural water content (w) is around 37%. The liquid limit (w_L) is 21-24% and the plastic limit (w_P) 15-18%, corresponding to liquidity indexes (IL) of 3.4-4.3, and plasticity indexes (IP) of 4.4-6.3%.

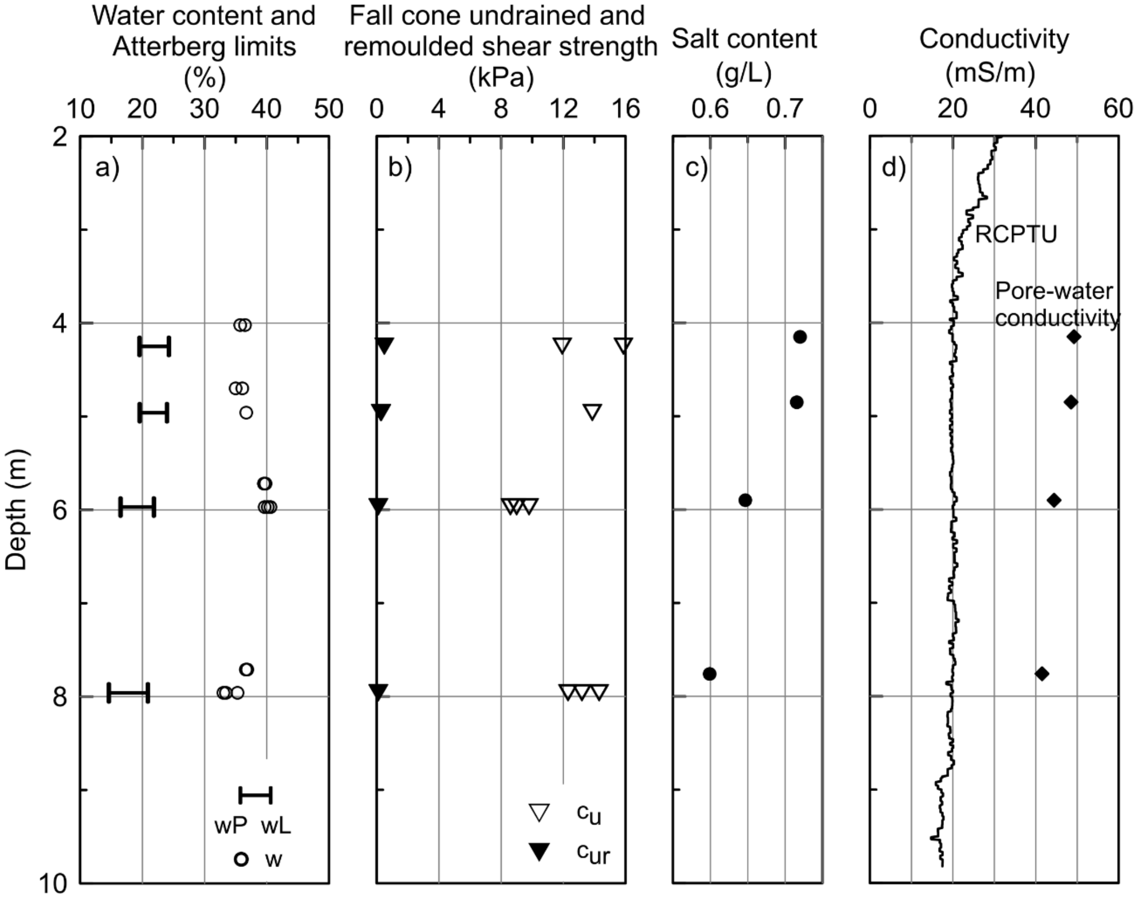

Figure 1. a) Water contents (w) and Atterberg limits (w_P and w_L), b) fall cone undrained (c_u) and remoulded shear strength (c_{ur}), c) salt content, and d) soil and pore-water conductivity in the quick clay at Dragvoll.

