Tonje Eide Helle

Quick-clay landslide mitigation using potassium chloride

Doctoral thesis

Tonje Eide Helle

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Civil and Environmental
Engineering

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of
Science and Technology

NTNU

Tonje Eide Helle

Quick-clay landslide mitigation using potassium chloride

Thesis for the Degree of Philosophiae Doctor

Trondheim, September 2017

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Preface

The present PhD study is carried out at the Geotechnical Group at Department of Civil and Environmental Engineering at Norwegian University of Science and Technology (NTNU). The work is presented as a collection of journal and conference and workshop papers complemented by a summary. Professor Steinar Nordal from NTNU was the main supervisor, and Professor Emeritus Per Aagaard from University of Oslo was the co-supervisor.

The study is made possible by the financial support from the research programme "Natural hazards: infrastructure for floods and slides" (NIFS) which was a collaboration between the Norwegian Public Roads Administration (NPRA), the Norwegian Water Resources and Energy Directorate (NVE) and the Norwegian Railway Directorate (JBV).

The evaluation committee consisted of Professor Tim Länsivaara (1st opponent) from Tampere University of Technology, Professor Emeritus Elen Roaldset (2nd opponent) from Natural History Museum in Oslo, and Associate Professor Fjola Gudrun Sigtryggsdottir (administrator) from NTNU.

Abstract

Highly sensitive postglacial marine clays, termed quick clays, represent a risk for large retrogressive or progressive landslides such as the well-documented Rissa quick-clay landslide in 1978. Landslide susceptibility presents great challenges for construction work, even in the construction of landslide mitigation measures. Establishing large prevention berms is a commonly used method for increasing slope stability, but can often result in undesirable changes to the terrain. Ground improvement by potassium chloride (*KCl*) is herein considered as a possible alternative. However, detailed knowledge on geochemistry and its impact on the mechanical behaviour in clays is needed in developing efficient ground-improvement methods based on introducing salt into the clay-water system.

In 1972, salt wells filled with potassium chloride (*KCl*) were installed in a quick-clay deposit at Ulvensplitten, Oslo, Norway with the intention to improve the mechanical properties in the quick clay prior to excavation. Great emphasis was made in documenting the improved geotechnical properties with sampling and vane shear testing in the 2-3 years following the salt-well installations. The ground investigations revealed a significant increase in undrained and remoulded shear strength as well as in the Atterberg limits with increasing concentrations of potassium in the pore water. The collected pore-water chemistry data was, however, scarce and inconclusive with regard to determination of when the clay ceased to be quick; vital for estimating the time required to stabilize the quick-clay volume. The salt-well method is not used as ground improvement today, mainly due to the fact that it is time consuming and the effects are not fully understood or documented with regard to short and long-term effects.

In order to establish understanding and documentation, six salt wells filled with *KCl* were installed in January 2013 in a highly sensitive, low plastic quick-clay deposit at Dragvoll, Trondheim, Norway. The changed pore-water chemistry and improved properties around the wells were investigated by monitoring systems, sampling, laboratory and in-situ tests. The in-situ experiment at Dragvoll provides unique results on improvement of the geotechnical properties isolated to the impact of changed pore-water chemistry. The computer program PHREEQC was used for back calculations of the observed geochemical changes, suggesting that such simulations could be used for estimating the required time to stabilise the quick-clay volume surrounding the wells. Resistivity cone penetrations tests (RCPTU) were conducted in order to evaluate its effectiveness on detecting improved geotechnical properties in-situ. In addition, ground investigations were carried out 40 years after salt-well installations at Ulvensplitten to document the long-term effect of *KCl*-treated clays. The herein presented correlations between geotechnical properties and pore-water compositions in the salt-treated clay deposit at Dragvoll together with the data from Ulvensplitten, contributes to understand the mechanisms around *KCl* as ground improvement and its feasibility, as well as determining at which pore-water composition the clays render to be quick.

The collected historical and new data validate the *KCl*-well method as a landslide mitigation method inhibiting retrogressive landslide development, also reducing the risk for progressive development.

Acknowledgments

This project would have been very difficult to realise without the support, encouragement and help from the people I am lucky to have around me. I am so grateful to have had the opportunity to work on this challenging, but incredibly exciting topic.

Back in 2007/2008, Eirik Traae (NVE) asked me to check out the possibility for using salt to stabilise one of the many quick-clay slopes in their landslide mitigation program. After discussing the matter with my colleagues at the time, I replied that we didn't know enough about the method to apply it. Today there is a large prevention berm in the foot of that particular slope. But, my curiosity grew, and after more discussions with late Odd Gregersen, Tor Løken and Øyvind Høydal (all NGI) we got funding from the Norwegian Geotechnical Society to carry out a pre study that led to the PhD application.

The encouragement, enthusiasm and support from my boss Roald Aabøe (NPRA) is greatly appreciated. Thank you for believing in the project from the first time you heard about it, bringing it to the right people to get enough funding for the PhD. This work could not have been realised without the generous support from the research program "Natural hazards: infrastructure for floods and slides" (NIFS). To my colleagues in the NPRA, especially Bjørn Kristoffer Dolva, Vikas Thakur (now NTNU), Kristian Aunaas (now Norconsult), Elisabeth Gundersen, Frode Oset, Ole Vidar Kirkevollen, Eigil Haugen, Tor Kringlåk, and late Harald Skarvang: Thank you for all good discussions and help!

I would like to thank my supervisors Professor Steinar Nordal (NTNU) and Professor Emeritus Per Aagaard (UiO) for guiding me through it all, being so helpful and patient, and for providing insightful comments. Associate professor Arnfinn Emdal (NTNU): Thank you for enthusiastic discussions, valuable advice, and never-ending encouragement. Jan Jønland, Gunnar Winther, Einar Husby (all NTNU): Thank you for great support, never saying no, and continuously feeding me with chocolate and coffee. Not everybody wants to install salt wells in cold -15 ºC, but you did! Karl Ivar Kvisvik and Espen Andersen: Thank you for joining the Geotechnical Group and finalise the last ground investigations. Anders Samstad Gylland (NTNU/now Multiconsult): Thank you for helping out installing the salt wells at Dragvoll and all the discussions in the beginning of the project. I would also like to thank PhD candidate Helene A. Amundsen (NTNU/NPRA) for all the help and guidance in the lab, nice and supportive conversations and discussions. Marit Skjåk-Bræk (NTNU): Thank you for keeping track of all the administrative work, making sure that everything went smoothly during the final stages of my PhD. The tidy job Mufak Naoroz (UiO) did on analysing numerous pore-water samples is highly appreciated. The valuable work carried out by master students Ingelin Gjengedal (NTNU/now Norconsult), Rikke Nornes Bryntesen (NTNU/now NPRA), Fredrikke Syversen (UiO/now BaneNOR), Karl Fredrik Hvoslef Moe (NTNU/now Sweco) and PhD candidate Beyene Girma Haile (UiO) is greatly appreciated.

I have also had the pleasure to visit Professor Emeritus J. Ken(neth)Torrance (Carleton Unviversity) twice. His insightful advice and comments have been of great value improving my research. I will be forever grateful for your time and interest. Every summer I have been looking forward to Associate Professor Michael Long's (UCD) annual "working holiday" at NTNU. Thank you for inspiring and motivating discussions. The "geophysical group" Sara Bazin

(NGI), Guillaume Sauvin (UiO/NGI), Helgard Anschütz (NGI) and Isabelle Lecomte (UiO/Norsar) are acknowledged for their investigations on the site.

In the daily life, the employees and co-PhD candidates in the Geotechnical Group at NTNU has helped me out, and made these years productive and joyful. Thank you for meaningful, and maybe most importantly meaning*less* conversations during lunch breaks, numerous Friday-cakes, coffee and tea breaks, salary beer and Christmas-party dancing.

To my parents who taught me to work hard to achieve my goals: Thank you! To my always supporting husband, Stian Tandberg: Thank you for not divorcing me yet, thank you for listening and being my rock when days were not as fun, and thank you for being just as happy as me when things went my way! And to my precious little ones, Sindre and Brage: "I love you to the moon, and back!"

Contents

Table of figures

List of tables

Nomenclature

Latin letters

a	attraction (kPa)
A	long-range attraction
Ab	albite
Am	amphibole
BET	Brunauer-Emmet-Teller theory
BP	before present
B_q	pore-pressure parameter (-)
Cal	calcite
CAU_c	anisotropically consolidated undrained compression triaxial test
CEC	cation exchange capacity (meq/100 g dry soil)
Chl	chlorite
CPTU	cone penetration test with pore pressure measurements
CRS	constant rate of strain oedometer test
c_u	undrained shear strength (kPa)
c_{uc}	peak undrained shear strength from CAU_c (kPa)
c_{ur}	remoulded shear strength (kPa)
D	dielectric constant (-)
D_e	effective diffusion coefficient (m^2/s)
D_f	diffusion coefficient in free water (m^2/s)
D*	apparent diffusion coefficient (m^2/s)
e	void ratio (-)
e_i	void ratio at time of deposition (-)
e_0	present void ratio, after secondary compression (-)
EB	electric charge balance (%)
Hbl	hornblende
IL	liquidity index (-)
Ill	illite
ip	ionic potential
IP	plasticity index (%)
k	hydraulic conductivity (m/s)
k_h	horizontal hydraulic conductivity (m/s)
k_v	vertical hydraulic conductivity (m/s)
Kfs	K-feldspar
K_0'	coefficient at rest (-)
L	length
m	Archie's exponent (-)
Mc	microcline
Ms	muscovite
M	oedometer modulus (MPa)
M_{OC}	oedometer modulus in the OC range (MPa)
MCD	multi-component diffusion

n	exponent used in MCD simulations in PHREEQC
N_m	normalised tip-resistance (-)
OC	over consolidated
OCR	over-consolidation ratio
p'	mean effective stress (kPa)
p_c'	apparent pre-consolidation stress (kPa)
PE	polyethylene
q	deviatoric stress (kPa)
Qtz	quartz
r_{ion}	atomic radius (nm)
R	repulsion
RCPTU	resistivity cone penetration test with pore pressure measurements
TDS	total dissolved solids (ppm)
V	volume
u	pore pressure (kPa)
u_0	initial or measured pore pressure
w	water content (%)
w_L	liquid limit (%)
w_P	plastic limit (%)
XRD	X-ray diffraction
XRF	X-ray fluorescence
z	ionic charge or valence (-)

Greek letters

γ_f	shear strain at failure (%)
γ_{80}	shear strain at 20% reduction of c_{uc}
$\Delta\varepsilon_{KCl}$	immediate deformations at loads exceeding p_c' in *KCl*-treated clay
$\Delta\varepsilon_{KCl}$	immediate deformations at loads exceeding p_c' in quick clay
$\Delta\gamma_{80}$	brittleness parameter
ε	vertical strain (%)
ε_f	vertical strain at failure (%)
ε_{vol}	volumetric change due to water extrusion during consolidation in CAUc tests
ε_w	water-filled porosity (-)
$1/\kappa$	thickness of the diffuse double layer (nm)
ρ	density (g/cm^3)
ρ_{KCl}	density of the KCl solute in the salt wells (g/cm^3)
σ_{vi}'	effective overburden stress at time of deposition (kPa)
σ_{vP}'	apparent pre-consolidation stress (kPa)
σ_{v0}	vertical overburden stress (kPa)
σ_{v0}'	effective vertical overburden stress (kPa)
φ	friction angle (º)
ψ	electric potential (mV)
ψ_0	electric potential at mineral surface (mV)

Chemical symbols

Al^{3+}	aluminum
Alk	alkalinity
Br^-	bromide
Ca^{2+}	calcium
$Ca\text{-}X_2$	adsorbed calcium
Cl^-	chloride
CO_3^{2-}	carbonate
F^-	fluoride
$Fe^{2+/3+}$	iron
H^+	hydrogen
HCl	hydrochloric acid
HCO_3^-	bicarbonate
K^+	potassium
KCl	potassium chloride
$K\text{-}X$	adsorbed potassium
Mg^{2+}	magnesium
$Mg\text{-}X_2$	adsorbed magnesium
$N_2(g)$	nitrogen gas
Na^+	sodium
$NaCl$	sodium chloride
$Na\text{-}X$	adsorbed sodium
NO_3^-	nitrate
O^{2-}	oxygen
OH^-	hydroxyl
PO_4^{3-}	phosphate
Si^{4+}	silicon
SO_4^{2-}	sulphate

1 Introduction

1.1 Background and motivation

Leached low-saline, highly sensitive marine clays, termed quick clays, are found in formerly glaciated parts of Scandinavia, Canada and northern Russia. Quick-clay deposits are located under the marine limit. In Norway, the marine limit (Figure 1-1a) is found up to an elevation of 220 m above current sea level in the areas around Oslo, and up to 200 m above current sea level in the inner part of Trøndelag county. Quick clays are characterised by a remoulded shear strength of less than 0.5 kPa (Norwegian Geotechnical Society 2011), often with a liquid limit lower than the natural water content. Normally, quick clays are just as strong as non-quick clays, whereas remoulded these soils may behave as a liquid, causing severe challenges in slope stability. An initial slide comprising quick clay may flow out of the initial slide-pit, triggering further back-scarp instability and a retrogressive or progressive development of the landslide (Figure 1-2), which may stretch several hundred meters backwards from the initial back scarp. The well-documented Rissa quick-clay landslide in 1978 stretched catastrophically 1.5 km behind the initial slide in a relatively flat area (inclination approximately 1:10), covering an area of 330 000 m^2 with a total volume of slide debris of 5-6 million m^3 (Gregersen 1981). After the Rissa landslide, great emphasis has been made mapping areas, or hazards zones, that pose a risk for large quick-clay landslides, and to increase the awareness around the risk related to construction work in quick clays.
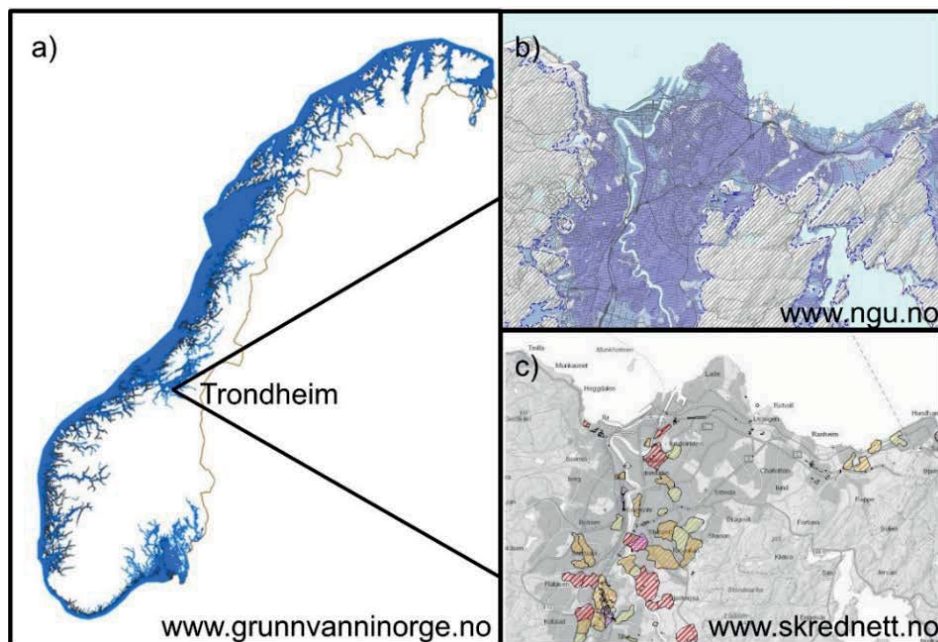
Figure 1-1 a) Quick clays are found in areas under the marine limit marked with blue areas and b) purple areas. c) Quick-clay hazard zones are limited by topographic constraints
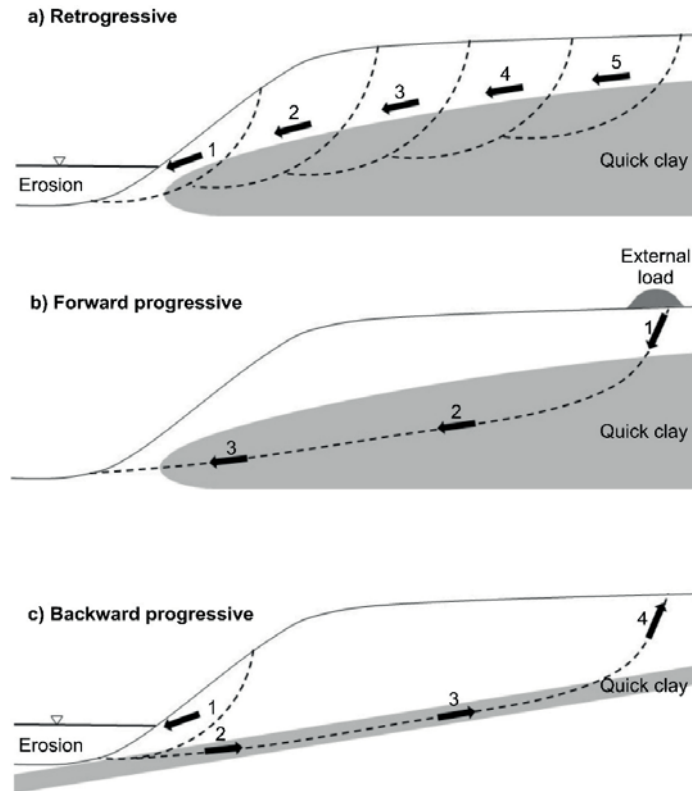
Figure 1-2 a) Retrogressive quick-clay landslide with successive back-scarp failures. b) Forward progressive quick-clay landslide due to external loading. c) Backward progressive development along a thin quick-clay layer

All clay deposits under the marine limit pose a risk for quick-clay landslides (Figure 1-1b). However, the over 1800 (www.nve.no) mapped quick-clay hazard zones (Figure 1-1c) fulfils certain topographic criteria such as area (> 10 000 m^2), height differences (> 10 m), gradually sloping terrain, or a slope inclination larger than 1:15. Furthermore, the thickness of the quick-clay deposit, sensitivity, and degree of erosion, amongst others, are included in evaluating the risk of quick-clay landslides (Gregersen 2001). The Norwegian Water Resources and Energy Directorate (NVE) have the responsibility for landslide mitigation in inhabited areas within the quick-clay hazard zones. The evaluation of risk within the zones is used when giving preference to certain quick-clay areas in their landslide mitigation program.

Rivers or creeks often run in the foot of the slopes in the quick-clay hazard zones, and erosion pose a risk for triggering landslides. Stability measures along rivers and creeks often comprise adding soils or a carpet of boulders of rock in the foot of the slope to balance out the driving forces in a potential landslide, and protect against erosion. This is, however, not always feasible due to terrain constraints. Conventional methods such as sheet-pile walls and lime/cement piles may be too expensive, or create excess pore pressures in the slopes during installation, temporarily reducing the stability.

Figure 1-3 The quick-clay landslide caused by terrain work led to the collapse of the Skjeggestad bridge. The yellow bulldozer carrying out the work is seen in the left part of the slide pit. Photo: F. Oset

Even though erosion pose a serious threat in quick-clay areas, most quick-clay landslides are induced by human impact; such as the Rissa landslide in 1978, and more recently the landslide causing the collapse of the Skjeggestad bridge in 2015 (Figure 1-3). There exist strict regulations for construction work in quick-clay areas in Norway. Increased safety factors are aimed for in design of embankments, fills and cuts in quick clay areas. The necessity and degree of stability measures depend on which design category the construction is in. In some cases, it is satisfactory not to reduce the stability, whereas in other cases the stability must be increased in percentages. Stability measures to increase the safety factor must be finalized before construction commences (Norwegian Water Resources and Energy Directorate 2014). Land development either for housing, schools, hospitals or infrastructure, may not be possible due to marginal safety in the quick-clay areas, and inadequate and/or expensive landslide mitigation methods. Furthermore, many inhabited areas lie in quick-clay areas with a high potential risk for large quick-clay landslides. Developing a cost-efficient method eliminating the quick clay threat without posing a risk for reduced stability during installation, may expose new areas for land development, and make it possible to increase the safety in already inhabited areas where existing landslide mitigation methods are not applicable.

Re-establishing high salt concentration in leached low-saline quick clays significantly improves their mechanical properties (Rosenqvist 1946, 1953, 1955; Bjerrum 1955; Løken 1968, 1970; Moum et al. 1968; Quigley 1980; Torrance 1983). In 1972, wells filled with potassium chloride (*KCl*) were installed in a quick clay at Ulvensplitten, Oslo, Norway (Eggestad and Sem 1976). Ground investigations carried out 2 to 3 years after installation revealed a significant increase in undrained and remoulded fall-cone shear strength, and Atterberg limits with increasing concentration of potassium (K^+) in the soil volume surrounding the wells. Despite these promising results, the salt-well method is not in use today, probably due to installation costs and time for the salt to migrate into the clay, and the effects are not

fully understood or documented. The motivation for the present PhD research is to contribute to documentation and understanding the processes in improving the geotechnical properties in quick clays by introducing *KCl* to the clay-water system. Finally, the method will be validated so that it can be further developed as a ground-improvement method to eliminate quick clay in slide-prone areas with marginal safety. The PhD is funded by the research program "Natural hazards: infrastructure for floods and slides" (NIFS) which is a collaboration between the Norwegian Public Roads Administration (NPRA), the Norwegian Railway Directorate (JBV) and the Norwegian Water Resources and Energy Directorate (NVE).

1.2 Scope and objectives

The scope of the present PhD research is to investigate how the geotechnical properties in highly sensitive quick clays respond to changed pore-water chemistry by introducing potassium chloride (*KCl*) to their soil-water system, as well as investigating the migration of *KCl* in clays. The project is primarily a field and laboratory study. The main results are restricted to the Dragvoll research site in Trondheim, Norway with its specific mineralogy and geochemical composition in the soil-water system. However, results from the Ulvensplitten site in Oslo, Norway stabilised with *KCl* in the 1970s, are made accessible to this project, and are used for validation of the method. 1D simulations of the observations in field and laboratory are carried out with the computer program PHREEQC (www.usgs.gov) with the available codes and mineralogical and chemical databases given in the program.

The objective of the PhD research is to:

- Contribute to knowledge on the effect of pore-water chemistry on the geotechnical properties in Norwegian low-saline marine clays (quick clay)
- Describe how *KCl* migrates around salt wells, and to what extent it changes the pore-water chemistry and geotechnical properties with time
- Establish correlations between the ion composition in the pore water and the post-failure properties in clays to evaluate when the clays cease to be quick
- Study the migration of *KCl* based on simulations of field and laboratory observations to evaluate the time needed to improve the post-failure properties in quick clays based on the established correlations between ion composition and post-failure properties
- Use the obtained field and laboratory results to evaluate the potential of *KCl* wells as ground improvement in quick-clay areas

1.3 Outline of the thesis

The PhD thesis is paper based and written as a summary followed by a collection of papers. The main results in the papers are included in the chapters. The summary of the PhD research is organised as follows:

1. *Introduction*: presents the background, motivation, scope and objectives and a list of publications from the present PhD work.

2. *Mineralogy and pore-water chemistry in sensitive clays:* reviews mineralogy and pore-water chemistry and their impact on developing highly sensitive clays.

3. *Pilot studies:* summarises the main findings from the study on mineralogy, pore-water chemistry and geotechnical properties in collected Norwegian clays presented in

Appendix A, as well as results from two laboratory setups using *KCl* to improve the geotechnical properties in clay samples described in Paper I and II.

4. *Long-term effect of in-situ improvement:* documents the effect of *KCl*-treated clay around salt wells 30-40 years after installation in a quick-clay deposit at Ulvensplitten, Oslo, Norway in 1972. The chapter relates to Paper III.

5. *In-situ experiment improving geotechnical properties of the Dragvoll quick clay*: describes the in-situ field experiment improving the geotechnical properties in the quick clay at the Dragvoll research site by salt migration from *KCl* wells. The main results and findings from the monitoring system, resistivity cone penetration tests (RCPTU) and extracted clay samples are presented. Results from the simulations of the monitored pore-water chemistry can be used for prediction of the required time to stabilise the quick-clay volume. The chapter relates to Papers IV-IX.

6. *Summary*

7. *Conclusions*: summarises the main conclusions from the present PhD research.

8. *Further research*: suggestions to further research on the topic.

Appendix:

A *Pilot study: Mineralogy, pore-water chemistry and post-failure properties in Norwegian clays:* presents and evaluates the results from the collected data on mineralogy, pore-water chemistry and geotechnical properties in Norwegian clays conducted spring 2013. The samples were prepared for mineralogical analyses by master student F Syversen (UiO) who also helped collecting the geotechnical data. The bulk and clay mineralogy was quantified by PhD Candidate BG Haile (UiO). Results from the PhD research by BO Hilmo (1989) are included.

1.4   List of publications and declaration of authorship

The thesis is paper based and consists of in total nine papers. Three of the papers are published in peer-reviewed journals (Papers III, V and VIII). One of the papers are accepted for publication in a peer-review journal (Paper VI), and one is under review (Paper IX). Out of the four peer-reviewed conference and workshop papers, two are published in conference proceedings (Papers II and IV) and two as book chapters (Papers I and VII). The ideas for the papers are provided by TE Helle, who also wrote the manuscripts with contributions from the co-authors as listed below together with acknowledgments.

Paper I: Helle TE, Gjengedal I, Emdal A, Aagaard P and Høydal Ø (2014) *Potassium chloride as ground improvement in quick clay areas – a preliminary study.* In Landslides in Sensitive Clays: From Geosciences to Risk Management. Advances in Natural and Technological Hazards Research 36, Springer. 1st International Workshop on Landslides in Sensitive Clays, Quebec, October 2013: 63-74.

- The paper presents the laboratory study carried out by master student I Gjengedal studying the migration of *KCl* and its impact on the geotechnical properties in clay specimens from two different sites in mid-Norway. The idea for the study was provided by TE Helle, who together with A Emdal (NTNU) supervised I Gjengedal. The paper also presents simple estimations of the diffusion of *KCl* in the clay carried out by TE

Helle. P Aagaard (UiO) and Ø Høydal (NGI) contributed greatly with discussions of the laboratory setup and during the writing of the manuscript. J Jønland (NTNU), G Winther (NTNU), E Gundersen (NPRA), V Thakur (NPRA), F Oset (NPRA), T Løken (NGI), late O Gregersen (NGI), E Traae (NVE) and S Nordal (NTNU) are acknowledged for valuable discussions on the laboratory setup and the topic in general. Reviewer Professor Yudhbir is acknowledged for his feedback on the manuscript.

Paper II: Helle TE, Bryntesen RN, Amundsen HA, Emdal A, Nordal S and Aagaard P (2015) *Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway.* In Proceedings for GeoQuebec2015 - Challenges from North to South. Quebec, September 2015: 8 pp.

- The paper presents the laboratory study on mini-block samples extracted from the Dragvoll research site, Trondheim, Norway and stored in *KCl* slurry. The idea for the study was provided by TE Helle, who also made the correlations between the pore-water chemistry and the geotechnical properties. The geotechnical laboratory work was carried out by master student RN Bryntesen with great help from HA Amundsen (NTNU/NPRA). A Emdal (NTNU), S Nordal (NTNU) and P Aagaard (UiO) were all involved in discussing the results and the manuscript. J Jønland (NTNU) and G Winther (NTNU) are acknowledged for carrying out the ground investigations, and designing the storage containers. M Naoroz (UiO) is acknowledged for analysing the pore-water chemistry. One unknown reviewer is acknowledged for his/hers comments on the manuscript.

Paper III: Helle TE, Nordal S, Aagaard P and Lied OK (2016) *Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay – Ulvensplitten, Norway.* Canadian Geotechnical Journal 53(3): 410-422. One of the Editor's choice papers in 2016.

- Salt wells filled with *KCl* were installed in a quick clay deposit at Ulvensplitten, Oslo, Norway in 1972. The paper presents the results from geotechnical investigations prior to installation, in the first two years, and 30-40 years after the installation. OK Lied (Geovita AS) helped gathering the existing ground-investigation data, as well as organizing the new ground investigations in the area. S Nordal (NTNU) and P Aagaard (UiO) contributed greatly on discussing the results and manuscript. Å Eggestad and H Sem are acknowledged for their valuable discussions and information on the original installations, as well as T Løken (NGI) and late O Gregersen (NGI). K Aunaas, F Oset and R Aabøe are acknowledged for encouraging investigations of the site within the present PhD work. M Naoroz (UiO) is acknowledged for analysing the pore-water chemistry. The archive in the municipality in Oslo and several people in the Norwegian Public Roads Administration (NPRA) are acknowledge for making the data accessible. Three unknown reviewers are acknowledged for their valuable comments, greatly improving the manuscript.

Paper IV: Helle TE, Aagaard P, Emdal A and Nordal S (2016) *Monitoring the plume of potassium chloride from wells used as ground improvement in highly sensitive clays.* In Proceedings of the 5th International Conference on Geotechnical and Geophysical Site

Characterization (ISC'5), Gold Coast, Australia. Australian Geomechanics Society, vol. 2, pp. 1501-1506.

- The paper describes how the salt-plume extent and migration of *KCl* was monitored around the salt wells at Dragvoll, Trondheim, Norway. Results from the conductivity divers and ground-water samples extracted from the BAT filters are presented, as well as resistivity cone penetration test (RCPTU) data around one of the wells. The collection of groundwater samples, interpreting the results, and data correlations were carried out by TE Helle. P Aagaard (UiO) was heavily involved in discussing the results, and A Emdal (NTNU) and S Nordal (NTNU) were involved in discussing the manuscript. J Jønland, E Husby and G Winther (all NTNU) are acknowledged for carrying out the ground investigations. AS Gylland (NTNU/Multiconsult) and E Gundersen (NPRA) are acknowledged for their contributions on discussing installation methods and well design. M Naoroz is acknowledged for analysing the pore-water chemistry. One unknown reviewer is acknowledged for his/hers comments on the manuscript.

Paper V: Helle TE, Aagaard P and Nordal S (2017) *In-situ improvement of highly sensitive clays by potassium chloride migration.* Journal of Geotechnical and Geoenvironmental Engineering ASCE 143(10), published online ahead of print.

- The paper presents the results and correlations from the geotechnical and geochemical investigations around all the salt wells at Dragvoll, Trondheim, Norway. The geotechnical laboratory work and interpretation of data was carried out by TE Helle. P Aagaard (UiO) and S Nordal (NTNU) were heavily involved in discussing the results and manuscript. The authors express their sincere gratitude to Professor Emeritus JK Torrance (Carleton University) and assistant professor A Emdal (NTNU) for their discussions on the topic. J Jønland, E Husby, G Winther, E Andersen and KI Kvisvik (all NTNU), and late H Skarvang, T Kringlåk and OV Kirkevollen (all NPRA) are acknowledged for carrying out the ground investigations. M Naoroz (UiO) is acknowledged for analysing the pore-water chemistry, J Schönenberger (NGU) for carrying out the XRF analyses, and PhD candidate Yahao Li (NTNU) for determining the specific surface area. Two unknown reviewers are acknowledged for their valuable comments, greatly improving the manuscript.

Paper VI: Helle TE and Aagaard P (2017) *Predicting required time stabilising quick clays by potassium chloride.* Accepted for publication in Environmental Geotechnics ICE in July 2017.

- The paper presents the simulation results of the monitored salt-plume migration from salt wells installed in the quick-clay deposit at Dragvoll, Trondheim, Norway. It also includes predictions of the required time to improve the post-failure properties in the quick-clay deposit. The simulations were conducted by TE Helle, who also did the interpretation of data. P Aagaard (UiO) was heavily involved in discussing the simulation results and manuscript. Post.doc. Y Bekele and S Nordal (both NTNU) are acknowledged for their valuable discussions on the topic. Two unknown reviewers are acknowledged for their comments on the manuscript.

Paper VII: Helle TE, Aagaard P and Nordal S (2017) *Improving the post-failure properties in quick clays by treatment with potassium chloride.* In Landslides in sensitive clays: From

research to implementation. Advances in Natural and Technological Hazards Research 46, Springer. 2nd International Workshop on Landslides in Sensitive Clays, Trondheim, June 2017: 45-55.

- The paper presents the general concept of using *KCl* to improve the post-failure properties in quick clays. Electrical conductivity data, geotechnical and geochemical results around one of the wells are presented. P Aagaard (UiO) and S Nordal (NTNU) were involved in discussing the results and ideas in the manuscript. Reviewer Professor Emeritus JK Torrance (Carleton University) is greatly acknowledged for his valuable comments and discussions on the paper. A Emdal (NTNU), M Long (University College Dublin), T Løken (NGI), ØA Høydal (NGI), E Gundersen (NPRA) and AS Gylland (NTNU/Multiconsult) are acknowledged for the discussions on the topic during the project period.

Paper VIII: Helle TE, Long M, Nordal S and Aagaard P (2017) *Effectiveness of resistivity cone penetration tests in salt-treated highly sensitive clay.* Proceedings of the Institution of Civil Engineers - Ground Improvement 170(3): 173-184.

- The paper presents the results from the resistivity cone penetration tests (RCPTU) around the salt-wells at Dragvoll. The paper evaluates the various existing criteria for detecting highly sensitive clays. M Long (UCD) was heavily involved in discussing the results and manuscript. S Nordal (NTNU) and P Aagaard (UiO) were involved in discussing the manuscript. J Jønland, G Winther, E Husby, KI Kvisvik and E Andersen (all NTNU), and late H Skarvang and T Kringlåk in the Norwegian Public Roads Administration (NPRA) are greatly acknowledged for carrying at the ground investigations. The discussions with E Haugen and OV Kirkevollen (NPRA), T Lunne (NGI), A Emdal (NTNU), and late R Sandven (Multiconsult) are greatly appreciated. Two unknown reviewers are acknowledged for their comments on the manuscript.

Paper IX: Helle TE, Nordal S and Aagaard P (Under review) *Improved geotechnical properties in salt-treated highly sensitive landslide-prone clays.* Submitted to Proceedings of the Institution of Civil Engineers - Geotechnical Engineering in April 2017.

- The paper presents results from constant rate of strain oedometer tests conducted on clay samples with varying salt contents, as well as index parameters and pore-water chemistry. The impact of *KCl* on the apparent pre-consolidation stress (p_c') and reduced immediate deformations at loads exceeding p_c' related to the brittleness of the Dragvoll quick clay is discussed and evaluated in the paper. The geotechnical laboratory work and interpretation of data was carried out by TE Helle. S Nordal (NTNU) and P Aagaard (UiO) were heavily involved in discussing the results and manuscript. J Jønland, E Husby and G Winther (all NTNU) are acknowledged for carrying out the ground investigations. M Naoroz (UiO) is acknowledged for analysing the pore-water chemistry, and RN Bryntesen (NTNU/now NPRA) for carrying out laboratory work on mini-block samples stored in *KCl* slurry. The discussions on the laboratory results with HA Amundsen (NTNU/NPRA), and on progressive landslides with Petter Fornes (NTNU/NGI) are greatly appreciated.

2   Mineralogy and pore-water chemistry in sensitive clays

2.1   Introduction

Most of Norway was covered with ice during the last ice age, Weichselian maximum. Norwegian soils are from a geological perspective considered as young sediments, originating from the time during glaciation and after the withdrawal of the ice sheet, consisting of grinded bedrock. Soils are characterised as clays when more than 30% of the soil consists of clay particles (< 2 μm), and are denoted as clays together with their conjugate fractions of soils when the clay content is 15-30%; for instance, silty clay (Norwegian Geotechnical Society 2011). As little as 10% clay can affect the engineering properties in soils (Mitchell and Soga 2005). Clays are cohesive and plastic and their behaviour is affected by the presence of water. Water has a great impact on the clay behaviour, as clays are electrochemically very active (van Olphen 1963). The clay-water system is essential in understanding the behaviour of clays.

The clays sedimented in seawater or brackish water during and after deglaciation stages of the last ice age. The clay particles flocculated and created a fabric resembling a 'house-of-cards' with large voids filled with highly saline water. Isostatic uplift exposed these sediments to leaching (advective flow and diffusion), which diluted the pore water and changed its chemical composition, weakening the structure (Rosenqvist 1946). The clays behaviour is greatly affected by their depositional environment and the post-depositional changes such as compression, unloading, leaching and weathering (Rosenqvist 1955; Torrance 1983; Mitchell and Soga 2005). In the following, the compositional factors, as clay mineralogy and pore-water chemistry, and their effect on the geotechnical properties will be discussed.

2.2   Clay mineralogy

Soils consist of particles of various sizes and mineral types. Clay minerals are weathering products (both physical and chemical) of eroded and transported detrital minerals. The glacial and post-glacial clays of Scandinavia and eastern part of Canada and northern Russia are physical weathering products from grinding of the bedrock by the glacier during the last ice age. The clay minerals are layered silicate minerals (phyllosilicates), each mineral type with its definite crystal structure and chemical composition. The main groups are kaolinite, smectite, vermiculite, illite and chlorite. In Norway, the clays mainly consist of low-active (non-swelling) illite and chlorite (Rosenqvist 1955, 1975; Løken 1968; Mitchell and Soga 2005).

The mineral types are defined by their combinations and stacking of two or three sheets of *silicon tetrahedra* and *aluminium* or *magnesium octahedra*, shown and explained by several authors such as Moore and Reynolds (1997) and Mitchell and Soga (2005). The tetrahedral and octahedral sheets consist ideally of silicon (Si^{4+}) and aluminium (Al^{3+}) surrounded by oxygen (O^{2-}) or hydroxyls (OH^-). The tetrahedral-sheet structure is built up with a silicon in the middle surrounded by four oxygen oriented around it, forming a tetrahedron, a pyramid with four triangular sides. The octahedral sheet is formed of aluminium in the middle surrounded by six oxygen atoms, a structure with eight triangular faces looking like two oppositely directed pyramids stacked on top of each other. The octahedral is termed di-octahedral if two-thirds of the cationic positions are filled with trivalent ions such as Al^{3+}, or tri-octahedral if all positions are occupied by divalent ions such as magnesium (Mg^{2+}).

Clay minerals are normally net negatively charged, caused by isomorphous substitution and/or charged mineral edges. Isomorphous substitution means that Al^{3+} replaces Si^{4+} in the tetrahedral sheet, or magnesium (Mg^{2+}) or iron (Fe^{2+} or Fe^{3+}) replaces Al^{3+} in the octahedral sheet. The mineral edges are charged due to unsatisfied bonds on the edges of the structural patterns (van Olphen 1963; Moore and Reynolds Jr. 1997; Mitchell and Soga 2005 amongst others). The charge caused by isomorphous substitution is considered a permanent charge, whereas the charge caused by broken bonds at the edges of the minerals are variable. The variable charges can be either positive or negative depending on the pH of the solute. The edge is positively charged when H^+ is attached to the edge, and negative when OH^- holds this position. Which ion is attached to the edge at certain pHs is mineral dependent. The edge charge constitutes normally less than 1% of the total charge in minerals with a permanent charge, and is of little or no importance in Norwegian clays that mainly consist of illites and chlorites.

