Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martínez & Kelly (Eds)
© 2016 Australian Geomechanics Society, Sydney, Australia, ISBN 978-0-9946261-2-7

Monitoring the plume of potassium chloride from wells used as ground improvement in highly sensitive clays

T.E. Helle
Norwegian University of Science and Technology (NTNU), & the Directorate of Public Roads, Trondheim, Norway

P. Aagaard
University in Oslo, Norway

A. Emdal & S. Nordal
Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ABSTRACT: Potassium chloride (KCl) may be used as ground improvement in low-saline, highly sensitive clays termed quick clays. KCl improves the mechanical behaviour of quick clays to such an extent that they no longer appears as quick. Six salt wells filled with potassium chloride were installed in January 2013 at the Dragvoll research site, Trondheim, Norway. The migration of KCl from of the salt wells into the quick clay deposit, is monitored by Schlumberger Divers, BAT ground water monitoring system and a CPTU with resistivity module (RCPTU). The resistivity, normalised tip resistance and pore-pressure parameter clearly indicate the changed behaviour of the clay. In particular, the salt treated clay shows a significant increase in remoulded shear strength and do no longer liquefy when remoulded. The arrival of the plume to the divers and BAT filters reflects a non-symmetrical flow and diffusion pattern around the wells.

1 INTRODUCTION

The Holocene clays in Scandinavia were deposited in a marine environment at the end of the last ice age. Leaching and diffusion has in many clay deposits decreased the originally high salt content in the pore water (~30-35 g/l), and changed the ion composition (Rosenqvist 1946). Clays with a remaining salt content of less than 1 g/l may liquefy completely when remoulded (Bjerrum et al. 1969; Moum et al. 1971, Torrance 1975). In Norway, quick clays are defined by a remoulded shear strength of less than 0.5 kPa. The liquid limit in quick clays is lower than the natural water content, and the clay particles float in their own pore water when remoulded.

This paper presents results from research on improving the properties of the highly sensitive Dragvoll quick clay by installing salt wells. Potassium chloride (KCl) has a beneficial effect on increasing the undrained and remoulded shear strength, as well as the Atterberg limits of quick clays (Moum et al. 1968; Eggestad & Sem 1976; Helle et al. 2015).

It should be noted that low salt content does not necessarily imply that the clay is quick, as the specific ion composition at low salt content highly affects the geotechnical properties (Moum et al. 1971). The clays' negatively charged mineral surfaces attract cations to maintain neutral charge. At the normally occurring pH in Norwegian clays (~8) (Løken 1970; Mitchell and Soga 2005), calcium (Ca^{2+}) is favoured over magnesium (Mg^{2+}), and potassium (K^+) over sodium (Na^+) due to valence, hydrated radius and available concentration (Løken 1970; Appelo and Postma 2005; Mitchell and Soga 2005).

Na^+ is the abundant ion in the pore water in quick clays, whereas Ca^{2+} and Mg^{2+} dominate the adsorbed positions. Ca^{2+} and Mg^{2+} are introduced by the leaching water and weathering of the soil minerals (Moum et al. 1971). Under ordinary pore water compositions in clays, Ca^{2+} and Mg^{2+} are favoured over K^+ by the mineral surface. However, introducing a high concentration of K^+, Ca^{2+} and Mg^{2+} are replaced by K^+ on the mineral surface regardless of its lower exchange power (Mitchell and Soga 2005). K^+ has a greater impact than Na^+, Mg^{2+} and Ca^{2+} on improving the undrained and remoulded shear strength as well as the Atterberg limits (Moum et al. 1968; Løken 1968). According to Moum et al. (1968), as little as 0.5 g K^+/l is sufficient to increase the remoulded shear strength to more than 0.5 kPa.

Salt wells filled with KCl were successfully used as ground improvement in a quick clay deposit at Ul-vensplitten, Oslo, Norway in the 1970s (Eggestad and Sem 1976). Two years after installation, the remoulded shear strength was increased from less than 0.5 kPa to the order of 10-45 kPa, reducing the sensitivity from 12-80 to 1-3. The liquid limit increased beyond the natural water content (Eggestad and Sem 1976). Ground investigations carried out thirty to forty years after installation confirm that the non-quick properties remain in an engineering time scale (Helle et al. 2016).