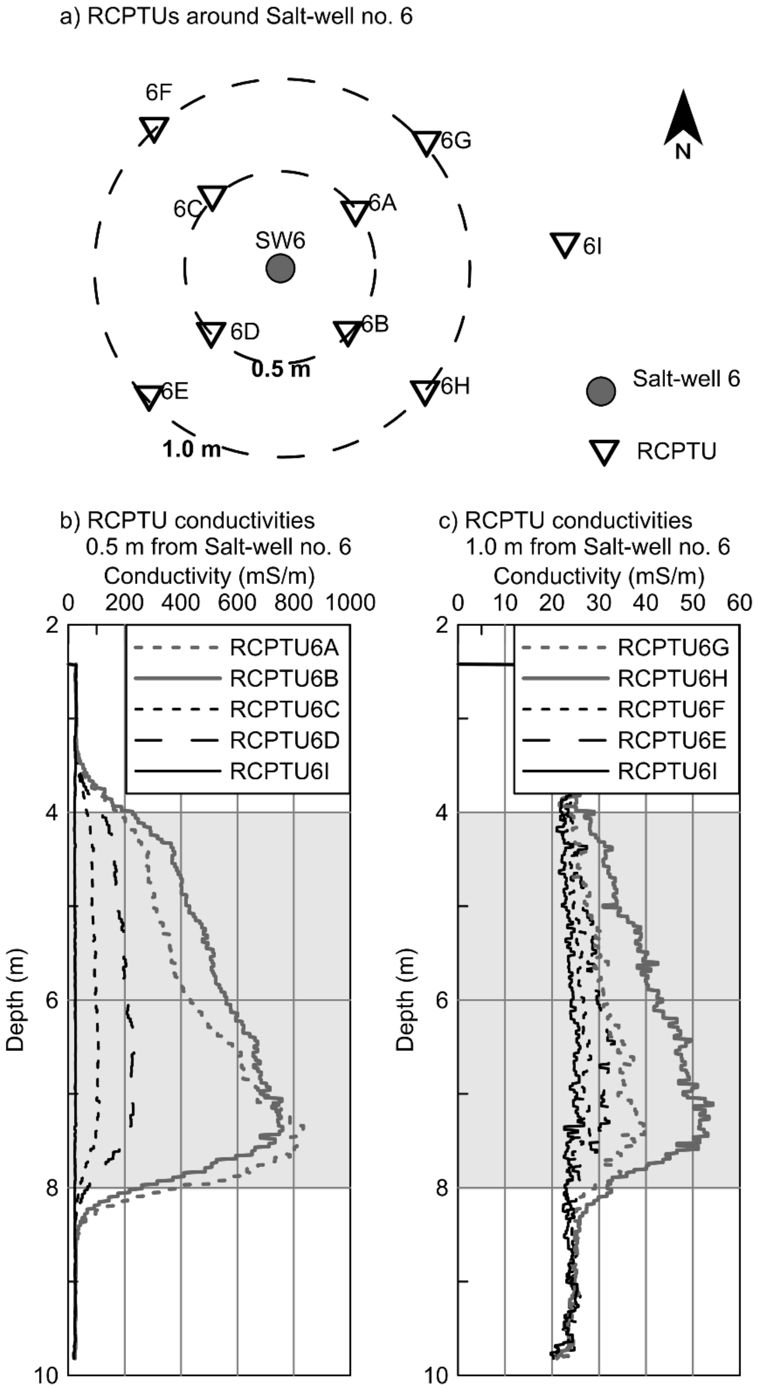

Figure 2. a) RCPTUs conducted around Salt-well no. 6 (SW6), 3 years and 5 months after installation of the salt well, at a distance of b) 0.5 m from the well, and c) 1.0 m from the well. The salt migrates from the well from 4 m to 8 m depth (shaded area). The soil conductivity from sounding RCPTU6I is in the original quick clay 1.5 m from the well. Note that the scales on the x-axis are changed from the plot from 0.5 m to 1.0 m.

Six salt wells were installed with a centre-to-centre distance of about 10 m. The wells were constructed of 63 mm polyethylene (PE) pipes, allowing the salt to be in contact with the clay through slotted sections from 4 m to 8 m depth. The wells were refilled regularly to ensure fully saturated KCl solution in the wells during the whole project period of 3 years and 5 months. RCPTUs were conducted at various distances around the wells at various time intervals after installation in order to determine the salt-plume extent, and to detect improved geotechnical properties (Figure 2).

2.2 Piezocone soundings

Three probes from two different manufacturers were used in the study. Two of the probes are from manufacturer no. 1 (M1) and one of the probes is from manufacturer no. 2 (M2). Both of the probe types allow an electrical resistivity module to be attached behind the conventional CPTU, and no extra measures are necessary to carry out the sounding. The electrical resistivity module from M2 has the same cross-sectional area as the CPTU probe (10 cm^2), whereas the two from M1 have a slightly larger cross-sectional area. Four electrodes with a spacing of 5 cm are placed in a Wenner-α configuration on the resistivity modules, sending impulses of direct current of equal intensity 200 times per second from the two outer rings. The probes were pushed into the ground with a penetration rate of 20 mm/s ∓ 5 mm/s, logging every centimetre (ISO, 2012). The raw-data file provides the uncorrected tip resistance (q_c), uncorrected sleeve friction (f_s), pore pressure behind the cone (u_2) and the conductivity of the soil (σ_t). It is a common experience that the measured sleeve friction is less predictable than the measured tip resistance and pore pressure (de Ruiter, 1982; Lunne et al., 1986). In soft clays, the measured sleeve friction may be at the lower bound of the transducer resolution, and inaccuracies may occur. The measured f_s in the Dragvoll quick-clay varied from one probe to the other, even between probes from the same manufacturer. Thus, results dependent on f_s are not included in this paper.

In total 64 RCPTUs were conducted on the site. The fact that they are located rather close to the salt wells, previous RCPTU soundings and piston-sample boreholes (in some cases < 0.5 m apart), represent a challenge as closely spaced drillings may influence one another due to reduced horizontal stresses (Lunne et al., 1997). The problem is studied by conducting RCPTU soundings close to a dummy well with no salt. The readings should be as in virgin soil. Based on such considerations and a critical study of the quality of all measurements, it was seen that in particular the pore-pressure readings (u_2) in some of the tests were low, in the order 50-100 kPa lower. Soundings where this problem was encountered were ruled out from further interpretation. Thus, only data from 34 of the soundings are presented herein. Twenty-three of these are in application class 1 (ISO, 2012). Out of the 18 soundings conducted with the probe from M2, 11 are classified as application class no. 2 due to too large zero-point deviations in the tip resistance. Adding the deviation to the uncorrected tip-resistance along the whole depth, the q_t corresponded well with soundings in application class 1. Therefore, the corrected results are included herein. Deviations between the conductivity measured by the RCPTUs from M1 and M2 were also observed. It was found that the probe from M2 occasionally produced unrepeatable results. Therefore, conductivity data from the RCPTUs presented herein are solely results from the M1 probes.