Minerals without isomorphic substitution, as kaolinite and serpentine, may be electrically neutral. Here, the octahedral sheet has two thirds of trivalent cations in the octahedral sites and one vacancy (di-octahedral), or with divalent cations in all positions in the octahedral sheet (tri-octahedral), and there is no substitution for Si^{4+}. In mineral types with interlayer sheet, cations such as potassium (K^+), sodium (Na^+) or calcium (Ca^{2+}) in the mica group, or octahedral sheet in the chlorite group, may neutralize the charge. Illite, or hydrous mica, is composed of 2:1 unit-layers; one octahedral sheet sandwiched in between two tetrahedral sheets (Figure 2-1a), fixating K^+ in its interlayer positions between the 2:1 unit-layers (Figure 2-1b). The complete chemical formula for illite is *$(K,H_2O)_2(Si)_8(Al,Mg,Fe)_{4,6}O_{20}(OH)_4$* (Mitchell and Soga 2005). The interlayer K^+ is fixed in the hexagonal holes in the tetrahedral sheets, and balances the charge deficit caused by Al^{3+} replacing Si^{4+} in some of the positions in the tetrahedral sheet. The Al^{3+} in the octahedral sheet may be substituted by either an ion of equal or smaller size, such as Mg^{2+} or Fe^{2+}, creating an excess of negative charge in the crystal lattice. Chlorites (Figure 2-1c) have many variations of the 2:1 unit-layers and the octahedral interlayers, and a variety of chlorites form depending on the stacking of the unit layers, various amounts and combinations of substitutions (van Olphen 1963; Moore and Reynolds 1997; Mitchell and Soga 2005).

The net negative charge on the clay mineral surfaces is balanced by adsorbing cations to the mineral surfaces. Some ions are strongly fixed in interlayer positions such as K^+ in the non-swelling clay mineral illite. In some minerals, such as the swelling clay mineral vermiculite, the ions in the interlayer positions are exchangeable. The surplus of negative charge not accounted for by ions in the interlayer positions, are balanced by attracting ions to the mineral surfaces. The cation exchange capacity (*CEC*) in meq/100 g dry soil reflects the size of the surface charge. Illites with fixed K^+ in their interlayer positions have smaller *CEC* than for instance vermiculite with exchangeable hydrated ions in their interlayer positions. According to Grim (1968), illites and chlorites have a *CEC* in the range of 10-40 meq/100 g dry soil, whereas vermiculite may have a *CEC* of 100-150 meq/100 g dry soil. The wide ranges depend on which substitution is present in the tetrahedral and/or octahedral sheets, degree of crushing and weathering, bedrock origin, depositional physio-chemical environment, present physio-chemical environment amongst others. Property ranges for each mineral type are found in various textbooks, and may be applied in the interpretation of data of similar geological history. Properties for clay mineral types of diagenetic origin differ from the properties in the same clay mineral types found in detrital clastic clays. The sensitive clays accumulated during and after
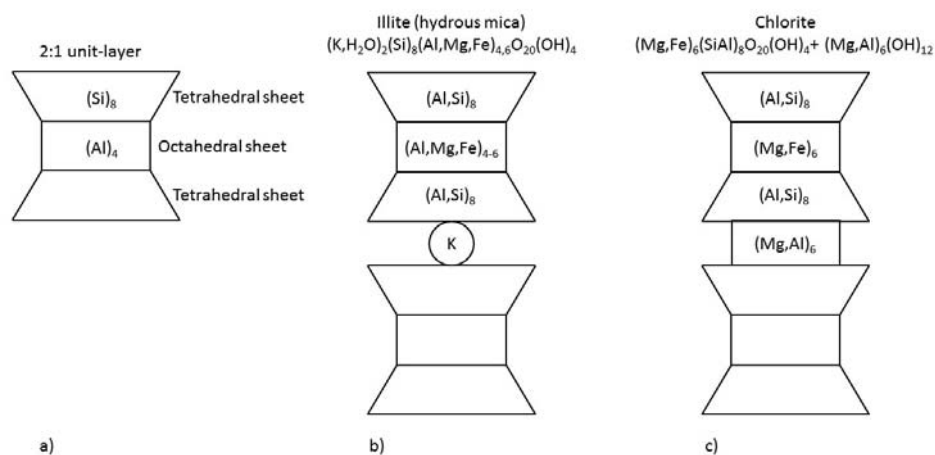
Figure 2-1 a) Illustration of 2:1 unit-layer with silica (Si^{4+}) and aluminium (Al^{3+}) in the cations positions in the tetrahedral and octahedral sheets respectively. b) Schematic structure of illite, and c) chlorite. Adapted from Mitchell and Soga 2005

the last ice age consist of grinded rock flour mainly consisting of low-active minerals. Grinded rock flour has normally small amounts of clay minerals, and the clayey soils in Norwegian marine glacial/post-glacial sediments are dominated by detrital primary minerals. Therefore, the specific surface area, thus also the *CEC*, may be small (Quigley 1980; Torrance 1983). Kenney (1967) reports a *CEC* of three Norwegian very sensitive illitic-chloritic clays of 9-11 meq/100 g dry soil at clay contents of 42-44%. Locat and St-Gelais (2014) report *CEC* of Quebec chloritic-illitic clays in the range of 6-17 meq/100 g dry soil in clays with clay contents of 30-83%.

Both bulk and clay mineralogy affects the geotechnical properties. However, the geotechnical properties are also influenced by the presence of water and the in-situ pore-water composition. The negatively charged exterior of the minerals, as for instance in illites and chlorites, is balanced by the cations in the pore water. How the pore-water chemistry influences the clay-water system is discussed in the following sections.

2.3   The clay-water system

The behaviour of clays is very much influenced by the presence of water. All clay-rich soils consist of solid mineral phases and a liquid phase. The liquid phase is an electrolyte consisting of water, cations and anions. The negative charge in the clay particles is compensated for by accumulating an equivalent amount of positively charged ions, often referred to as counter-ions, from the liquid near the particle surface to reduce the surface charge to a minimum. Water molecules form the first layer around the surface. The hydrogens in the water molecules orient themselves towards the clay mineral surface, strongly held by hydrogen bonding. The negatively charged oxygen is oriented towards the voids, thus the clay mineral together with the surrounding water molecules are still negatively charged. This negative charge is accounted for by attracting oppositely charged ions from the pore water in the voids to the surface. The
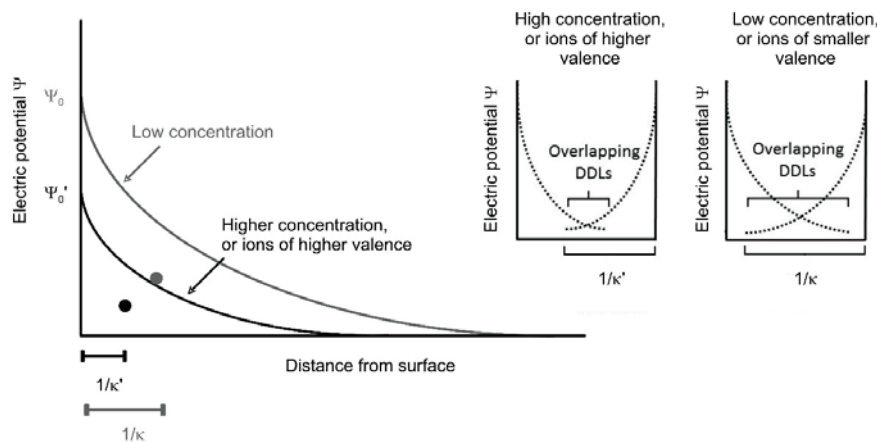
Figure 2-2 The decay of electric potential with distance from the mineral surface. The surface potential (ψ_0) is higher at low electrolyte concentrations (grey line) than at high concentrations (ψ_0') (black line). Of two electrolytes of same concentration, the surface potential is lower for the electrolyte consisting of ions of higher valence. Thus, the thickness of the diffuse double layer ($1/\kappa$) is smaller. The overlap of the diffuse double layers (DDL) determines the repulsion between the clay particles. Adapted from van Olphen (1963) and Moore and Reynolds Jr. (1997)

surface charge and the counter-ions together with water forms the electric diffuse double layer around the particles, which describes the thickness of the immobile water layer surrounding clay particles. Due to the swarm of cations attracted to the particle surface, anions from the pore water migrate towards the particle surface to balance the charge. The cation concentration in the clay-water system is highest at the particle surface, and decreases with distance from the surface towards the free water in the pores. The anions avoid the surface due to equal charge, and increase in concentration with distance from the surface towards the free pore water, where the total charge of cations and anions is equal. Thus, the bulk salt content in the pores is found in the mid-plane between two parallel surfaces.

The surface charge on clays is constant at constant pH. Thus, the electric potential on the surface varies with varying electrolyte concentration. The thickness of the diffuse double layer ($1/\kappa$) is considered as the distance from the clay mineral surface to the centre of gravity of the decaying electric potential from the mineral surface to the free pore water (Figure 2-2). Clays suspended in an electrolyte with low concentration will have higher electric potential at the surface and a slower decay of potential with distance to the surface than clays suspended in electrolytes of higher concentrations. Thus, the diffuse double layer thickness in clays with low salt content is larger than in clays with high salt content. Likewise, clays suspended in two electrolytes of same concentration, but consisting of cations of different valence, the clay suspended in a monovalent solution will have a higher electric potential than clays suspended in a divalent solution (van Olphen 1963). The diffuse double layer thickness also decreases due to decreasing dielectric constant (D) of the liquid. The D in water is 80, and is reduced by increasing concentration of electrolytes (Levy et al. 2012). It is also reduced adding organic solvents such as alcohols and acetone to the liquid (Mitchell and Soga 2005).

In suspension, the clay particles move around with small random movements called Brownian motions (van Olphen 1963; Moore and Reynolds 1997). Clay particles in suspension will either attract or repel each other. Inter-particle attraction and repulsion act simultaneously. Even though the van der Waals forces cause attraction between the particles, there will be a simultaneous repulsion due to overlapping diffuse double layers (Figure 2-2). The repulsion is larger in dilute solutions than in solutions with large electrolyte concentrations, or in solutions of same concentrations but with ions of higher valence. In solutions with high concentration of dissolved salt, the repulsion is smaller than the attraction, and the particles cluster or flocculate, creating large enough particles to settle. This is of crucial importance influencing whether clay particles flocculate or are dispersed in water. The repulsive forces predominate between clay particles accumulated in freshwater. Therefore, the clay particles are homogenously dispersed in the water, and may settle very slowly in a face-to-face orientation if the particles are heavier than the liquid. The repulsive forces decrease with increasing salt content in the pore water due to smaller diffuse double layer overlap. In salt water repulsion is reduced, and attractive forces between the clay particles become dominating. This allows the particles to flocculate in a structure with as large distance as possible between the equally charged faces of the platy clay particles, either in an edge-to-face, or an edge-to-edge orientation. The edge-to-face orientation occurs when the clay minerals have opposite charges on the face and on the edges. The charge on the edges is pH dependent. The 1:1[a] clay mineral kaolinite may create edge-to-face orientations. The 2:1[b] clay mineral montmorillonite do not (Rand et al. 1980; Santamarina et al. 2002). The 2:1 montmorillonite orient themselves in an edge-to-edge orientation at pHs in the range 4-11 (Rand et al. 1980). At very high electrolyte concentrations, the thickness of the diffuse double layer decreases to such an extent that there is practically no repulsion, only attraction between the particles, and rapid coagulation occur (van Olphen 1963). In these cases, the particles are both flocculated and aggregated. The diffuse double layer thickness does not only determine how the clay particles orient themselves during accumulation. It also plays an important role when it comes to clay sensitivity.

2.4   Pore-water chemistry and clay sensitivity

Clays found under the marine limit were deposited in a marine environment with a salt content of 30-35 g/L (Moum et al. 1971; Appelo and Postma 2005). The clay minerals flocculated in an open structure accommodating high water content, entrapping seawater in the large voids (Rosenqvist 1946). Isostatic uplift has exposed these clays to leaching by meteoric groundwater flow. Post-depositional changes decreased the salt content in the pores, and simultaneously increased the electrostatic repulsion between the clay particles, and the structure became like a 'house-of-cards'. Due to the increased repulsive forces at low salt contents, the clays liquefy when remoulded (Bjerrum et al. 1969). In Norway, quick clays are defined by a remoulded shear strength (c_{ur}) of less than 0.5 kPa (Norwegian Geotechnical Society 2011). Quick clays normally have a salt content of less than 2 g/L (Torrance 1979). Leached marine clays with a salt content of less than 1 g/L may even behave as a liquid when remoulded, depending on the ion composition in the pore water (Bjerrum et al. 1969; Penner 1965; Moum et al. 1971; Torrance 1983).

---

[a] 1:1 clay minerals consist of one octahedral and one tetrahedral sheet
[b] 2:1 clay minerals consist of one octahedral sheet sandwiched in between two tetrahedral sheets
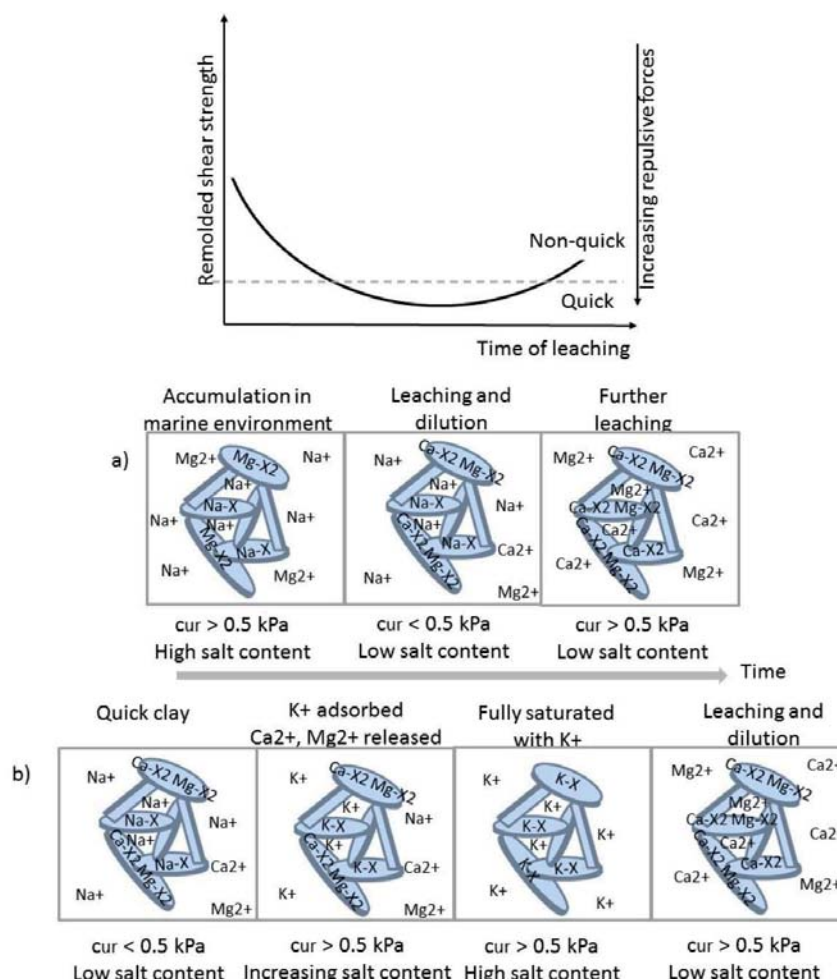
Figure 2-3 Ions in solution (I^{i+}) and adsorbed on the mineral surfaces (I-X_i), where i is the valence and X_i is the number of occupied charge sites on the mineral surface. a) The natural process of leaching and diluting the pore water in marine clays, and b) the introduction of KCl to the clay-water system

Sodium (Na^+) is the abundant cation in seawater, thus also originally the abundant cation in the pore water in clays accumulated under the marine limit. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) are normally the abundant cations occurring in groundwater (Appelo and Postma 2005). Sodium, potassium (K^+), magnesium and calcium, often referred to as the major cations, are the most commonly found cations in the pore water in clays. Even though groundwater flow dilutes and changes the ion composition in the pore water, Na^+ is still the abundant cation in the pore water in quick clays (Moum et al. 1971). This is due to the ongoing ion exchange taking place between the continuously changing pore water and the clay mineral surfaces.

The clay mineral surfaces attract available cations in the pore water to minimise the electric charge. In pore water of heterogeneous ion composition, the clay mineral surfaces will give preference to the cations in the following order:

$Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Al^{3+} < Fe^{3+}$ (Løken 1968; Mitchell and Soga 2005)
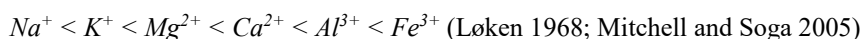
A high concentration of Na^+ in the pore water, will lead to adsorption of the readily available Na^+ to the clay surface even though Ca^{2+} are of higher exchange power. Thus, most of the adsorbed positions on the clays that were accumulated in seawater, were originally occupied by Na^+ (Figure 2-3a). Groundwater flow dilutes and introduces cations of higher valence and exchange power, Ca^{2+} and Mg^{2+}, to the clay-water system. Therefore, more di- or trivalent cations than monovalent cations are present in the adsorbed positions in quick clays, even though Na^+ still dominates the pore-water composition (Moum et al. 1971).

As long as Na^+ is released from the mineral surfaces into the pore water, the ratio of Na^+ to the other major cations in the pore water is large. High sensitivity may develop in clays with low salt content when the ratio of the sum of monovalent cations to the sum of major cations (all in meq/L) exceeds 75% (Mitchell and Soga 2005). After a sufficiently long period (thousands of years), Na^+ will be completely replaced by cations of higher exchange power in the adsorbed positions, and will also be depleted in the pore water. The clays cease to be quick as cations of greater impact on suppressing the diffuse double layers, thus reducing the repulsive forces between the clay particles, dominate the pore-water composition (Talme et al. 1966; Penner 1965; Moum et al. 1971; Andersson-Sköld et al. 2005). This basic knowledge on how the pore-water chemistry influences the sensitivity in clays may be utilised decreasing the sensitivity in quick clay deposits by chemical addition (Figure 2-3b).

2.5 The impact of pore-water chemistry on geotechnical properties

Geotechnical properties are a result of stress history and current overburden, compositional factors such as mineralogy, pore-water composition and electrolyte concentrations (salt content), and environmental factors such as fabric, water content and degree of saturation (Mitchell and Soga 2005). The fabric of clays is determined by the depositional environment where the clays either flocculate or remain dispersed, and the volume change due to consolidation after deposition. Clays with the same fabric may not have the same properties due to differing interparticle properties. The term structure includes both the fabric and the interparticle properties. The particles and their arrangements, interparticle forces and applied stresses affect the soil structure. All undisturbed, natural occurring soils are referred to as structured, whereas remoulded soils are de-structured. Even though the interparticle forces greatly affect the clays' behaviour, factors influencing the interparticle forces in the clays are rarely investigated in geotechnical engineering.

In classic geotechnical engineering, the effective stress (σ') in clays is determined by subtracting the pore pressure (u) from the total stress (σ): $\sigma' = \sigma - u$. The intergranular stress (σ_i') between the particles is then considered equal to the effective stress. However, the intergranular stress is the sum of interparticle forces acting over the contact areas between the particles. The interparticle forces may consist of *skeletal forces due to external loading* (e.g. weight of soil in the overburden, foundation loading), *particle level forces* (particle weight force, buoyancy force, hydrodynamic forces) and *contact level forces* (electrical forces, capillary forces, cementation-reactive forces) (Santamarina 2001). Chemical addition will
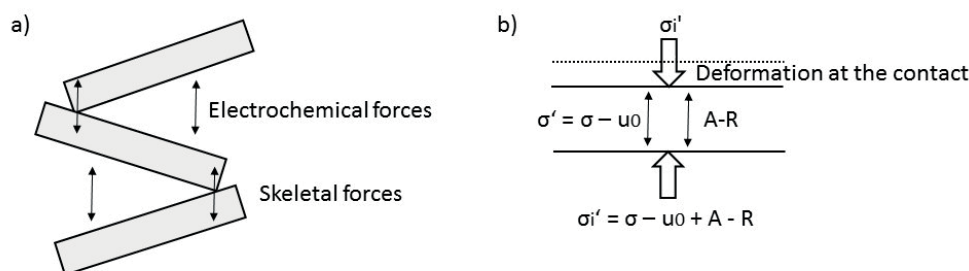
Figure 2-4 a) The interparticle forces are the sum of skeletal and electrochemical forces. In fully saturated soils, the skeletal forces are caused by external loading that is transmitted thorough the particles minus the buoyancy. The electrochemical forces are caused by van der Waals attraction minus the diffuse double layer repulsion. b) The intergranular stress (σ_i') is the sum of the effective stress (σ' = σ - u_0) and the electrochemical stress caused by attraction (A) and repulsion (R). Adapted from Mitchell and Soga (2005)

influence the contact level forces due to the impact of the chemicals on the diffuse double layer and interparticle repulsion. The intergranular stress may be expressed by:

$$\sigma_i' = \sigma - u_0 + A - R \qquad \qquad \text{Eq. 2-1}$$

Where u_0 is the measured pore pressure, *A* is the long-range attraction and *R* is the repulsion (Figure 2-4). In clays with low plasticity, both *A* and *R* are considered to be small (Mitchell and Soga 2005). Thus, the effective stress may be considered to be almost equal to the intergranular stress, which is also the case if *A* is equal to *R*. However, marine sensitive clays in Norway often have low plasticity, but the plasticity increases with increasing salt content in the pore fluid (Løken 1968). Introducing salt reduces the repulsion. Thus, the intergranular stress increases, and the mechanical properties in clays will be improved due to increased salt content.

Normally consolidated clay profiles often have an over-consolidation ratio (*OCR*) larger than 1 in the upper part of the profile, which also may have higher plasticity than the underlying clay. The over-consolidation in the unsaturated zone is influenced by the capillary suction in the voids, and weathering and percolating of freshwater contributing to feed the clay-water system in the upper part of the soil profile with stabilising cations (often referred to as aging). Therefore, the clay appear to have experienced a pre-consolidation larger than the overburden stress (Bjerrum 1967). After deposition, the void ratio (*e*) decreases due to secondary compression, or consolidation, and possibly leaching (Figure 2-5). The effective overburden is the same, but the void ratio is decreased (*e$_0$*). With time, changes in the structure may appear due to cementation or changes in the interparticle forces (Leroueil and Vaughan 1990), resulting in an even higher apparent vertical stress (σ_{vP}'). Introducing high salt contents, or ions of greater effect on suppressing the diffuse double layer to the clay-water system, decreases the repulsion and increases the net interparticle forces. Thus, the apparent pre-consolidation stress (p_c') and the peak undrained shear strength may increase.

At high salt contents, the pore-water composition is of less importance as the diffuse double layer is reduced to a thickness of one single layer of ions at concentrations exceeding 1 mol/L (Appelo and Postma 2005). However, at low salt contents their valence and hydrated radius
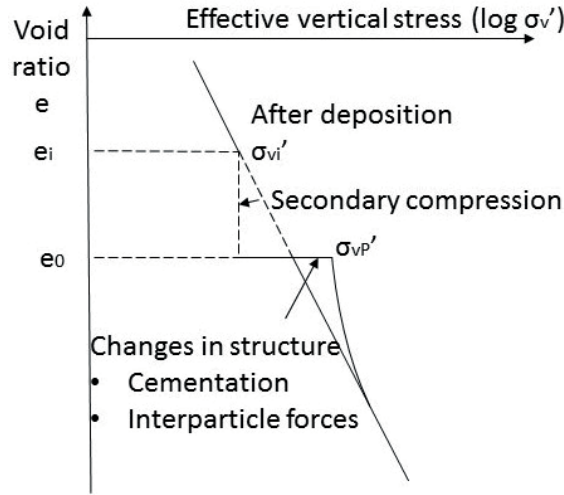
Figure 2-5 Vertical effective stress (σ_{vi}') and void ratio (e_i) after deposition of the clay. Secondary compression decreases the void ratio (e_0). With time, and without any excess loading or changes in the void ratio, changes in the structure may result in a further apparent increase of the vertical stress (σ_{vP}'). Modified from Leroueil and Vaughan (1990)

has a great impact on the geotechnical properties, and improved properties may even occur by changing the composition of ions at low salt contents. In the laboratory study presented by Moum et al. (1968), as little as 0.5 g K^+/L (12.8 meq/L) was found to be sufficient to increase the remoulded shear strength to as much as 9 kPa, reducing the sensitivity from more than 100 to 2.2. Furthermore, the fall-cone undrained shear strength increased with increasing salt content. The cations increase the shear strength in the following order (Moum et al. 1968; Løken 1968):

$$Na^+ < Fe^{2+} \leq Mg^{2+} \leq Ca^{2+} < Fe^{3+} < K^+ < Al^{3+}$$

The Atterberg limits are improved by the cations in the following order:

$$Na^+ < Fe^{2+} = Mg^{2+} = Ca^{2+} < Fe^{3+} < Al^{3+} = K^+$$
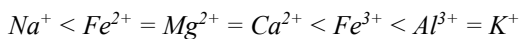
Even though, K^+ is of lower exchange power, it has a greater impact on the geotechnical properties than most cations of higher valence (z). The reason for this lies in the atomic radius (r_{ion}), ionic potential (ip) and the hydration of the various ions.

$$ip = \frac{z}{r_{ion}}$$ Eq. 2-2

Water molecules (H_2O) consist of two positively charged hydrogen atoms (H^+) and one negatively charged oxygen atom (O^{2-}), having a strong dipole. The dipole is why water is a good solvent for most polar substances. The alkali metals found in the pore water in soils (Na^+, K^+, Mg^{2+} and Ca^{2+}) are hydrated due to low ionic potential (Equation 2-2). The water molecules

surround the cations with their negative oxygen-end towards the positively charged ion. The degree of hydration strongly affects the possibility for the ions to be adsorbed to the clay mineral surface (Mitchell and Soga 2005; Bjørlykke 2010 amongst others).

Potassium (K^+) has a larger atomic radius (0.23 nm) than Na^+, Mg^{2+} and Ca^{2+}; 0.19 nm, 0.16 nm and 0.20 nm respectively (Aylward and Findlay1994). Due to larger ionic potential, the hydrated radius of K^+ is smaller (0.38-0.53 nm) than for Na^+, Mg^{2+} and Ca^{2+}; 0.56-0.79 nm, 1.08 nm and 0.96 nm respectively (Mitchell and Soga 2005). This leaves K^+ with a more effective positive surface charge than for instance Na^+, even though Na^+ is of same valence (Bjørlykke 2010). Ions in the diffuse double layer are hydrated. At maximum suppression, one single layer of ions, the thickness of the diffuse double layer in clays fully saturated with K^+ may be reduced to 0.76-1.06 nm, whereas for Na-saturated clays it may be of 1.12-1.58 nm, explaining the greater effect of K^+ than of Na^+ on the post-failure properties. The more effective surface charge on K^+ and Ca^{2+} facilitates adsorption onto clay minerals, and the ions will be removed more rapidly from a multi-component pore-water composition than Na^+ and Mg^{2+} (Bjørlykke 2010).

In addition to having a very "effective" charge, K^+ has the highest diffusion coefficient of the major cations in free water at 25 °C; 1.96 x 10^{-9} m^2/s (Appelo and Postma 2005). Therefore, accompanied by Cl^-, it will migrate faster in the clay volume than the other major cations. Potassium may, however, be delayed or retarded by the ion exchange reactions on the mineral surfaces. KCl is readily available on the market and relatively cheap, and is considered as the best choice applying salt as ground improvement in quick clays.

Research on how various salts, including KCl, affected the geotechnical properties was carried out on Norwegian leached clays in the 1960s and 1970s. The undrained and remoulded fall-cone shear strength and Atterberg limits increase with increasing salt content. The plasticity increases with increasing salt content, and the deformation as a response to loading (compressibility) may decrease. Bjerrum (1967) presented a laboratory experiment conducted on lean Drammen clay that was first consolidated at a higher stress than the original overburden. After consolidation, K-rich water was percolated through the clay specimen until the ratio between the adsorbed K^+ (K-X) to the adsorbed Na^+ (Na-X) was of 34.2. The original (K-X)/(Na-X) was of 0.21. The consolidated specimen was incrementally loaded in small steps. The applied stress during consolidation was of 353 kPa, whereas the apparent pre-consolidation stress (p_c') in the K-treated clay was after consolidation found to be 549 kPa. At further loading exceeding p_c', the compressibility was clearly reduced compared to unaltered quick clays. The peak undrained shear strength was also higher than found in unaltered quick clays (Bjerrum 1967). The leaching tests presented by Torrance (1974), reveal larger compressibility and a reduction in p_c' in leached clays with salt contents of less than 2 g/L than in clays with higher salt contents. Increased salt content decreases the repulsion between the clay particles, improving the structure of the clay. Therefore, the clay structure can take higher loads before it collapses (de-structures), as the particles can move closer together before the diffuse double layers overlap. Thus, the compressibility decreases, and the shear strength increases when the diffuse double layer thickness decreases (Santamarina 2002).

In June 1972, salt wells filled with KCl were successfully installed and used as ground improvement in a quick-clay deposit at Ulvensplitten, Oslo, Norway (Eggestad and Sem 1976). The salt wells had a diameter of 15 cm and a depth of 15-16 m, and were installed with an internal spacing of approximately 1.5 m covering an area of 6000 m^2. The wells were filled with granular KCl. Twenty-two months after installation the remoulded shear strength was

increased from less than 0.5 kPa, to the order of 10-45 kPa. The sensitivity was decreased from 12-80 to 1-3 in the quick clay, and the liquid limit was increased beyond the natural water content. Twenty-one months after installation, the remoulded shear strength was improved from less than 0.5 kPa to 3.5 kPa in a distance of 60 cm from the wells, thus improving a soil volume over a diameter of around 1.2 m. The installation methods used in 1972 are time consuming and costly, making the *KCl* improvement less attractive. However, modern drilling methods may be more effective, making *KCl* improvement a relevant method for ground improvement. Nevertheless, more knowledge on how and to what extent *KCl* improves the geotechnical properties, as well as information on time consumption, is needed in order to make the method current.

2.6 Concluding comments

Clay deposits with remoulded shear strength of less than 1 kPa, or a liquidity index exceeding 1.2, pose a risk for developing into retrogressive quick-clay landslides if remoulded (Leroueil et al. 1983; Thakur et al. 2014a). Conventional landslide mitigation methods in use today may not always be feasible. Even though *KCl* improved the geotechnical properties in the quick clay at Ulvensplitten, the salt-well method is not in use today probably due to the fact that it is assumed to be costly and time consuming, and not fully understood or documented. Information on the long-term effect of *KCl*-treated clays has not been available, and it is necessary to establish at which salt contents or pore-water compositions the clays cease to be quick, as well as establishing accurate information on how long it takes for *KCl* to improve the clays' geotechnical properties.

The glaciomarine clays found in Norway were accumulated in seawater with salt contents of 30-35 g/L, with sodium as the abundant cation. As long as the salt content was high, the flocculated structure was stable due to small repulsive forces. Isostatic uplift has exposed these clays to leaching and diffusion, which diluted the salt content in the pore water and increased the repulsive forces. Therefore, the structure became weak, often described as a 'house-of-cards'-like structure, and the clays are easy to remould. Leaching by meteoric groundwater flow introduces stabilising cations such as calcium and magnesium to the clay-water system. At some point the composition of cations in the pore water will cause a decrease in the repulsion and the remoulded shear strength improves beyond what is considered to be quick. Increasing the salt content, and changing the ion composition in the pore water by introducing *KCl* to the clay-water system, speeds up the natural ongoing process of changing the clay behaviour from quick to non-quick by changing the ionic content in the pore water.

According to van Olphen (1963), the differences in the initial double-layer structure in the clays cause the different clays to react differently on electrolyte addition. Therefore, predicting the clay behaviour due to the addition of salt may be difficult, emphasizing the importance of collecting information on mineralogy and pore-water chemistry when considering *KCl* as a ground improvement method. The following chapter presents a collection of data comprising mineralogy and pore-water chemistry correlated to geotechnical properties in highly sensitive quick clays from various sites in Norway. In addition, results from two different laboratory studies treating clay samples with *KCl* are presented.

3 Pilot studies

3.1 Introduction

This chapter presents the main findings from the three pilot studies on mineralogy, pore-water chemistry and their impact on the geotechnical properties. In pilot study no. 1, clay samples were collected from various sites throughout Norway to correlate the mineralogy, pore-water chemistry and geotechnical properties in low-saline Norwegian clays (section 3.2 and Appendix A). In pilot study no. 2, simple diffusion experiments treating clays from two different sites in Mid-Norway with potassium chloride (*KCl*) were conducted in the laboratory to investigate the impact of increased *KCl* in the pore water on the geotechnical properties (section 3.3 and Paper I). Finally, a pilot study was conducted in the laboratory on mini-block samples (downsized Sherbrooke samples) submerged in *KCl* slurry in order to investigate to what extent the geotechnical properties were improved with a pore-water composition fully saturated with *KCl* (Section 3.4 and Paper II).

3.2 Mineralogy, pore-water chemistry and post-failure properties in Norwegian clays

3.2.1 *Project description and motivation*

Clay samples were collected from ongoing projects throughout Norway from January until April 2013 in order to correlate the mineralogy, pore-water composition and the post-failure properties, herein defined as the remoulded shear strength (c_{ur}), liquidity (*IL*) and plasticity index (*IP*). The geotechnical parameters were determined at several geotechnical laboratories. Due to limited access to clay samples, data from the PhD thesis by Hilmo (1989) are included. All the results are presented and evaluated in Appendix A. Data that did not pass a detailed quality check are ruled out based on the criteria regarding pore-water chemistry outlined in section A.2.4 in Appendix A. In total 23 samples from 10 different sites are considered to be of adequate quality and are included in the study:

- Eastern part of Norway:
    - Holm
    - Rakkestad municipality
    - Kleppe bridge
- Mid-Norway
    - Dragvoll
    - Esp
    - Lade
    - Leira
    - Klett
    - Tiller
- Northern part of Norway
    - Furubakken

Out of the 42 collected samples in the recent study, 26 were excluded, and 48 of the specimens from Hilmo's data set were excluded. With the exception of those in section 3.2.2, only results considered to be of adequate quality with regard to pore-water chemistry are presented herein.

The pore-water samples were analysed with regards to sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), phosphate (PO_4^{3-}) and alkalinity (*Alk*) at the laboratory at the Department of Geosciences at University of Oslo. Alkalinity is defined as the acid neutralizing capacity where bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) normally are the main neutralizing constituents. Appelo and Postma (2005) states that at pH below 8.3, less than 1% of the total carbonic acid is present as CO_3^{2-}. Even though some of the samples in this project has pH exceeding 8.3, the bicarbonate concentrations are set equal to the alkalinity. The salt content is equivalent to the total dissolved solids (*TDS*), and is calculated as the sum of cations and anions. The concentrations of the ions are reported in ppm, which in dilute freshwater is equivalent to mg/L.

The XRD software Diffrac.Suite (www.bruker.com) was used for bulk mineralogy identification and quantification. Difrac.Eva was used for identifying the occurring mineral types, and the Diffrac.Topas was used for quantification of the bulk mineralogy. The clay mineralogy was quantified using the software NEWMOD II (www.newmod-for-clays.com).

3.2.2 *Geotechnical properties*

The complete data sets from the pilot study and Hilmo (1989) are included in the correlations of geotechnical properties in Figure 3-1-Figure 3-3. The clay content may have an impact on the geotechnical properties, and the reported clay contents in the collected data lies in the range of 25-67%. Even though the clay contents vary, no coherent pattern is found in the correlations between clay content and the remoulded shear strength (c_{ur}), liquidity (*IL*) and plasticity index (*IP*) (Figure 3-1a, c and e).

A c_{ur} less than 0.5 kPa (Norwegian Geotechnical Society 2011) defines quick clays. Clays with a larger *IL* than 1.2, and a c_{ur} lower than 1 kPa may pose a risk to develop into large flow slides when remoulded (Leroueil et al. 1983; Thakur et al. 2014a). The *IL* in the collected data increases exponentially with decreasing c_{ur} (Figure 3-2a), in agreement with the findings of Leroueil et al. (1983) and Locat and Demers (1988). In general the *IL* decreases below 1.2 at c_{ur} exceeding 1 kPa (Figure 3-2a). The *IP* increases with increasing c_{ur} (Figure 3-2b), and clays with a larger *IL* than 1.2 seem to be of low plasticity and of medium plasticity when *IL* decreases below 1.2 (Figure 3-3).