To further investigate the correlation between geochemistry and geotechnical properties, six salt wells filled with KCl were installed at the Dragvoll research site in Trondheim, Norway (Fig. 1). Monitoring over time is carried out to quantify the extent of the salt plume and the effectiveness of the ground improvement over time.

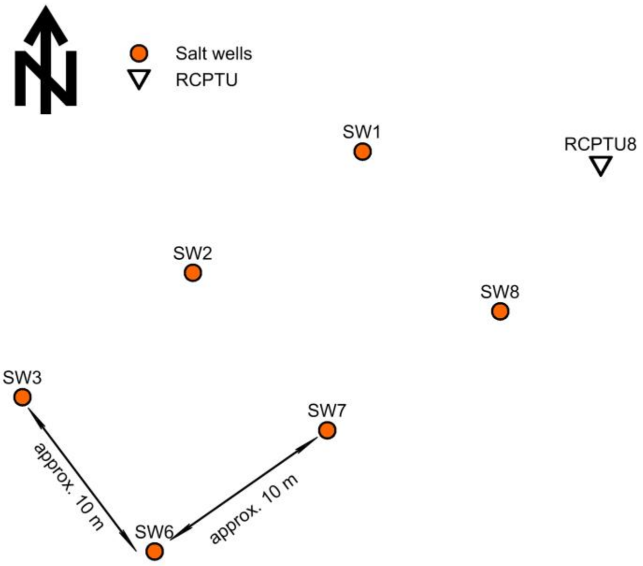

Figure 1. The salt wells are positioned with ~10 m spacing. RCTU8 is located in the outskirt of the test site.

2 SITE DESCRIPTION AND GROUND INVESTIGATION METHODS

2.1 *Dragvoll research site*

The Dragvoll research site is located in an area with clay deposit thickness of up to 40 m (Hafsten and Mack 1990). The marine limit in the Trondheim area is 175-180 m above current sea level (Kjemperud 1981; Hafsten 1983), whereas the research site is located at 156 m above current sea level.

Six salt wells were installed in January 2013 in the quick clay deposit at the Dragvoll research site. The wells are constructed of PE pipes with an outer diameter of 63 mm. The pipes are perforated with slits from 4 m to 8 m depth, allowing the salt to migrate into the quick clay deposit (Fig. 2). To prevent clay entering the salt well, a geotextile is lashed around the perforated pipes. The wells are refilled with granular KCl regularly to maintain a high concentration of KCl in the wells (~4 mol/kgw).

Salt well no. 6 is monitored by BAT groundwater monitoring system (www.bat-gms.com), and Schlumberger divers. The divers log the water head, conductivity and temperature once a day. Ground water samples are extracted from the BAT standard filter tips every 2-3 months. The four instruments are installed at 6 m depth, in a distance of 0.5 m and 1.0 m on opposite sides of the well (Fig. 3).

2.2 *Ground investigations*

A GeoTech CPTU connected to a resistivity module (RCPTU) was used to survey the migration of the salt plume from Salt-well no. 8. The electrodes on the resistivity module are placed in a Wenner-α configuration with electrode spacing of 5 cm. The signals are sent as impulses of direct current of equal intensity, 200 times per second. Seven RCPTU soundings to 12 m depth were carried out around SW8 in September/October 2015; 2 yrs and 9 months after installation. Undisturbed samples were extracted from 4.0 m to 8.8 m depth in a distance of 0.5 m from the salt well (borehole P8A). In the following, most emphasis is made on the results from RCPTU9 correlated to the samples extracted from borehole P8A.

2.3 *Laboratory tests*

The soil samples were tested in the NTNU geotechnical laboratory within 24 hours after extraction from the ground. Index testing was carried out on all samples.