A dummy well was installed on the site in the same manner and with the same construction as the salt wells, except that is was filled with groundwater. Soundings 0.5 m and 1.0 m from this well showed that the well installations had a moderate, but measureable, effect on the pore-pressure measurements in top of the soil, down to approximately 6 m depth. Some of the soundings in the original quick clay and the salt-treated clay using porous-bronze filter with anti-freeze as saturation fluid seemed to be sensitive to loss of saturation in the top soil penetrating through coarser layers or due to occurrence of stones/gravel in the soil. The loss or decrease of saturation caused a lower pore-pressure response affecting the results down to approximately 6 m depth, and in worst cases affected the sounding results over the entire depths, possibly due to air-bubbles in the saturation chamber. Therefore, the effect of using slot versus porous bronze-filters in the CPTU equipment for measuring u_2 was investigated both in the original quick clay and around the dummy well. In general, there was no difference using the two filter types, except that the sounding results using the slot filter with grease and oil as saturation fluid were not affected by loss of saturation. According to Robertson and Campanella (1983), when there is loss of saturation in top of the soil profile, the probes normally measure the correct pore pressures from around 5-6 m depth since the in-situ pore pressure then is high enough to saturate or compress any air-bubbles in the saturation chamber. The results presented in the following section are from RCTPUs conducted with both slot and porous bronze-filters. The sounding results that were greatly affected by saturation loss are ruled out, and the correlations are based on results from 5 m depth downwards to avoid any influence by saturation loss in the top soil.

3 Detection of improved properties by RCPTU

3.1 Salt-plume extent and orientation

RCPTUs were conducted in a distance of 0.5 m, 1.0 m and 1.5 m from the salt-wells. The conductivity measurements revealed that the extent of the salt plumes were non-symmetrical around the wells (Helle et al., 2017), with salt migrating to further distances in predominant directions (Figure 2b and c). This was also confirmed by analysing the pore-water compositions in the pore-water extracted from clay samples from boreholes positioned in these pronounced directions. Surprisingly, the predominant directions of the salt plumes varied from one well to another, indicating that there is no distinct hydraulic gradient in the area. The density of the KCl-solution in the well is higher than in the low-saline pore fluid in the quick clay, creating density gradients. The clay deposit is interbedded with thin silt/sand layers that may aid advective flow. Therefore, the salt-plumes may migrate faster in one direction from a particular well due to local variations around the wells.

In addition to the RCPTUs, electric resistivity tomography (ERT) was conducted on the site (Bazin et al., 2016) as an attempt to map the directions and extent of the salt plumes from the wells. Six ERT profiles were positioned in two directions in a grid spacing of 10 m. One survey was conducted prior to salt-well installations, and two after the installation using an electrode spacing of 0.25 m, 0.50 and 1.00 m over lengths of 20 m, 40 m and 80 m, achieving a maximum depth penetration of 15 m. Even though the RCPTU and ERT conductivity corresponded well in the quick clay, ERT detected neither the salt wells nor the salt plumes due to poor resolution at depth.

3.2 Pore-water and soil conductivity

The conductivity in soils is greatly influenced by the salt content in the pore fluid. The pore-water conductivity in the extracted pore-water in the clay samples from around salt-well no. 2 and 3 were measured in the laboratory. Conductivity is affected by the composition and concentrations of the ions in the pore water. The salt content and pore-water composition were determined on all samples extracted around the wells. The geochemical computer program

PHREEQC (Parkhurst and Appelo, 2013) was used to calculate the pore-water conductivity. The PHREEQC calculated conductivity corresponded well with the laboratory measured pore-water conductivities from the pore water extracted from clay samples around salt-wells no. 2 and 3. The in-situ soil temperature at Dragvoll is around 6 ^{o}C. As conductivity is influenced by temperature, the pore-water conductivity should be correlated to the in-situ soil conductivity at corresponding temperature. The pore-water conductivity in the samples from around salt-wells no. 2 and 3 were determined at a laboratory temperature of around 25 ^{o}C. The pore-water conductivity for all the pore-water compositions was therefore adjusted to 6 ^{o}C by the geochemical computer program PHREEQC which is given in Figure 3. The pore-water conductivity increases non-linearly with increasing salt content up to around 6700 mS/m at 98 g/L (Figure 3a), whereas the soil conductivities measured with the RCPTU, increases far less and are about 300 mS/m at 98 g/L. There is no unique correlation between pore-water conductivity and soil conductivity (Figure 3b), although the lower bound of soil conductivity tends to increase with pore-water conductivity.

The soil conductivity in clays has contributions from both the pore water and the minerals (Waxman and Smits 1968; Glover et al., 2000), explaining the non-coherent trend between pore-water conductivity and soil conductivity. Sand grains are non-conductive, thus the measured conductivity in the sandy soil (σ_t) is directly correlated to the pore-water conductivity (σ_w) and the formation factor (F) of the soil by $F = \sigma_w/\sigma_t$. However, clay particles are conductive due to their surface charge and surrounding diffuse double-layer. Therefore, the ratio between pore-water and soil conductivity does not apply, complicating the interpretation of soil conductivity in clays. Even so, the soil conductivity in clays is affected by the salt content in the pore fluid, and can be used to detect increasing salt contents in clays surrounding salt wells, thus effectively map the salt-plume extent. Correlations between the improved geotechnical properties in the Dragvoll clay and increasing soil conductivity due to added salt is investigated by RCPTU and presented in the following.