The geotechnical properties in clays are greatly affected by the salt content and the ion composition in the pore water (e.g. Rosenqvist 1946, 1953, 1955; Bjerrum 1955; Løken 1968, 1970; Moum et al. 1968; Quigley 1980; Torrance 1983). According to Torrance (1979), quick clays often have salt contents of less than 2 g/L, equivalent to total dissolved solids (*TDS*) of 2000 ppm. Most of the collected samples have a salt content of less than 2 g/L. However, many of the low-saline clays have c_{ur} exceeding 0.5 kPa, but an *IL* exceeding 1.2 (Figure 3-1b and d). Most samples are of low plasticity, with exception of three of the samples with the lowest *TDS* which are of medium plasticity (Figure 3-1f). The impact of the mineralogy and pore-water chemistry on the geotechnical properties in the collected data will be discussed in the following sections.
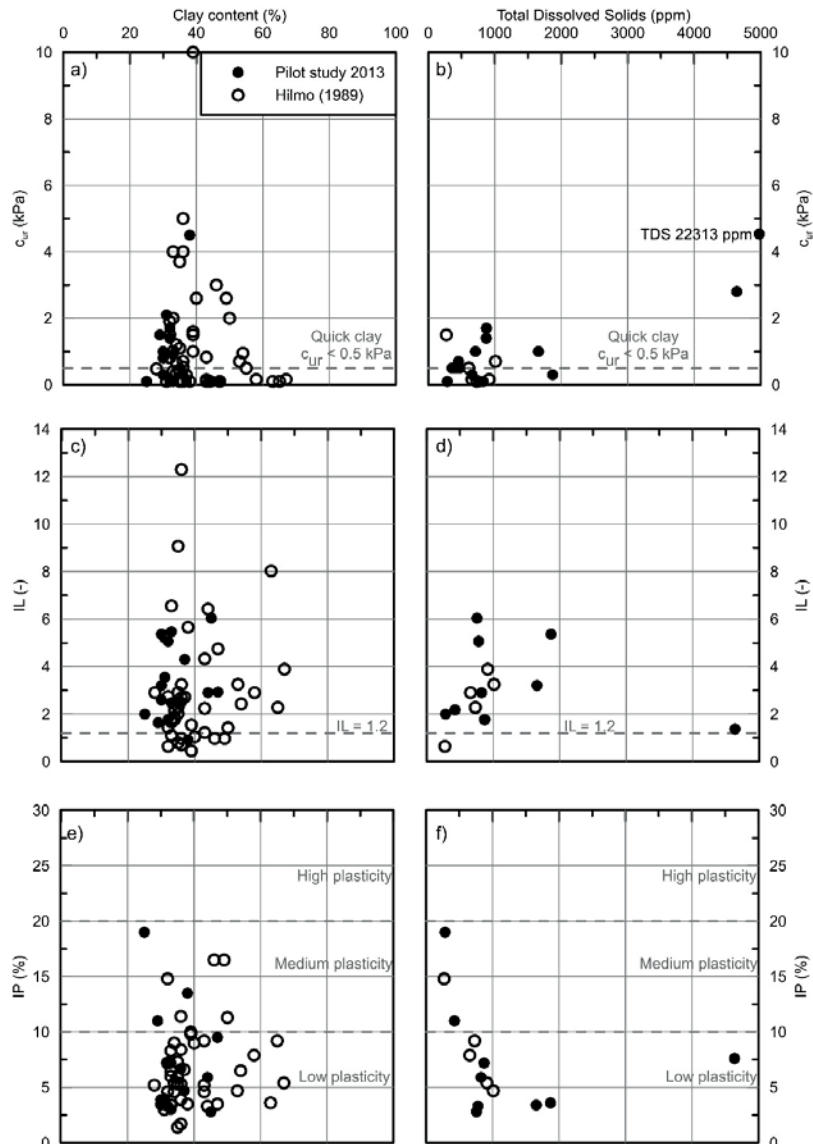
Figure 3-1 Results from the recent pilot study (filled symbols) and Hilmo (1989) (open symbols). Clay content and total dissolved solids (TDS) correlated to a) and b) remoulded shear strength (c_{ur}), c) and d) liquidity index (IL), and e) and f) plasticity index (IP)
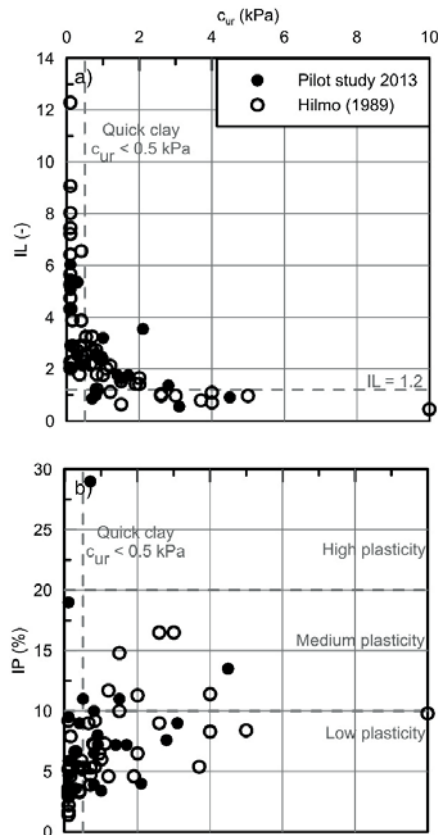
Figure 3-2 Remoulded shear strength (c_{ur}) correlated to a) liquidity index (IL) and b) plasticity index (IP)
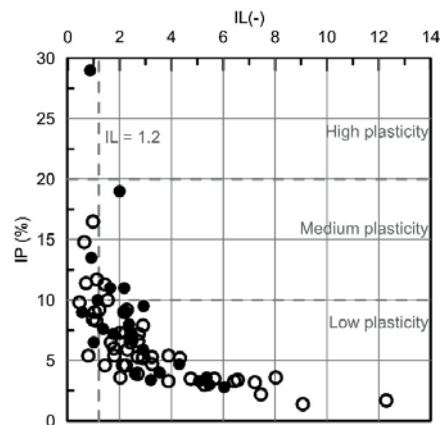
Figure 3-3 Correlation between liquidity (IL) and plasticity index (IP). The legend is the same as in Figure 3-2

3.2.3 Mineralogy of bulk sample and clay-sized fraction

The collected clays are all consisting of low-active mineral types (Table 3-1), essential for developing highly sensitive, quick clays (Torrance 1983). The mineralogical composition of both bulk samples and clay-sized fraction is in agreement with the three Norwegian sensitive clays reported by Kenney (1967). The chlorite content is in general lower, whereas the quartz and muscovite/illite content is higher than found in the clays in Quebec, Canada (Locat and St-Gelais 2014), which are dominated by plagioclase.

Table 3-1 Bulk mineralogy

Site	Depth	Qtz[a] %	Ms/Ill[b] %	Kfs/Mc[c] %	Pl/Ab[d] %	Am/Hbl[e] %	Cal[f] %	Chl[g] %
Rakkestad	7.7	23.1	23.8	12.6	28.1	4.9	2.1	5.4
Kleppe bridge	4.25	17.1	22.3	15.1	32.5	6.5		6.5
Dragvoll	4.6[h]	20.5	14.2	9.8	27.2	16.4	4.5	7.4
Dragvoll	5.6[h]	22.8	25.8	7.7	23.6	8.6	3.4	8.1
Esp	8.4	21.7	32.7	8.5	18.9	7.0	2.1	9.1
Esp	8.8	23.6	31.1	10.7	19.5	5.5	3.2	6.4
Esp	9.7	28.6	17.8	5.1	30.6	9.1	3.5	5.4
Klett	11.3	24.5	36.4	9.3	15.1	6.5		8.2
Lade	9.5	21.6	21.1	11.4	24.3	8.6	5.9	7.2
Leira	29.4	29.6	13.8	8.3	32.9	8.5	3.3	3.7
Leira	31.5	26.5	29.1	8.3	24.0	6.3		5.9
Furubakken	11.4	9.5	37.6	5.3	23.9	21.0		2.7

[a]quartz, [b]muscovite/illite, [c]K-feldspar/microcline, [d]plagioclase/albite, [e]amphibole/hornblende, [f]calcite, [g]chlorite. [h] not from the same depths as the analysed pore-water chemistry.

The clay mineralogy in the collected samples is dominated by illite followed by chlorite with some occurring mixed-layer clay minerals of chlorite and smectite (Table 3-2). In the Quebec clays, chlorite was the abundant clay mineral followed by illite and mixed-layer clay minerals consisting of vermiculite. The Quebec clays are all of high plasticity (up to 52%), also having much higher clay content (up to 83%) than found in the collected Norwegian clays. The clay sample from Kleppe bridge actually has higher content of plagioclase/albite and K-feldspar/microcline than the others, and is of medium plasticity (19%) even at low salt content (0.3 g/L). The data collection is, however, too scarce to be able to conclude on whether the higher plasticity is caused by the mineralogical composition.

Locat et al. (1984) correlate the amount of phyllosilicates and amorphous materials on bulk samples to the Atterberg limits and plasticity index (*IP*). Both liquid limits (w_L), plastic limits (w_P) and *IP* increase due to increased content of phyllosilicates and amorphous materials. The amorphous content is not analysed in the recent collected data. The sum of illite and chlorite in the bulk mineralogy correlated to the recent collected data with a salt content of less than 2 g/L is inconclusive (Figure 3-4). The impact of the ionic composition in the pore water on the geotechnical properties will be discussed in the following section.

Table 3-2 Clay mineralogy

Site	Depth	Chlorite %	Illite[a] %	Mixed layers[b] %
Rakkestad	4.7	27.8	72.3	
Rakkestad	7.7	21.2	78.8	
Kleppe bridge	4.25	30.7	69.3	
Dragvoll	4.6[c]	37.4	62.7	
Dragvoll	5.6[c]	33.2	66.8	
Esp	8.4	30.5	69.5	
Esp	8.8	34.4	65.6	
Esp	9.7	39.4	60.7	
Klett	11.3	10.4	88.8	0.8
Lade	9.5	25.8	72.6	1.6
Leira	29.4	23.7	74.9	1.5
Leira	31.5	26.7	73.3	
Furubakken	11.4	15.9	77.2	6.9

[a]Dioctahedral mica of Muscovite type + Trioctahedral mica of biotite type, [b]Chlorite-smectite.
[c] not from the same depths as the analysed pore-water chemistry.

3.2.4 The impact of pore-water chemistry on the geotechnical properties

Clays accumulating in a marine environment entrap seawater in their voids. As long as the salt content is high, the repulsive forces between the clay particles are small, thus the clay will have a high remoulded shear strength. Leaching by meteoric groundwater flow has diluted the salt content, thus increased the repulsive forces. Therefore, the remoulded shear strength decreases, and at a remoulded shear strength of 0.5 kPa or less, the clay is characterised as quick. Quick clays often have salt contents of less than 2 g/L with a cation composition dominated by sodium (Na^+) (Moum et al. 1971, 1972; Torrance 1979). However, the occurrence of divalent cations such as magnesium (Mg^{2+}) and calcium (Ca^{2+}) may prevent the development of high sensitivity in clays (Penner 1965; Moum et al. 1971; Torrance 1983). Clays with low salt content in their pore water may develop high sensitivity when the ratio of monovalent cations to the sum of major cations (Na^+, K^+, Mg^{2+}, Ca^{2+}), all concentrations in meq/L, exceeds 75% (Equation 3-1) (Mitchell and Soga 2005).

$$\frac{Na^+ + K^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}} \qquad \text{Eq. 3-1}$$

The scatter in the remoulded shear strength (c_{ur}) correlated to the ratio in Equation 3-1 is wide (Figure 3-5a). Nevertheless, the majority of the data cluster at a c_{ur} of less than 2 kPa when the ratio in Equation 3-1 exceeds 75%. Even though the pore-water composition does not favour development of high sensitivity, the c_{ur} in some data points is less than 0.5 kPa at the same time as having an *IL* larger than 1.2 (Kleppe bridge and Rakkestad in Figure 3-5b). The *IP* in the clays from Kleppe bridge and Rakkestad, however, increases as the ratio in Equation 3-1 decreases below 75% (Figure 3-5c). This may indicate that even though the pore-water composition does not favour development of high sensitivity, the clays may still be quick but of medium plasticity rather than of low plasticity as the majority of the collected quick-clay samples.
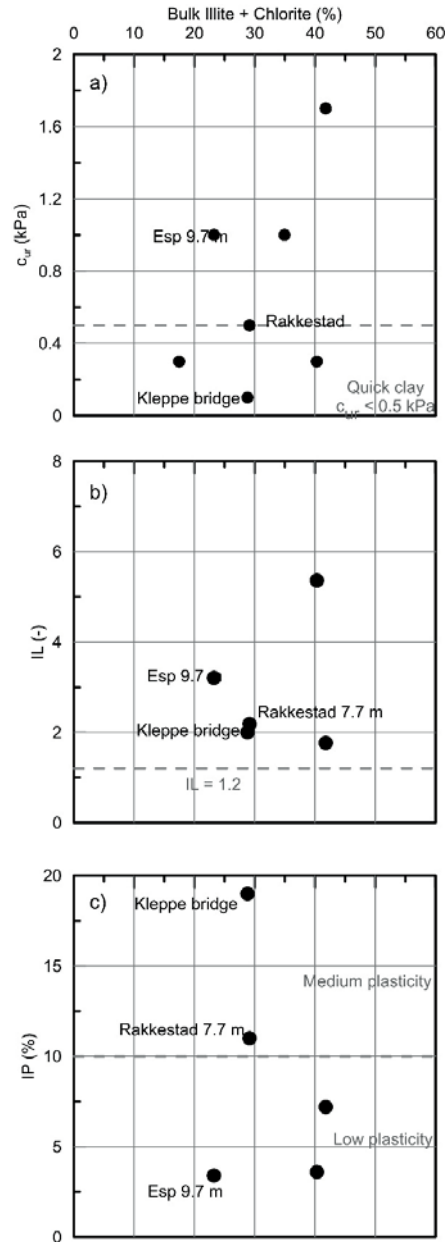
Figure 3-4 The sum of clay minerals in the bulk mineralogy correlated to a) remoulded shear strength (c_{ur}), b) liquidity index (IL) and c) plasticity index (IP) at salt contents lower than 2 g/L
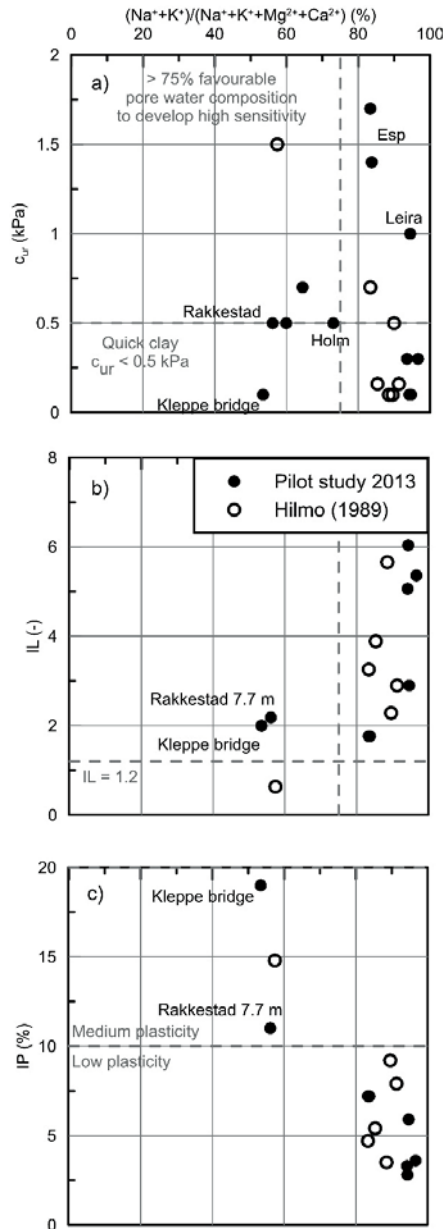
Figure 3-5 The ratios of the sum of sodium (Na^+) and potassium (K^+) to the sum of major cations (Na^+, K^+, magnesium (Mg^{2+}) and calcium (Ca^{2+})) correlated to a) remoulded shear strength (c_{ur}), b) liquidity index (IL), and c) plasticity index (IP) at salt contents lower than 2 g/L. Only results considered to be of adequate quality are included

3.3 Diffusion experiments on clay samples to investigate the impact of KCl on improving the geotechnical properties

3.3.1 Project description and motivation

A small-scale laboratory study was conducted on clay samples from the Rissa municipality (close to Rein kirke), Mid-Norway, and the NTNU research site Tiller, Trondheim, Norway to investigate the influence of pore-water salinity and ion composition on the geotechnical properties. Two laboratory setups were used in the study. The simplified diffusion cells (Figure 3-6a) were constructed of Plexiglas cylinders. A cutter was attached to the Plexiglas cylinder, and the clay samples from Tiller were cut into the Plexiglas and pushed in place in the centre of the cylinder. The bottom reservoir was filled with either dissolved *KCl* or *KCl* slurry, and the reservoir in the top was filled with de-aired deionized water. The clay samples were in direct contact with the top and bottom reservoir. The simplified diffusion cells were stored in the cold-storage room for pre-set time intervals prior to testing. In addition to the simplified diffusion cells, a mini salt-well was drilled in the centre of the bottom-half of a Sherbrooke block sample from the Rissa municipality (Figure 3-6b). The mini-well was filled with *KCl* slurry, and the clay sample sealed and left in the cold-storage room for 60 days before testing in the laboratory. Fall-cone undrained and remoulded shear strengths, water content, Atterberg limits, mineralogy and pore-water composition was determined on the clay samples prior to adding *KCl* to the clay. Determination of the geotechnical properties and the pore-water composition was repeated after treating the clays with *KCl*.
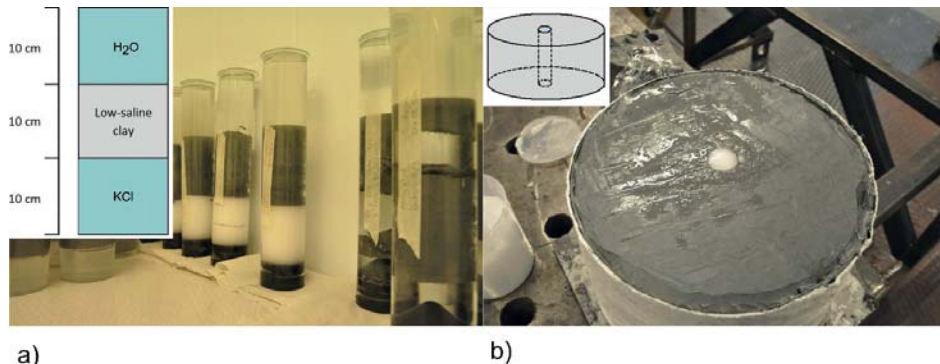
Figure 3-6 a) Simplified diffusion cells. b) Mini salt-well drilled in a Sherbrooke block sample

3.3.2 Main findings from the diffusion experiments

The *KCl* seemed to move faster through the clay samples using *KCl* slurry in the bottom reservoir than using dissolved *KCl*. In both the simplified diffusion cells and in the Sherbrooke block sample, there seem to be an upper limit beyond where increased salt content does not result in a further increase in undrained and remoulded fall-cone shear strengths, and Atterberg limits (Figure 3-7 and Figure 3-8). The water content is practically unaffected, whereas the liquid limit is significantly increased from around 30% to 50-60%. The plastic limit is increased from around 20% to around 25%.
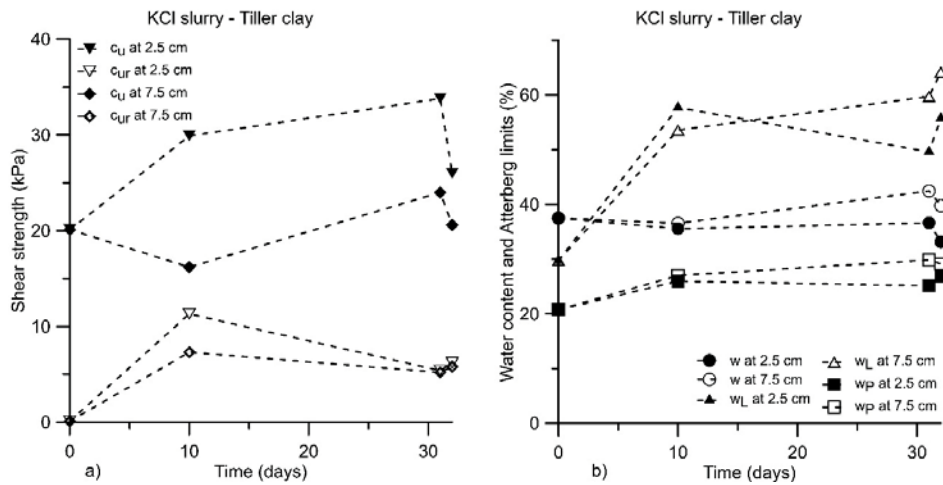
Figure 3-7 a) Improved fall-cone undrained (c_u) and remoulded shear strength (c_{ur}) with time, and b) water content (w) and improved liquid (w_L) and plastic limit (w_P) with time in clay samples in contact with KCl slurry
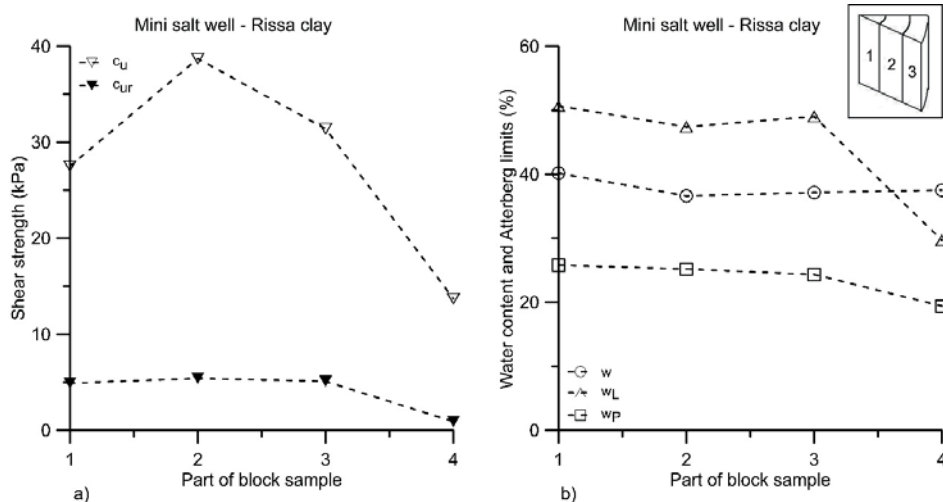
Figure 3-8 a) Improved fall-cone undrained (c_u) and remoulded shear strength (c_{ur}) in sections 1-3, and b) water content (w) and improved liquid (w_L) and plastic limit (w_P) in sections 1-3. Section 4 shows the initial condition

3.4 Mini-block samples stored in KCl slurry

3.4.1 Project description and motivation

To evaluate the applicability of installing salt wells in a quick-clay area, it is necessary to quantify the effect on the geotechnical properties. In-situ diffusion of *KCl* from salt wells is a time consuming process. Therefore, a laboratory setup allowing diffusion into a small clay volume for rapid quantification of the improved geotechnical properties is suggested in Paper II.

Mini-block samples were extracted from 3.3 m to 9.0 m depth from the quick-clay deposit at the Dragvoll research site. The samples were stored wrapped in cling-film in the cold-storage chamber at around 7 °C prior to testing. Six samples were opened and tested in the NTNU geotechnical laboratory within 52 days after extraction from the ground. These samples are referred to as the *reference samples*, and the results are shown with orange symbols in the figures. Four samples were stored in containers submerged in *KCl* slurry (Figure 3-9a). In order to evaluate the effect of storage on the geotechnical properties, four samples were submerged in de-aired, de-ionized water (blue symbols in the figures), still wrapped in cling-film and stored in the same manner as the samples submerged in *KCl* (black symbols in the figures). The samples were stored in the containers for 42-102 days to ensure that the clay-water system was fully saturated with *KCl* (~260 g/l).

After storage in the containers, the samples were cut in sections to allow testing of the fall-cone undrained and remoulded shear strength, Atterberg limits and pore-water compositions in three different sections in the samples (Figure 3-9b). Constant rate of strain oedometer tests (CRS) and anisotropically consolidated undrained compression tests (CAU$_c$) were conducted on all samples.
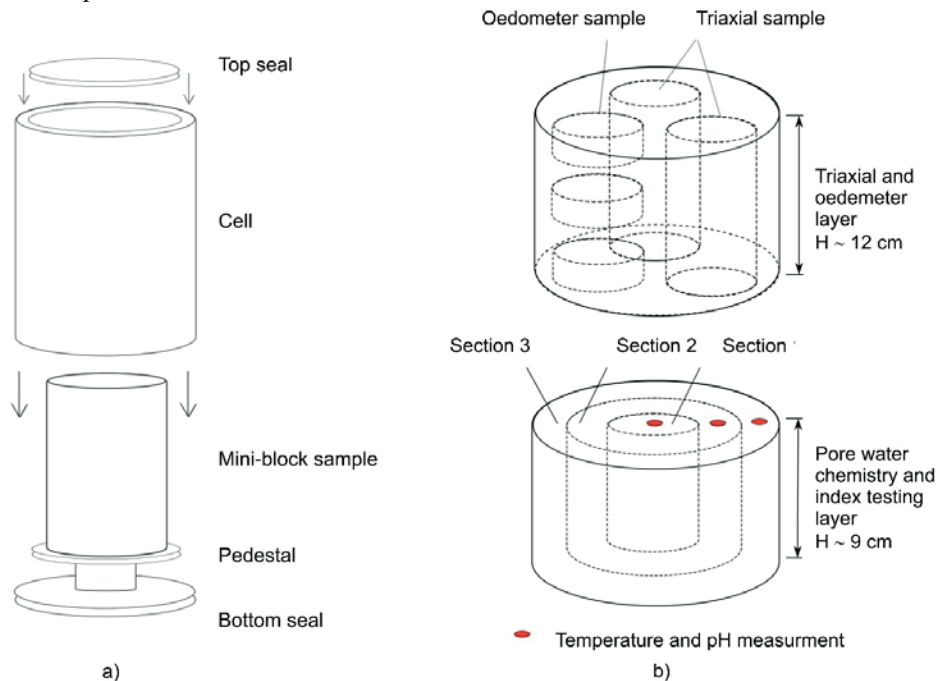
Figure 3-9 a) Storage cell used for samples submerged in de-aired water and KCl slurry. b) Sectioning of the mini-block sample

3.4.2 Main findings from the KCl-saturated clay samples

The clay samples were fully saturated with *KCl* at the time of opening. All samples with the exception of the one at 4.25-4.50 m depth for unexplainable reasons, were fully saturated with *KCl* (~260 g/l) at the day of testing, having an even distribution of *KCl* throughout the sample diameter. The remoulded shear strength (c_{ur}) in the *KCl*-saturated clays in sections 1-2 increased

from 0.1-0.4 kPa to 3.7-5.6 kPa (Figure 3-10); similar to the maximum c_{ur} found in the *KCl*-treated clays from Tiller and Rissa in section 3.3.2. The liquidity index decreased from 1.6-4.6 in the reference samples to 0.5-0.9, and the plasticity changed from low to medium with a plasticity index of 10.0-17.4% in the *KCl*-treated clays. The liquid limit increased up to and beyond the natural water content (Figure 3-11). The plastic limit was practically unaffected. Increased salt contents increase the total weight of solids in the pore water, also increasing the density. This may together with osmoses explain the decreased water content in the salt treated clay.

The peak undrained shear strength from the anisotropically consolidated, undrained compression triaxial test (CAU$_c$) of the *KCl*-treated clay at 4.36 m depth is slightly increased compared to the reference sample from 4.17 m depth (Figure 3-12); from 20 kPa to 25 kPa. The reference sample was stored in cling-film for 45 days before testing, which actually may have reduced the peak shear strength. The strength after peak is much higher in the salt-treated clay than in the reference sample and the one submerged in water.

Another interesting observation is seen in the results from the constant rate of strain oedometer tests (CRS). The apparent pre-consolidation stress (p_c') increases from around 90 kPa in the reference sample to around 120 kPa in the *KCl*-treated clay sample (Figure 3-13a). The modulus in the OC range increases from a peak of 2.5 MPa to around 5.5 MPa (Figure 3-13b), and the sample deforms far less at stresses beyond p_c' than in the reference sample.
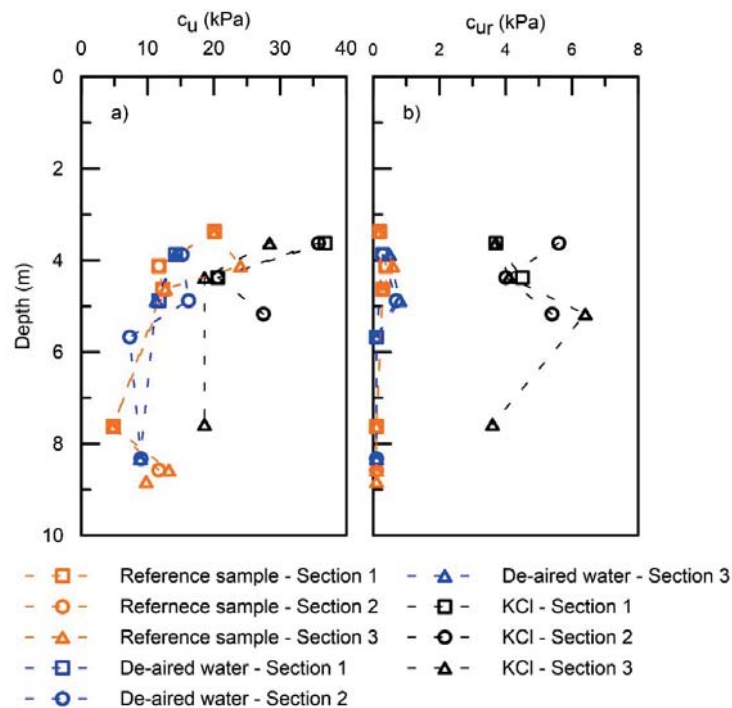
Figure 3-10 Fall-cone a) undrained shear strength (c_u) and b) remoulded shear strength (c_{ur}) in sections 1-3
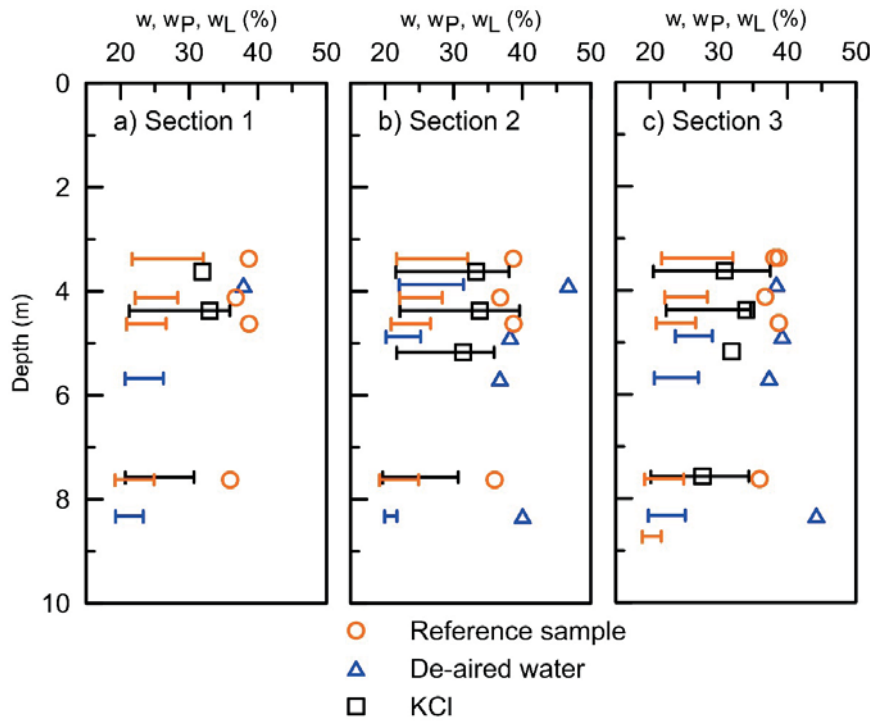
Figure 3-11 Water content (w) and Atterberg limits (wL, wP) in sections 1-3
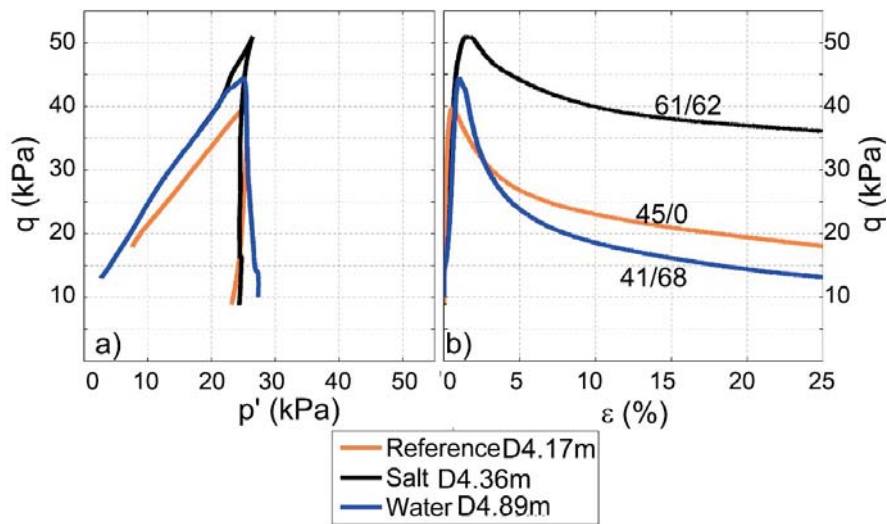
Figure 3-12 CAUc triaxial tests on reference sample and samples stored in de-aired water and KCl slurry from 4.17-4.89 m depth. a) Deviatoric (q) versus mean effective stress (p'), and b) deviatoric stress versus strain (ε). Days stored in cling-film/days stored in cell is denoted in b)
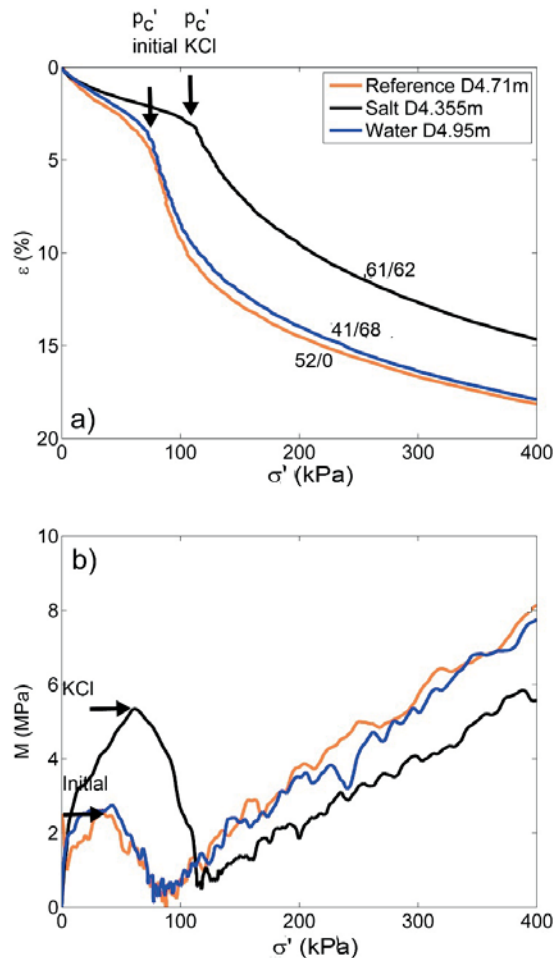
Figure 3-13 CRS oedometer tests on samples from 4.4-5.0 m depth. a) Strain (ε) versus effective stress (σ'). b) Oedometer modulus (M) versus effective stress. Days stored in cling-film/days stored in cell is marked in a). Apparent pre-consolidation stress (p_c') and M is marked by arrows

3.5   Concluding comments

The pilot studies imply the importance of the salt content and the composition of cations in the pore water on governing the geotechnical properties in low-saline clays. Both the depositional environment and the changes in their environment until present influence the geotechnical properties of clays. Leaching by meteoric groundwater flow have diluted the salt content and changed the ion composition in the pore water. The quick clays in the herein presented collection of Norwegian clays all have salt contents of less than 2 g/L. However, not all of them are quick. The variations in mineralogy does not explain their variation in the geotechnical properties. Correlating the remoulded shear strength, liquidity and plasticity index to the pore-water compositions, the ratio of monovalent to the major cations in most of the quick clays

exceeds 75%, which favours development of high sensitivity (Mitchell and Soga 2005). Some of the clays have a remoulded shear strength equal to or less than 0.5 kPa and a liquidity index larger than 1.2, but a ratio below 75% and a salt content of less than 0.5 g/L. However, these clays were of medium plasticity rather than of low plasticity as the remainder data points. According to Penner (1965), low plasticity index may be a result of higher content of coarser material, or it may be caused by the ratio of monovalent to divalent cations in the pore water. As the clay content in the collected data does not explain the deviating plasticity, it is likely to believe that in this case the pore-water composition does not impede high sensitivity, but may improve the plasticity index.

Introducing *KCl* to quick clays clearly improves the post-failure properties of the clays as the remoulded shear strength increases beyond 0.5 kPa and the liquidity index decreases below 1.2. Triaxial and oedometer tests on *KCl*-treated clay imply increased peak and post-failure shear strength, as well as increased oedometer modulus and apparent pre-consolidation stress. The laboratory results from the pilot studies indicate that there is a limit beyond where increased salt content does not induce further improvement of the geotechnical properties.

Quantification of improved geotechnical properties as a result of increased concentration of *KCl* can be found using small-scale laboratory tests. Laboratory experiments may be useful to determine the applicability of the method to specific clays with its specific pore-water composition and adsorbed ions on the mineral surfaces.

4   Long-term effect of in-situ improvement

4.1   Introduction

Salt wells filled with granular potassium chloride (*KCl*) were installed in a quick-clay deposit at Ulvensplitten, Oslo, Norway in June 1972. In total 2629 wells were installed with an internal spacing of 1.5 m, covering an area of about 6000 m^2 (Figure 4-1). The purpose of the salt-wells installation was to stabilise the quick clay prior to excavation in connection with construction of a new highway crossing the Ulvensplitten area (Eggestad and Sem 1976). The subsurface is well documented with several ground investigations prior to the installation of the salt wells, during the first 2-3 years after installation and a few investigations conducted 30-40 years after installation.

Despite the fact that the geotechnical properties were significantly improved during the first couple of years after installation, the salt-well method is not used as ground improvement today. The method is considered time consuming as chemical diffusion is slow. Thus, planning many years ahead might be necessary to ensure that the clays are stabilised in time for construction work. Furthermore, the effect of chemical stabilisation on clays' mechanical properties is not fully understood, or documented. The results from ground investigations carried out in 2013, 40 years after installation (boreholes 2016-2 and 2016-7 in Figure 4-1), provide unique information on the long-term effect of *KCl* treatment of quick clays necessary to validate the method. The following chapter presents the main findings in Paper III.

4.2   Soil properties and salt-well installations

The weathered zone, or the "dry crust", in the Ulvensplitten area stretched down to 3 m depth. Quick clay was found from 3 m to 15 m depth. At further depths, the clay contained gravel and sand and were of moderate sensitivity (~8), down to bedrock at 20-35 m depth (Eggestad and Sem 1970, 1974). Both wash boring and mandrel drilling, commonly used sand-drain technology at the time, was applied to install the wells in salt-stabilised areas north and south, and in the small-scale test area to the left in Figure 4-1. Granular *KCl* was poured into the wash-boring holes, and into the steel pipes used for mandrel drilling. The homogeneity and depths of the salt columns may have varied due to uncertainty in whether the wash-boring holes were open over the full diameter of 15 cm and along the whole depth down to 15-16 m. The salt may also have clogged in the steel pipes used for mandrel drilling, causing uneven salt columns while extracting the steel pipes from the ground. The salt wells were installed in a grid with an internal spacing of 1.5 m. However, the mud on the surface may have caused inaccurate positioning of the wells due to difficult working conditions.