The pore water composition was analysed at the laboratory at the Department for Geosciences at the University in Oslo. The cations were analysed using a Dionex ICS-1000 Ion Chromatography System (ICS-1000). The anions were analysed using a Dionex ICS-2000 Ion Chromatography System (ICS-2000).

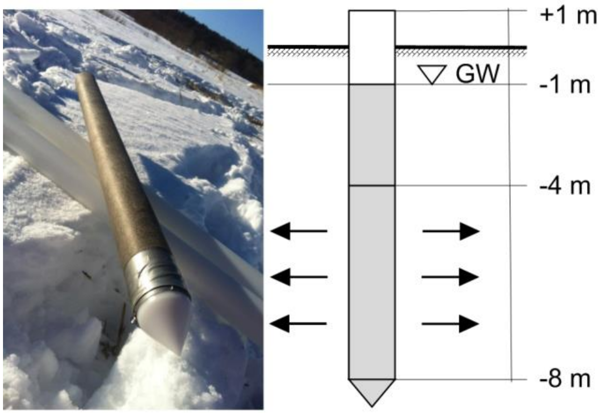

Figure 2. The salt wells are constructed using PE- pipes with an outer diameter of 63 mm. The pipes have slits covered with a geotextile in the depth interval 4-8 m.

3 RESULTS

3.1 *Plume arrival around Salt-well no. 6*

Divers and BAT filters placed around SW6, monitor the progression of the salt plume over time (Fig. 3). The conductivity started to increase in the diver well 0.5 m from SW6 approx. 80 days after installation. Around 450 days, the conductivity increase stopped.

At the same time, the salt concentration in the salt well may have been low due to long refill intervals. The diver conductivity started to increase immediately after refilling the well with salt. This indicate a direct contact between the diver well and the salt well, either due to a communicating silt layer, or a rift caused by installation. A slight increase in the conductivity was observed 1.0 m from the well ~600 days after installation.

The chloride concentration arrived 0.5 m approx. 300 days after installation (Fig. 4a). The K-front is retarded due to ion exchange reactions, and arrived around 600 days after installation. Similar findings were made for the Cl-front 1.0 m from the well (Fig. 4b). The salt plume propagates faster in an eastward direction due to a small hydraulic gradient in that direction (Helle et al. In prep).

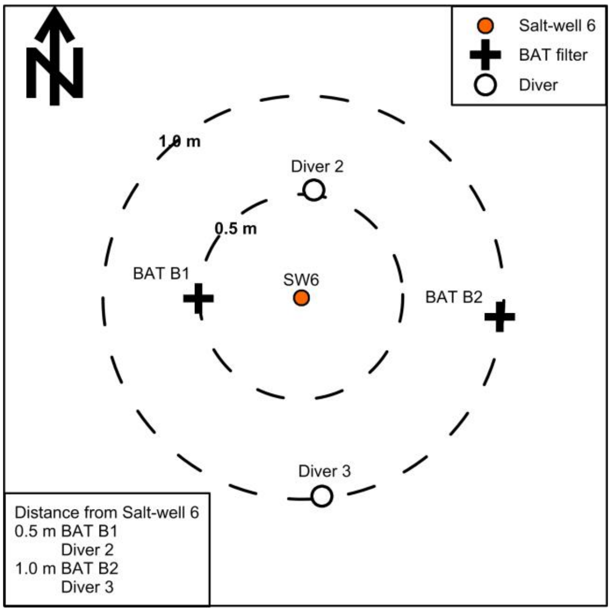

Figure 3. Positioning of BAT filter tips and divers used for monitoring the salt plume arrival over time.

3.2 *Extent of the salt plume around SW8 – 2 years and 9 months after installation*

The salt plume did not spread uniformly around salt-well no. 8 (Fig. 5). The resistivity correlates to the salt content in the pore water (Fig. 6a). Initially, the resistivity in the quick clay at Dragvoll was around 50 Ωm. RCPTU9 correlates well with the increased salt content along the whole depth range of the perforated screen (Fig. 6a). However, on the opposite side of the well (RCPTU 11 north of SW8, Fig. 6b), the resistivity decrease is not as significant as in RCPTU9. Consequently, the salt migration from the salt wells is most likely not only driven by molecular diffusion, but may also be influenced by advective flow. The salt plume surrounding SW8 seem to migrate in a south-western direction. The plume had not yet arrived the locations of RCPTU5 and -7 at the time of investigation; 1 m and 1.5 m from the well respectively.