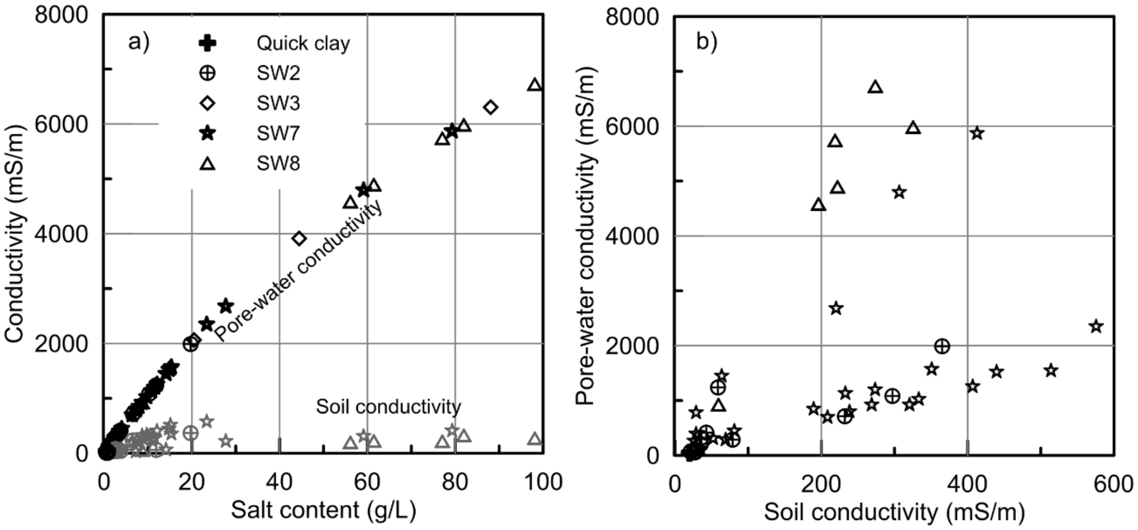

Figure 3. a) Soil conductivity (grey symbols) from RCPTUs and PHREEQC estimated pore-water conductivity (black symbols) at 6 ^{o}C correlated to salt content. b) Pore-water conductivity correlated to soil conductivity.

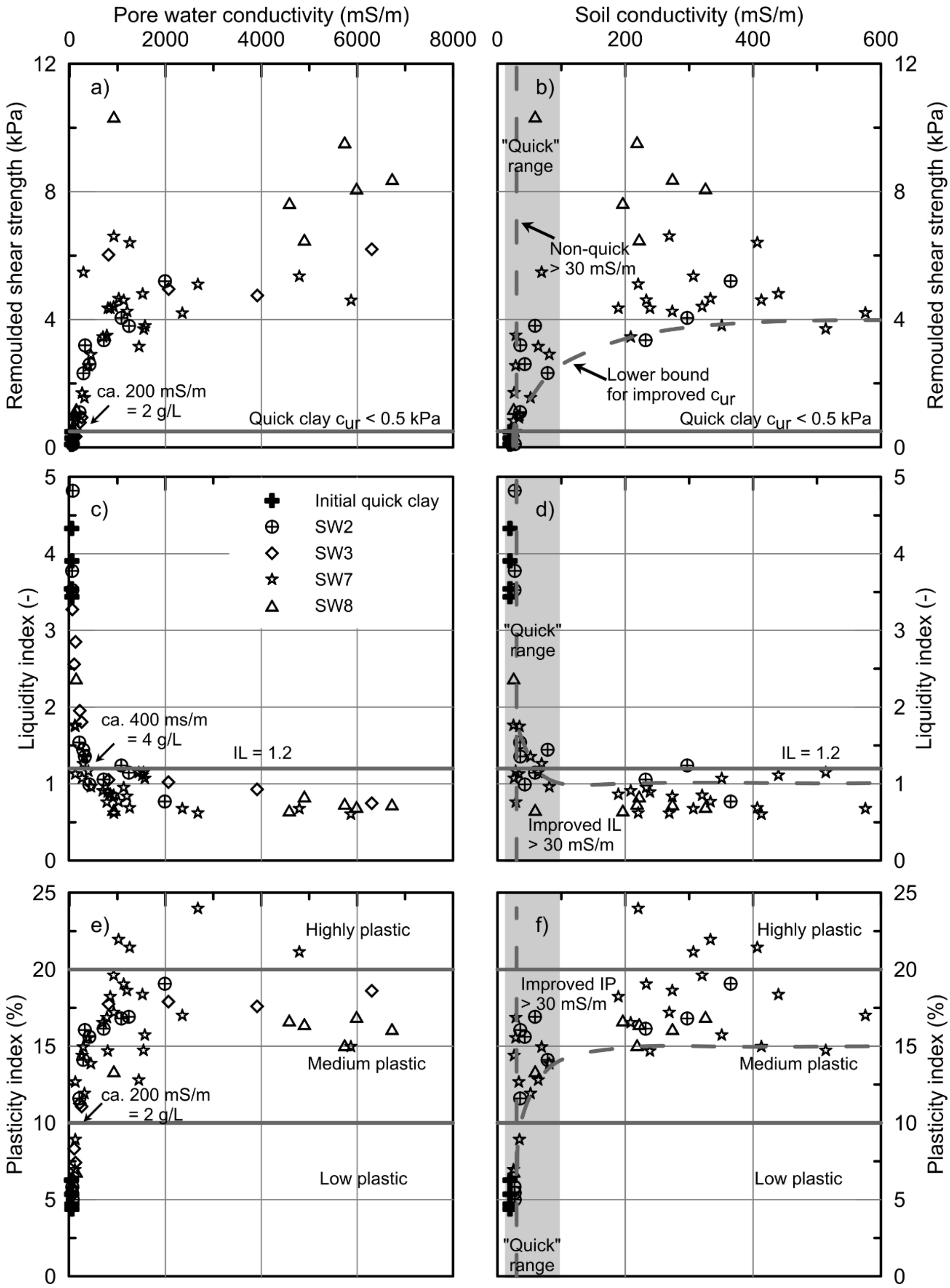

Figure 4. Pore-water and soil conductivity correlated to a) and b) remoulded shear strength (c_{ur}), c) and d) liquidity index (IL), and e) and f) plasticity index (IP). Soil conductivity in the range 10-100 mS/m (grey shading), may indicate possible, quick clay. Improved geotechnical properties are detected within the dashed grey lines in b), d) and e) having soil conductivities exceeding 30 mS/m.