4.3   Pore-water chemistry and geotechnical properties 1970-1974

The pore-water composition in the quick clay prior to salt-well installation was dominated by sodium (*Na$^+$*) with small amounts of potassium (*K$^+$*), magnesium (*Mg^{2+}*) and calcium (*Ca^{2+}*) present. The concentration of *K$^+$* increased rapidly in the clay surrounding the salt wells, significantly improving the geotechnical properties. Ten months after installation, the salt migration influenced the shear strength of the clay to a distance of 50 cm from the well, increasing to 60-65 cm 14 months after installation. The concentration of *K$^+$* increased from originally 31-33 mg/L to approximately 50 mg/L at 5.5 m depth in a distance 60 cm from the

well 21 months after installation (Figure 4-2). The corresponding undrained shear strength increased from 20 kPa to 28.5 kPa, and the remoulded shear strength increased from less than 0.5 kPa to 3.5 kPa (Eggestad and Sem 1976).

The vane and fall-cone undrained and remoulded shear strengths and Atterberg limits, were improved in area south and north (Figure 4-3 and Figure 4-4). Twenty-two months after installation, the remoulded shear strength was increased from less than 0.5 kPa (Figure 4-3a and c) to the order of 10-45 kPa (Figure 4-3b and d), reducing the sensitivity from 12-80 to 1-3. The improvement of the clay extracted from borehole 407U in area south (Figure 4-3b) was not homogenous along the whole depth. Possibly caused by uneven salt columns, or due to silt/sand layers promoting salt migration at distinct depths. The liquid limit increased beyond the natural water content in the salt-treated clay, and the plastic limit was also slightly improved by the increased salt content (Figure 4-4a).
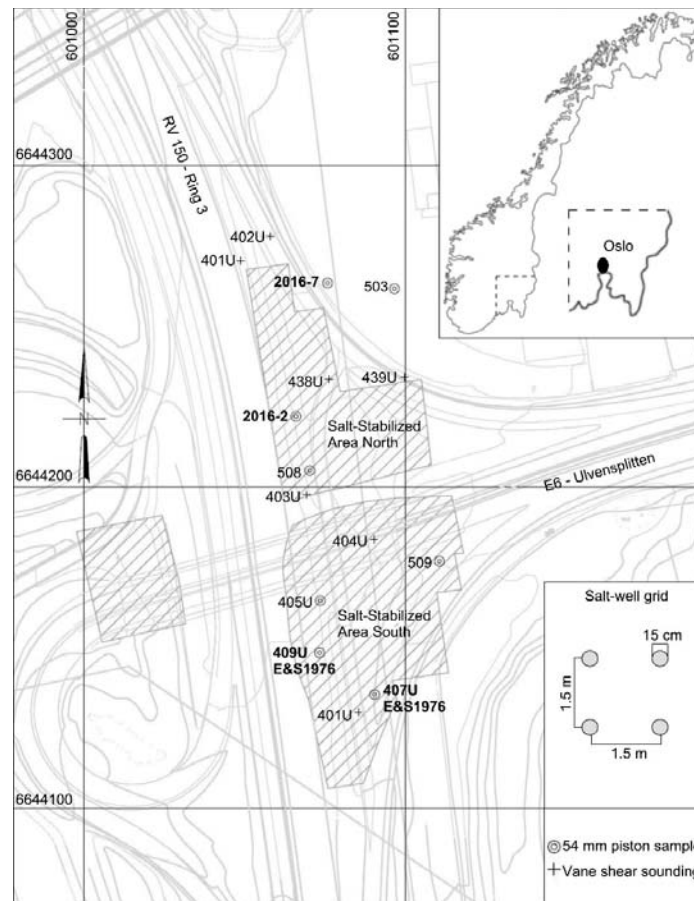
Figure 4-1 Salt-treated area (shaded) at Ulvensplitten showing location of ground investigations. Those presented in Eggestad and Sem (1976) have bold fonts and are marked E&S 1976. Recent investigations carried out in 2013 also have bold fonts (2016-2 and 2016-7). Information on type and year of the other ground investigations is found in the legend in Figure 4-3. The coordinates are given in UTM 32 EUREF 89
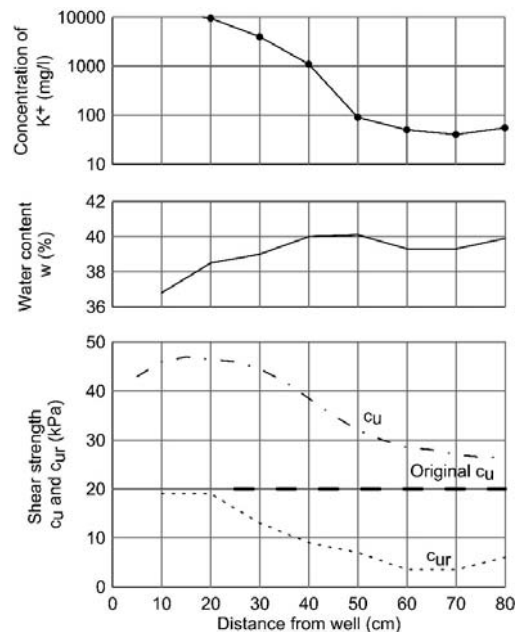
Figure 4-2 Concentration of K$^+$, water content, and undrained (c$_u$) and remoulded shear strength (c$_{ur}$) with distance to well at 5.5 m depth, 21 months after installation. The results are from the part of area south where the salt wells were installed by the wash-boring method. Reproduced from Eggestad and Sem 1976

4.4 Pore-water chemistry and geotechnical properties 40 years after installation

In 2013, 54 mm piston-core samples were extracted from two boreholes; 2016-2 and 2016-7 in Figure 4-1. Borehole no. 2016-2 was extracted within salt-stabilised area north, whereas borehole no. 2016-7 was extracted outside salt-stabilised area north. Fall-cone undrained and remoulded shear strength and Atterberg limits were determined at the geotechnical laboratory at Multiconsult (Morel-Vulliez et al. 2013), and pore water was extracted from clay specimens in the geotechnical laboratory at NTNU and sent for chemical analyses at the Department of Geosciences at University of Oslo.

The clay in the area outside salt-stabilised area north, was interestingly enough not quick. However, the salt content, equivalent to total dissolved solids was very low, 0.4-0.6 g/L (Figure 4-5). Even though this low-saline, non-quick clay had a remoulded shear strength in the range 1.1-2.8 kPa (Figure 4-6a), the liquid limit was lower than the natural water content. The liquidity index (*IL*) was in the range of 0.96-1.27 (Figure 4-6b). The salt content within the salt-stabilised area was 12 g/L at 4.5 m depth, and 0.5 g/L at 14.5 m depth. The dilution of the salt content may be a result of artesian groundwater flow bringing dissolved ions upwards in the soil profile, in combination with downwards and outwards directed diffusion to clays of lower salinity. Within the salt-treated area the remoulded shear strength was 11-12 kPa in the sample at 6.0-6.8 m depth with a salt content of 9 g/L, and around 2.4-3.6 kPa in the sample from 14.0-14.8 m depth where the salt content was only 0.5 g/L. Thus, the compositional factors inducing development of quick clay is not explained by low salt content, but rather by the pore-water composition.
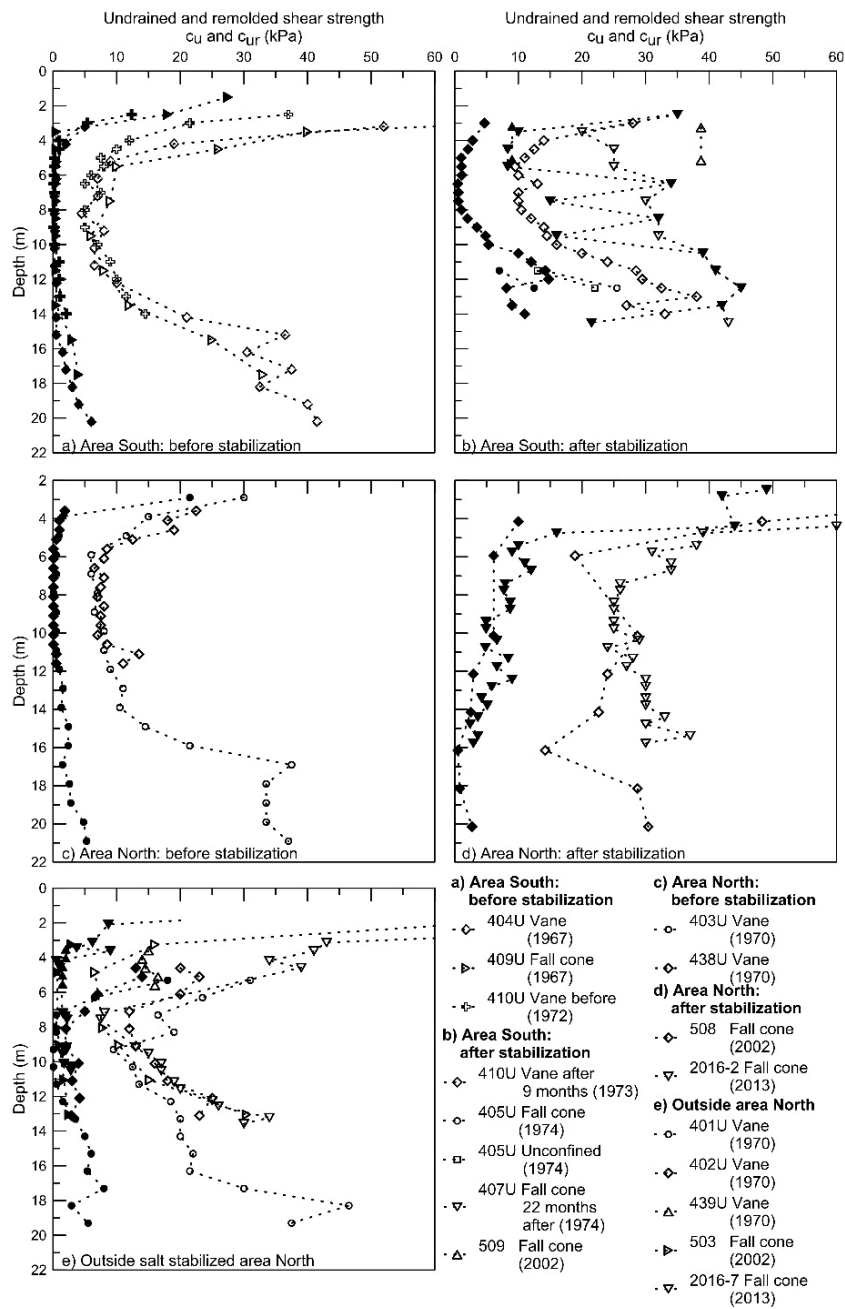
Figure 4-3 Undrained (open symbols) and remoulded (filled symbols) shear strength with depth in a) and b) area south, and c) and d) inside and e) outside area north before and after treating the areas with potassium chloride
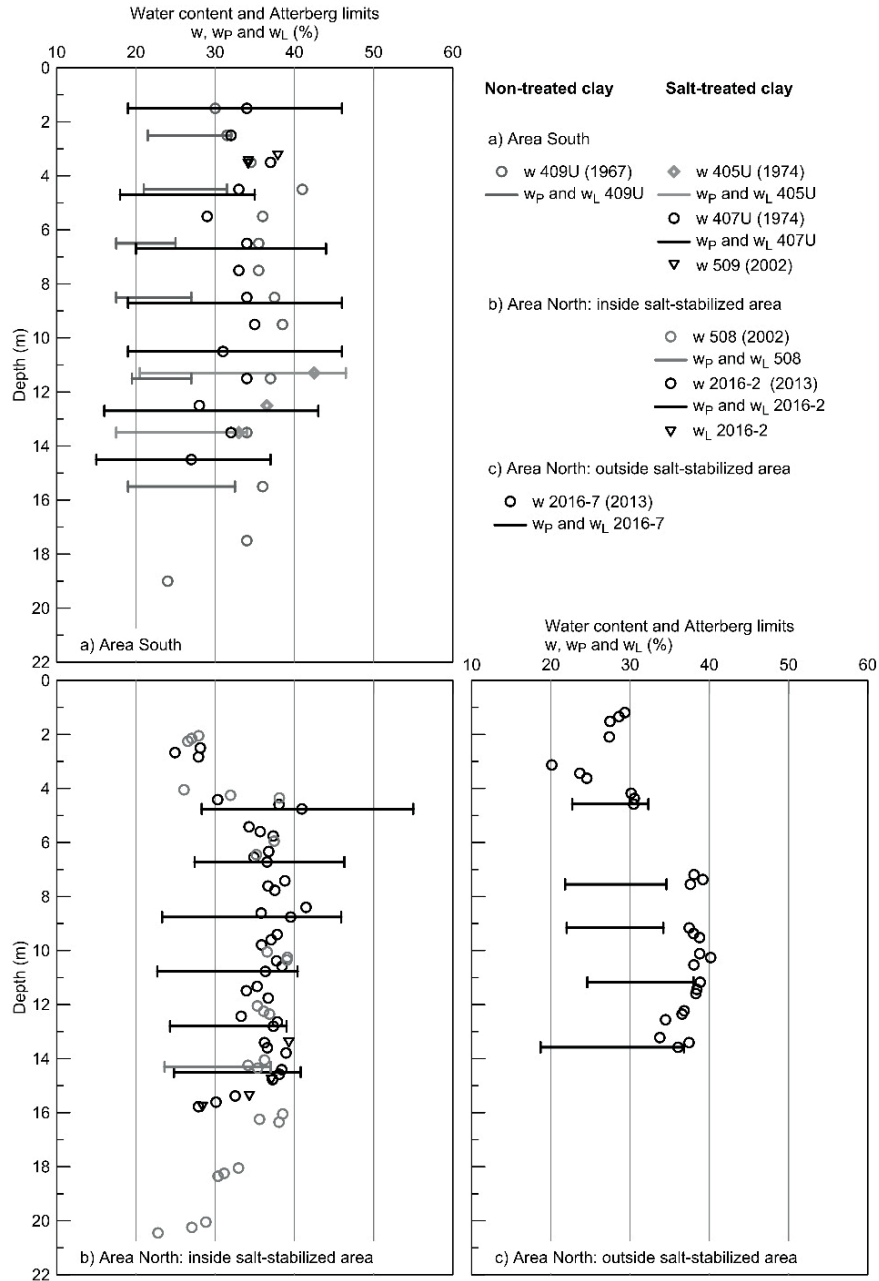
Figure 4-4 Water content and Atterberg limits in a) area south, b) inside salt-stabilised area, and c) outside salt-stabilised area north
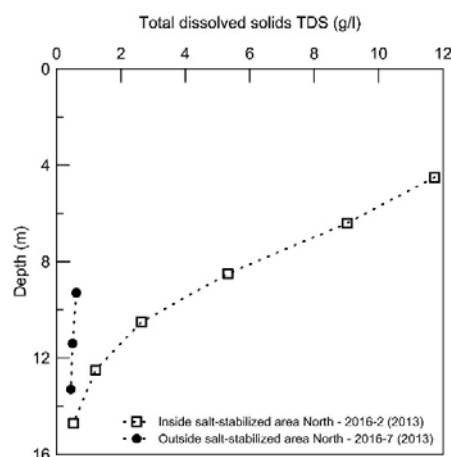
Figure 4-5 Total dissolved solids (TDS) in the pore water inside (borehole 2016-2) and outside (borehole 2016-7) salt-stabilised area north

Even though, the pore water in the salt-treated clay was diluted by freshwater during the 40 years that had passed after installation, potassium (K^+) was still the abundant cation down to 10.5 m depth, where the salt content was around 2 g/L. The pore water in quick clays is normally dominated by sodium (Na^+) (Moum et al. 1971; Hilmo 1989). Introducing large concentrations of K^+ to the pore water, K^+ will be adsorbed to the clay mineral surfaces which release the adsorbed sodium (Na^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) to the pore water. Thus, in the beginning until all adsorbed positions are occupied by K^+, there will be an accumulation of Na^+, Mg^{2+} and Ca^{2+} in the pore water. As more and more K^+ is introduced, both the adsorbed positions and the pore-water composition will be dominated by K^+ (Figure 2-3b). Groundwater is normally dominated by Ca^{2+} and/or Mg^{2+} (Appelo and Postma 2005). Therefore, as calcium-rich freshwater with time dilutes the pore water in the salt-treated clay, the pore-water composition is changed as well. Sodium (Na^+) is washed out of the system, and the pore-water composition does no longer favour development of high sensitivity.

The low-saline non-quick clay found outside the salt-stabilised area had a ratio of the sum of monovalent cations to the major cations (Equation 3-1), all concentrations in meq/L, lower than 70% (Figure 4-6c). According to Mitchell and Soga (2005), a ratio exceeding 75% favours the development of high sensitivity. Thus, as Na^+ no longer was the abundant cation in the pore water, it is likely to believe that leaching in this area had progressed further than in the quick-clay area. Potassium (K^+) has a much greater effect than Na^+ on suppressing the diffuse double layer surrounding the clay particles, even though they are of same valence. Therefore, considering whether the clay may develop high sensitivity or not based on the ratio suggested by Mitchell and Soga (2005) may not be applicable in salt-treated clay. Pore-water compositions that governs whether the clay is quick or not is further discussed in Chapter 5.

The fraction of divalent ions increased as the salinity decreased (Figure 4-6c). Divalent ions have a greater impact on suppressing the diffuse double layer than monovalent ions. Thus, the repulsive forces between the clay particles decrease, and the clay is inhibited from turning into a liquid when remoulded. Estimating the thickness of the diffuse double layer by the ionic strength of the electrolyte, show that a decrease in the diffuse double layer is followed by
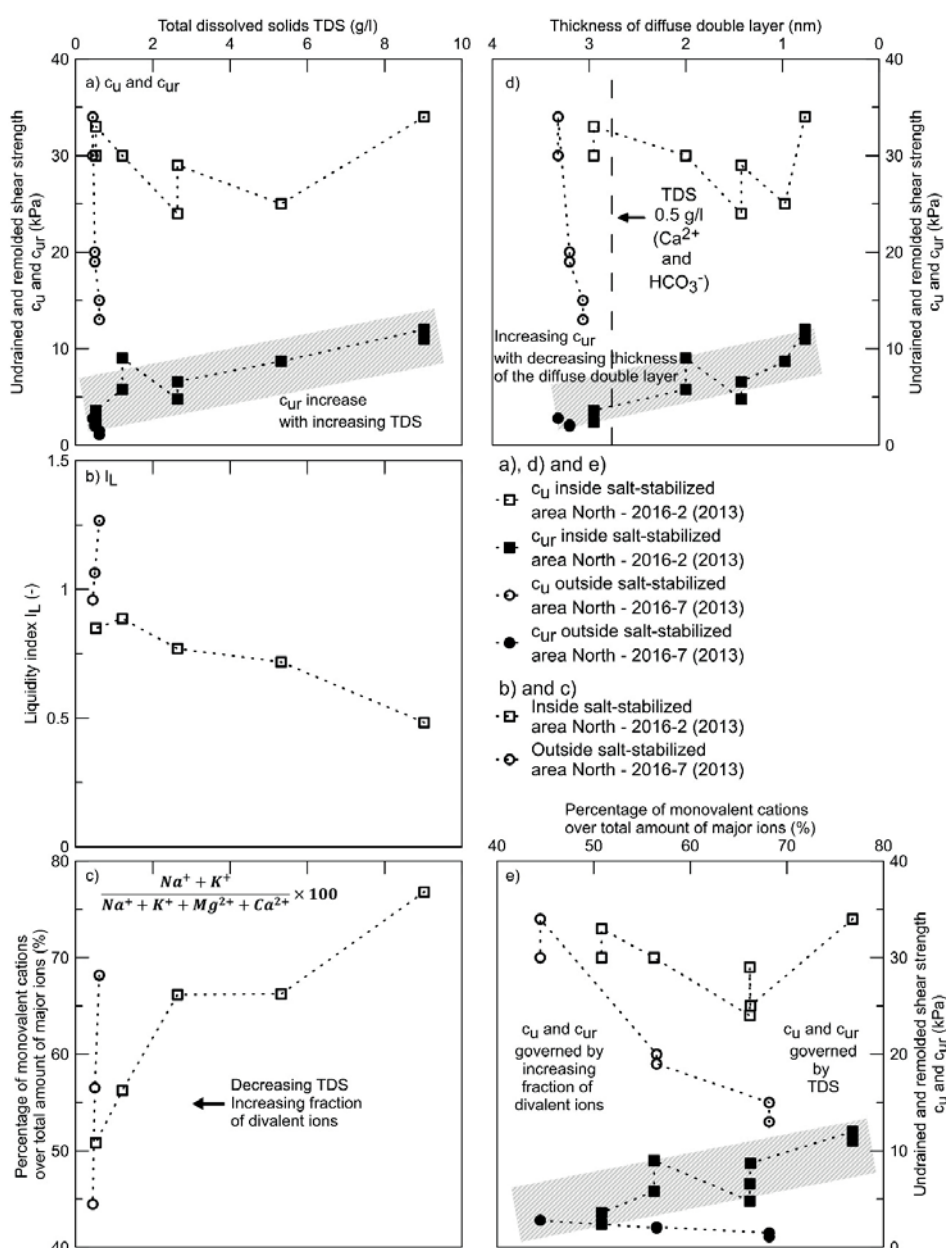
Figure 4-6 The impact of total dissolved solids (TDS) 40 years after salt-well installation on a) undrained and remoulded shear strength and b) liquidity index. c) Correlation between TDS and percentage of monovalent cations to total amount of major cations. d) Impact of the thickness of diffuse double layer on undrained and remoulded shear strength. Dashed vertical line shows calculated TDS of 0.5 g/L solely consisting of calcium (Ca^{2+}) and bicarbonate (HCO_3^-). e) Impact of percentage of monovalent cations to total amount of major cations on undrained and remoulded shear strength

increased remoulded shear strength (Figure 4-6d). Imagining a salt content of 0.5 g/L, with cations only consisting of Ca^{2+} as a result of leaching, the thickness of the diffuse double layer is estimated to 2.8 nm corresponding to a c_{ur} in the Ulvensplitten clay of 4 kPa. Therefore, as leaching progress and the introduced K^+ is washed out of the clay-water system and replaced by Ca^{2+}, the remoulded shear strength might stabilise at around 4 kPa.

4.5   Concluding comments

The recent ground investigations at Ulvensplitten show that the improved geotechnical properties remain 40 years after installation of the salt wells. Leaching has diluted the salt content in the salt-treated clay. Even though the salt content in the upper part of the soil profile is higher than deeper down, the fall-cone undrained shear strength is unaltered, and stable around 30 kPa from 6 m depth downwards (Figure 4-6a). This confirms the suggestion in Chapter 3, that there is an upper limit where further increase of the salt content does not induce further improvement of the undrained shear strength. The remoulded shear strength in the salt treated clay does, however, increase and the liquidity index (*IL*) decreases with increasing salt content. Thus, the salinity in the clay at the time of investigations is below what may be considered as the threshold for further improvement of the post-failure properties. Nevertheless, the clay remains non-quick even though the salt content is decreased back to its original 0.5 g/L in the deepest part of the investigated profile due to its changed pore-water composition.

The geotechnical properties are improved by increasing salt content due to its suppressing impact on the diffuse double layer. Therefore, in high saline clays, the composition of ions is of less importance (Bjerrum 1954; Rosenqvist 1955; Bjerrum and Rosenqvist 1956; Bjerrum et al. 1969; Løken 1970; Torrance 1975, 1999; Quigley 1980; Locat and Demers 1988). At salt contents lower than approximately 5 g/L, the composition of ions has a great impact on the geotechnical properties, and governs whether the clays are quick or not (Bjerrum et al. 1969; Torrance 1999). Most quick clays have salt contents of less than 2 g/L (Torrance 1979). The non-quick clay outside the salt-treated area north had a salt content of only 0.4-0.6 g/L, with a remoulded shear strength of 1.1-2.8 kPa. Both the fall-cone undrained and remoulded shear strength in this clay increase with increasing fractions of divalent cations present in the pore water (Figure 4-6e). Increased fractions of divalent ions, also decreases the *IL* below 1.2, which may inhibit failure in clay slopes to develop into large flow slides (Leroueil et al. 1983).

Potassium (K^+) has a greater impact on the remoulded shear strengths and Atterberg limits than for instance sodium (Na^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) (Løken 1968, 1970). Forty years after installation of the salt wells at Ulvensplitten, the salt content at level with bottom of the wells has decreased to its original 0.5 g/L. Even so, the improved properties remain in the salt-treated clay as Na^+ is depleted and the pore water consist of larger fractions of divalent cations which has a greater impact on suppressing the diffuse double layer than Na^+.

5   In-situ experiment on improving the geotechnical properties of the Dragvoll quick clay

5.1   Introduction

Six salt wells were installed at the Dragvoll quick clay research site in Trondheim, Norway in January 2013 in order to determine how and how fast potassium chloride (*KCl*) migrates into the surrounding clay and improves its geotechnical properties. Focus is on measuring and relating the changing geotechnical properties to the changing pore-water composition. Investigations around the wells were performed over a period of more than 3 years after installation. Soil samples were extracted from around the wells using a mini-block sampler and piston samplers. Laboratory tests were performed to determine mineralogy, ion composition in the pore water and geotechnical properties. In addition, groundwater samples were extracted around one of the wells and the pore-water compositions were determined. Resistivity cone penetration tests (RCPTU) were conducted to map the salt-plume extent and orientation, as well as detecting improved geotechnical properties.

Most research on *KCl* treatment of quick clays is carried out in the laboratory. One exception is related to salt-well installations at Ulvensplitten, Oslo, Norway in 1972. Significantly improved properties were measured based on sampling and vane-shear testing at Ulvensplitten in the following 2-3 years, but unfortunately limited pore-water chemistry data was obtained. Further, uncertainties relating to actual salt-well depths and no refilling of the wells creates difficulties in interpretation. Thus the tests remain inconclusive with respect to the time needed for when the clay at a certain distance ceased to be quick; vital for estimating the time required to stabilise a given, large quick-clay volume.

The purpose of the Dragvoll field experiments is to determine the required time to improve the post-failure properties sufficiently to inhibit retrogressive landslide development in this type of quick clay. Chapter 5 relates to Paper IV-IX, summarising the main findings and conclusions from the in-situ experiment at Dragvoll.

5.2   Site description, site installations and ground investigations

5.2.1   The Dragvoll research site

The Dragvoll research site in Trondheim, Norway is located at around 156 m above present sea level, close to the marine limit (Figure 5-1) which in the Trondheim area is 175-180 m above present sea level (Kjemperud 1981; Hafsten 1983).The research site is located in a relatively flat area used for farmland. The sediments are around 50 m thick (Hafsten and Mack 1990), located in between outcropping bedrock at distance in the small hills on the northwest and southeast side of the site.

Hafsten and Mack (1990) describe the geological history at Dragvoll. At the time of deglaciation, the fjord was covering most of the area (ca. 11 500-10 500 before present (BP)). In this period, the glacier front was located approximately 1 km east of the NTNU Dragvoll campus. The isostatic uplift following the deglaciation, elevated the area so that the fjord 10 500 years BP was at the level which now is 160 m above the sea level. Beach sediments were accumulated in the NTNU Dragvoll campus area and west of the site (dark blue area in Figure 5-1). At this time, the area were the site is located was covered with brackish water,

where tides from the fjord was flowing in and out of the area from the north. Because of the rapid deglaciation following the Ra-period, the rate of the isostatic uplift increased, and the elevation of the shoreline decreased by in average 6 cm per year the next millennium. For several centuries, the area was covered by a fresh-water lake within the thresholds in north and west. The lake was drained towards north, through the sand and gravel deposits 8 900-8 400 years BP, and the area turned into a swamp. Some 5 000 years BP the bog or peat stage started. Traces of cultivation is dated back to around 2 500 years BP. Today, the area is still used as farmland, and the top soil is drained. Wet areas (peat) are still present in the eastern part of the marked brown area in Figure 5-1, and directly west of the site.
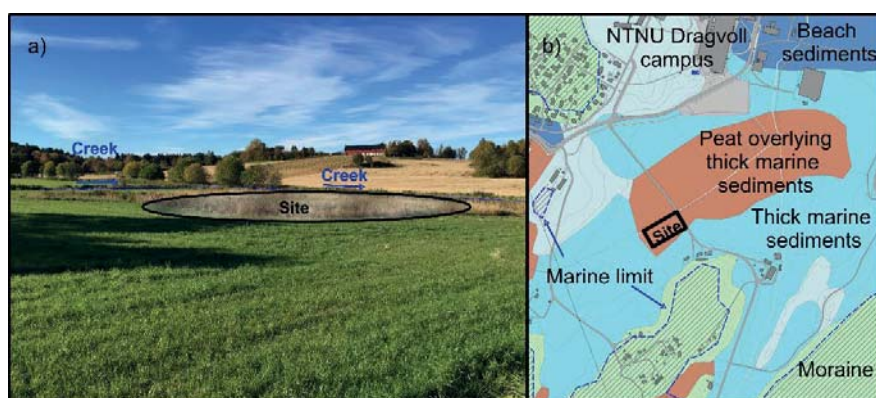
Figure 5-1 The Dragvoll research site is located next to two creeks used for drainage of surface water. The site is located close to the marine limit in an area with thick marine sediment package, and with some peat in the top sediments. The background map is from www.ngu.no

5.2.2 Salt-well installations and monitoring system

Six salt wells were installed in the quick clay deposit at the Dragvoll research site in January 2013 (Figure 5-2). The wells were made of polyethylene (PE) pipes with an outer diameter of 63 mm, and were installed to a depth of 8 m, with a slotted section from 4 m to 8 m depth and a 1 m empty stand pipe above ground (Figure 5-2a). In addition, one well (no. 5) was installed in the same manner as the salt wells, except that it was filled with groundwater. To prevent clay entering the salt wells through the slotted section, a geotextile was lashed around the slotted pipes. To limit disturbance of the soil, boreholes were pre-drilled to 6.5 m depth (salt wells no. 1, 2, 3 and 8), and 7.9 m depth (wells no. 5, 6 and 7).

Initially the wells were filled with granular potassium chloride (*KCl*) to 1 m below the terrain surface. A few litres of water were added so that it fluctuated with the groundwater level, which at the time of installation was approximately 1 m below surface. After installation, the wells were regularly refilled with granular *KCl* to maintain fully saturated solutions of *KCl* in the wells. The total salt consumption per well during the project period of approximately 3 years, was 66-80 kg.

In order to monitor the migration of *KCl*, two Schlumberger divers measuring the hydraulic head, temperature and conductivity once a day were installed close to salt-well no. 6 (SW6). The divers were positioned in measuring wells 0.5 m and 1.0 m from SW6; D2 and D3

respectively in Figure 5-3f. The measuring wells were constructed in the same manner as the salt wells, with a slotted section (screen) from 5.5 m to 6.5 m depth. In addition, BAT standard filter tips (Figure 5-2b) connected to 1" PE pipes were installed at 6 m depth 0.5 m and 1.0 m from SW6, BAT B1 and B2 in Figure 5-3f. Groundwater samples were extracted from the BAT filters regularly. To monitor any seasonal changes in the groundwater in the original clay deposit, one diver and BAT standard filter tip was installed in measuring point 4 (MP4). Well no. 5, which was filled with groundwater, was installed to investigate the impact of the well installation on the in-situ tests. The extent and orientation of the salt plumes around the remaining salt wells were investigated by resistivity cone penetration tests (RCPTU), and clay samples were extracted at various distances from the salt wells to study the improved geotechnical properties and changed pore-water compositions (Figure 5-3).
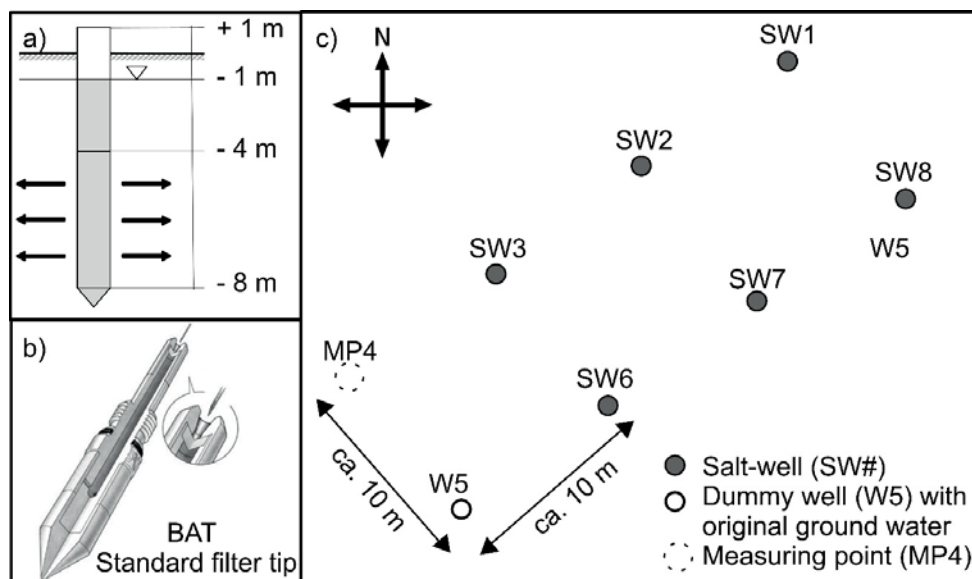
Figure 5-2 Installations at the Dragvoll research site. a) salt-well design, b) BAT standard filter tip (www.bat-gms.com) and c) principal sketch of the salt-well installations. The salt wells (SW#) are installed with a centre-to-centre distance of approximately 10 m. A Schlumberger conductivity diver and BAT filter tip are installed in monitoring point 4 (MP4) to measure any seasonal changes. The dummy well (W5) is installed in the same manner as the salt wells, only filled with groundwater

5.2.3 Sampling and laboratory tests

The initial geotechnical properties in the Dragvoll quick clay were determined on high quality mini-block samples extracted from 4 m to 8 m depth approximately 10 m northeast from salt-wells no. 1 and 8. Mini-block samples are downsized Sherbrooke block samples with a diameter of approximately 16 cm and a height of 25-30 cm. For further description, see Emdal et al. (2016). Fall-cone undrained (c_u) and remoulded shear strength (c_{ur}), water content (w), density (ρ), Atterberg limits and pore-water chemistry and pH were determined on samples from 4.0-4.3 m, 4.7-5.0 m, 5.7-6.0 m and 7.7-8.0 m depth within 24 hours after extraction from the

ground to delimit storage effects. In addition, constant rate of strain oedometer tests (CRS) and anisotropically consolidated, undrained compression triaxial tests (CAU$_c$) were conducted, and the over-consolidation ratio (*OCR*) and peak undrained shear strength (c_{uc}) were determined. The CRS tests were conducted with a strain rate of 0.75%/hr. The CAU$_c$ were anisotropically consolidated to its overburden stresses applying a coefficient at rest (K_0') of 0.7. The samples were consolidated for approximately 16 hrs before applying a backpressure of 250 kPa, and left to rest prior to shearing at a strain rate of 1.5%/hr.

Samples were extracted from the clay surrounding the salt wells to correlate the improved geotechnical properties to the changed pore-water chemistry (Figure 5-3 and Table 5-1). Undisturbed 54 mm piston samples were extracted from 4.0 m to 8.8 m depth in various distances from salt wells no. 2, 3, 7 and 8 (SW#). In addition, mini-block samples were extracted in a distance of 0.5 m north of salt-well no. 1 (SW1) down to 4.75 m depth, and 75 mm piston-core samples were extracted from 5.5 m to 8.3 m depth. All samples were tested within 48 hours after extraction to delimit storage effects. Fall-cone tests, water content, density and Atterberg limits were determined on all samples, as well as pH and the chemical composition of the pore water. In addition CRS tests were conducted on the mini-block sample extracted from 4.35-4.75 m depth north of SW1, and the 54 mm piston samples extracted around SW7 from 5.0-5.8 m depth. Triaxial tests were only conducted on the mini-block from 4.35-4.75 m depth north of SW1. The CRS and CAU$_c$ test were carried out in the same way as for the original quick clay.

Table 5-1 Resistivity cone penetration tests (RCPTU) and sampling around the individual salt wells in the years after installation

RCPTU and sampling around salt-well no.	Time after installation
SW1	2 years and 5 months
SW2	3 years and 3 months
SW3	3 years and 3 months
SW6	3 years and 5 months
SW7	3 years and 2 months
SW8	2 years and 9 months

The grain-size distribution was determined by hydrometer tests. X-ray diffraction analysis (XRD) were used for determining the bulk and clay mineralogy. The specific surface area was analysed by nitrogen ($N_2(g)$) adsorption analysis (BET), and the cation exchange capacity (*CEC*) was found by x-ray fluorescence (XRF) analysis of both major and trace elements on clay specimens fully saturated with strontium.