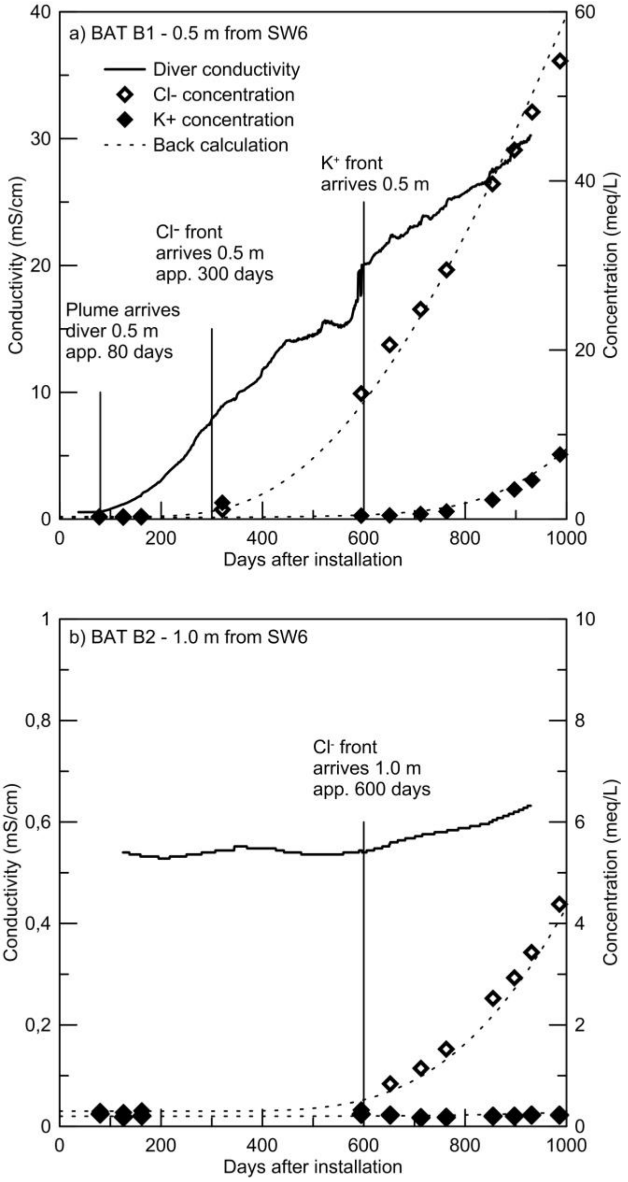

Figure 4. Diver conductivity and concentration of potassium (K^+) and chloride (Cl^-) in the extracted pore water in the BAT filters positioned a) 0.5 m and b) 1.0 m from salt-well no. 6.

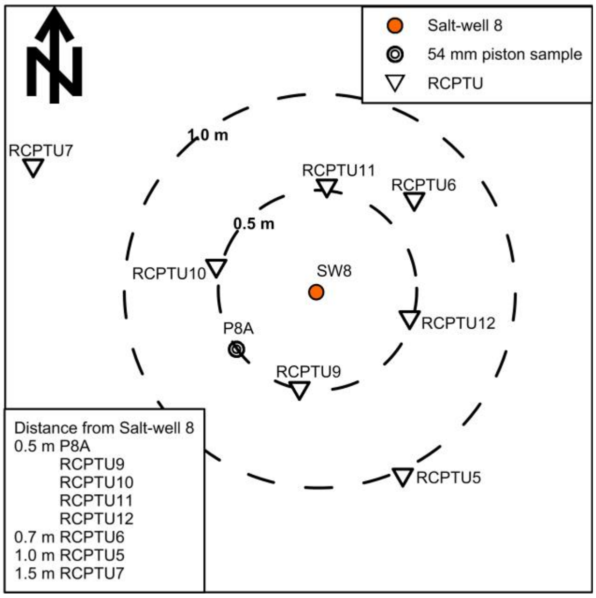

Figure 5. Ground investigations carried out around salt-well no. 8 2 years and 9 months after installation.