3.3 Conductivity and improved geotechnical properties

Quick clays are in Norway defined by a remoulded shear strength (c_{ur}) of less than 0.5 kPa (NGF, 2011), often having a liquidity index (IL) above 1.2 (Leroueil et al., 1983), and salt contents less than 2 g/L (Torrance, 1979). Both the pore-water and soil conductivity is low in quick clays. Increased salt contents above 2 g/L, i.e. pore-water conductivity > 200 mS/m, improve the remoulded shear strength beyond 0.5 kPa (Figure 4a) and the plasticity index (IP) increases beyond 10% (Figure 4e); the Dragvoll clay ceases to be quick and goes from being of low plasticity to medium plasticity. At a salt content of 4 g/L, the IL decreases below 1.2 (Figure 4c).

According to Solberg et al. (2012) and Long et al. (2012), soil conductivities in the range 10-100 mS/m may indicate low-saline quick clay (shaded grey area in Figure 4), herein referred to as the "quick range". Considering the in-situ measured soil conductivity in the salt-treated clay at Dragvoll (Figure 4b, d and f), a large proportion of the clay where the c_{ur} is improved beyond 0.5 kPa is within the "quick range", even though the salt contents are up to 14 g/L (shaded area in Figure 5a). For these cases, high salt content in the pore water did not result in high soil conductivity.

The Dragvoll quick clay has a soil conductivity of around 20 mS/m. Applying a lower bound to the measured soil conductivities in Figure 4b, the improved properties commence at soil conductivity values exceeding only 30 mS/m, corresponding to salt contents exceeding 1 g/L. At soil conductivities exceeding 200 mS/m, the salt content in nearby clay samples exceeds 6 g/L (Figure 5a), c_{ur} is improved beyond 3.5 kPa, IL decreased below 1.2, and the clay is of medium plasticity (Figure 4b, d and f).

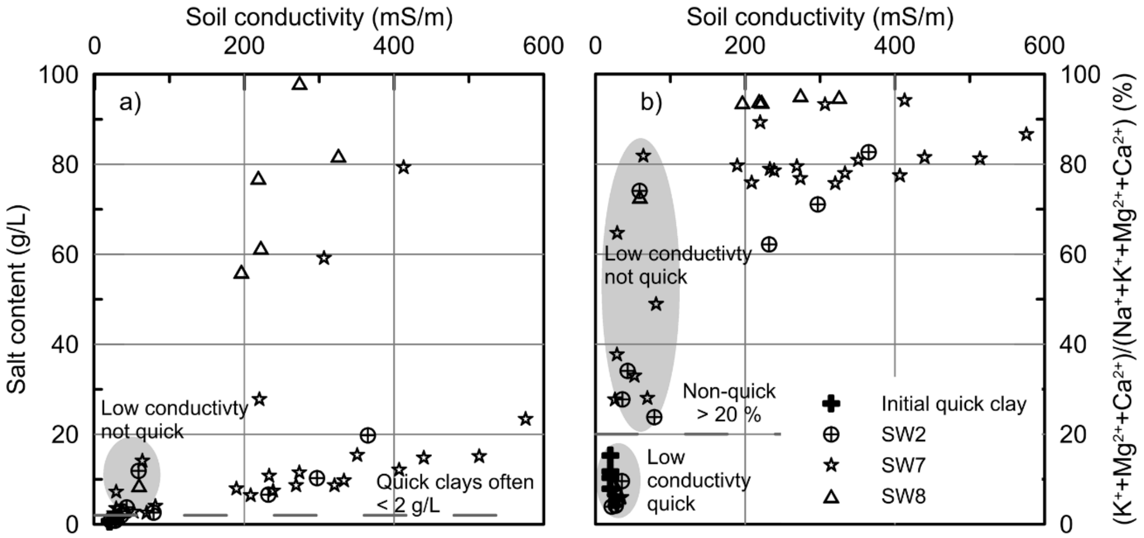

Figure 5. Soil conductivity correlated to a) salt content, and b) the ratio of the sum of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) over the sum of sodium (Na^+), K^+, Mg^{2+} and Ca^{2+} (all concentrations in meq/L). Quick clays often have a salt content of less than 2 g/L, and a ratio of K^+, Mg^{2+} and Ca^{2+} over the major cations of less than 20%.

The pore-water conductivity is directly correlated to the salt content. However, at low salt contents the pore-water composition determines whether the clay is quick or not (e.g. Penner, 1965; Moum et al., 1971; Torrance, 1983; Helle et al., 2016, 2017). Correlating the soil conductivity to the occurring pore-water composition in nearby clay samples, clearly illustrates the challenge in distinguishing quick from non-quick clay based solely on soil conductivity (Figure 5b). Clays with a pore-water composition with a ratio of the sum of K^+, Mg^{2+} and Ca^{2+} over the major cations exceeding 20 % (all concentrations in meq/L) are not quick even at low salt contents (Helle et al. 2017). Therefore, clays with low salt contents (< 2 g/L), and in the case at Dragvoll actually up to 14 g/L, with a pore-water composition that inhibits development of high sensitivity, may be found in the "quick range". Thus, improved soil properties may not always be detected by soil conductivity measurements alone based on the suggested "quick range". The RCPTU soundings provide additional valuable information on the geotechnical properties that may be used in distinguishing quick from non-quick clay at low soil conductivities (< 100 mS/m).