Pore-water samples were extracted from the clay specimens centrifuging four 50 ml polyethylene (PE) centrifuge bottles filled with clay for 60 minutes at 4000 rounds per minute. The extracted pore water (total 10-20 ml) was filtered through 0.45 μm, in some cases 0.20 μm, syringe filters, into PE containers and frozen until analysis of the pore-water composition at the laboratory at the Department of Geosciences at University of Oslo. Groundwater samples extracted from the BAT filter tips (Figure 5-3f) were also filtered through syringe filters, and frozen prior to testing in the same manner as the extracted pore water from the clay samples.
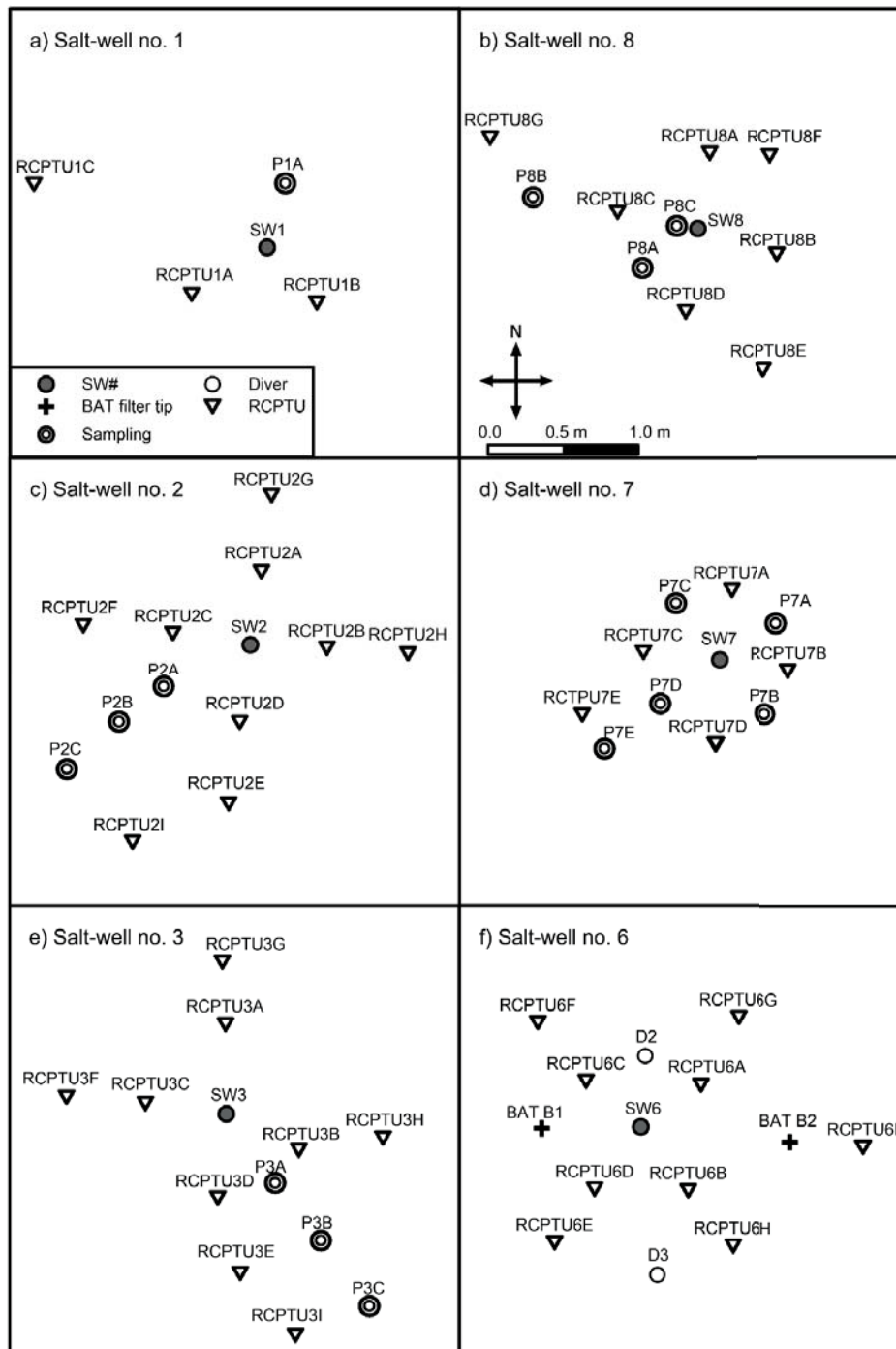
Figure 5-3 Index map showing the conducted ground investigations around each well. The centre-to-centre distance between the wells are approximately 10 m. a) Salt-well no. 1, b) salt-well no. 8, c) salt-well no. 2, d) salt-well no. 7, e) salt-well no. 3, and f) salt-well no. 6

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). The alkalinity was determined by HCl-titration in Metrohm 702 SM Titrino, and pH was measured in the pore-water samples by Methrom 702 SM Titrono at 25 ºC. pH was also measured directly on remoulded clay specimens at approximately 25 ºC using a Sentix SP electrode.

The extent of the salt plumes around the wells was investigated by resistivity cone penetration tests (RCPTU) (Figure 5-3). A resistivity module connected behind the conventional piezocone (CPTU) allowed soil-conductivity measurements (often inverted to resistivity). The RCPTU tests were carried out with a 5 tons GeoTech CPTU Nova and a 2 tons Envi CTPU probe, both with a tip area of 10 cm^2. Sampling and RCPTU tests around each well were carried out within 1-2 weeks.

5.3 Initial soil properties of the Dragvoll quick clay

The current groundwater table at Dragvoll fluctuates between the terrain surface and 1 m below. The weathered zone (or the "dry crust") stretch down to 1-2 m below surface. Gravel/rock fragments, shells and shell fragments are commonly found in the upper 4 m of the soil and are occasionally found at greater depths. Between 3 m and 4 m, the clay turns quick as the remoulded shear strength (c_{ur}) in the clay gradually decreases below 0.5 kPa (Bryntesen 2013, 2014). The clay deposit at Dragvoll is interbedded with millimetre thick silt/sand layers, increasing to 1-2 cm thickness at 7-8 m depth. The clay content (< 2 μm) is of 34-41%, with a bulk mineralogy dominated by the non-clay minerals quartz and albite, and clay mineralogy dominated by illite (Table 5-2).

Table 5-2 Bulk and clay (< 2 μm) mineralogy in the Dragvoll clay

Bulk mineralogy	%	Clay mineralogy	%
Quartz	24-31	Illite	67
Albite	21-23	Chlorite	33
Illite	15-17		
Chlorite	12-13		
Calcite	2-3		

The quick clay at Dragvoll is very soft and highly sensitive, with a fall-cone undrained shear strength (c_u) of 8-16 kPa, and a remoulded shear strength (c_{ur}) of 0.5 kPa at 4 m depth, decreasing to less than 0.1 kPa at 5 m depth (Figure 5-4). The plastic limit (w_P) decreases from 18% at 4 m depth to 15% at 8 m depth. The liquid limit (w_L) is 21-24% also decreasing with depth, and much lower than the natural water content. The quick clay is of low plasticity with a plasticity index (IP) of 4.4-6.3%. The liquidity index (IL) is in the range 3.4-4.3. The average volumetric porosity is 0.51, the average bulk density is 1.87 g/cm^3 and the average dry bulk density 1.36 g/cm^3. The in-situ hydraulic conductivity (k) in the clay at 6 m depth was determined carrying out an inflow test in the BAT filters (section 5.2.2). The k in the original quick clay was of 2.3 x 10^{-10} m/s.

Triaxial tests (CAU$_c$) were run on all samples. The clay has a brittle contracting behaviour with a distinct peak before failure, and a significant drop in the post-peak strength, characteristic

for quick clays (Figure 5-5). The samples at 4.07 m and 4.90 m had a slightly dilatant behaviour before peak undrained shear strength (c_{uc}) was reached, indicating that the samples are consolidated well within their failure envelope. The c_{uc} in the quick clay is in the range of 27.5-29.5 kPa, reaching the c_{uc} at strains at failure (ε_f) of 0.3-0.5 % (Table 5-3).

The apparent pre-consolidation stress (p_c') at 4.18 m depth is 90 kPa, decreasing to 85 kPa at 4.78 m depth and 67 kPa at 5.78 m depth (Figure 5-6a), corresponding to an over-consolidation ratio of 2.2 in the top, decreasing to 1.2 at 5.78 m depth. The deformations at
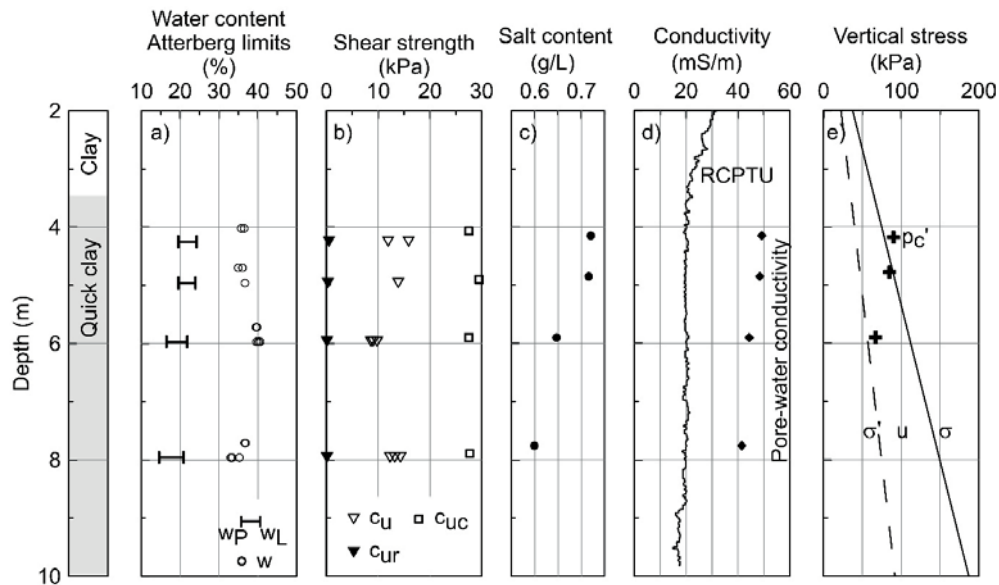
Figure 5-4 a) Water contents (w) and Atterberg limits (w_P and w_L), b) Peak-undrained shear strength (c_{uc}) and fall-cone undrained (c_u) and remoulded shear strength (c_{ur}), c) salt content, d) soil and pore-water conductivity, and e) total vertical stress (σ), effective vertical stress (σ'), pore pressure (u) and apparent pre-consolidation stress (p_c') in the quick clay at Dragvoll before salt well installation

Table 5-3 Anisotropically consolidated, undrained compression (CAU_c) test results on quick clay samples from Dragvoll. Peak undrained shear strength (c_{uc}), strain at failure (ε_f), attraction (a) and friction angle (φ). The quality assessment is based on the water extrusion during consolidation (ε_{vol}) and over-consolidation ratio (OCR) found in the oedometer tests

Depth m	OCR (-)	ε_{vol} %	Quality	c_{uc} kPa	ε_f %	a kPa	φ -
4.07	2.2	1.3	Perfect	27.5	0.5	2.5	36.0
4.90	1.8	1.4	Perfect	29.5	0.3	1.5	35.2
5.90	1.2	2.0	Perfect	27.5	0.4	1.0	30.9
7.89	1.0	2.7	Perfect	27.7	0.4	4.0	26.5
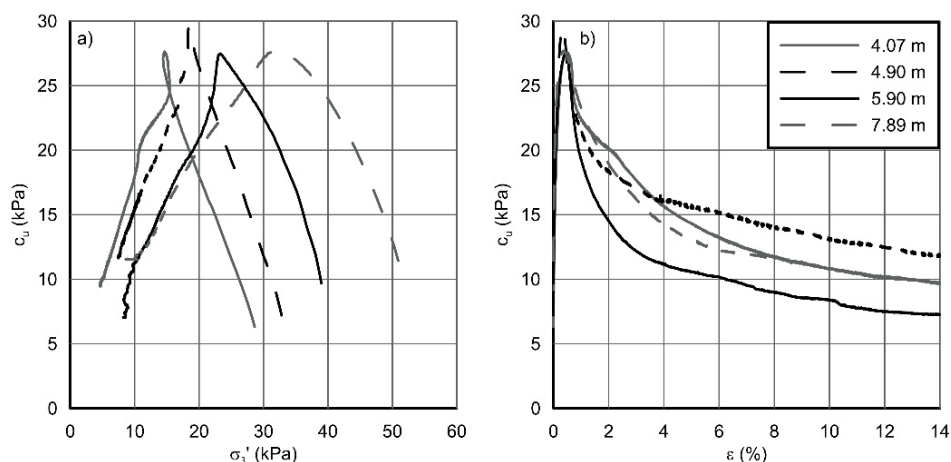
Figure 5-5 Undrained shear strength (c_u) versus a) effective horizontal stress (σ_3') and b) vertical strain (ε) in anisotropically consolidated, undrained compression triaxial tests (CAU$_c$) on Dragvoll quick clay samples before salt well installation

loads exceeding p_c' are larger at 5.78 m depth than seen in the samples from 4.18 m and 4.78 m. The oedometer modulus in the over-consolidated clay (M_{OC}) is higher in the top than deeper down in the investigated profile: 5.5 MPa and 5.0 MPa respectively (Figure 5-6b). The vertical hydraulic conductivity (k_v) determined at in-situ overburden effective stresses, is in the range of 1.3-1.5 x 10^{-9} m/s (Figure 5-6c), larger than found in the in-situ test carried out in the BAT filter tips at 6 m depth. It is possible that the installation of the BAT filters may have remoulded the clay surrounding the filter tip. Thus, the in-situ hydraulic conductivity may have been measured on reconsolidated clay with slightly lower permeability, thus lower hydraulic conductivity.

In the original quick clay at Dragvoll, the salt content in the pore water is of only 0.6-0.7 g/L, with sodium (Na^+) as the abundant cation (85-92%) (Table 5-4), which is typical in quick clays (Moum et al. 1971; Torrance 1979). The ratio of monovalent cations ($Na^+ + K^+$) to the sum of major cations[c] (Equation 3-1) is of 88-95%. There is very little chloride (Cl^-) remaining from the seawater at time of sedimentation; 0.3 meq/L. Bicarbonate (HCO_3^-) is the dominating constituent of the alkalinity at the occurring pH, and is the abundant anion in the electrolyte, typical for freshwater.

The cation exchange capacity (*CEC*) in the Dragvoll quick clay determined by XRF is around 25 meq/100 g dry soil. The specific surface area is in the range 18.3-27.8 m^2/g, increasing with depth from 4.0 m to 5.9 m. PHREEQC (www.usgs.gov) simulations of the altering pore-water chemistry around salt-well no. 6 showed that the *CEC* in the Dragvoll clay probably is much lower (see section 5.7.2). Glaciomarine clays of low activity (non-swelling) have small specific surface areas, thus low *CEC* (Quigley 1980). According to Grim (1968), the specific surface areas for illites is in the range of 65-100 m^2/g when the *CEC* is in the range

---

[c] Sodium Na^+, potassium K^+, magnesium Mg^{2+}, calcium Ca^{2+}
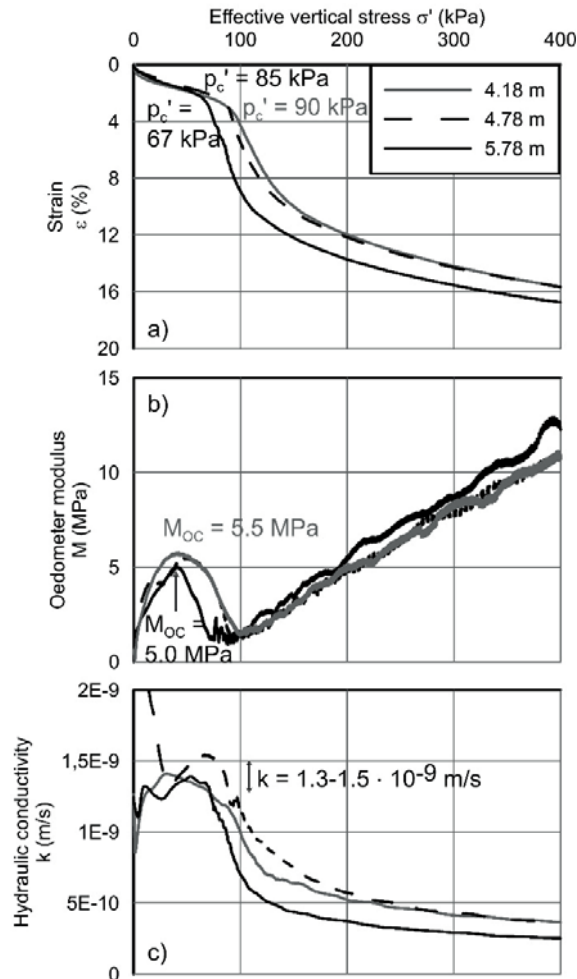
Figure 5-6 Constant rate of strain oedometer results from quick-clay samples at 4.2-5.8 m depth. Effective vertical stress (σ') versus a) vertical strain (ε), b) oedometer modulus (M), and c) hydraulic conductivity (k). Interpreted apparent pre-consolidation stresses (p_c') are indicated in a), oedometer modulus in OC range (M_{OC}) in b), and hydraulic conductivity (k) in c)

of 10-40 meq/100 g dry soil; much larger specific surface areas than found in the Dragvoll clay. The clays presented by Grim (1968) are, however, of diagenetic origin with smaller grains, consequently larger specific surface areas than will be the case for detrital clastic clays found in Scandinavia. Locat and St-Gelais (2014) report specific surface areas in chloritic-illitic Quebec clays in the order of 10-36 m^2/g and a *CEC* in the range of 6-17 meq/100 g dry soil in clays with clay contents of 30-83%. Lower *CEC* than found in the Dragvoll clay even though having specific surface areas in the same range. Kenney (1967) report *CEC* of three Norwegian very sensitive clays saturated with Ca^{2+} of 9-11 meq/100 g dry soil at clay contents of 42-44%. The laboratory determined *CEC* at Dragvoll is rather high considering the low specific surface area. The presence of calcite in the clay from Dragvoll is sensitive to dissolution and may have given too high *CEC* values (Jackson 1979). It is therefore suggested that *CEC* may be estimated

by Equation 5-1 when the clay mineralogy and the clay fraction is known, applying empirical values in the low range for the various mineral types. Applying the lowest *CEC* of illites and chlorites found in Appelo and Postma (2005) of 20 meq/100 g dry soil and 10 meq/100 g dry soil respectively, the *CEC* in the Dragvoll clay is estimated to 5.7-6.8 meq/100 g dry soil. This corresponds well with the *CEC* fitted in the PHREEQC simulations, and is therefore assumed to represent the *CEC* in the Dragvoll quick clay.

$$CEC = \sum (\% \text{ clay}/100) \cdot (\% \text{ mineral type}/100) \cdot CEC_{\text{low range}} \qquad \text{Eq. 5-1}$$

The initial soil properties greatly affects the migration of salt in the soil volume, and the velocity of the salt migration is highly influenced by the *CEC* and hydraulic conductivity in the soil.

Table 5-4 Pore-water chemistry in the Dragvoll quick clay before KCl treatment

	Depth			
	4.15 m	4.85 m	5.9 m	7.76 m
Chemical specie	meq/L	meq/L	meq/L	meq/L
Sodium Na^+	7.78	7.83	7.50	6.84
Potassium K^+	0.33	0.30	0.24	0.26
Magnesium Mg^{2+}	0.61	0.41	0.18	0.26
Calcium Ca^{2+}	0.47	0.33	0.22	0.26
Chloride Cl^-	0.27	0.27	0.27	0.26
Fluoride F^-	0.26	0.25	0.28	0.30
Bromide Br^-	0.00	0.04	0.04	0.00
Nitrate NO_3^-	0.00	0.00	0.00	0.00
Sulphate SO_4^{2-}	0.06	0.05	0.05	0.06
Phosphate PO_4^{3-}	0.00	0.00	0.02	0.08
Alkalinity as bicarbonate HCO_3^-	8.10	8.07	7.16	6.60
Electric charge balance EB (%)	2.71	1.08	2.01	2.23
pH in pore water	8.7	8.6	8.8	8.9
pH in soil	8.3	8.6	8.7	9.1
$\dfrac{Na^+ + K^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}}$	88%	92%	95%	93%
$\dfrac{Na^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}}$	85%	88%	92%	90%
Total dissolved solids TDS (ppm)	720.11	715.58	646.75	599.01
Salt content (g/L)	0.72	0.72	0.65	0.60

5.4   Salt-plume extent

Resistivity cone penetration tests (RCPTU) were conducted around the wells to map the extent of the salt plumes, and monitoring systems were installed around salt-well no. 6 (SW6) to investigate the salt-plume migration and changes in the pore-water chemistry with time. The RCPTU measures the electrical conductivity, often inverted to and presented as electrical resistivity. The measured electrical conductivity is presented and discussed in the following. Salt content in the pore water is directly correlated to the pore-fluid conductivity. Leached quick clay often have salt contents of less than 2 g/L (Torrance 1979). Thus, the pore water conductivity is low (< 200 mS/m). The soil conductivity in clays does not necessarily correlate directly to the pore-water conductivity, as clay minerals are conductive due to their charged surfaces and diffuse double layers (Waxman and Smits 1968; Glover et al. 2000). Nevertheless, the soil conductivity is influenced by the salt content in the pore fluid. Therefore, RCPTU was used for detecting the extent and direction of the salt plumes around the salt wells at Dragvoll.

Even though the site is geotechnical homogenous, the RCPTUs showed that the salt plumes migrated nonsymmetrically moderately off-centred from the wells (Figure 5-7b). The non-symmetry also varied with depth (Figure 5-7a and Figure 5-8). The fact that the fastest direction of migration varied almost randomly from one well to the other, indicated that there was no dominating direction of groundwater flow in the area. The salt plume migrating from the wells was similar to what is seen in saltwater intrusion in freshwater aquifers, where the salt plume
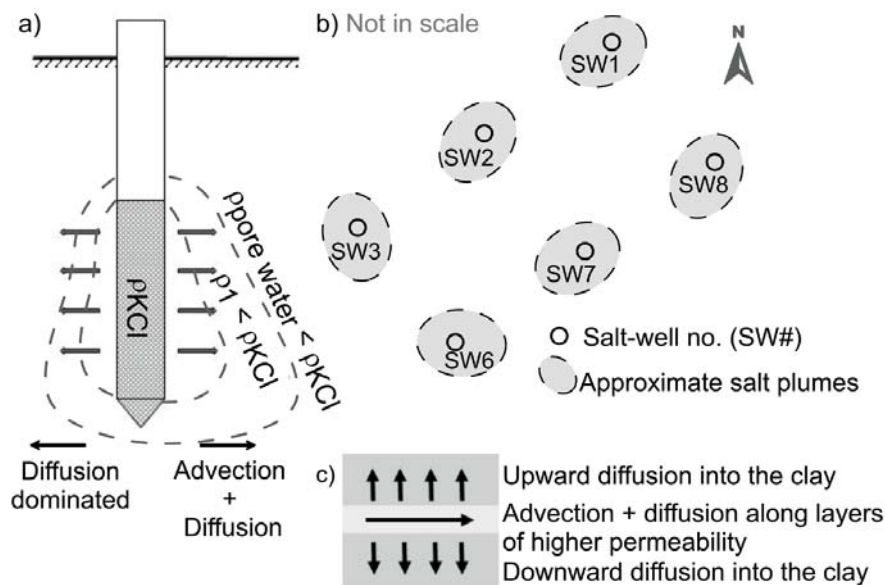
Figure 5-7 a) Diffusion dominated the salt migration around the wells, with contribution from advection due to density (ρ) gradients between the well and the pore water in the quick clay along layers of higher permeability illustrated in c). The salt plume migrated faster with depth. b) The fastest direction of the salt migration varied from one well to the other
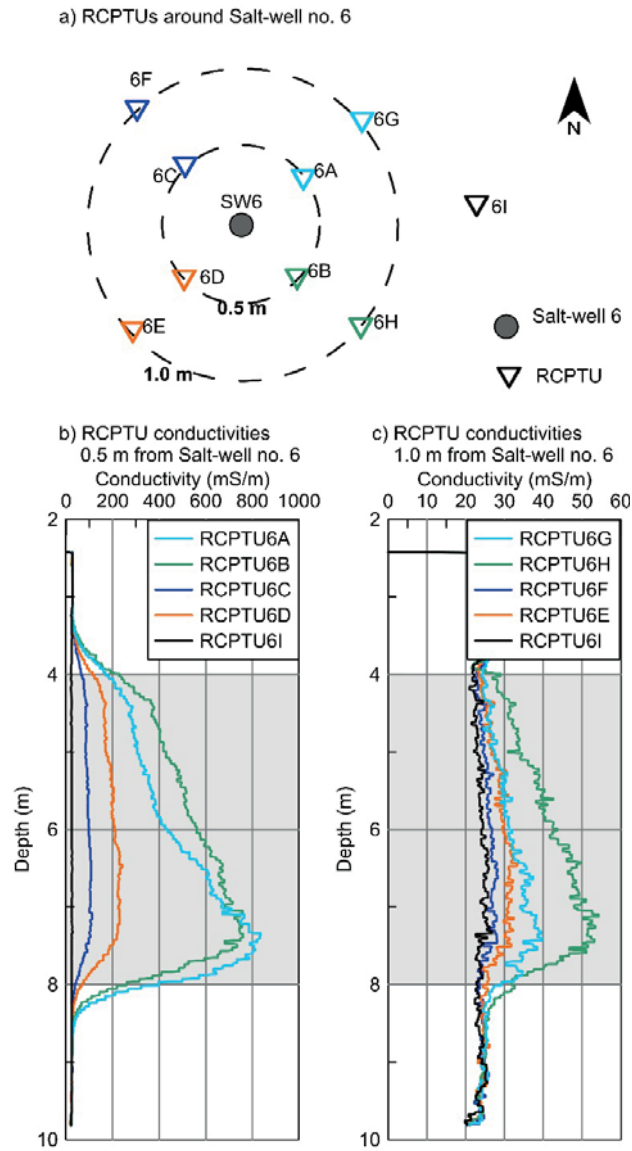
Figure 5-8 a) RCPTUs conducted around Salt-well no. 6. Measured soil conductivities b) 0.5 m and c) 1.0 m from the well 3 years and 5 months after installation. The salt migrated from the well from 4 m to 8 m depth (shaded area). The conductivity in sounding RCPTU6I was in the original quick clay 1.5 m from the well. Note that the scales on the x-axis are different in b) and c)

migrates to further distances with depth under the groundwater plume (e.g. Robinson et al. 2006). The density of the salt plume was higher than in the surrounding pore water in the quick clay, also typically found in leachates from landfills causing a sink of the plume into the soil (e.g. Zhang and Schwartz 1995; Post and Prommer 2007). The pore water in the clay had a density of 1 g/cm^3, whereas the solute in the wells had a density (ρ_{KCl}) of around 1.2 g/cm^3. The RCPTUs and pore-water compositions revealed that the plumes migrated at greater distances with depth, which may indicate that the plumes sank. The plumes seemed to stop, however, at around 8.5 depth; 0.5 m below the wells (Figure 5-8). Due to the low permeability in the clay and no dominating groundwater flow, the clay inhibited the plume from sinking further below the well, forcing it to migrate horizontally along layers of higher permeability (Figure 5-7c). In soils of higher permeability than found at Dragvoll, a salt plume like this would sink considerably deeper.

Salt-well no. 6 (SW6) was monitored with Schlumberger conductivity divers and BAT filter tips installed at 6 m depth on opposite sides of the well. Approximately 300 days after installation, the salt plume arrived the BAT filter tip installed 0.5 m from the salt well (B1 in Figure 5-9). In the opposite direction, one meter from the well (BAT B2), the salt plume arrived approximately 600 days after installation. RCPTU soundings around SW6 indicated that the direction of fastest migration was towards BAT B2. This may explain why the diver conductivity half a meter from the salt well indicated salt-plume arrival already 80 days after installation (Diver 2 in Figure 5-9). The difference in salt-plume arrival in D2 compared to BAT B1 may also be caused by direct contact between the salt well and the diver well through silt/sand layers. The diver conductivity in D3, one meter from the well, corresponded quite well with the salt plume arrival in BAT B2, approximately 600 days after installation, even though this might not be easy to see from Figure 5-9 due to the scale on the axis.
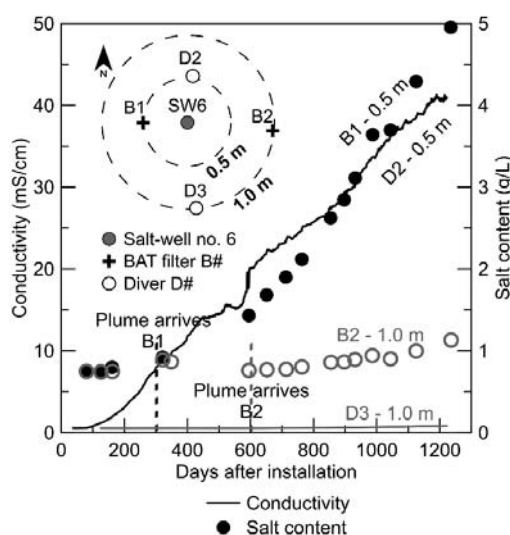
Figure 5-9 Diver conductivity and salt contents found in groundwater samples extracted from the BAT filter tips installed 0.5 m (black line and symbols) and 1.0 m (grey line close to the x-axis and grey symbols) from salt-well no. 6 at 6 m depth
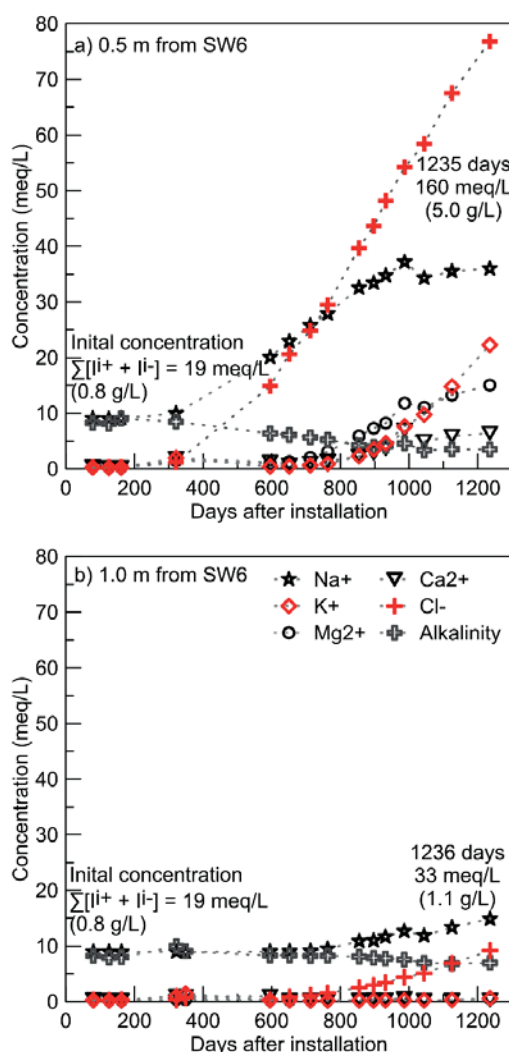
Figure 5-10 Concentration of major cations, chloride and alkalinity found in groundwater samples extracted from the BAT filter tips installed a) 0.5 m and b) 1.0 m from salt-well no. 6. The arrival of K^+ is retarded compared to the arrival of Cl^-, both in red. Values at installation are found in Table 5-4

The analysed ground-water samples extracted from the BAT filter tips, showed that Na^+ (Figure 5-10) initially dominated the cations in the pore water, balanced by the alkalinity; here considered to be dominated by bicarbonate (HCO_3^-). Chloride (Cl^-) is a conservative tracer as it travels unhindered through the soil volume, not involved in any ion-exchange reactions. Thus, the Cl-front arrived first accompanied with available cations to maintain an overall charge balance. The Cl-front arrived 0.5 m from the salt well after approximately 300 days, accompanied by the Na-front (Figure 5-10a). As *Cl-* increased in the pore water, the alkalinity decreased. Around 600 days after installation, the K-, Mg- and Ca-fronts arrived at approximately the same time. The Na-concentration seemed to stabilise around 1000 days after

installation, indicating that most of the Na^+ was released from the clay mineral surfaces in the clay volume closest to the well, and was on its way out of the clay-water system. The concentrations of Mg^{2+} and Ca^{2+} were still increasing, indicating that ion exchange still occurred. The concentration of the delayed K^+ was also increasing, indicating that more and more of the adsorbed positions on the clay mineral surfaces were dominated by K^+. One meter from the well, the salt plume and the Cl-front arrived the BAT filter approximately 600 days after installation (Figure 5-9), also followed by increased Na-concentration and decreased alkalinity (Figure 5-10b). The K-, Mg and Ca-fronts had not arrived when the last groundwater sample was extracted 3 years and 5 months after installation of the salt well.

The in-situ measured soil conductivity and groundwater samples extracted from the BAT filter tips provide valuable information about the salt-plume extent and direction, how fast *KCl* migrates in a clay deposit, and how it affects the migration and concentrations of the other major cations with distance and time from the salt well. Correlations of geotechnical properties to the occurring pore-water composition is necessary for evaluating *KCl* as a ground improvement method. Undisturbed clay samples were extracted around the wells for determination of the geotechnical properties and pore-water chemistry.

5.5 Improved geotechnical properties

5.5.1 *Improved post-failure properties*

Properties of the clay in remoulded state determines the propagation of landslides. Quick clays are defined by a remoulded shear strength (c_{ur}) of less than 0.5 kPa (Norwegian Geotechnical Society 2011), often having liquid limits (w_L) less than the natural water content (w), a liquidity index (IL) larger than 1.2 (Leroueil et al. 1983) and salt contents of less than 2 g/L (Torrance 1979). As quick clays liquefy when remoulded, these clays pose a serious risk for successive back-scarp failures, developing into large retrogressive or progressive landslides. In Norway, clays with a remoulded shear strength of less than 1 kPa are considered as posing a risk for backwards, successive retrogressive landslides due to their brittle behaviour (Thakur et al. 2014a). Introducing potassium chloride (*KCl*) to the clay-water system suppresses the diffuse double layer, consequently decreases the repulsive forces between the clay particles, and the structure and the geotechnical properties improve. The clay volume is in the following considered as stabilised at $c_{ur} > 1$ kPa.

Both the fall-cone undrained (c_u) and remoulded shear strength (c_{ur}) in the Dragvoll quick clay were significantly improved by increasing salt contents up to 10 g/L due to the introduced *KCl* (Figure 5-11a). At salt contents exceeding 10 g/L, the c_u did not increase further, but stabilised around 25-30 kPa. This is in agreement with the findings in the pilot study in section 3.3, suggesting that there is a threshold whereas further increase in salt content does not lead to further increase in fall-cone c_u. Triaxial tests with determination of peak and post-peak strength in the in-situ salt-treated clay was unfortunately not investigated due to time restrictions. A slight improvement of peak undrained shear strength (c_{uc}) and significantly improved post-failure strength due to increased salt contents was, however, detected in the mini-block samples stored in *KCl* slurry (section 3.4.2). It is therefore likely to believe that both c_{uc} and post-peak strength were improved in the in-situ treated clay. To what extent is however, not known.

In the direction of fastest migration from the wells, the salt treated clay had $c_{ur} > 1$ kPa along the whole salt-treated depth range 1 m from salt-wells no. 2 and 7, and from 7 m to 8 m depth 1 m from salt-well no. 3 (Table 5-5). An improvement of the c_{ur} to more than 1 kPa was

Table 5-5 Salt contents and remoulded shear strengths (c_{ur}) in directions dominated by diffusion (boreholes P7A, B and C), and in direction of fastest migration 0.5 m from salt-wells no. 3 and 7, and 1.0 m from salt-wells no. 2, 3 and 7. The results 0.5 m from salt-well no. 8 are in brackets

| | Diffusion | | Advection and diffusion | | | |
| | 0.5 m | | 0.5 m | | 1.0 m | |
Depth	Salt content g/L	c_{ur} KPa	Salt content g/L	c_{ur} kPa	Salt content g/L	c_{ur} kPa
4.3	6.4-7.9	3.5-4.4	-	-	-	-
5.3	8.6-10.8	4.4-4.6	20.5-27.7 (77.1)	5.0-5.1 (9.6)	1.1-2.4	0.3-1.7
6.3	11.5-14.8	4.3-4.8	44.4-59.1 (98.1)	4.8-5.4 (8.4)	1.4-3.8	0.3-2.6
7.3	15.1-23.4	3.7-4.2	79.3-88.1 (82.0)	4.6-6.2 (8.1)	2.4-11.9	0.9-3.8

also found half a meter underneath the salt wells, within the investigated distance of 50 cm. There is a steep increase in both fall-cone c_u and c_{ur} with increasing salt contents up to 10 g/L by introducing *KCl* (Figure 5-11a). The c_{ur} increased from <0.1-0.5 kPa to around 4-8 kPa at salt contents up to around 75 g/L. At salt contents exceeding 75 g/L, the c_{ur} increased up to as much as 9.6 kPa 0.5 m from salt-well no. 8 (SW8) at 5.4 m depth, and 13.5 kPa at 4.3 m depth 10 cm from SW8. Solutes of such high salt contents have greater densities than water: 1.05-1.10 g/cm^3. Therefore, the bulk density increased from 1.87-1.90 g/cm^3 in the original quick clay to 1.97 g/cm^3 in the salt-treated clay 10 cm from SW8. The increased density found in the salt treated clays around SW8 may have affected the geotechnical properties.

The water content in the original quick clay is around 37% (Figure 5-11b), and was unaffected 0.5 m from the salt wells. Ten cm from salt-well no. 8, however, the water content decreased to around 30%. The increased salt content increased the total solids in the soil volume, and consequently the water content decreased. At 4 m depth, 54% of the reduction in water content was due to increased total solids, whereas 46% may be due to osmosis towards the well. At 5 m depth, as much as 83% of the reduction in water content may be due to osmosis. Therefore, at very high salt contents (> 80-100 g/L), the water content is reduced and some of the improved post-failure properties may be a result of reduced water content, in addition to reduced repulsive forces.

Referring to Figure 5-11b, the liquid limit (w_L) increased with increasing salt contents up to around 40 g/L, reaching the natural water content at salt contents of around 3-4 g/L. At salt contents exceeding 40 g/L, w_L decreased with increasing salt contents. Nevertheless, still larger than the natural water content in the salt-treated clay; from 21.6-25.4% to 34.6-43.9%. The plastic limit (w_P) increased from 15-19% to 20.0-23.7%; in average to 22% regardless of increasing salt contents beyond approximately 2 g/L. The plasticity index (IP) increased from low plasticity to the range of medium and high plasticity. The liquidity index (IL) decreased from more than 3.4 in the non-treated quick clay, to less than 1.2 in the salt treated clay 0.5 m from the salt wells. In clays with c_{ur} slightly above 1 kPa, IL did not necessarily decrease below 1.2, which was seen at certain depths 1 m from the wells in the direction of fastest migration. Re-introducing high salt content obviously improves the geotechnical properties. However, the

Dragvoll quick clay ceased to be quick at salt contents as low as 1.2 g/L, which may be explained by the ion composition in the pore water.