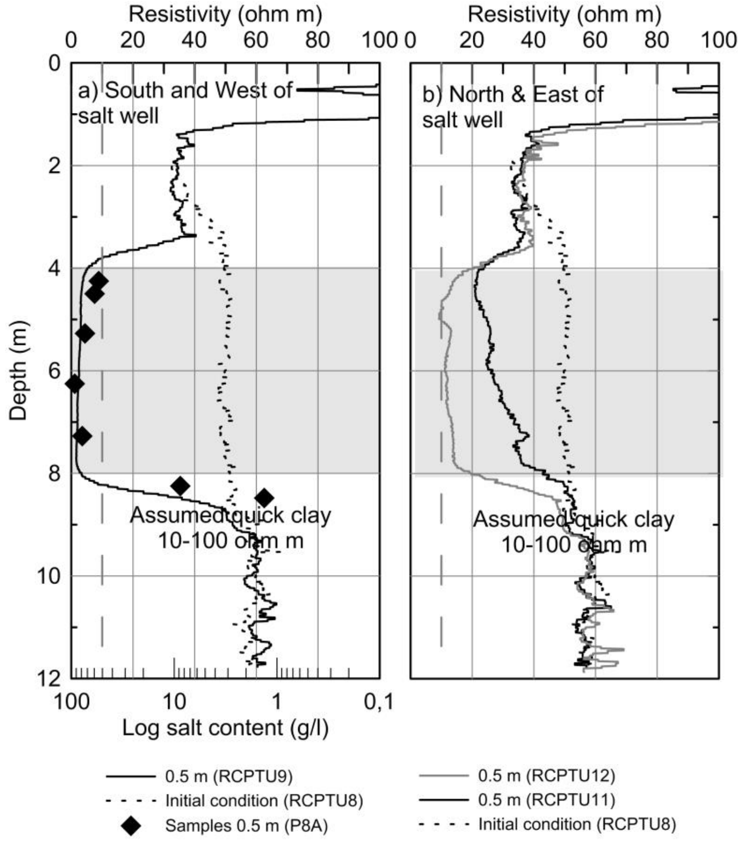

Figure 6. Resistivity profiles 0.5 m from salt-well no. 8. The initial condition is shown by dotted line. a) RCPTU9 and salt content 0.5 m west of salt-well no. 8. Note that the axis for the salt content is in log scale and reverse order. b) RCPTU11 and 12 north and east of the well.