3.4 Detecting improved properties by normalised parameters

The RCPTU data were interpreted using an average unit weight of the soil of 18.7 kN/m^3, a ground-water table at 0.5 m, and no attraction. The normalised tip-resistance (N_m) and pore-pressure parameters (B_q) are correlated to geotechnical properties from 5-8 m depth in Figures 6 and 7. The results are evaluated based on the suggested criterion that $N_m < 4$ and $B_q > 1$ in highly sensitive clays, thus $N_m > 4$ and $B_q < 1$ in the salt-treated clays with improved properties. All N_m within the "quick range" are below 4 (Figure 6a), increasing towards and beyond 4 as the geotechnical properties are improved (Figure 6b). At low conductivity, B_q is both above and below 1 (Figure 6c), decreasing below 1 as the geotechnical properties are improved (Figure 6d). Using N_m of 4 as indicator of highly sensitive clays may lead to misinterpretation of quick clays based on conductivity and N_m up to a remoulded shear strength (c_{ur}) of around 4 kPa (Figure 6b). The B_q is both below and above 1 in the quick clays, but in general lower than 1 at c_{ur} higher than approximately 1 kPa (Figure 6d).

The piston boreholes are positioned in between two RCPTUs, thus the geotechnical properties determined at the laboratory are correlated to the average of the conductivity data and normalised parameters found in the adjacent RCPTUs. Due to the fact that the salt-plume extent is non-symmetrical around the salt wells and that the salt migrates faster in distinct directions, the soil conductivity and normalised parameters may vary around the wells as well. Therefore, the average values of the RCPTU results may in some cases not correspond exactly to the improved properties found in the clay samples positioned in between the soundings. This is especially the case for some of the N_m and B_q from the RCPTUs around salt-well no. 2, differing slightly from the remainder of the data points. The conductivity in the soundings are within the "quick range". However, the B_q in the sounding closest to the direction of fastest salt migration is around 0.9-1.0 (indicated by dotted line and "?" in Figure 6 and 7) rather than the average values of 1.1-1.2 which implies highly sensitive clay. The N_m determined from the sounding positioned in the direction of the fastest salt migration is 3.3-3.7, which implies greater improvement than the average N_m of 2.7-3.3. All in all, the improvement of the geotechnical properties may be detected by increased N_m and decreased B_q.

Increased salt contents decrease the liquidity index (IL) and increase the plasticity index (IP) in the clays. The N_m increases towards 3.5 as the clay changes from being of low plasticity to medium plasticity (Figure 7a), and the B_q decreases below 0.9 in the salt-treated clay as it changes to medium plasticity (Figure 7c). According to Leroueil et al. (1983), clays with IL > 1.2 may pose a risk to develop into large retrogressive quick-clay landslides when remoulded. The N_m increases towards and beyond 3.5, and B_q less than approximately 0.9 as the IL decreases below 1.2 (Figure 7b and d). This implies that an N_m exceeding 3.5 and a B_q decreasing below 0.9 may indicate that the Dragvoll clay ceases to be quick. At an N_m of 3.5 and B_q of 0.9, c_{ur} is about 1 kPa (Figure 6b and d). A site-specific correlation model by correlating geotechnical properties from the site to the RCPTU results can be used in determining improved geotechnical properties based on the CPTU data.