5.5.2 The impact of pore-water chemistry on the post-failure properties

Quick clays often have salt contents of less than 2 g/L (Torrance 1979), and may even behave as a liquid at salt contents of less than 1 g/L (Moum et al. 1971). However, low-saline non-quick clays occur in nature due to the presence of cations of greater effect on suppressing the
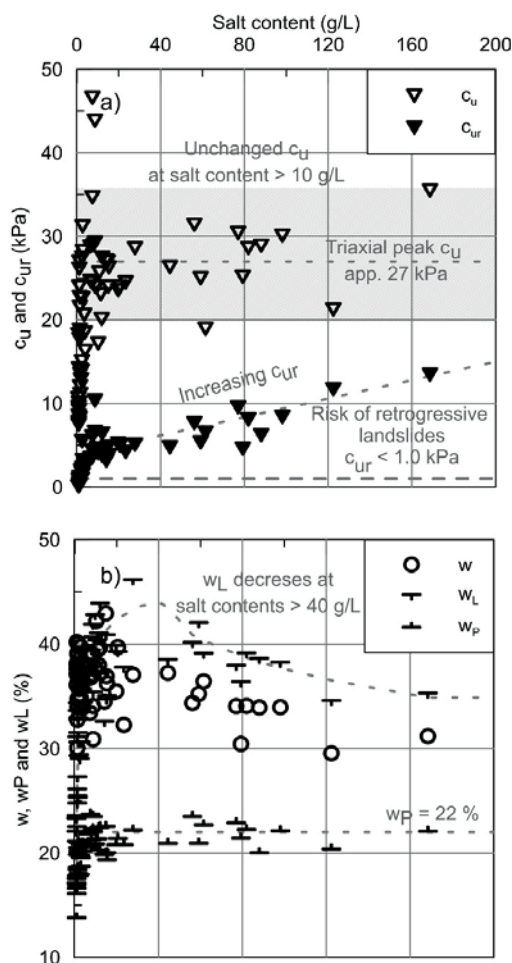
Figure 5-11 a) Fall-cone undrained and remoulded shear strength. The peak c_{uc} found in undrained, anisotropically consolidated compression triaxial tests (CAU$_c$) on quick-clay specimens was around 27 kPa (dashed line). b) Natural water content (w), plastic limit (w$_P$) and liquid limit (w$_L$) correlated to salt content in original quick clay and KCl-treated clay from the research site Dragvoll

diffuse double layer (Penner 1965; Quigley 1980; Torrance 1983; Mitchell and Soga 2005). Low-saline non-quick clay was found in close vicinity to the salt-stabilised area north at Ulvensplitten (Chapter 4). The salt content was of only 0.5 g/L, nevertheless having a remoulded shear strength (c_{ur}) larger than 1 kPa. According to Mitchell and Soga (2005), quick behaviour may develop in sediments where the sum of the normalities of sodium (Na^+) and potassium (K^+) to the sum of major cations in the pore water exceeds 75% (Equation 3-1). The impact of cations on suppressing the diffuse double layer varies from one ion to another of same valence due to differences in the hydrated radius and ionic potential (see section 2.5). Due to the smaller hydrated radius, K^+ has a much greater impact on suppressing the diffuse double
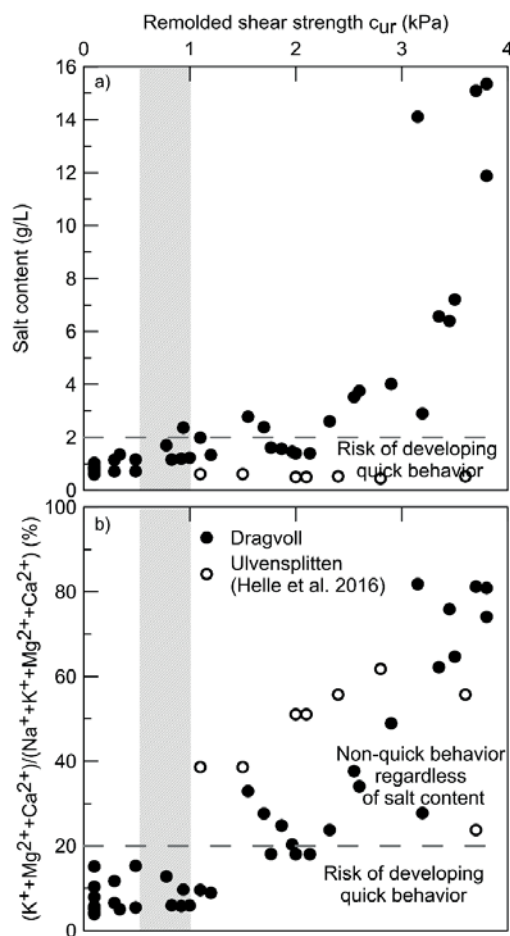
Figure 5-12 Remoulded shear strength correlated to a) salt content and b) ratio of the sum of normalities of K^+, Mg^{2+} and Ca^{2+} to the sum of major cations. The shaded area shows the transition between quick clay with a $c_{ur} < 0.5$ kPa and clays that pose a risk for retrogressive landslides ($c_{ur} < 1$ kPa). The Ulvensplitten data are from the non-treated, non-quick clay found outside salt-treated area north
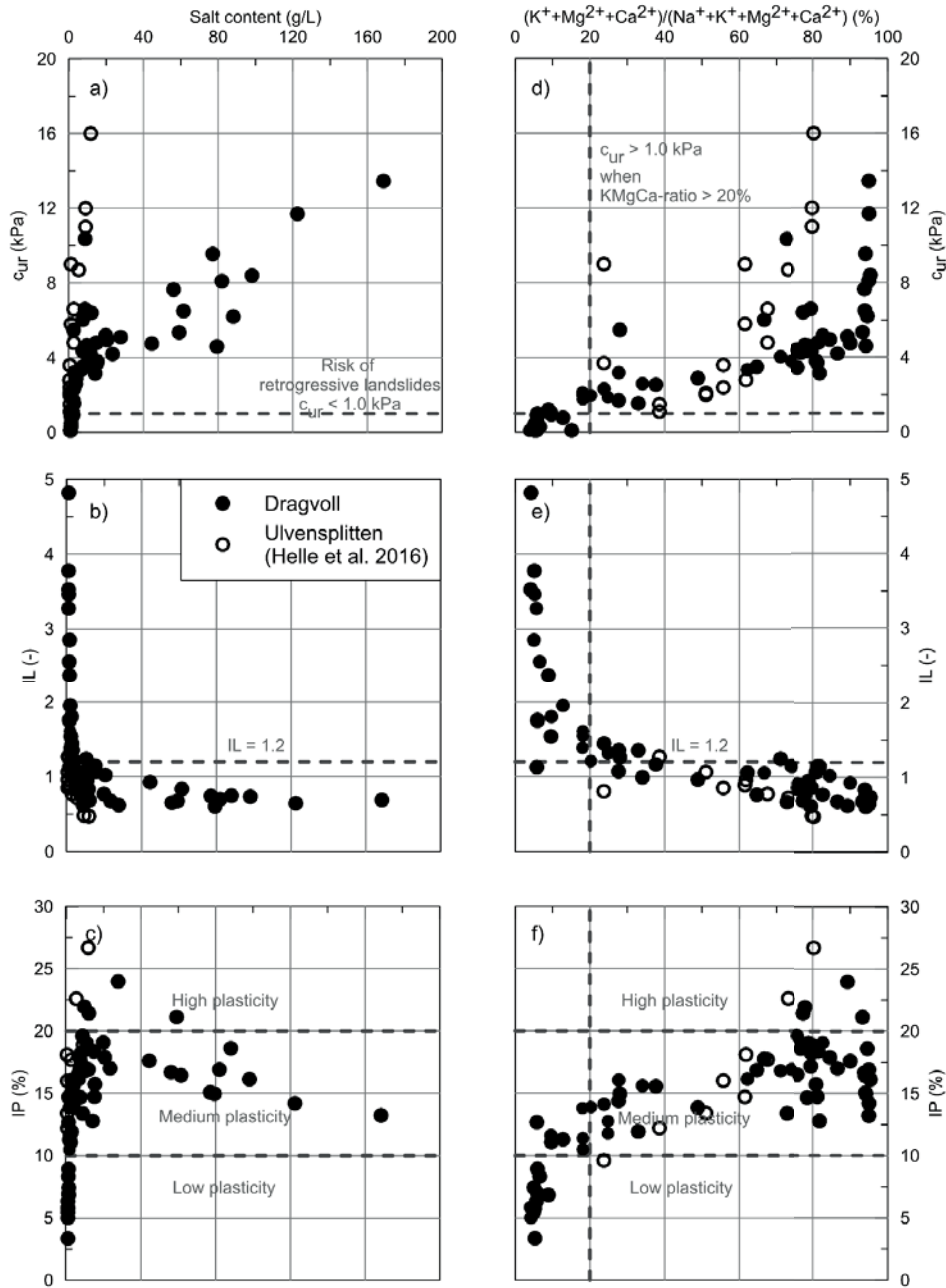
Figure 5-13 Salt content correlated to a) remoulded shear strength (c_{ur}), b) liquidity index (IL) and c) plasticity index (IP). Ratio of the sum of K^+, Mg^{2+} and Ca^{2+} to the sum of major cations correlated to d) c_{ur}, e) IL and f) IP. The Ulvensplitten data are from both the salt-treated and the low-saline non-quick area

layer than Na^+. Rather than considering the ratio of the sum of Na^+ and K^+ to the sum of major cations, the results from the in-situ experiment at Dragvoll and Ulvensplitten show that clay sensitivity is governed by the occurrence of K^+, Mg^{2+} and Ca^{2+} in the pore water (Equation 5-2, all concentrations in meq/L), in the following referred to as the KMgCa-ratio. The remoulded shear strength increased beyond 1 kPa at a KMgCa-ratio of only 20% even at salt contents of less than 2 g/L (Figure 5-12).

$$KMgCa\text{-}ratio = \frac{K^+ + Mg^{2+} + Ca^{2+}}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}} \qquad \text{Eq. 5-2}$$

The improvement of the liquidity (IL) and plasticity index (IP) in the KCl-treated clay at Ulvensplitten and Dragvoll as well as in the low-saline, non-quick, non-treated Ulvensplitten clay was also detected at a KMgCa-ratio of 20% (Figure 5-13). At a pore-water composition with a KMgCa-ratio exceeding 20%, IL decreased below 1.2 and the clays changed from being of low to medium plasticity. Introducing KCl to the clay-water system inhibits retrogressive landslide development due to favourable changed pore-water chemistry. The impact on design parameters and progressive landslide development is discussed in the next section.

5.5.3 *Improved pre-consolidations stresses and reduced deformations and brittleness*

Constant rate of strain oedometer tests (CRS) and triaxial compression tests (CAU$_c$) were conducted on the mini-block sample extracted from 4.4-4.8 m depth 0.5 m from salt-well no. 1 (SW1) 2 years and 5 months after installation. Oedometer tests were also conducted on the 54 mm piston samples extracted from 5.0-5.8 m depth around salt-well no. 7 (SW7) 3 years and 2 months after installation (Figure 5-14). The CRS data from boreholes P7B, C and E showed poor quality, and are not included herein.

The salt content in the clay extracted 0.5 m from SW1 was increased from 0.7 g/L to 1.6 g/L, and the pore-water composition was changed compared to the quick clay, having a KMgCa-ratio of 25%. The clay was no longer quick, having a remoulded shear strength (c_{ur}) of 1.8 kPa, a liquidity index (IL) of 1.6 (still higher than 1.2 due to a liquid limit lower than the natural water content), and a plasticity index (IP) of 12.8%. Even though the post-failure properties were improved, the apparent pre-consolidation stress (p_c') was not; still at 85 kPa as before installing the salt wells (Figure 5-15). There was no improvement of peak undrained shear strength (c_{uc}) and post-peak strength in the CAU$_c$ tests.

The salt content in the pore water extracted from the clay samples around SW7 showed that the salt migrated faster in direction of boreholes P7D and E, also migrating faster with depth in all directions. At 5.25 m depth, the salt contents were 9.7 g/L in the sample from borehole P7A, and 27.7 g/L in the sample from borehole P7D. The sodium (Na^+) was depleted, and the KMgCa-ratios were of 78% and 89% respectively. The increased salt contents and concentrations of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) improved the c_{ur} way beyond what is considered to be quick, to around 5 kPa. The fall-cone undrained shear strength (c_u) increased to 24.0-28.6 kPa. The IP improved from low to high, and the IL in the salt treated clay decreased to 0.6-0.8. The p_c' increased from 67 kPa in the original quick clay to 90 kPa at a salt content of 9.7 g/L and 110 kPa at a salt content of 27.7 g/L, with a corresponding increase
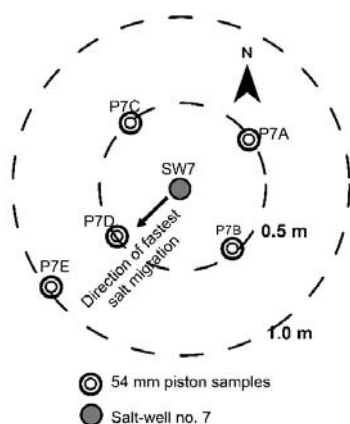
Figure 5-14 Undisturbed 54 mm piston samples were extracted 0.5 m (P7A, B, C and D) and 1.0 m (P7E) from salt-well no. 7 (SW7) 3 years and 2 months after installation. The direction of the fastest salt migration is indicated by the arrow in direction of boreholes P7D and P7E

of the over-consolidation ratio (*OCR*) from 1.2 to 1.7-2.1. The immediate deformations at loads exceeding p_c' are far less in the salt-treated clay ($\Delta\varepsilon_{KCl}$ in Figure 5-15c) than in the original quick clay ($\Delta\varepsilon_{QC}$). The oedometer modulus (M_{OC}) is practically unchanged (Figure 5-15d). Many authors suggest that the peak undrained shear strength is correlated to the *OCR* (e.g. Bjerrum 1967; Ladd and Foot 1974; Karlsrud and Hernandez-Martinez 2013). Therefore, it is likely to believe that the increased *OCR* in the in-situ salt-treated clays is related to an increased peak-undrained shear strength (c_{uc}), thereby reducing the risk for initiating progressive failures.

Progressive development of landslides in highly sensitive quick clays may be explained by a process consisting of two parts (Jostad and Grimstad 2011). The first part is where the progressive failure is initiated along a shear band, and the second part comprises the post-failure movement. At initiation of failure along a failure plane, peak strength is mobilised. A progressive landslide may be initiated if the post-peak strength thereafter is sufficiently reduced leading to a domino effect with subsequent deformations with large strains and reduced strength along a shear plane (Fornes 2014; Gylland 2014; Thakur et al. 2014b). The degree of softening after peak describes the brittleness of the clay. Fornes (2014) introduces the brittleness parameter $\Delta\gamma_{80}$ where values in the range of 0-2% may indicate high brittleness, 2-5% medium brittleness and > 5% low brittleness. The $\Delta\gamma_{80}$ is defined as the difference between the shear strain (γ_{80}) at 20% reduction of the c_{uc} after peak and the shear strain at failure (γ_f).

The laboratory study storing mini-block samples extracted from the Dragvoll site in *KCl* slurry was presented in section 3.4. Parallel samples were stored wrapped in cling-film submerged in de-aired water to account for the storage effect. The mini-block samples stored in *KCl* slurry had much higher salt contents than found in the in-situ experiment at Dragvoll (170-260 g/L), increasing the bulk and dry density of the clay due to introduction of more solids. Thus, for the samples stored in *KCl* slurry, some of the effect on the decreased deformation at loads beyond p_c', may at very high salt contents ($> \sim 80$ g/L) be caused by increased solids in the voids in addition to a maximum suppression of the diffuse double layer. The bulk and dry
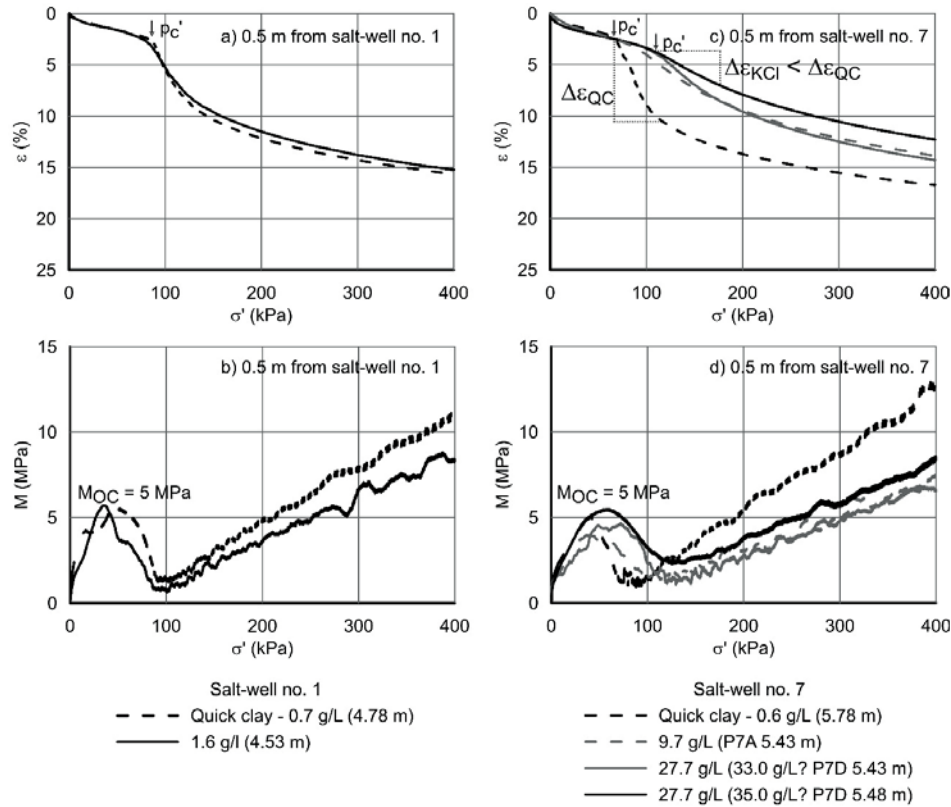
Figure 5-15 Oedometer results from original quick clay and salt-treated clay. a) strains (ε) and b) oedometer stiffness (M) versus effective vertical stress (σ') on mini-block sample extracted 0.5 m from salt-well no. 1 at 4.5-4.8 m depth. c) ε and d) M versus σ' on 54 mm samples extracted 0.5 m from salt-well no. 7 at 5.4-5.8 m depths. The apparent pre-consolidation stress (p_c') is indicated in a) and b). The immediate collapse of the structure at loads beyond p_c' is decreased in the KCl-treated clay ($\Delta\varepsilon_{KCl}$) compared to in the original quick clay ($\Delta\varepsilon_{QC}$) in b)

density in the samples extracted around SW7 with salt contents up to 27.7 g/L were unaltered. The oedometer stress-strain curves for the samples stored in *KCl* slurry and in the in-situ treated clays corresponded quite well. Both the peak undrained shear strength was improved and the post-peak undrained shear strength was significantly improved in the mini-block sample stored in *KCl* slurry having an *OCR* of 2.7 (Figure 5-16). Furthermore, $\Delta\gamma_{80}$ increased from 1.5% in the sample stored in de-aired water, to 11.5% in the sample stored in *KCl* slurry, significantly reducing the brittleness. It is likely to believe that this is also the case for the in-situ treated clay, due to the similar behaviour comparing the oedometer tests. The decreased collapse of the structure seen at loads exceeding p_c' in the oedometer tests on the in-situ salt-treated clay, may be related to reduced brittleness. Thus, installing *KCl* wells in quick clay slopes may reduce the risk for initiating progressive failures, and reduce potential post-failure movements. The reduced risk for initiating progressive failures commence at larger salt contents and different
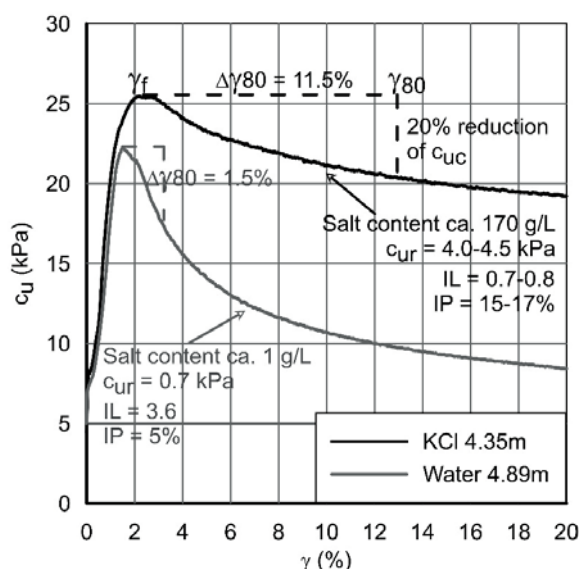
Figure 5-16 Triaxial test results on a sample stored in KCl slurry (black line) compared to a sample stored in de-aired water (grey line). The brittleness parameter ($\Delta\gamma_{80}$) is found by subtracting the shear strain at failure (γ_f) from the shear strain (γ_{80}) found at 20% reduction of peak-strength (c_{uc}). The $\Delta\gamma_{80}$ increased from 1.5% in the sample stored in de-aired water to 11.5% in the sample stored in KCl slurry

KMgCa-ratios than for inhibiting retrogressive landslide development. The leaching tests conducted on clay samples presented by Torrance (1974), reveals larger compressibility and a reduction in p_c' in leached clays with Na-dominated pore fluids with salt contents of less than 2 g/L than in clays with higher salt contents. Combining these findings with the findings at Dragvoll, this may imply that the improved p_c' and decreased deformations at loads beyond p_c' commence at salt contents somewhere in the range of 2-9 g/L. Both Bjerrum (1967) and Sridharan and Nagaraj (2000) relate decreasing compressibility to increasing plasticity. The *IP* in the samples stored in *KCl* slurry was in the range of 10.0-17.4%. In the in-situ salt-treated clay around SW7 the *IP* was in the range of 21.9-24.0%, and in the sample extracted 0.5 m from SW1, *IP* was of 12.8%. These results imply that improved p_c' and decreased immediate deformations at loads beyond p_c' may commence at an *IP* of around 15%, which in the clays at Dragvoll and Ulvensplitten require either a salt content larger than 6 g/L or a KMgCa-ratio exceeding 60%.

Sampling and laboratory tests provides accurate information about the geotechnical properties. It is, however, time consuming and expensive. In-situ tests may therefore be a cost-efficient alternative in detecting improved properties.

5.6 Detecting improved geotechnical properties by resistivity cone penetration tests

According to Solberg et al. (2012) and Long et al. (2012) clays with an electrical soil conductivity in the range of 10-100 mS/m may indicate quick clay. A large proportion of the Dragvoll clays with improved remoulded shear strength (c_{ur}) beyond 1 kPa was within the
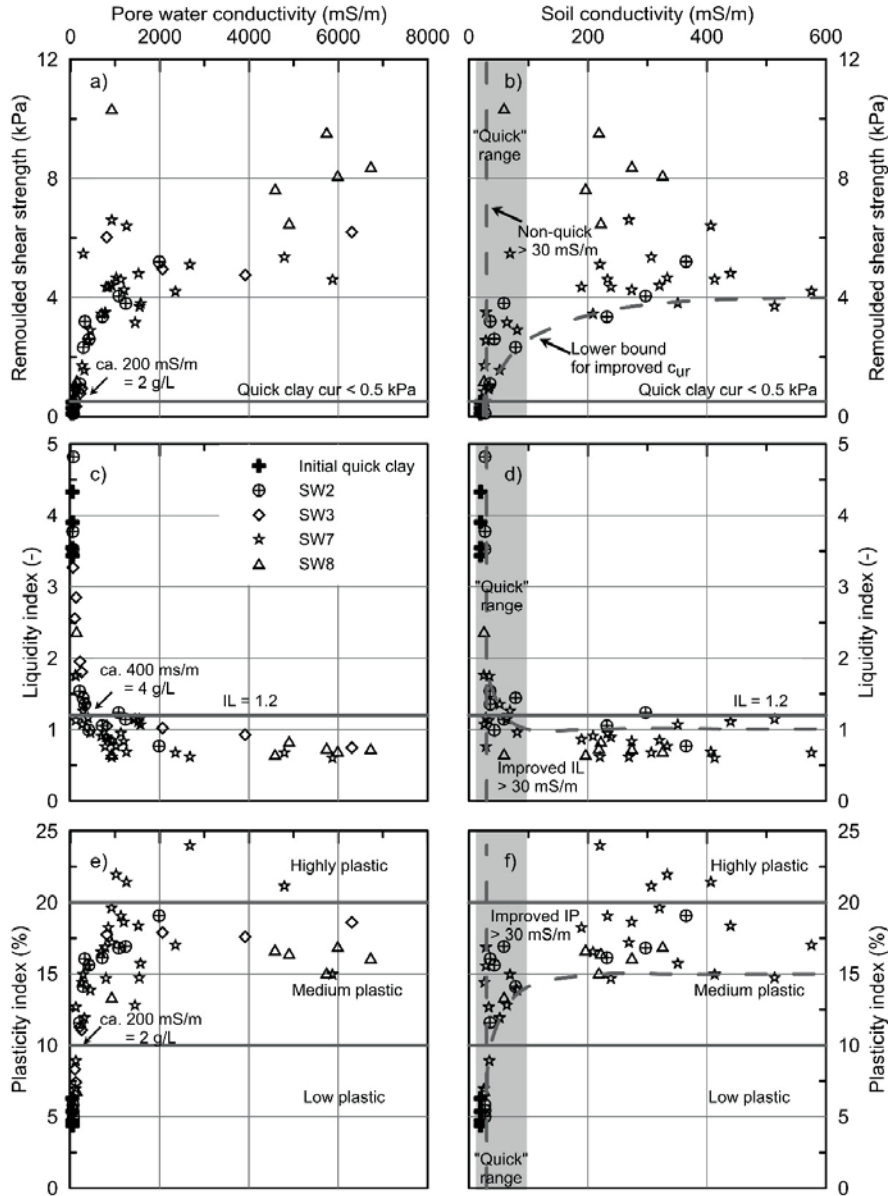
Figure 5-17 Pore-water and soil conductivity correlated to a) and b) remoulded shear strength (c_{ur}), c) and d) liquidity index (IL), and e) and f) plasticity index (IP). Soil conductivity in the range 10-100 mS/m (grey shading), may indicate possible, quick clay. Improved geotechnical properties are detected within the dashed grey lines in b), d) and e) having soil conductivities exceeding 30 mS/m

"quick soil conductivity range", even at salt contents up to 14 g/L. The c_{ur} is improved beyond 1 kPa at pore-water compositions with a KMgCa-ratio exceeding 20% even at low salt contents, explaining why clays with improved properties may be found in the "quick range". This emphasizes the importance of establishing a site-specific interpretation model based on laboratory determined geotechnical properties and in-situ test results for distinguishing quick clay from non-quick clay, also suggested by others (e.g. Campanella and Weemees 1990; Pfaffhuber et al. 2014).

The RCPTU measured conductivity in the original Dragvoll quick clay was around 20 mS/m. In the salt-treated Dragvoll clay, soil conductivities exceeding 30 mS/m implied that the clay was no longer quick. Applying a lower bound for improved properties in Figure 5-17, the c_{ur} is improved beyond 2 kPa at conductivities exceeding 100 mS/m, and beyond 3.5 kPa at soil conductivities larger than 200 mS/m. In order to detect improved properties in clays with
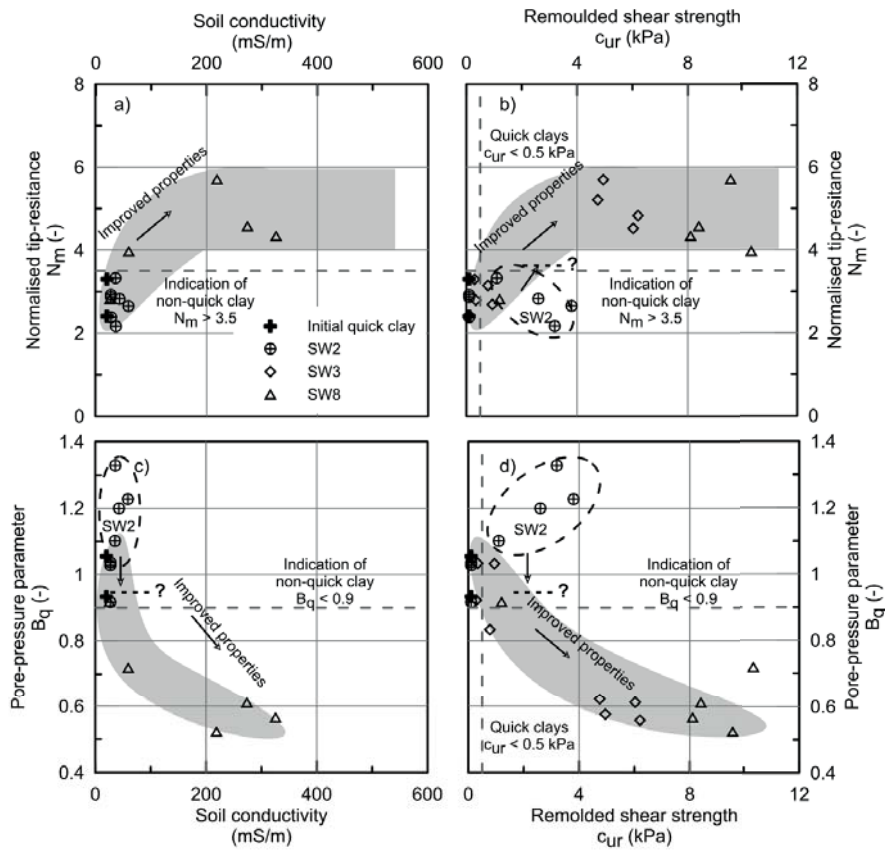
Figure 5-18 Normalised tip-resistance (N_m) correlated to a) soil conductivity and b) remoulded shear strength (c_{ur}), and pore-pressure parameter (B_q) correlated to c) soil conductivity and d) c_{ur}. The N_m and B_q values within the dotted circles may be moved in the direction of the arrow. All data are from 5-8 m depth

soil conductivities lower than 100 mS/m, a criterion based on changes in normalised parameters derived from the tip resistance and measured pore pressure may be applied. In salt-treated clays, increased tip resistance indicate improved geotechnical properties. A normalised tip-resistance (N_m) below 4 and a pore-pressure parameter (B_q) larger than 1 may indicate highly sensitive, quick clays (Sandven et al. 2015, 2016). Thus, improved properties due to introduced *KCl* may be detected at increasing N_m and decreasing B_q. Combining soil conductivity with measuring improved normalised parameters provide a good basis for a local, site-specific interpreting model distinguishing highly sensitive, low-saline/low conductive clays from low-saline clays of low sensitivity.

The improvement of the Dragvoll clay even at low conductivities (< 100 mS/m) was detected by a B_q falling from about 1 or larger to less than 0.9, and an N_m climbing above 3.5. This indicated that the clays ceased to be quick (Figure 5-18), changed from being of low to medium plasticity, and with a liquidity index (*IL*) below 1.2 (Figure 5-19). Even though, the c_{ur} increased up to 10 kPa, B_q and N_m stabilised around 0.6 and 4-6 respectively at c_{ur} exceeding 4 kPa.
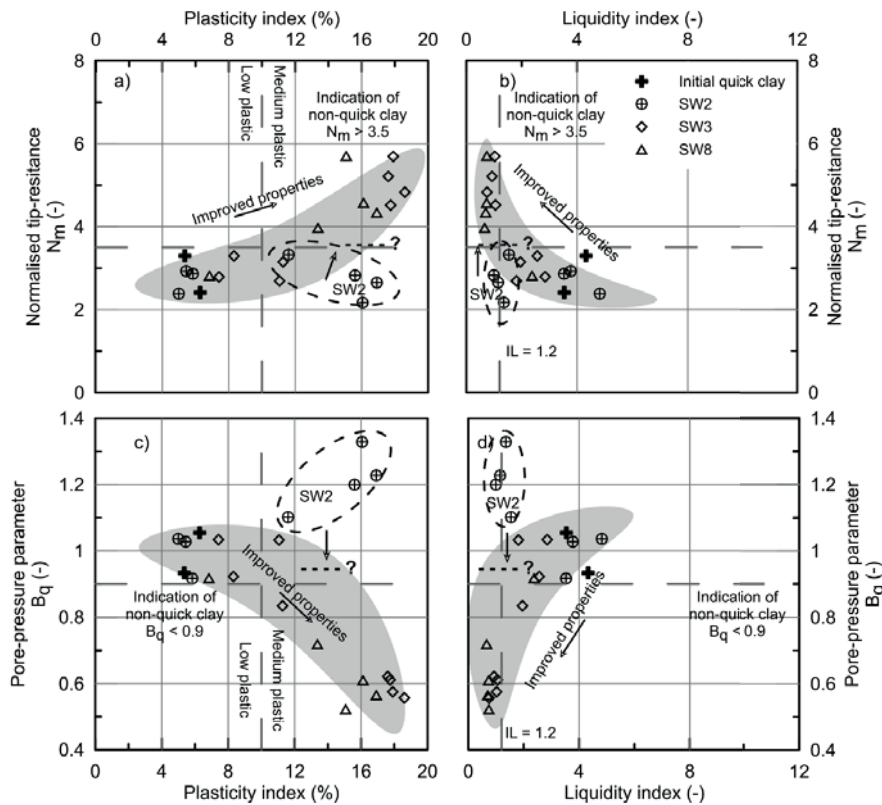
Figure 5-19 Normalised tip-resistance (N_m) and pore-pressure parameter (B_q) correlated to a) and c) plasticity index (IP), and b) and d) liquidity index (IL). The N_m and B_q values within the dotted circles may be moved in the direction of the arrow. All data are from 5-8 m depth

The compressibility of the clay influences the measured tip-resistance in cone penetration tests (CPTU) as decreased compressibility increases the resistance against deformation, thus penetration (Lunne et al. 1997). The compressibility decreases with increasing plasticity (Bjerrum 1967; Sridharan and Nagaraj 2000). Correlations between the in-situ test results at Dragvoll and laboratory-determined geotechnical properties showed that the measured tip resistance increased significantly at a c_{ur} of around 3.5 kPa, corresponding to an *IP* of around 15% (Figure 5-13). This may imply that the improved apparent pre-consolidation stress (p_c') and decreased immediate deformations at loads beyond p_c' discussed in the previous section may commence when $c_{ur} > 3.5$ kPa and *IP* > 15%. Which again imply that the peak and post-peak shear strength improve and the brittleness decreases due to significantly improved c_{ur} and *IP*. Improved *IP* > 15% was detected by the RCPTUs at Dragvoll when N_m exceeded 4 and B_q decreased to around 0.6 (Figure 5-19a and c).

The above findings show that RCPTU can be used for detecting improved geotechnical properties around the salt wells by site-specific interpretation models based on normalised parameters derived from the tip resistance and geotechnical laboratory tests. In addition, the RCPTUs effectively detect changes in the soil conductivity mapping the salt plume extent.

5.7 Required time to stabilise quick clays

5.7.1 Monitored alteration of pore-water composition

Diffusion is a slow process depending on hydrogeological conditions on the site, mineral specific properties such as mineral type and specific surface area influencing the cation exchange capacity (*CEC*), as well as geochemical composition of the original groundwater and in the adsorbed positions. The groundwater samples extracted from the BAT filter tips positioned 0.5 m and 1.0 m from salt-well no. 6 provide valuable information on the migration and ion exchange reactions. The clays at Dragvoll ceased to be quick at a KMgCa-ratio exceeding 20%. Applying this criterion to the analysed pore-water chemistry in the extracted groundwater samples from BAT B1 and B2, the clay ceased to be quick 0.5 m from the salt-well in the westward direction, approximately 2.2 years (800 days) after installation (Figure 5-20a). One meter from the salt-well in eastern direction, the clay was still quick at the time of the last groundwater sample, 3.4 years after installation (Figure 5-20b). However, the chloride front had arrived, and the clay behaviour is expected to change to non-quick as soon as the KMgCa-ratio exceeds 20%.

The salt migration around the wells was dominated by diffusion. However, the small component of advective flow along coarser layers changed the pore-water composition and also improved the geotechnical properties at greater distances in predominant directions. The remoulded shear strength (c_{ur}), salt contents and KMgCa-ratios plotted towards distance in Figure 5-21 shows the results from 6.3 m depth (symbols); in the middle of the depth range of the plume (4-8 m). Choosing the influence zone conservatively, the plume stretched over a radius of 0.5 m in the directions dominated by diffusion, increasing to 1.0 m in the directions of fastest migration (Figure 5-21a). Thus, a clay volume with a diameter of around 1.5 m was stabilised 2.9-3.3 years after installation. However, considering the KMgCa-ratio (Figure 5-21c) obtaining a $c_{ur} > 1$ kPa, the effective salt-plume extent had a radius of around 0.75 m around the wells even at the lowest concentrations found at 5.3 m depth (dotted black lines in Figure 5-21). The greatest effective salt plume radius seem to be around 1.4 m at 7.3 m depth
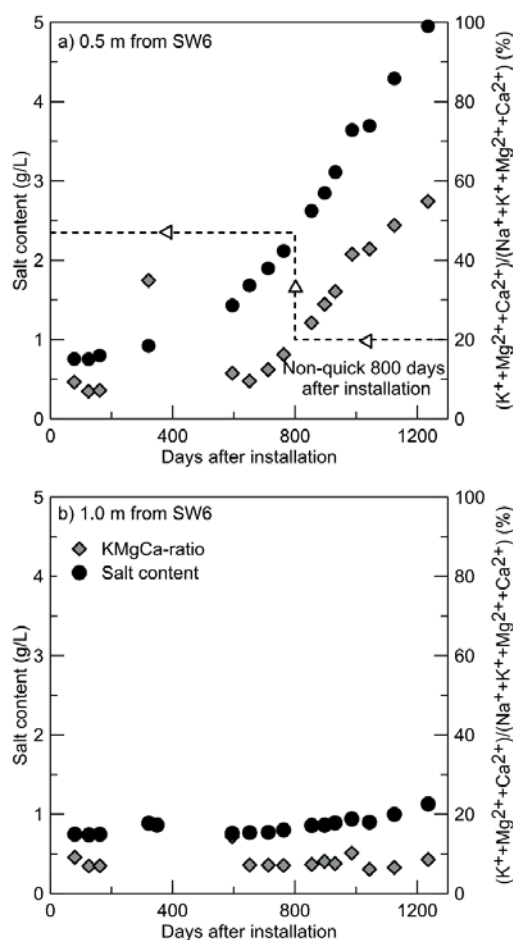
Figure 5-20 The development of salt content and ratio of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) to the sum of major cations with time a) 0.5 m and b) 1.0 m from salt-well no. 6

in the direction of fastest migration. The results from the BAT groundwater samples are used in simulations providing time estimates for stabilising the quick clay volume around the wells.