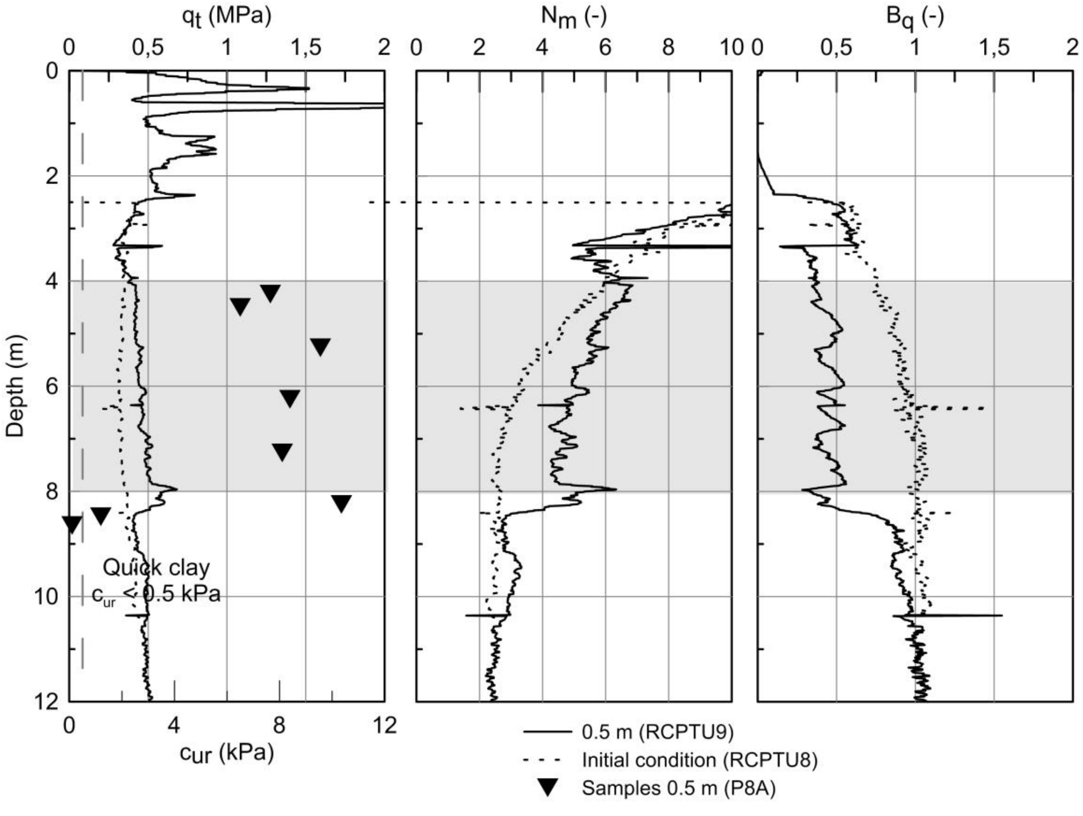

Figure 7. Corrected tip resistance (q_t), normalised tip resistance (N_m) and pore pressure parameter (B_q) in RCTPU, 2 years and 9 months after installation of salt well no. 8 The remoulded shear strength (c_{ur}) found in the samples extracted 0.5 m from the well is shown with black triangles. The initial condition is shown by dotted line.

The remoulded shear strength (c_{ur}) is greatly affected by the salt content in the pore water. The salt content in the salt treated clay is increased to as much as 98 g/l. The improved remoulded shear strength (c_{ur}) in the clay samples extracted 0.5 m from SW8, is in the range 6.5 to 10.4 kPa (Fig. 7).

A slight increase is seen in the corrected tip resistance (q_t) in the salt treated clay 0.5 m from SW8 (RCPTU9). Both the normalised tip resistance (N_m) and pore-pressure parameter (B_q) may indicate the occurrence of quick clay. The normalised tip resistance (N_m) is calculated by dividing the net tip resistance on the effective overburden pressure and an average attraction of 5 kPa. According to Sandven et al. (2015), N_m of less than 4 may indicate quick clay, as was also detected in the Dragvoll quick clay. However, at around 4 m depth, N_m is around 6, even though the clay is quick. N_m exceeds 4 in the salt treated clay. B_q decreases from approximately 1 in the quick clay, to around 0.5 in the salt treated clay.

4 DISCUSSION AND CONCLUSIONS

The non-symmetrical flow pattern around the wells at Dragvoll makes it difficult to monitor the salt plume. The instruments should be placed in the fastest and slowest flow-path directions. These directions were not known prior to installing the wells and instruments at Dragvoll. The salt plume seem to expand slightly different in various directions at the test site. Around SW8, it seems to expand more in a west-ward and slightly southward direction. Around SW6, however, it seems to expand more in an eastward direction.

RCPTU is a powerful tool to track the salt plume extent, as well as providing valuable information on the soil properties. The remoulded shear strength exceeds 0.5 kPa in the salt treated clay. Considering both resistivity, N_m and B_q, the salt-treated, improved clay can be distinguished from quick clay. According to Long et al. (2012), the resistivity seems to be unaffected by salt contents exceeding 8 g/l. The resistivity data from the RCPTUs correlated to the salt content from nearby boreholes confirm this (Fig. 8a).