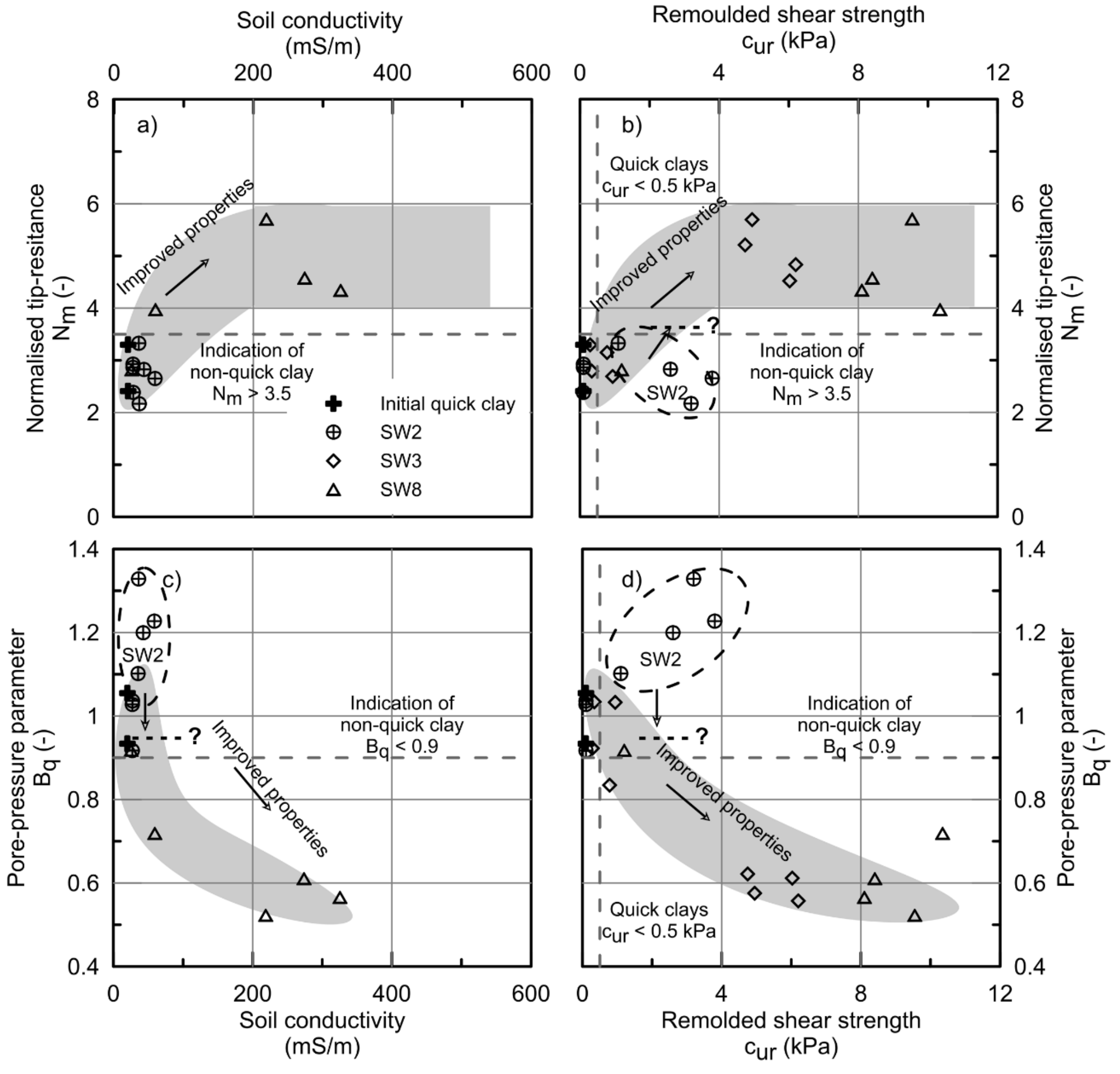

Figure 6. Normalised tip-resistance correlated to soil conductivity and remoulded shear strength (a and b), and pore-pressure parameter correlated to soil conductivity and remoulded shear strength. The N_m and B_q values within the dotted circles may be moved in the direction of the arrow. All data are from 5-8 m depth.

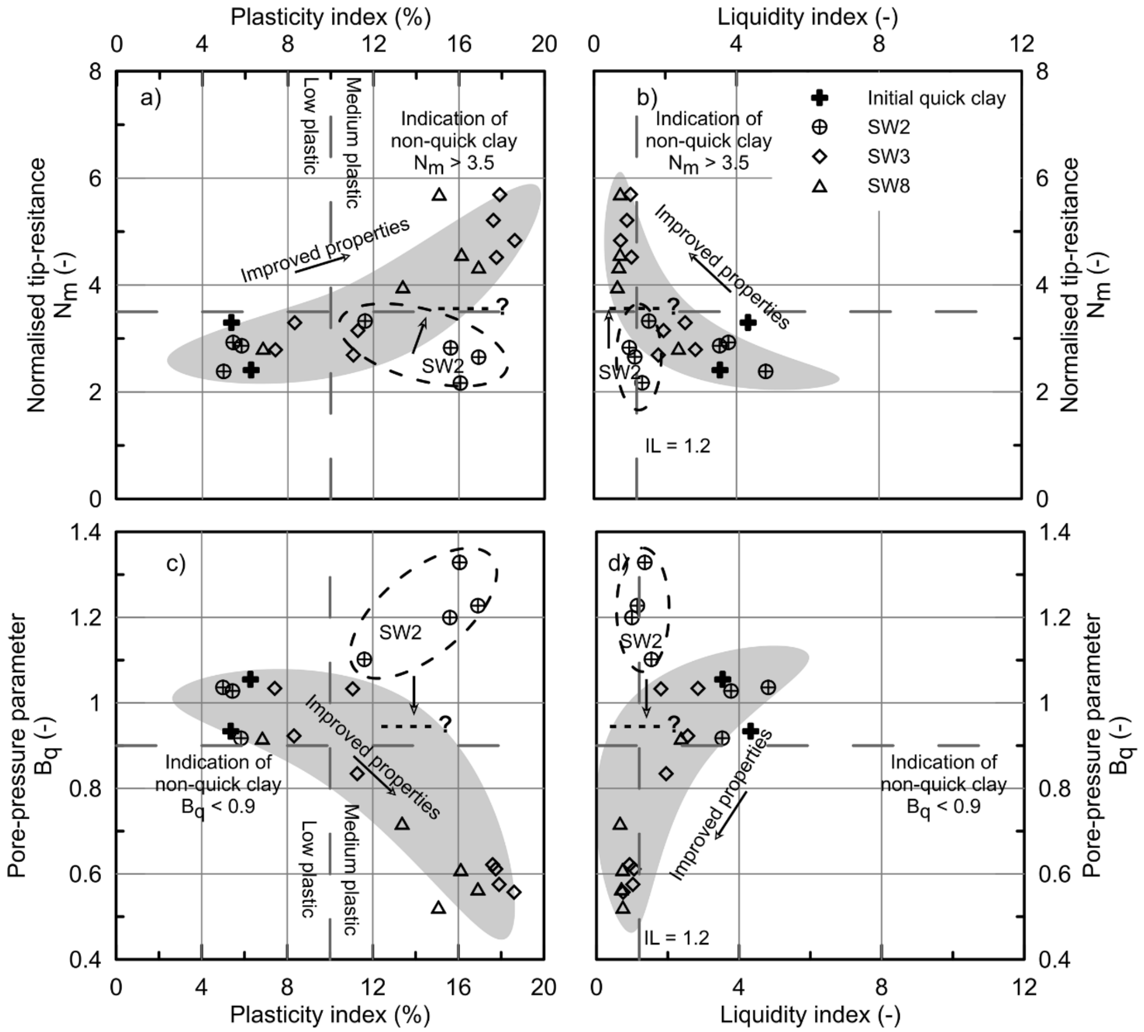

Figure 7. Normalised tip-resistance (N_m) and pore-pressure parameter (B_q) correlated to a) and c) plasticity index, and b) and d) liquidity index. The N_m and B_q values within the dotted circles may be moved in the direction of the arrow. All data are from 5-8 m depth.