5.7.2   Simulations of altering pore-water composition at Dragvoll

PHREEQC version 3 (Parkhurst and Appelo 2013) is used for estimating the velocity of the salt migration from the wells. Alteration of the ion composition with time around Salt-well no. 6 (SW6) is simulated to estimate the diffusion coefficients and to calibrate the model. PHREEQC models 1D diffusion by applying either an effective diffusion coefficient, or simulates multi-component diffusion (MCD) by applying the diffusion coefficient in free water (D_f) at 25 ºC for the conservative tracer, in this case chloride (Cl^-). The diffusion coefficients for the other species are given in the database file (phreeqc.dat). To account for the grain skeleton, PHREEQC includes tortuosity assuming that Archie's law is valid for all soil types, estimating the effective diffusion coefficient by $D_e = D_f \cdot \varepsilon_w^{(m-1)} = D_f \cdot \varepsilon_w^{\,n}$. Therefore, the water filled
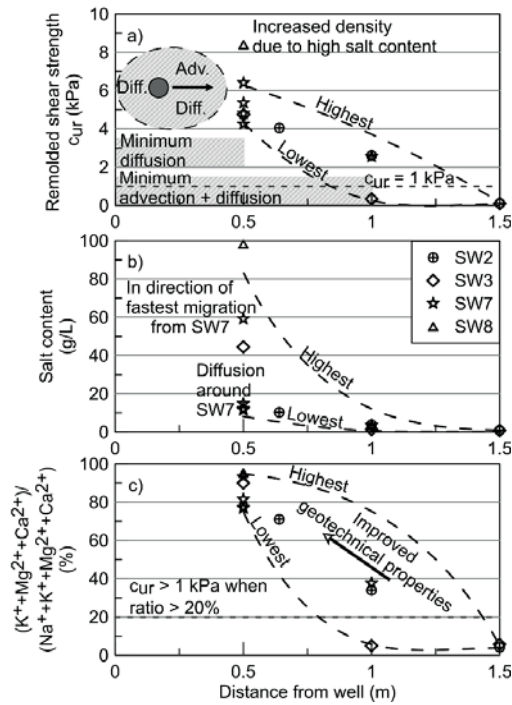
Figure 5-21 a) Remoulded shear strength (c_{ur}), b) salt content and c) KMgCa-ratio at 6.3 m depth with distance from the well. The lowest and highest concentrations and c_{ur} at 5.3 m and 7.3 m depth are indicated with black dashed lines. The inset in a) indicates the variation of the salt plume around the well, indicating minimum influence zones with stabilised clays defined by $c_{ur} > 1$ kPa around 3 years after installation

porosity (ε_w), and the exponent $n = (m - 1)$ must be defined in the input file, where *m* is Archie's exponent. Radial diffusion is simulated by decreasing length of the cells with distance from the well as the volume in the cells is equal by default (Figure 5-22d). The simulations of the radial diffusion were first carried out by applying D_e. Since the radial diffusion is conducted with cells of unequal length, advective flow cannot be simulated simultaneously. Thus, dispersivity was set to 0, and the applied diffusion coefficient is in reality the apparent diffusion coefficient (D^*) which includes both the effective diffusion and any advection.

The BAT filter tips were installed at 6 m depth. The conductivity profiles from the RCPTU clearly show that the salt plume migrated faster towards BAT B2 than towards BAT B1 (Figure 5-22). The apparent diffusion coefficient (D^*) determined by PHREEQC simulations is more than two times larger towards BAT B2 than BAT B1; 6.6 x 10^{-10} m^2/s and 3.1 x 10^{-10} m^2/s respectively (Figure 5-22b), confirming that some advection is involved in the salt migration towards BAT B2. The simulated concentrations of potassium (K^+) and sodium (Na^+) with time showed that the laboratory determined *CEC* of 0.659 moles (25 meq/100 g dry soil) was too high; overestimating the retardation of K^+, releasing too much Na^+ from the clay surfaces to the pore water. Therefore, the *CEC* was fitted to the K-concentration with time; 0.180 moles (6.8 meq/100 g dry soil), corresponding well with the estimated *CEC* based on the mineralogical content applying Equation 5-1 (section 5.3).
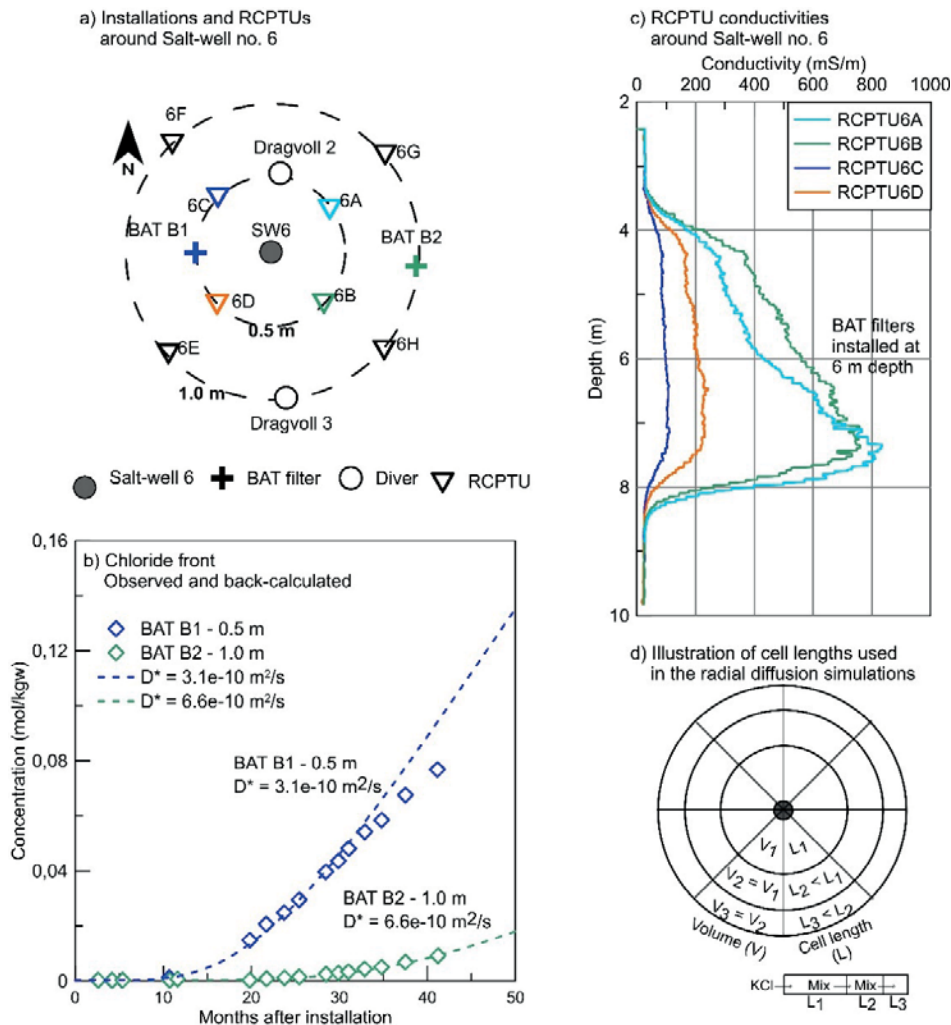
Figure 5-22 a) Installations and resistivity cone penetration tests (RCPTU) around salt-well no. 6 (SW6). b) Chloride concentration with time in BAT B1 (blue symbols) and BAT B2 (green symbols), 0.5 m and 1.0 m from the well respectively, and simulated values of the apparent diffusion coefficient (D*). c) RCPTU conductivities around the well 3 years and 5 months after installation. d) Illustration of decreasing cell length (L) with distance from the well in radial diffusion PHREEQC simulations

Multi-component diffusion (MCD) simulations were carried out to find any deviations between the D^* and D_e. Knowing the volumetric porosity and changing concentrations of Cl^- with time, the exponent n was fitted by PHREEQC simulations, assuming that Archie's law is valid in clays choosing an exponent m larger than 2 ($n > 1$). The results in the MCD simulations are greatly affected by the applied exponent n (Figure 5-23). The MCD simulations fit well with the Cl-concentrations in BAT B1 applying an exponent n of 1.55, corresponding to Archie's exponent m of 2.55. The K-concentrations also fit reasonably with the observations in BATB1.
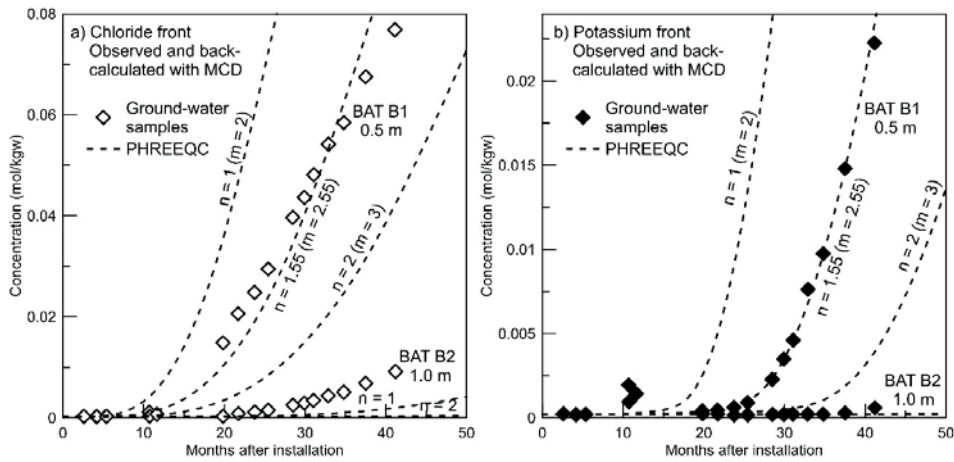
Figure 5-23 Simulations of the a) chloride and b) potassium concentrations in BAT B1 (0.5 m distance) and BAT B2 (1.0 m distance) using multi-component diffusion (MCD) with a porosity of 0.51 and an exponent n in $D_e = D_f \cdot \varepsilon_w^{(m-1)} = D_f \cdot \varepsilon_w^n$ of 1, 1.55 and 2
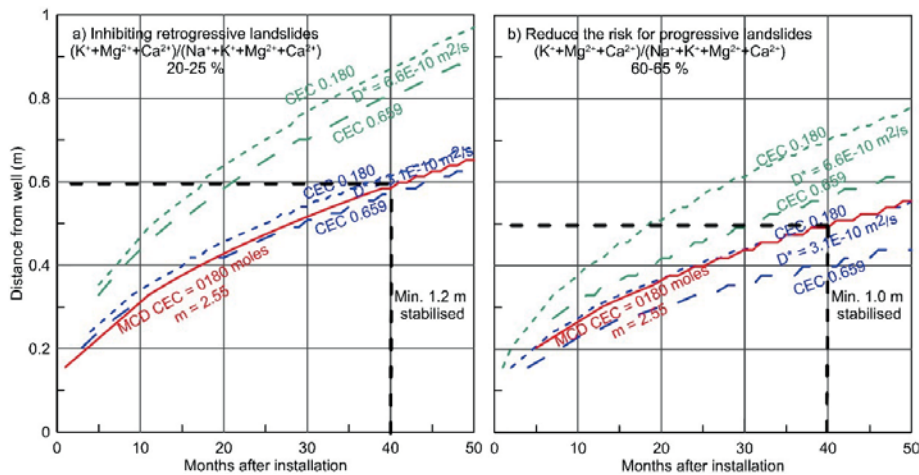
Figure 5-24 Time consumption to stabilise the quick clay in a distance from the salt well. a) The $c_{ur} > 1$ kPa at a KMgCa-ratio > 20%, inhibiting retrogressive quick clay landslides. A diameter of minimum 1.2 m is stabilised within 3.3 years (40 months). b) KMgCa-ratio > 60% may reduce the risk for progressive landslides. A diameter of minimum 1.0 m is stabilised within 3.3 years

The Cl-concentrations in BAT B2 did not fit in between simulations carried out with exponent *n* within the range of 1-2. Therefore, there must be advective transport in the direction of BAT B2 increasing the velocity of the salt migration from the well in that particular direction.

Diffusion dominated the solute transport around the salt wells. However, in the direction of fastest migration, the analysed concentrations of K^+ and Cl^- in the extracted pore water from

the clay samples around salt-wells no. 2, 3, 7 and 8, exceeded the values obtained in the simulations. Nevertheless, the simulations can be used for giving a rough estimate of how long it takes to change the pore-water composition in the clay so it ceases to be quick. Retrogressive development is inhibited when the KMgCa-ratio exceeds 20%, and the risk for progressive landslides may be reduced at KMgCa-ratio exceeding 60%. Sorting the simulated data by a KMgCa-ratio of 20-25%, the Dragvoll quick clay is stabilised inhibiting retrogressive development over a diameter of minimum 1.2 m 40 months (3.3 years) after installation assuming only diffusion (MCD) around the well (Figure 5-24a). A minimum diameter of 1.5 m is stabilised assuming a minimum D^* of 6.6 x 10^{-10} m^2/s in one direction combined with diffusion in the other directions. This is fairly consistent with the observed stabilised clay volumes found around the salt wells at Dragvoll. Sorting the simulation results by a KMgCa-ratio of 60-65% (Figure 5-24b), a minimum diameter of 1.0 m is stabilised within 3.3 years, possibly reducing the risk for progressive landslides. Including the direction of fastest migration, a minimum diameter of 1.2 m is stabilised.

5.8 Concluding comments

Three years after installation, the measured remoulded fall-cone shear strength (c_{ur}) is improved from less than 0.5 kPa to 3.5-9.6 kPa 0.5 meter from the salt wells, and the clay is no longer characterised as quick. The clay is changed from having low to having medium and high plasticity, and the liquid limit (w_L) is increased beyond the natural water content (w). Thus, the liquidity index (IL) is decreased from more than 3.4 to less than 1.2. Landslides comprising clays with a $c_{ur} < 1.0$ kPa and an $IL > 1.2$ may flow out of the initial slide pit, and develop into large backwards successive, retrogressive landslides (Leroueil et al. 1983; Thakur et al. 2014a), such as the Rissa landslide (Gregersen 1981). Improving the clays to a c_{ur} beyond 1 kPa prevents successive back-scarp failures. The effective salt-plume extent in which the clay attain a $c_{ur} > 1$ kPa covers a minimum diameter of 1.0 m around the salt-wells at Dragvoll 2.2 years after installation, and minimum 1.5 m in diameter 3 years after installation. The salt plume will continue to migrate in the years to come, improving the geotechnical properties in a larger soil volume surrounding the wells. Diffusion will equalize the concentration differences and the geotechnical properties in the soil volume. Within the next decades, the salt content will most likely decrease in the salt-treated clay at Dragvoll due to leaching groundwater and diffusion to the surrounding clay volume. The recent ground investigations carried out in the salt-treated clay at Ulvensplitten in Oslo, Norway, showed that the clay remained non-quick 40 years after installation due to favourably changed pore-water chemistry, even at salt contents down to 0.5 g/L.

The results from the in-situ experiment at Dragvoll together with data from Ulvensplitten suggest that quick or non-quick behaviour is to a large extent determined by the ratio of the sum of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) to the sum of major cations in the pore water (Equation 5-2). The c_{ur} is improved beyond 1 kPa, consequently inhibiting retrogressive landslide development at KMgCa-ratios exceeding 20%. Calcium and magnesium, normally dominate the cations in the groundwater that leaches through the clays. Therefore, improved c_{ur} and Atterberg limits will be maintained in leached salt-treated clays with low salt contents due to the fact that the pore water is dominated by K^+ or Ca^{2+} rather than sodium (Na^+), as is the case in low-saline quick clays.

The apparent pre-consolidation stress (p_c') increases and the deformations expected when loading *KCl*-treated clays decreases with increasing salt contents. The increased p_c' and over-

consolidation ratio (*OCR*) imply increased peak undrained shear strength. Loading the samples beyond p_c', the immediate deformations in the in-situ salt treated clay samples were significantly reduced compared to the rapid structural collapse and immediate large deformations seen in the original quick clay. Highly sensitive quick clays have a characteristic strain-softening behaviour with a distinct peak undrained shear strength (c_{uc}), and a rapid collapse of the structure after peak dramatically reducing the post-peak strength. This mechanism is central when quick clays develop into forwards or backwards progressive landslides (Figure 1-2b and c). The significantly reduced collapse of the structure and decreased deformations at loads exceeding p_c' seen in the CRS tests on the salt-treated clay may imply that the brittleness (softening after peak) is reduced, and that the clay may have a higher post-peak strength at deformations exceeding strains at failure. This decreased brittleness in the salt-treated clays may reduce the risk for initiating progressive landslides in quick clay areas. The brittleness may be sufficiently reduced when the salt treatment provides $c_{ur} > 3.5$ kPa and $IP > 15\%$, which commence at a KMgCa-ratio exceeding 60%, or at salt contents exceeding 6 g/L. Clays treated with *KCl* will maintain the non-quick behaviour and improved plasticity even at future low salt contents due to favourably changed pore-water chemistry.

Sampling in such an extent as carried out at Dragvoll is not cost-efficient in a full-scale project. In-situ tests calibrated by a limited number of laboratory tests may be a realistic alternative in practice. Resistivity cone penetration tests (RCPTU) effectively maps the salt plume extent and directions by changes in the soil conductivity, also detecting improved properties at Dragvoll when the normalised tip-resistance (N_m) climbs above 3.5 and the pore-pressure parameter (B_q) decreases below 0.9. Improved p_c' and reduced brittleness may be indicated when N_m exceeds 4 and B_q decreases to around 0.6.

The geochemical computer program PHREEQC can be used for estimating the migration velocity and give a rough estimate of how long it takes to stabilise the clay volume based on a KMgCa-ratio exceeding 20% and 60%. At 6 m depth in the directions dominated by diffusion,
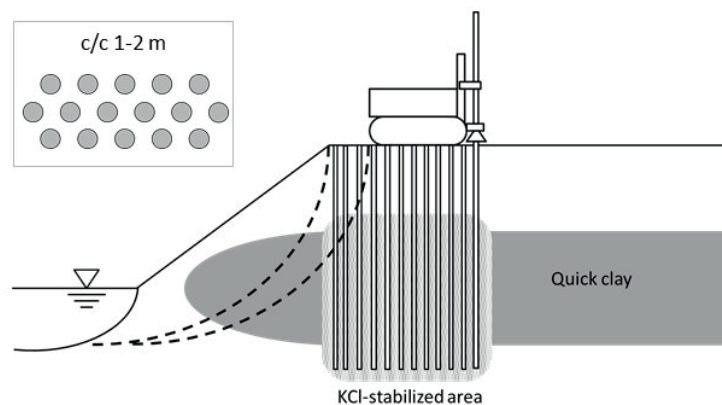
Figure 5-25 The KCl-stabilised clay works as a barrier against successive back-scarp failures

the apparent diffusion coefficient (D^*) was determined to 3.1 x 10^{-10} m^2/s. In the direction of fastest migration, D^* was of minimum 6.6 x 10^{-10} m^2/s. The estimated effective salt-plume extent based on the KMgCa-ratios corresponded well with the observed pore-water chemistry in the stabilised clay volume around the salt wells at Dragvoll.

5.9 Suggestions for practical application

In order to stabilise the quick-clay volume within 3 years, it is recommended to install the salt wells with a centre-to-centre distance of 1.5-2.0 m. Denser salt-well grid is recommended to reduce the time to stabilise the clay volume (Figure 5-25). The effectiveness on improving the geotechnical properties, as well as the time required to do so depends on:

- Cation exchange capacity, affected by
  - Mineral type
  - Specific surface area
  - Clay content
- Effective diffusion coefficient, affected by
  - Water-filled porosity
- Hydrogeological conditions on the site
  - Hydraulic gradients
  - Permeability
  - Bedding
- Geochemical conditions
  - Original pore-water composition
  - Adsorbed ions

The post-failure properties are significantly improved in *KCl*-treated clays, and the clay will no longer behave as a liquid when remoulded. Retrogressive landslide development is inhibited when the remoulded shear strength is improved beyond 1 kPa. An initial slide in the foot of a *KCl*-treated quick-clay slope will not cause successive back-scarp failures, as the *KCl*-treated clay will work as a barrier against retrogressive development (Figure 1-2a and Figure 5-25). In addition to improved remoulded properties, the obtained reduced collapse of the structure in the salt-treated clays implies reduced brittleness and the increased apparent pre-consolidation stress may imply improved peak shear strength. Thus, treating quick clays with *KCl* may in addition to inhibit retrogressive landslide development, also reduce the risk for progressive landslide development (Figure 1-2b and c).

6   Summary

The present PhD work was carried out to study the improvement of geotechnical properties in highly sensitive quick clays due to changed pore-water chemistry by introducing potassium chloride (*KCl*) to the clay-water system. A field and laboratory study was conducted on the Dragvoll research site in Trondheim, Norway studying the migration of *KCl*, changed pore-water chemistry and improved geotechnical properties around salt-wells filled with *KCl*. In addition, results from ground investigations carried out 40 years after installing *KCl* wells at Ulvensplitten, Oslo, Norway, were made accessible to the present PhD work. The present study contribute to understanding how pore-water chemistry improves the geotechnical properties in highly sensitive quick clays, establishing criteria for when the clays cease to be quick and the required time to stabilise a certain clay volume around the wells. The results from Dragvoll and Ulvensplitten validates *KCl* wells as a landslide mitigation method in quick-clay areas inhibiting retrogressive and reducing the risk for progressive development of quick-clay landslides.

Six salt wells were installed at the Dragvoll research site in January 2013. The salt wells were slotted from 4 m to 8 m depth, allowing the salt to migrate into the quick-clay volume. The wells were refilled regularly to maintain a high concentration of *KCl* in the wells during the whole project period of 3 years and 5 months. Sampling and resistivity cone penetration tests (RCPTU) were conducted around the wells to measure and trace the salt plume extent, direction of the plumes, changed pore-water chemistry and improved geotechnical properties. One of the wells was monitored with Schlumberger conductivity divers and BAT filter tips for groundwater sampling, all installed at 6 m depth.

The salt migration around the wells was dominated by diffusion. Local heterogeneity in the clays aided some advective flow caused by density gradients between the high saline solute in the wells and the low-saline quick clay, forcing the plumes horizontally along coarser layers of higher permeability. Consequently, the salt plumes were moderately nonsymmetrical and slightly off-centred from the wells. The orientation of the plumes varied from one well to the other, and the extent of the plumes increased with depth.

Based on historical Canadian and Norwegian quick-clay landslides, a remoulded shear strength $c_{ur} < 1$ kPa and a liquidity index $IL > 1.2$ may be used as indicators on clays that pose a risk for large retrogressive landslides (Leroueil et al. 1983; Thakur et al. 2014). Therefore, retrogressive development may be inhibited at $c_{ur} > 1$ kPa.

The original quick clay at Dragvoll has a remoulded shear strength (c_{ur}) of <0.1-0.5 kPa, is of low plasticity and has a liquidity index (*IL*) larger than 3.4.Half a meter from the salt wells, the salt content increased from around 0.7 g/L in the original quick clay to the range of 6-98 g/L around 3 years after installation. The c_{ur} was improved to 3.5-9.6 kPa. The *IL* decreased below 1.2, and the plasticity of the clays changed from low to medium and high. At salt contents exceeding 10 g/L, the fall-cone undrained shear strength improved from 8-16 kPa to 25-30 kPa, close to the peak undrained shear strength found in the triaxial tests on original quick clay. This together with findings at Ulvensplitten and in laboratory studies imply that there is a threshold from where increased salt contents does not induce further improvement of the fall-cone undrained shear strength.

One meter from the wells, the c_{ur} improved beyond 1 kPa in the direction of fastest migration even though the salt contents were lower than found 0.5 m from the wells. The composition of cations in the pore water at salt contents of less than 2 g/L greatly affects the c_{ur} and Atterberg limits. The pore water in quick clays has low salt content, with a cation composition dominated by sodium (Na^+). Salt migration and ion exchange reactions change the composition of cations in both the pore water and in the adsorbed positions on the clay mineral surfaces. The Dragvoll and Ulvensplitten clays ceased to be quick obtaining a c_{ur} larger than 1 kPa when the KMgCa-ratio (Equation 5-2 p. 64) exceeded 20% (all concentrations in meq/L), even at salt contents less than 2 g/L.

With time, leaching will reduce the salt contents in the salt-treated clays. The leaching groundwater will, however, feed the clay-water system with cations (Ca^{2+} and Mg^{2+}) which suppress the diffuse double layers further than Na^+ at same normality. Therefore, the repulsive forces between the clay particles in leached salt-treated clays are reduced compared to in quick clays, even at low salt contents. The improvement of the post-failure properties beyond what is considered quick are therefore considered to be permanent in an engineering timescale.

At a KMgCa-ratio exceeding 20%, c_{ur} increased beyond 1 kPa, *IL* decreased below 1.2, and the clay changed from being of low to medium plasticity. Clays with a c_{ur} improved beyond 1 kPa and a KMgCa-ratio exceeding 20% covered a minimum diameter of 1.0 m around the salt-wells at Dragvoll 2.2 years after installation, and minimum 1.5 m in diameter 3 years after installation. It is therefore recommended to install the salt-wells with a centre-to-centre distance of 1.5-2.0 m in order to stabilise illitic-chloritic quick clays within 3 years.

Constant rate of strain oedometer tests (CRS) were conducted on samples extracted from the salt-treated clay. The apparent pre-consolidation stress (p_c') increased from 67 kPa to 90 kPa and 110 kPa in the specimens with salt contents of 9.7 g/L and 27.7 g/L respectively, both having high plasticity. The immediate and rapid structure collapse in quick clays resulting in large deformations at loads beyond p_c', decreased significantly in the salt-treated clays, implying reduced brittleness. No alteration of the compressibility or p_c' was found in the sample containing a salt content of 1.6 g/L with a c_{ur} of 1.8 kPa and a plasticity index (*IP*) of 12.8%. Mini-block samples from Dragvoll stored in *KCl* slurry obtaining salt contents of around 170-260 g/L and *IP* of 10.0-17.4%, showed decreased compressibility and increased p_c' corresponding to the findings in the in-situ salt-treated clay. In addition, the peak undrained shear strength was slightly improved, and the post-peak strength was significantly improved. The findings in the present study suggest that settlements upon loading decrease, and p_c' and peak and post-peak strength increase at *IP* > 15% which commence at a KMgCa-ratio exceeding 60%, or at salt contents exceeding 6 g/L.

Decreased compressibility and increased remoulded shear strength affect the tip-resistance in cone penetration tests (CPTU). At Dragvoll, the resistivity cone penetration test (RCPTU) detected improved post-failure properties at normalised tip-resistance (N_m) above 3.5, and a pore-pressure parameter (B_q) less than 0.9. Increased p_c' and decreased brittleness may be indicated when N_m exceeds 4 and B_q decrease to around 0.6.

The time required to stabilise the quick-clay volume is greatly dependent on the cation exchange capacity (*CEC*) affected by the mineral type, specific surface area and clay content, and the effective diffusion coefficient which is influenced by the water filled porosity. In addition, hydrogeological conditions on the site, original pore-water composition and adsorbed ions on the mineral surfaces may influence the required time to stabilise the quick-clay volume. The geochemical computer program PHREEQC was used for giving a rough estimate of the

required time to stabilise the clay volume around the wells at Dragvoll. The simulation results corresponded well with the observed changed pore-water compositions on the site. The apparent diffusion coefficient in the directions dominated by diffusion was of 3.1×10^{-10} m^2/s, and at least 6.6×10^{-10} m^2/s in the directions of fastest migration.

The present study validates *KCl* wells as a landslide mitigation method, permanently improving the post-failure properties in illitic-chloritic quick-clays of low plasticity due to favourable changes in the composition of cations in the pore water. The decreased repulsion between the clay particles inhibits the clay to liquefy when remoulded. Therefore, potential initial slides in the foot of a *KCl*-treated quick-clay slope with $c_{ur} > 1$ kPa will not cause successive back-scarp failures, as the *KCl*-treated clay will work as a barrier against retrogressive development. Improving the *IP* to more than 15%, the barrier may also reduce the risk for initiating progressive landslides due to improved peak and post-peak strength.

7   Conclusions

The field and laboratory study at Dragvoll aimed to investigate how the geotechnical properties in highly sensitive quick clays respond to changed pore-water chemistry by introducing potassium chloride (*KCl*) to the clay-water system. The results from Dragvoll are complemented by collecting data from previous and recent ground investigations from the quick clay improved by *KCl* at Ulvensplitten, Oslo, Norway in 1972. The objectives of the PhD research was to:

- Contribute to knowledge on the effect of pore-water chemistry on the geotechnical properties in Norwegian low-saline marine clays (quick clay)
- Describe how *KCl* migrates around salt wells, and to what extent it changes the pore-water chemistry and geotechnical properties over time
- Establish correlations between the ion composition in the pore water and the post-failure properties in clays to evaluate when the clays cease to be quick
- Study the migration of *KCl* based on simulations of field and laboratory observations to evaluate the time needed to improve the post-failure properties in quick clays based on the established correlations between ion composition and post-failure properties
- Use the obtained field and laboratory results to evaluate the potential of *KCl* wells as ground improvement in quick-clay areas

The pore-water chemistry greatly influences the geotechnical properties. Clays' sensitivity depend not only on the salt content in the pore water, but also on the composition of cations in the pore fluid. At what pore-water composition the clays cease to be quick was established based on the correlations between the geotechnical properties and pore-water chemistry found in the clays from Dragvoll and Ulvensplitten. Quick clays normally have low salt contents (<2 g/L) with sodium being the abundant cation. At low salt contents, as little as 20% of the cations in the pore water consisting of potassium, magnesium and calcium was sufficient to improve the remoulded shear strength beyond 1 kPa. Even though the salt-treated clay at Ulvensplitten was leached back to its original salt content in parts of the soil profile, the clay remained non-quick due to the favourable changed pore-water chemistry. Based on these findings, the non-quick properties are considered permanent in an engineering time scale.

The extent and orientation of the salt plumes around the wells were studied by resistivity cone penetration tests (RCPTU) providing soil-conductivity profiles. The soil-conductivity profiles revealed that the plumes migrated nonsymmetrical, slightly off-centred from the wells. Simulations of the altered pore-water composition in the groundwater samples extracted from BAT filter tips around salt-well no. 6, confirmed that the plume migrated faster in one direction from the well. Sorting the simulated pore-water composition by the criterion for at what pore-water composition the clays cease to be quick, the simulation results can be used for predicting the distance between the wells in order to stabilise the clay volume within certain time restrictions.

The results from Dragvoll and Ulvensplitten suggest that retrogressive landslide development is inhibited, and the risk for progressive landslides may be reduced treating quick clays with *KCl*.

The main conclusions from the present PhD work are listed in the following.

- The in-situ experiment at Dragvoll, Trondheim, Norway show that three years after installation, the salt contents half a meter from the wells increased from 0.7 g/L to the range of 6-98 g/L. The increased salt contents improved the remoulded fall-cone shear strength (c_{ur}) from less than 0.5 kPa to 3.5-9.6 kPa. The clays are no longer characterised as quick. The liquid limit increased beyond the natural water content, and the liquidity index (I_L) decreased below 1.2. The plastic limit is moderately increased, and the clay changed from having low to medium and high plasticity.

- At salt contents exceeding 10 g/L, the fall-cone undrained shear strength improved from around 8-16 kPa up to 25-30 kPa, around peak undrained shear strength found in the triaxial tests. Findings at Dragvoll, Ulvensplitten and in laboratory studies imply that there seem to be a threshold where increased salt content does not induce further improvement of the fall-cone undrained shear strength.

- Large retrogressive landslides may develop in clays with a $c_{ur} < 1$ kPa. Therefore, quick clays are considered stabilised when c_{ur} is improved beyond 1 kPa. The salt plumes were moderately nonsymmetrical slightly off-centred from the wells. In the directions of fastest migration, c_{ur} was improved beyond 1 kPa one meter from the wells even at low salt contents.

- The geotechnical properties at salt contents less than 2 g/L are governed by the composition of cations in the pore water. At KMgCa-ratios exceeding 20% (Equation 5-2 p. 64), c_{ur} increases beyond 1 kPa, I_L decreases below 1.2, and the clays change from being of low to medium plasticity.

- With time, leaching will reduce the salt content in the salt-treated clays. Nevertheless, the clays remain non-quick as the leaching groundwater continues to feed the clay-water system with cations (Ca^{2+} and Mg^{2+}). Both of which have greater impact on suppressing the diffuse double layer than Na^+, which is the abundant cation in the pore water in quick clays. The *KCl*-well method is therefore suitable to prevent large flow slides in quick-clay areas, as the improvement is considered to be permanent in an engineering timescale.

- The apparent pre-consolidation stresses (p_c') increase from 67 kPa to 90 kPa at 9.7 g/L, and 110 kPa at 27.7 g/L, increasing the over-consolidation ratio from 1.2 to 1.7-2.1. The immediate and rapid collapse of the structure seen in the original quick clay at loads beyond p_c' is significantly reduced in the salt-treated clay, indicating reduced brittleness. The compressibility decreases with increasing plasticity index (I_P). The results from Dragvoll imply that the compressibility decreases, and p_c' and the peak and post-peak shear strength increases when $I_P > 15\%$. This corresponds to a KMgCa-ratio exceeding 60% even at low salt contents, or at salt contents exceeding 6 g/L.

- The transport mechanism around the wells is dominated by diffusion, with a small contribution from advection in predominant directions from the wells. Local heterogeneity in the soil may aid some advective flow driven by density gradients

between the solute in the well and the low-saline surrounding clay, forcing the plume horizontally along coarser layers.

- The salt plume extent and orientation around the wells was detected by soil and pore-water sampling as well as resistivity cone penetration tests (RCPTU). At Dragvoll, the RCPTU detected improved $c_{ur} > 1$ kPa, decreased $IL < 1.2$ and increased $IP > 10\%$ at normalised tip-resistance (N_m) above 3.5, and a pore-pressure parameter (B_q) less than 0.9. The N_m exceeded 4 and B_q decreased to around 0.6 when IP improved beyond 15%, which may indicate increased p_c' and decreased brittleness.

- The effective salt-plume extent in which the clay attain a $c_{ur} > 1$ kPa and a KMgCa-ratio > 20% at low salt contents, covers a minimum diameter of 1.0 m around the salt-wells at Dragvoll 2.2 years after installation, and minimum 1.5 m in diameter 3 years after installation. It is therefore recommended to install the salt-wells with a centre-to-centre distance of 1.5-2.0 m in order to stabilise the quick clay volume within 3 years. A KMgCa-ratio > 60% is obtained over a minimum diameter of 1.0 m 3.3 years after installation.

- The required time to stabilise a quick-clay volume depend on hydrogeological conditions at the site (especially geological heterogeneity), cation exchange capacity (*CEC*) which is greatly influenced by mineral type, specific surface area and clay content, as well as original pore-water composition and concentration, and adsorbed ions.

- Higher *CEC* than found at Dragvoll will cause greater retardation of K^+, thus requiring longer time to stabilise the quick-clay volume. The clay mineralogy in the collected Norwegian quick clays are dominated by the non-swelling clay minerals illite followed by chlorite. Clays of glacial or post-glacial origin as found in Scandinavia, Canada and northern Russia are grinded rock flour, with small specific surface areas, thus smaller cation exchange capacities (*CEC*) than found in clay minerals of diagenetic origin. Glaciomarine clays with greater clay contents than found at Dragvoll may require longer time to stabilise the quick-clay volume.

- In saturated soils, both fully interconnected and entrapped pores are available for molecular diffusion. The diffusion of *KCl* in clays with the same *CEC*, but larger porosity than found in the Dragvoll clay will have a higher effective diffusion coefficient. Thus, the time it takes to stabilise the clay volume will be shorter than in the in-situ experiment at Dragvoll.

- PHREEQC seems to be a convenient tool simulating the migration and cation exchange process. The simulated pore-water chemistry fits well with the collected data in the salt-treated clay at Dragvoll. The effect of soils with varying *CEC* can be taken into account using PHREEQC in design. The salt migration around the wells is dominated by diffusion having an apparent diffusion coefficient (*D**) of 3.1×10^{-10} m^2/s. In the direction of fastest migration, *D** is of at least 6.6×10^{-10} m^2/s. PHREEQC 1D simulations can be used for giving a rough estimate of the extent of the stabilised clay volume. The criteria could be based on a KMgCa-ratio > 20% inhibiting retrogressive

landslides, and KMgCa-ratio > 60% reducing the risk for progressive landslide development.

- The geotechncial properties are significantly improved in *KCl*-treated clays, and the clay will no longer behave as a liquid when remoulded. Improved c_{ur} beyond 1 kPa inhibit retrogressive landslide development, which commences at KMgCa-ratios exceeding 20% even at low salt contents. A potential initial slide in the foot of a *KCl*-treated quick-clay slope will not cause successive back-scarp failures as the *KCl*-treated clay will work as a barrier against retrogressive development.

- The risk for progressive landslide development may be reduced in clays with improved *IP* beyond 15% due to reduced brittleness, which seem to commence at KMgCa-ratios exceeding 60% even at very low salt contents, or at salt contents exceeding 6 g/L.

- The improvement of the post-failure properties beyond what is considered to be quick are permanent in an engineering timescale due to favourable changes in the pore-water composition.

8   Recommendations for future work

The present work includes two quick-clay sites treated with potassium chloride (*KCl*). The clays were quite similar with regard to origin, mineralogy, clay content and pore-water composition. Clays with other mineralogical content (e.g. kaolinite or swelling clays) and origin may respond differently on *KCl* treatment. Installing *KCl* wells on sites with different clays than at Ulvensplitten and Dragvoll will contribute to further understanding of how *KCl* treatment influences the behaviour of clays.

As one subproject and as a pilot study clay samples were collected from various sites throughout Norway to correlate data on mineralogy, pore-water chemistry and geotechnical properties. However, numerous sources of errors may have had an impact on the results. Collecting high quality samples gathering data on geotechnical properties, mineralogy, pore-water chemistry, cation exchange capacity and specific surface area, may give valuable insight on how the various compositional factors influence the geotechnical properties.

Simulations of the pore-water compositions at Dragvoll was carried out using the geochemical program PHREEQC. The PHREEQC 1D simulations of radial diffusion does not include advection and the impact of density differences. Simulations of the salt plumes around the wells including chemical reactions, density differences, diffusion and advection in 3D would be useful in predicting the required time to stabilise the clay volume around the wells.

The apparent pre-consolidation stress (p_c') increases, and the deformations at loads just beyond p_c' decreases with increasing salt contents. The decreased deformations after p_c' imply that the collapse of the structure is more moderate than typically seen in quick clays. It is therefore believed that the brittleness is reduced. The reduction in brittleness at various salt contents and ion compositions should be further investigated, and the durability of these improved properties must be obtained before applying them in design.

The present work demonstrate that the *KCl*-well method may be used as an alternative or supplement to conventional landslide mitigation methods in illitic-chloritic quick clays of low plasticity. The salt migration is a slow process driven by diffusion. Therefore, the method is restricted to situations that allows waiting for the improvement. It may take 2-3 years in a salt-well grid with a centre-to-centre distance of 1.5-2.0 m to improve the remoulded shear strength beyond 1 kPa in the whole clay volume. Therefore, salt-well installations must be planned early in the project. In order to make the *KCl*-well method applicable in practice, equipment and procedures must be developed to ensure cost-efficient installation. Installation methods creating excess pore-pressures must be avoided. The in-situ salt treatment at Dragvoll was conducted with wells that were regularly refilled to maintain high concentration in the wells in the whole project period. Installing salt wells and maintain them in the same manner in a full-scale project is too expensive. To avoid the necessity of refilling the wells, the amount of *KCl* needed to improve the clay volume between the wells should be quantified in advance.

The documentation of the pore-water chemistry correlated to improved geotechnical properties in the full-scale project at Ulvensplitten is scarce. The wells at Dragvoll were installed with a large centre-to-centre distance (10 m) to avoid interaction between the salt plumes. Monitoring of changing pore-water chemistry and quantification of improved geotechnical properties in a full-scale project with salt wells installed with a mutual distance of 1.5-2.0 m, should be carried out for further validation of the method prior to commercial use.