Even though, resistivity measured by RCPTU clearly identifies the increased salt content, resistivity measured by electrical resistivity tomography (ERT) with an electrode spacing of 0.5 m, was not able to detect the increased salt content due to poor resolution at depth (Bazin et al. 2016).

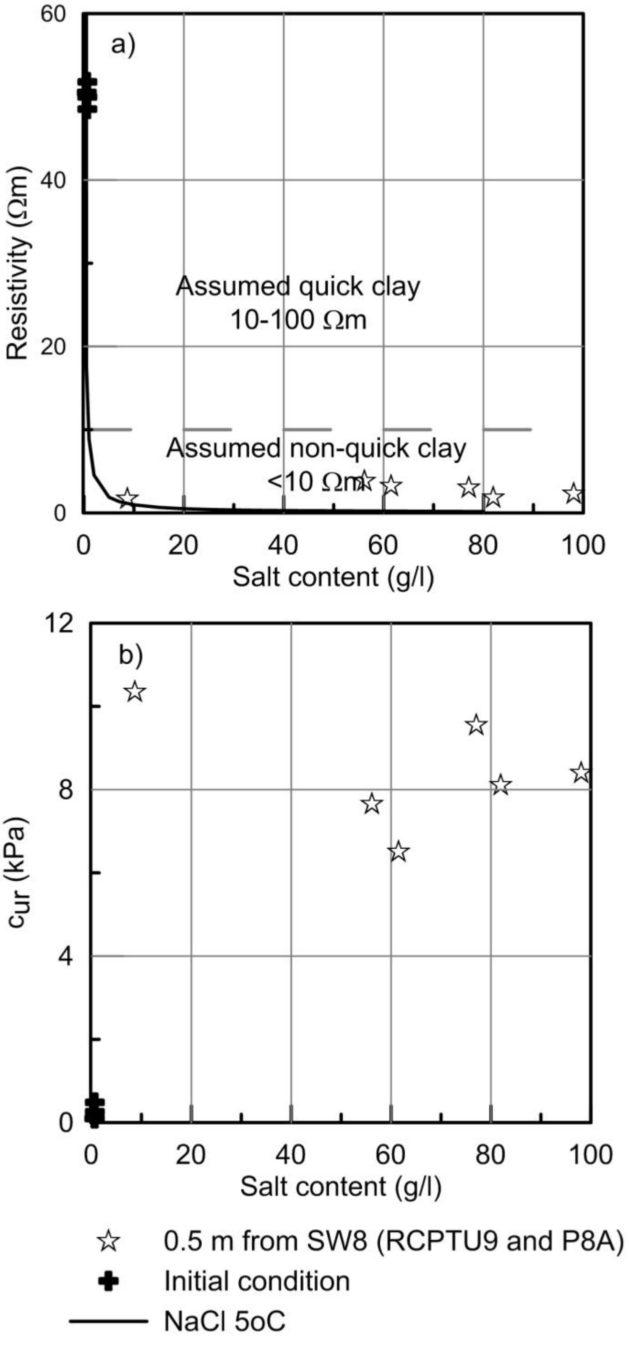

Figure 8. a) RCPTU resistivity correlated to salt content found in nearby samples. The dashed line shows the limit where the resistivity may indicate quick clay (10-100 Ωm) and non-quick clay (<10 Ωm) (Solberg et al. 2012). The black line shows PHREEQC calculated resistivity versus TDS equivalent to NaCl solutions at 5ºC. b) Remoulded shear strength correlated to salt content found in nearby samples.

5 ACKNOWLEDGMENTS

The authors express their sincere gratitude to Jan Jønland, Einar Husby and Gunnar Winter at NTNU Geotechnical Research Group for their thorough work carrying out the ground investigations. Anders Samstad Gylland, formerly at NTNU, and Elisabeth Gundersen in the Directorate of Public Roads are acknowledged for their contributions to discussing well design and installation methods. The tidy work by Mufak Naoroz at the laboratory at the University in Oslo analysing the pore water chemistry on small sample volumes, is highly appreciated. The work is funded by the Norwegian re-search program "Naturfare - infrastruktur, flom og skred (NIFS)".