4 Discussions and conclusions

Introducing high salt content to the clay-water system, increases the remoulded shear strength (c_{ur}) beyond 0.5 kPa, decreases the liquidity index (IL) below 1.2, and increases the plasticity from low to medium and high. The pore water in quick clays have low salt content, thus low conductivity (10-100 mS/m) may indicate quick clays (Long et al., 2012; Solberg et al., 2012). The pore-water conductivity is directly correlated to the salt content. The soil conductivity is, however, not directly correlated, but does generally increase with increasing salt content. The soil conductivity data from Dragvoll illustrates the challenges in distinguishing low-saline quick clay from non-quick clay at salt contents less than 14 g/L. Rather than interpret improved soil properties within the suggested "quick range", increasing soil conductivity beyond the original values of 20 mS/m may indicate improved properties due to salt treatment. Correlations between the soil conductivity and geotechnical properties, imply that the Dragvoll clay is no longer quick at soil conductivities exceeding 30 mS/m. For soil conductivities exceeding 100 mS/m, the c_{ur} is improved beyond 2 kPa, and beyond 3.5 kPa at soil conductivities larger than 200 mS/m. The findings suggest that a lower bound for the c_{ur} exist for measured soil conductivity. The results from Dragvoll illustrates that low soil conductivity (< 100 mS/m) does not necessarily imply quick clay. This emphasizes the importance of establishing a site-specific interpretation model for distinguishing quick clay from non-quick clay, also suggested by others (e.g. Campanella and Weemees, 1990; Pfaffhuber et al., 2014). Without the site-specific interpretation model the measured soil conductivity may fall within the “quick range”, and fail to detect the improved geotechnical properties in the clay. Even though, soil conductivity alone may not detect improved properties, increased soil conductivity implies increased salt content and provides important information on the salt-plumes extent and direction.

The CPTU tip resistance increased in the salt-treated clay compared to the soundings conducted in the original quick clay. Quick clays are strain-softening materials with a dramatically reduction in post-peak strength at strains exceeding the strain at failure. Penetrating CPTU probes remoulds the soil. Therefore, the tip resistance is affected by both the peak and the c_{ur}. The CPTU tip resistance increases with decreasing compressibility, i.e. volume change due to increasing loads (Lunne et al., 1997). The compressibility is affected by the plasticity and shear strength where the deformations due to increasing loads decreases when the plasticity index increases (Bjerrum, 1967). Adding large concentrations of KCl to quick clays increase the peak as well as post-peak undrained shear strength and the apparent pre-consolidation stress, and reduces the deformations due to increasing loads (Torrance, 1974; Helle et al., 2015). The plasticity and the c_{ur} in the salt-treated clay at Dragvoll is improved. Constant rate of strain oedometer tests conducted on the salt-treated clay at Dragvoll showed decreased deformations due to increasing loads with increasing salt contents and IP. Therefore, increasing tip-resistance may detect the improved geotechnical properties in salt-treated clay, and interpretation models based on normalized tip-resistance (N_m) in combination with a decreased pore-pressure parameter (B_q) may be applied in detecting improved properties beyond what is considered to be quick.

At soil conductivities exceeding 200 mS/m, which at Dragvoll correspond to a salt content of about 6 g/L, the c_{ur} is improved beyond 3.5 kPa. However, the clay at Dragvoll ceases to be quick at salt contents as low as 1-2 g/L due to pore-water compositions where the ratio of the sum of the equivalents of K^+, Mg^{2+} and Ca^{2+} over the major cations exceeds 20%, having soil conductivities of less than 100 mS/m. A site-specific interpretation model correlating geotechnical properties from laboratory tests to normalised parameters from the RCPTUs was made to distinguish quick from salt-treated non-quick clay. The normalised parameters detect the improvement even at low conductivities (< 100 mS/m), where a $B_q < 0.9$ and an $N_m > 3.5$ indicate that the clay ceases to be quick and is changed from being of low to medium plasticity, with an IL < 1.2. Even though, the c_{ur} increases up to 10 kPa, B_q and N_m stabilise around 0.6 and 4-6 respectively at c_{ur} exceeding 4 kPa. The above findings show that RCPTU effectively maps the salt-plume extent around the salt wells by soil conductivity measurements. Furthermore, the RCPTU can be used in detecting improved geotechnical properties beyond what is considered to be quick around the salt wells by site-specific interpretation models based on normalised parameters and geotechnical laboratory tests, and in the case at Dragvoll improvement commence at N_m exceeding 3.5 and B_q lower than 0.9.

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List of notation

a	attraction
α	area factor of the cone penetration test cone
B_q	pore-pressure parameter
c_{ur}	remoulded shear strength
F	formation factor
f_s	uncorrected sleeve friction
IL	liquidity index
IP	plasticity index
N_m	normalised tip resistance
q_c	uncorrected tip resistance
q_n	net tip resistance
q_t	corrected tip resistance
σ_t	soil conductivity
σ_{v0}	total overburden stress
σ_{v0}'	effective overburden stress
σ_w	pore-water conductivity
u_0	in-situ pore pressure
u_2	measured pore pressure behind the cone
w	natural water content
w_L	liquid limit
w_P	plastic limit