6 REFERENCES

Appelo, C. & Postma, D. 2005. Geochemistry. groundwater and pollution. 2nd edn. Balkema, Leiden, Netherlands.

Bazin, S., Anschütz, H., Sauvin G., Helle T.E., Gribben S., Donohue, S. & Long, M. 2016. Geophysical characterisation of marine and quick clay sites: field and laboratory tests. 5th International Conference on Geotechnical and Geophysical Site Characterization.

Bjerrum, L., Løken, T., Heiberg, S. & Foster, R. 1969. A field study of factors responsible for quick clay slides. Proceedings of 7th ICSMFE, 2, Mexico 1969, 531-540.

Eggestad. A. & Sem. H. 1976. Stability of excavations improved by salt diffusion from deep wells. Proceedings of the European conference on soil mechanics and foundation engineering, 6, Vienna, March 1976: 211-216.

Hafsten, U. (1983). Shore-level changes in South Norway during the last 13,000 years, traced by biostratigraphical methods and radiometric datings. Norsk geografi tidsskrift 37: 63-79.

Hafsten, U. & Mack, G. 1990. Den postglaciale landskapsutviklingen på Dragvoll universitetsområde, Trondheim. Norsk Geografisk Tidsskrift 44(3): 131-148.

Helle, T.E., Bryntesen, R.N., Amundsen, H.A., Emdal, A., Nordal, S. & Aagaard, P. 2015. Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway. Proceedings of GeoQuebec2015, Canada, September 2015.

Helle, T.E., Nordal, S., Aagaard, P. & Lied, O.K. 2016. Long-term-effect of potassium chloride treatment on improving the soil behaviour of highly sensitive clay – Ulvensplitten, Norway. Canadian Geotechnical Journal 53(3): 410-422.

Helle, T.E., Aagaard, P. & Nordal, S (In prep). In-situ improvement of highly sensitive clays by potassium chloride migration.

Kjemperud, A. 1981. A shoreline displacement investigation from Frosta in Trondheimsfjorden, Nord-Trøndelag, Norway. Norsk geologisk tidsskrift 61: 1-15.

Long, M., Donohue, S., L'Heureux, J.S., Solberg, I.-L., Rønning, J.S., Limacher, R., O'Connor, P., Sauvin, G., Rømoen, M. & Lecomte, I. 2012. Relationship between electrical resistivity and basic geotechnical parameters for marine clays. Canadian Geotechnical Journal 49(10): 1158-1168.

Løken, T. 1970. Recent research at the Norwegian Geotechnical Institute concerning the influence of chemical additions on quick clay. Proceedings of the Geologiska Föreningen i Stockholm, Förhandlingar 92(2): 133-147.

Mitchell. J.K. & Soga K. 2005. Fundamentals of soil behaviour. 3rd edn. John Wiley & Sons Inc. New Jersey, USA.

Moum, J., Sopp. O.I. & Løken T. 1968. Stabilization of undisturbed quick clay by salt wells. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication no. 81.

Moum, J., Løken, T. & Torrance, J.K. 1971. A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Géotechnique, 21(4): 329-340.

Rosenqvist, I.T. 1946. Om leirers kvikkaktighet. Available from the Norwegian Public Road Administrations, Meddelelsen fra Vegdirektøren, No. 3: 29-36.

Sandven, R., Montafia, A., Gylland, AS, Pfaffhuber, AA, Kåsin, K., Long, M. 2015. Detektering av kvikkleire-Sluttrapport. NIFS-report no. 126-2015.

Solberg, I.-L., Hansen, L., Rønning, J.S., Haugen, E.D., Dalsegg, E. & Tønnesen, J.F. 2012. Combined geophysical and geotechnical approach to ground investigations and hazard zonation of a quick clay area, mid Norway. Bulletin of Engineering Geology and the Environment 71(1): 119-133.

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: 326-335.