9   References

Andersson-Sköld Y, Torrance JK, Lind B, Odén K, Stevens, RL and Rankka K (2005) Quick clay – A case study of chemical perspective in Southwest Sweden. Engineering Geology **82(2)**: 107-118.

Appelo CAJ and Postma D (2005) Geochemistry. groundwater and pollution. 2nd edn. Balkema, Leiden, Netherlands.

Aylward GH and Findlay TJ (1994) SI Chemical data. 3rd edition. John Wiley & Sons, Bribane, Australia.

BAT Geosystems AB (2012) In situ permeability measurement with the BAT Permeameter: Quick manual inflow test. Available from www.bat-gms.com. pp. 1-15.

Bazin S, Anschütz H, Sauvin G, Helle TE, Gribben S, Donohue S and Long M (2016) Geophysical characterisation of marine and quick clay sites: field and laboratory tests. In *Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterization (ISC'5), Gold Coast, Australia* (Lehane BM, Acosta-Martinez HE and Kelly R (eds)). Australian Geomechanics Society, Sydney, Australia, vol. 2, pp. 831-836.

Berry RW and Jørgensen P (1971) Grain size, mineralogy and chemistry of a quick-clay sample from the Ullensaker slide, Norway. Engineering Geology **5(1)**: 75-84, https://doi.org/10.1016/0013-7952(71)90031-7.

Bjerrum L (1954) Geotechnical properties of Norwegian marine clays. Géotechnique **4(2)**: 49 -65, https://doi.org/10.1680/geot.1954.4.2.49.

Bjerrum L (1955) Norske marine leirers geotekniske egenskaper. Available from Norwegian Geotechnical Insitute, Oslo, Norway. NGI Publication no. 7.

Bjerrum L (1967) Engineering Geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. Géotechnique **17(2)**: 83-118, http://dx.doi.org/10.1680/geot.1967.17.2.83.

Bjerrum L and Rosenqvist IT (1956) Some experiments with artificially sedimented clays. Géotechnique **6(3)**: 124-136, http://dx.doi.org/10.1680/geot.1956.6.3.124.

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

Bjørlykke K (2010) Petroleum Geoscience: From sedimentary environments to rock physics. Springer, pp. 87-111.

Bryntesen RN (2013) Block Sample Testing at Dragvoll. Project thesis, Norwegian University of Science and Technology, Trondheim, Norway, pp. 1-53.

Bryntesen RN (2014) Laboratory investigation on salt migration and its effect on the geotechnical strength parameters in quick clay mini-block samples from Dragvoll. Master's thesis, Norwegian University of Science and Technology, Trondheim, Norway, pp. 1-105.

Campanella RG and Weemees I (1990) Development and use of an electrical resistivity cone for groundwater contaminant studies. Canadian Geotechnical Journal **27(5)**: 557-567, https://doi.org/10.1139/t90-071.

Eggestad A and Sem H (1970) Haslelinjen mellom Strømsvn. og Store Ringvei: Stabilitetsforholdene langs Store Ringvei. Oslo municipality, Oslo, Norway, Report no. R-894. pp. 1-3.

Eggestad A and Sem H (1974) Haslelinjen: Resultatet av markforsterkingen i krysset Haslelinjen – Store Ringvei. Oslo municipality, Oslo, Norway, Report no. R-894 part 8. pp. 1-8.

Eggestad A and Sem H (1976) Stability of excavations improved by salt diffusion from deep wells. In *Proceedings of the 6th European conference on soil mechanics and foundation engineering*, Vienna, Austria, pp. 211-216.

Emdal A, Gylland AS, Amundsen HA, Kåsin K and Long M (2016) Mini-block sampler. Canadian Geotechnical Journal **53(8)**: 1235-1245, http://dx.doi.org/10.1139/cgj-2015-0628.

Fornes P (2014) NGIs anbefalinger for krav til effekt av sprøbruddoppførsel. Naturfare: infrastrukture, flom og skred (NIFS), Oslo, Norway, report no. 88/2014. pp. 1-15.

Gregersen O (1981) The quick clay landslide in Rissa, Norway. In *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering*, 3, Stockholm, Sweden, pp. 421-426.

Gregersen O (2001) Program for økt sikkerhet mot leirskred - Metode for kartlegging og klassifisering av faresoner, kvikkleire. Norwegian Geotechnical Institute, Oslo, Norway, NGI-report no. 20001008-2, Revision no. 3. pp. 1-22.

Grim RE (1968) Clay mineralogy. McGraw-Hill Book Company, Inc., New York, NY, USA.

Gillot JE (1979) Fabric, composition and properties of sensitive soils from Canada, Alaska and Norway. Engineering Geology **14(2-3)**: 149-172, https://doi.org/10.1016/0013-7952(79)90082-6.

Glover PWJ, Hole MJ and Pous J (2000) A modified Archie's law for two conducting phases. Earth and Planetary Science Letters **180(3-4)**: 369-383, https://doi.org/10.1016/S0012-821X(00)00168-0.

Gylland AS (2014) The effect of deformation rate in progressive slope failure. In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J. (eds)). Springer Dordrecht, the Netherlands, pp. 267-277.

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 – Norwegian Journal of Geography **37(2)**: 63-79, http://dx.doi.org/10.1080/00291958308552089.

Hafsten U and Mack G (1990) Den postglaciale landskapsutviklingen på Dragvoll universitetsområde, Trondheim. Norsk Geografisk Tidsskrift – Norwegian Journal of Geography **44(3)**: 131-148, http://dx.doi.org/10.1080/00291959008552251.

Hilmo BO (1989) Marine sensitive leirers mineralsammensetning, kolloidkjemi og mekaniske egenskaper. Norwegian Technical Institute (NTH), Division for Geology and Rock Mechanics, Trondheim, Norway, Doctoral thesis 1989:21, pp. 1-222.

Jackson ML (1979) Soil chemical analysis – Advanced course. Published by the author, Madison, Wisconsin.

Jostad HP and Grimstad G (2011) Comparison of distribution functions for the nonlocal strain approach. *In Proceedings of the 2nd international symposium on computational geomechanics*, Cavtat-Dubrovnik, Kroatia.

Karlsrud K and Hernandez-Martinez FG (2013) Strength and deformation properties of Norwegian clays from laboratory tests on high-quality block samples. Canadian Geotechnical Journal **50(12)**: 1273-1293, http://dx.doi.org/10.1139/cgj-2013-0298.

Kenney TC (1967) The influence of mineral composition on the residual strength of natural soils. In *Proceedings of the Geotechnical Conference*, Oslo, Norway. pp. 123-129.

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

Ladd CC and Foot R (1974) New design procedure for stability of soft clays. Journal of the Geotechnical Engineering Division (ASCE) **100(7)**: 763-786.

Leroueil S and Vaughan PR (1990) The general and congruent effects of structure in natural soils and weak rocks. Géotechnique **40(3)**: 467-488, https://doi.org/10.1680/geot.1990.40.3.467.

Leroueil S, Tavenas F and Le Bihan JP (1983) Proprietes caracteristiques des argiles de l'est du Canada. Canadian Geotechnical Journal **20(4)**: 681–705, http://dx.doi.org/10.1139/t83-076.

Levy A, Andelman D and Orland H (2012) Dielectric Constant of Ionic Solutions: A Field-Theory Approach. Physical Review Letters **108:** 227801, http://dx.doi.org/10.1103/PhysRevLett.108.227801

Locat J and Demers D (1988) Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays. Canadian Geotechnical Journal **25(4)**: 799-806. http://dx.doi.org/10.1139/t88-088.

Locat J and St-Gelais D (2014) Nature of sensitive clays from Quebec. In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer, Dordrecht, the Netherlands, pp. 25-37

Locat J, Lefebvre G and Ballivy G (1984) Mineralogy, chemistry, and physical properties interrelationships of some sensitive clays from Eastern Canada. Canadian Geotechnical Journal **21(3)**: 530-540, https://doi.org/10.1139/t84-055.

Long M, Donohue S, L'Heureux JS, Solberg IL, Rønning JS, Limacher R, O'Connor P, Sauvin G, Rømoen M and Lecomte I (2012) Relationship between electrical resistivity and basic geotechnical parameters for marine clays. Canadian Geotechnical Journal **49(10)**: 1158-1168, http://dx.doi.org/10.1139/t2012-080.

Lunne T, Robertsson PK and Powell JJM (1997) Cone penetration testing in geotechnical practice. Spon Press, London, UK.

Løken T (1968) Kvikkleiredannelse og kjemisk forvitring i norske leirer. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 75, pp. 1-9.

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

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

Moore R (1991) The chemical and mineralogical controls upon the residual strength of pure and natural clays. Géotechnique **41(1)**: 35-47, https://doi.org/10.1680/geot.1991.41.1.35.

Moore DM and Reynolds Jr. RC (1997) X-ray diffraction and the identification and analysis of clay minerals. 2nd edition. Oxford University Press, Inc., New York.

Moum J, Løken T and Torrance JK (1971) A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Géotechnique **21(4)**: 329-340, https://doi.org/10.1680/geot.1971.21.4.329.

Moum J, Løken T and Torrance JK (1972) Discussion: A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Géotechnique **22(3)**: 542-544, https://doi.org/10.1680/geot.1972.22.3.542.

Moum J, Sopp OI and Løken T (1968) Stabilization of undisturbed quick clay by salt wells. Väg- och vattenbyggaren no. 8. Reprinted in Norwegian Geotechnical Insititue, Oslo, Norway, NGI publication no. 81, pp. 1-7.

Morel-Vulliez G., Ørbech T and Fürst C (2013) E31-Ulvensplitten – Geotekniske undersøkelse. Multiconsult AS, Oslo, Norway, Report no. 124691/1, pp. 1-7.

Norwegian Geotechnical Society (2011) Veiledning for symboler og definisjoner i geoteknikk: Identifisering og klassifisering i jord. Norwegian Geotechnical Society, Oslo, Norway, NGF-notification no. 2 2nd revision, first published in 1982. pp. 1-54.

Norwegian Water Resources and Energy Directorate (2014) Sikkerhet mot kvikkleireskred: Vurdering av områdestabilitet ved arealplanlegging og utbygging i områder med kvikkleire og andre jordarter med sprøbruddegenskaper. Norwegian Water Resources and Energy Directorate, Oslo, Norway, NVE Guidelines no. 7/2014. pp. 1-43.

Parkhurst DL and Appelo CAJ (2013) Description of Input and Examples for PHREEQC Version 3—A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations. U.S. Geological Survey, Denver, Colorado, USA. pp. 1-49.

Penner E (1965) A study of sensitivity in Leda clay. Canadian Journal of Earth Science **2(5)**: 425-441, https://doi.org/10.1139/e65-037.

Pfaffhuber AA, Bazin S and Helle TE (2014) An integrated approach to quick-clay mapping based on resistivity measurements and geotechnical investigations. In *Landslides in sensitive clays: From geoscience to risk management.* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, the Netherlands, pp. 63-74.

Post VEA and Prommer H (2007) Multicomponent reactive transport simulation of the Elder problem: Effects of chemical reactions on salt plume development. Water Resources Research **43(10)**: 1-13, http://dx.doi.org/10.1029/2006WR005630.

Quigley RM (1980) Geology, mineralogy, and geochemistry of Canadian soft soils: a geotechnical perspective. Canadian Geotechnical Journal **17(2)**: 261–285. http://dx.doi.org/10.1139/t80-026.

Rand B, Pekenc E, Goodwin JW and Smith RW (1980) Investigation into the existence of edge-face coagulated structures in Na-montmorillonite suspensions. Journal of the Chemical Society, Faraday Transaction I **76**: 225-235, http://dx.doi.org/10.1039/F19807600225.

Robinson C, Gibbes B and Li L (2006) Driving mechanisms for groundwater flow and salt transport in a subterranean estury. Geophysical Research Letters **33**: L03402, http://dx.doi.org/10.1029/2005GL025247

Rosenqvist IT (1946) Om leirers kvikkaktighet. Available from the Norwegian Public Road Administrations, Oslo, Norway. Meddelelsen fra Vegdirektøren No. 3. pp. 29–36.

Rosenqvist IT (1953) Considerations on the sensitivity of Norwegian quick-clays. Géotechnique **3(5)**: 195–200, https://doi.org/10.1680/geot.1953.3.5.195.

Rosenqvist IT (1955) Investigations in the clay-electrolyte-water system. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 9, pp. 1-125.

Rosenqvist IT (1975) Origin and mineralogy glacial and interglacial clays of Southern Norway. Clays and Clay Minerals **23**: 153-159.

Sandven R, Montafia A, Gylland AS, Pfaffhuber AA, Kåsin K and Long M (2015) Detection of brittle materials. Summary report with recommendations. Final report. Naturfare: infrastruktur, flom og skred (NIFS), Oslo, Norway, Report no. 126/2015. pp. 1-72.

Sandven R, Gylland A, Montafia A, Kåsin K, Pfaffhuber AA and Long M (2016) In situ detection of sensitive clays – Part I: Selected test methods. In *Proceedings of the 17th Nordic Geotechnical Meeting: Challenges in Nordic Geotechnics, Reykjavik, Iceland* (Ingimarsdóttir A, Jónsson A, Sigtryggsdóttir FG *et al.* (eds)). The Icelandic Geotechnical Society, Reykjavik, Iceland, pp 123-132.

Santamarina JC (2001) Soil behavior at the microscale: particle forces. In *Proceedings of Symposium on Soil Behavior and Soft Ground Construction Honoring Charles C. "Chuck" Ladd* (Germaine JT, Sheahan TC and Whitman RV (eds)). American Society of Civil Engineers, Massachusetts, USA, pp. 25-56, http://dx.doi.org/10.1061/40659(2003)

Santamarina JC, Klein KA, Palomino A and Guimaraes MS (2002) Micro-scale aspects of chemical-mechanical coupling: Interparticle forces and fabric. In *Chemo-Mechanical Coupling in Clays: From nano-scale to engineering applications* (Di Maio C, Hueckel T and Loret B (eds)). Swets & Zeitlinger, Lisse. pp. 47-63.

Solberg IL, Hansen L, Rønning JS, Haugen ED, Dalsegg E and Tønnesen JF (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, http://dx.doi.org/10.1007/s10064-011-0363-x.

Sridharan A and Nagaraj HB (2000) Compressibility behaviour of remoulded, fine-grained soils and correlation with index properties. Canadian Geotechnical Journal **37(3)**: 712–722, https://doi.org/10.1139/t99-128.

Syversen FSG (2013) Et studie av den mineralogiske sammensetningen i norske sensitive leirer – Med et geoteknisk perspektiv. University in Oslo, Oslo, Norway, Master thesis, pp. 1-77.

Talme OA, Pajuste M and Wenner CG (1966) Secondary changes in the strength of clay layers and the origin of sensitivity clay. Byggforskningsrådet, Stockholm, Sweden, report nr. 46.

Thakur V, Degago SA, Oset F, Aabøe R, Dolva BK, Aunaas K, Nyheim T, Lyche E, Jensen OA, Sæter MB, Robsrud A, Viklund M, Nigussie D and L'Heureux JS (2014a) Characterisation of post-failure movements of landslides in soft sensitive clays. . In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, the Netherlands, pp.91-104.

Thakur V, Jostad HP, Kornbrekke HA and Degago SA (2014b) How Well Do We Understand the Undrained Strain Softening Response in Soft Sensitive Clays? In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, the Netherlands, pp.291-302.

Torrance JK (1974) A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. Géotechnique **24(2)**: 155-173.

Torrance JK (1975) On the role of chemistry in the development and behavior of the sensitive marine clays of Canada and Scandinavia. Canadian Geotechnical Journal **12(3)**: 326-335, https://doi.org/10.1139/t75-037.

Torrance JK (1979) Post-depositional changes in the pore water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. Engineering Geology **114(2-3)**: 135-147, https://doi.org/10.1016/0013-7952(79)90081-4.

Torrance JK (1983) Towards a general model of quick clay development. Sedimentology **30(4)**: 547-555, https://doi.org/10.1111/j.1365-3091.1983.tb00692.x.

Torrance JK (1999) Physical, chemical and mineralogical influences on the rheology of remoulded low-activity sensitive marine clay. Applied Clay Science **14(4)**: 199–223, http://dx.doi.org/10.1016/S0169-1317(98)00057-X.

van Olphen H (1963) An introduction to clay colloid chemistry. John Wiley & Sons, Inc, New York, NY, USA.

Waxman MH and Smits LJM (1968) Electrical conductivities in oil-bearing shaly sands. Society of Petroleum Engineers Journal **8(2)**: 107-122, https://doi.org/10.2118/1863-A.

Zhang H and Schwartz FW (1995) Multispecies contaminant plumes in variable density flow systems. Water Resources Research **31(4)**: 837-847, http://dx.doi.org/10.1029/94WR02567.

Paper I

Paper I

Paper II

Paper II

Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway

TE Helle, RN Bryntesen, & H Amundsen
Norwegian University of Science and Technology, Trondheim, Norway
& Norwegian Public Roads Administration, Trondheim, Norway
A Emdal, & S Nordal
Norwegian University of Science and Technology, Trondheim, Norway
P Aagaard
Department of Geoscience – University of Oslo, Oslo,Norway

ABSTRACT

This laboratory study comprises testing of soft leached quick clay samples under three storage conditions; wrapped in plastic, submerged in de-aired water and submerged in a potassium chloride slurry. The main purpose is to reveal the potential of improving the soil strength by introducing salt ions to the soil in order to enable future use of unsafe clay areas. To enhance the precision of the study, the clay samples are taken by use of a miniature version (sample diameter 160 mm) of the Sheerbrooke block sampler to reduce the sample disturbance to a minimum. The clay is tested by index, triaxial and oedometer testing. Adding KCl to the clay, a 25 % increase is found in the undrained shear strength whereas the remolded undrained shear strength dramatically increased from <0.5 to 4 kPa. Further, increase in soil plasticity, preconsolidation pressure and stiffness is noticeable.

RESUME

Cette étude de laboratoire comprend des essais sur échantillons d'argile sensible lessivée ayant été conservés sous trois conditions ; enveloppés dans du plastique, submergés dans de l'eau désaérée et submergés dans une suspension de chlorure de potassium. Le but principal étant de révéler le potentiel d'amélioration de la résistance du sol par introduction d'ions de sel dans le sol afin de permettre l'utilisation future de zones argileuses à risque. Pour améliorer la précision de l'étude, les échantillons d'argile sont prélevés par l'utilisation d'une version miniature (diamètre d'échantillon 160mm) de l'échantillonneur Sherbrooke afin de réduire au minimum la perturbation de l'échantillon. L'argile est testée par indice, par triaxial et à l'œdomètre. En ajoutant du KCl à l'argile, une augmentation de 25% de la résistance au cisaillement non drainée a été observée tandis que la résistance au cisaillement non drainée du sol remanié a augmenté de façon importante de <0.5 à 4 kPa. De plus, une augmentation de la résistance a été constatée, ainsi qu'un accroissement de la plasticité du sol, de la pression de préconsolidation et de la rigidité.

1 INTRODUCTION

Potassium chloride (KCl) improves the geotechnical parameters in highly sensitive, low-saline clays (Moum et al. 1968; Eggestad and Sem 1976; Helle et al. 2013). In Norway, quick clay is defined by its remolded shear strength equal to or less than 0.5 kPa (Norwegian Geotechnical Society 1982). A field experiment where salt wells were installed in a quick clay deposit at Ulvensplitten, Oslo, Norway, was carried out in 1972 in order to improve the geotechnical properties prior to excavation (Eggestad and Sem 1976). Recent new investigations in the same area show that the effect remains thirty to forty years later, and the method is suggested to be applicable as ground improvement to prevent large landslides (Helle et al. Submitted, 2015). Installing salt wells in soft natural clay slopes is a challenge due to the marginal safety of the slope. This calls for moderate weight equipment and new technology development for a cost effective solution.

Using KCl as ground improvement is time consuming, and it takes a couple of years to improve the clay volume surrounding the salt well even though the salt wells have a center to center distance of 1.5 m (Eggestad and Sem 1976). In soils with a hydraulic conductivity of less than 1×10^{-10} m/s, the transport mechanism is dominated by diffusion, i.e. chemical transport from high concentration to low concentration (Appelo and Postma 2005; Mitchell and Soga 2005). The obtained improvement on the geotechnical properties and the time it takes, depend on the initial pore water chemistry and ion distribution in the adsorbed positions on the clay mineral surface, water-filled porosity, temperature and tortuosity, all of which are site specific.

Prior to installing salt wells in quick clay areas it is necessary to quantify the effect on the geotechnical properties. As diffusion is time consuming, a laboratory setup for quantifying the effect quickly is needed. As time and method of sample storage highly affects the geotechnical properties, it is important to also evaluate the laboratory results with respect to storage effects. A

laboratory setup and a testing regime for quantifying the necessary data prior to stabilizing quick clay areas with KCl is proposed in this paper.

2 BACKGROUND

2.1 Geochemistry in quick clays

The pore water in clays deposited in marine environment originally had seawater salt content (~30-35 g/l). The ion composition was similar to the depositional environment i.e. highly dominated by sodium (Na^+) in the pore water as well as in the adsorbed positions on the clay mineral surface. Leaching and diffusion decreased the salt content and changed the ion composition in the pore water (Rosenqvist 1946). A salt content of less than 5-10 g/l may develop quick clay (Bjerrum et al. 1969). Leached clays with a salt content of less than 1 g/l may behave as a liquid when remolded (Bjerrum et al. 1969; Moum et al. 1971). However, low salt content does not necessarily imply quick clay as the specific ion composition at low salt content highly affects the geotechnical properties (Moum et al. 1971).

Clay minerals are negatively charged, attracting cations from the pore water to maintain neutral charge. The adsorbed ions are affected by available ions in the pore water. Potassium (K^+) has higher exchanging power than Na^+, but less than Mg^{2+} and Ca^{2+} (Løken 1970; Appelo and Postma 2005; Mitchell and Soga 2005). The pore water composition in quick clays is dominated by Na^+, whereas the adsorbed positions are dominated by divalent ions such as magnesium (Mg^{2+}) and calcium (Ca^{2+}) introduced by the leaching water and weathering of the soil minerals (Moum et al. 1971). According to Mitchell and Soga (2005), introducing high concentration of monovalent ions, such as K^+, to the pore fluid will even so replace Mg^{2+} and Ca^{2+} on the mineral surface. K^+ has a higher beneficial impact on the undrained and remolded shear strength as well as the Atterberg limits than Na^+, Mg^{2+} and Ca^{2+} (Løken 1968). KCl is highly soluble in water and easily available, consequently it is highly applicable for ground improvement.

2.2 Storage effects on quick clay samples

Long term storing of soft clay over time may cause oxidation of the samples. Oxidation lead to changes in the chemical composition of the pore water as well as in the adsorbed positions on the clay mineral surface (Torrance 1976; Lessard and Mitchell 1985). Torrance (1976) and Lessard and Mitchell (1985) report increased salinity and increased percentage of divalent ions in the pore water as a result of storage, possibly due to dissolution of carbonates releasing Mg^{2+} and Ca^{2+} to the pore water. As divalent ions have higher exchanging power than monovalent ions, these may be adsorbed on the mineral surface releasing Na^+ and K^+ to the pore water. Increased salinity reduces the repulsive forces between the clay particles, improving the geotechnical properties of the clay (Rosenqvist 1946; Rosenqvist 1953; Bjerrum 1955;

Rosenqvist 1955; Løken 1968; Moum et al. 1968; Løken 1970; Quigley 1980; Torrance 1983).

Storage over time may cause migration of water and loss of moisture (Hvorslev 1949). This may be prevented by wrapping samples in clingfilm combined with waxing, or clingfilm and foil (La Rochelle et al. 1986; Heymann and Clayton 1999). La Rochelle et al. (1986) dipped the clingfoil in a wax compound prepared from equal weight of paraffin wax and vaseline prior to wrapping it around specimens cut out from larger samples. The clingfilm was evened out with the hands to avoid trapped air bubbles. The pH did not change due to storage, indicating that the technique prevents oxidation of the clay specimens. The stored clay specimens also maintained their natural water content and Atterberg limits over a time period of eight years.

Even though wrapping the samples in wax and clingfilm will prevent moisture loss, the geotechnical properties will change due to loss of its in situ overburden pressure. Bjerrum (1973) found a decrease in peak shear strength with 13.0-13.5 % within 2-3 days due to increased internal swelling in quick clay samples from the Oslo area. A decrease in the preconsolidation pressure (p_c') of 4.8 % was found in block samples of overconsolidated sensitive marine clay stored for 2 to 17 months (Bozozuk 1971).

3 METHOD

The NTNU research site at Dragvoll in Trondheim, Norway, is located 159 m above current sea level. The marine limit in the Trondheim area is 175-180 m above current sea level (Kjemperud 1981; Hafsten 1983). The clay deposit is up to 40 m thick in the area (Hafsten and Mack 1990).

3.1 Storage procedure

NTNU has developed a down-sized Sheerbrooke block sampler to easily extract samples of high quality. The sample has a diameter of 160 mm, and height of 250 mm.

Fourteen mini block samples covering the depth in the range of 3.25 m to 8.95 m were extracted from the quick clay NTNU research site Dragvoll (Table 1). Six of these were used for reference measurement of the soil properties. Four were stored in de-aired water before testing, and four were stored in KCl-slurry using a cell shown in Figure 1. All samples were wrapped in clingfilm directly after extraction from the ground, and stored in the cold storage chamber at approximately 7 °C for up to 2 months. The variety of storage time was due to capacity problems at the laboratory. However, the stored samples from the same depths are tested within the same week.

All cells were filled with de-ionized, de-aired water. The samples stored in de-aired water were submerged wrapped in clingfilm to avoid diffusion of ions from the clay into the reservoir. The samples stored in KCl-slurry were covered by KCl to ensure high concentration throughout the time of storage as well as rapid migration of the concentration front into the sample. The solute

concentration of KCl in the storage cells was about 3500 meq/l (~260 g/l).

Table 1. Storage time of samples used in the study. Amount of days stored in clingfilm prior to testing in the laboratory, and prior to submerging the samples in de-aired water or KCl-slurry. Total days of storage is the sum of days in clingfilm and days stored in the storage cells

Storage	Depth (m)	Clingfilm[1] (days)	Cells (days)	Total (days)
Reference	3.25-3.50	41		41
Reference	4.00-4.25	45		45
Reference	4.50-4.75	52		52
Reference	7.70-7.95	28		28
Reference	8.45-8.70	3		3
Reference	8.70-8.95	4		4
De-aired water	3.75-4.00	61	47	108
De-aired water	4.75-5.00	41	68	109
De-aired water	5.55-5.80	41	82	123
De-aired water	8.20-8.45	35	102	137
KCl	3.50-3.75	61	42	103
KCl	4.25-4.50	61	62	123
KCl	5.05-5.30	41	76	117
KCl[2]	7.45-7.70	35	96	131

[1]days the samples were stored in the cold storage room wrapped in clingfilm prior to submerged in cells
[2]leakage in cell. Consequently only partially stored in KCl-slurry

3.2 Laboratory tests

The mini-block samples were sectioned as shown in Figure 2. Fall cone undrained and remolded shear strength, water content, Atterberg limits, pH and ion composition in the pore water were determined in sections 1 to 3 shown in Figure 2c. CAU Triaxial and CRS oedometer tests were carried out on all samples.

Mineralogy was determined by x-ray diffraction analysis (XRD). The pore water was extracted from the clay by centrifuge, and filtered using a syringe filter of 45 µm prior to analysing the ion composition.

The concentration of ions in the pore water was analyzed at the laboratory at the Department for Geosciences at the University in Oslo. The cations were analyzed using a Dionex ICS-1000 Ion Chromatography System (ICS-1000). The anions were analyzed using a Dionex ICS-2000 Ion Chromatography System (ICS-2000). The alkalinity was determined by HCl-titration in Metrohm 702 SM Titrino. pH was measured in the pore water by the Methrom 702 SM Titrino at 25 ºC.

4 RESULTS

4.1 Soil description

The soil at Dragvoll is characterized as clay with a clay content (particle size < 2 µm) of 24-28 % down to 6 m depth, and of approximately of 38 % at 7-9 m depth.
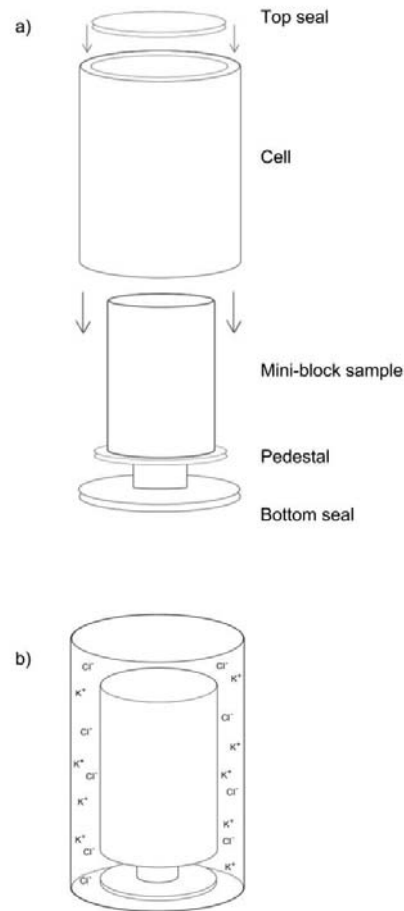
Figure 1 Storage cell used for the samples submerged in de-aired water and KCl-slurry. a) construction parts and b) sample submerged in KCl

The clay deposit is intersected with horizontal silt layers. Shells, shell fragments and drop stones were occasionally observed in the samples. The clay mineralogy is dominated by illite; 45 % in the top soil and 35 % at around 8 m depth. The amount of chlorite is generally around 14 %. Below 4.5 m, 2-3 % of the bulk mineralogy consisted of calcite.

4.2 Pore water chemistry

Horizontal cutting revealed discoloration with a lighter grey almost yellow colour along the circumference and along the thickest siltlayers throughout the samples stored wrapped in clingfilm, submerged in de-aired water. The discoloration was also evident in the reference samples stored for around 40 days. This may be an indicating of
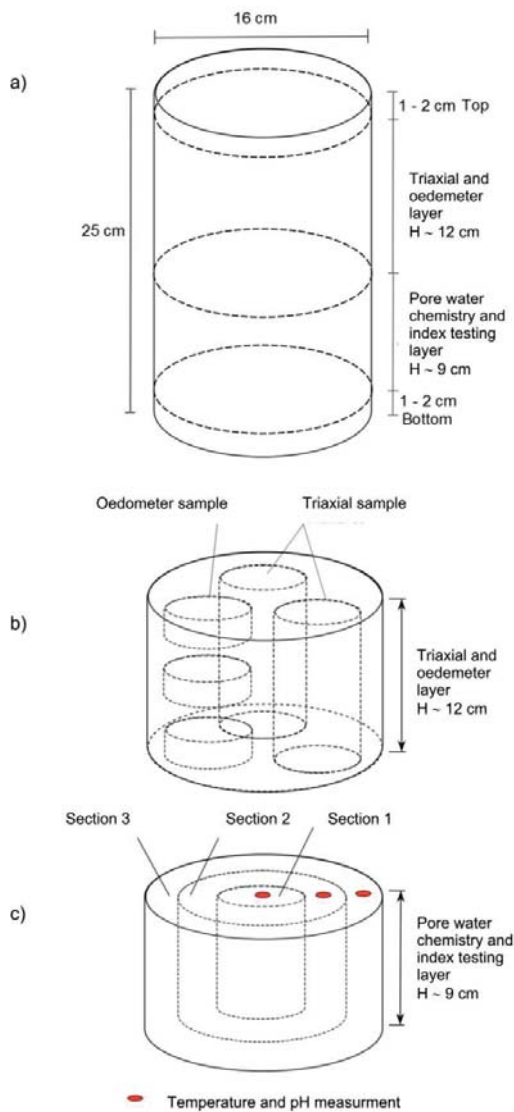
Figure 2. Sectioning of mini-block sample. A couple of cm in the top and bottom was removed (a). Approximately 12 cm was used for triaxial and oedometer testing (b). The remaining 9 cm was used for index testing, pH and pore water chemistry (c)

oxidation. The oxidation may have occurred in the time from extracting the samples until submerging the samples in the storage containers. Furthermore, some oxygen may have been trapped within the clingfilm contributing to oxidation of the samples. The samples stored in KCl did not have this discoloration. The sulphate concentration (SO_4^{2-}) is increased in section 2 and 3 compared to section 1 in the reference sample, and throughout the samples stored submerged in either water or KCl-slurry (Figure 4g). The increased concentration of SO_4^{2-} may be a result of oxidation of pyrite (FeS_2) to ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), ultimately precipitating as $Fe(OH)_3$ causing the slightly yellow discoloration of the circumference of the clay sample (Lessard and Mitchell 1985).

The pH in the reference samples compared to the ones submerged in de-aired water wrapped in clingfilm is almost unchanged (Figure 3). However, pH in the samples stored in KCl is decreased below 8. This may be caused by the de-aired water holding a lower pH, or due to oxidation of pyrite forming sulfuric acid (Lessard and Mitchell 1985). The decrease in pH may have caused dissolution of calcite releasing Ca^{2+} to the pore water.

The alkalinity (Figure 4f) at the occurring pH is governed by bicarbonate (HCO_3^-). The drastic drop in alkalinity in the samples stored in KCl may be explained by the high concentration of Cl^- entering the pore water, suppressing bicarbonate out of the system as well as bicarbonate being neutralized by sulfuric acid (Lessard and Mitchell 1985).

The cation concentrations change in the samples stored in de-aired water compared to the concentrations in the reference sample. Na^+ increase by approximately 5 meq/l in the deepest samples. K^+ and Mg^{2+} is increased by approximately 0.4 meq/l and 0.1 meq/l respectively, whereas Ca^{2+} is doubled by an increase of 0.7 meq/l. Storing the samples in KCl-slurry, the concentration of K^+ (Figure 4b) and chloride (Cl^-) (Figure 4e) is increased to the solute concentration in the storage container, of approximately 3500 meq/l (~260 g/l). As K^+ enters the adsorbed positions on the clay mineral surface, Na^+, Mg^{2+} and Ca^{2+} is released increasing the concentration in the pore water (Figure 4a, c and d).
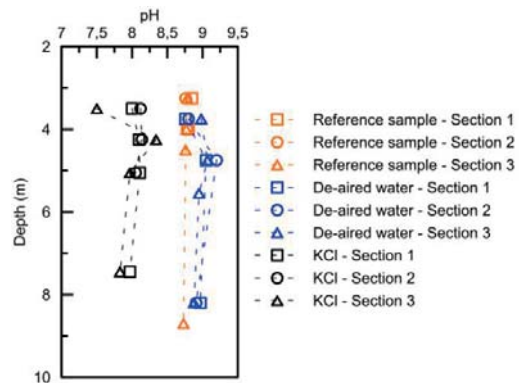
Figure 3. pH in sections 1-3
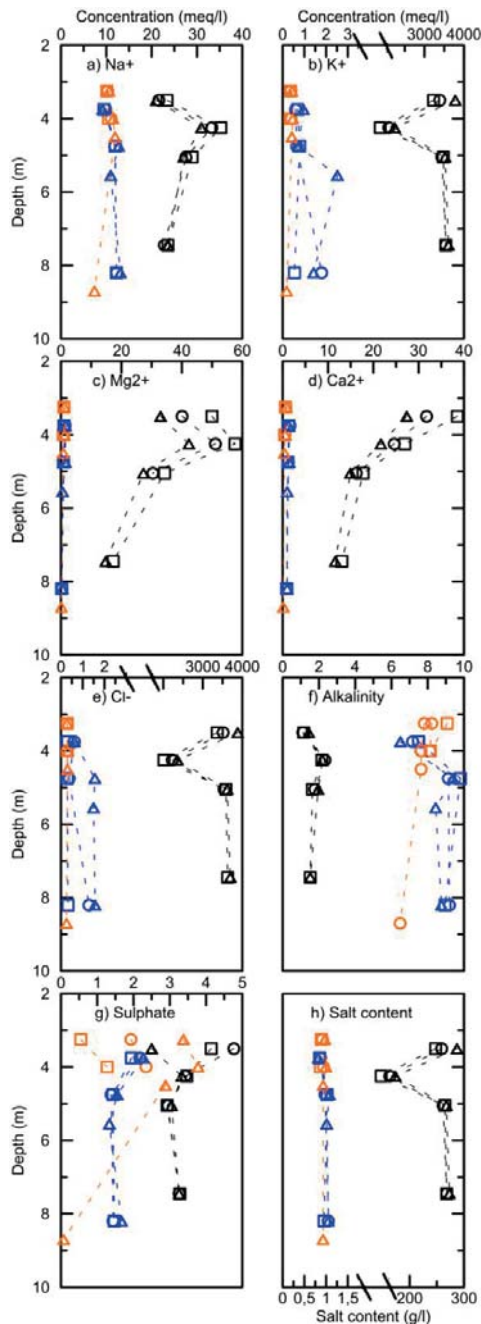
Figure 4. Ion composition in pore water over time for section 1 and 2. a) Sodium, b) potassium, c) magnesium, d) calcium, e) chloride, f) alkalinity, g) sulphate and h) total salt content. Legend as in Figure 3

4.3 Geotechnical properties

The circumference of the sample is the most disturbed part due to handling during sampling, oxidation and swelling due to unloading. The data from section 3 is never the less included as some of the samples have their index tests carried out in the top lid of the sample. However, most emphasis is made on interpreting data from Section 1 and 2. The clay is in-homogenous with depth due to an uneven distribution of horizontal silt layers affecting the results. Results clearly deviating from the lot due to occurence of silt layers are ruled out.

Storage effects have affected the geotechnical properties. However, storing the samples wrapped in clingfilm submerged in de-aired water seem to retain the fall cone undrained and remolded shear strength (Figure 5), water content and the Atterberg limits (Figure 6). However, considering the triaxial (Figure 7) and oedometer tests (Figure 8) the degradation of the geotechnical properties is considerable.

Storing the samples in KCl increase the fall cone undrained shear strength slightly compared to the reference sample. The remolded shear strength however, is increased from 0.1 kPa to as much as 6.4 kPa. The liquid limit is increased to the natural water content, whereas the plastic limit is practically unchanged. The density in the samples stored in KCl increased due to the increased salt content. The reduced water content in these samples may be due to higher content of solids. Osmoses may also have contributed to reduced water content. The liquidity index (IL) in the reference samples is in the range of 1.6 to 4.6, whereas the samples stored in KCl has an IL in the range of 0.5-0.9. IL is, however, greatly affected by the water content. Calculating IL in the samples stored in KCl using the water content from the reference sample increases IL to the range of 0.8-1.5. The plasticity index in the reference sample is in the range of 2.8-10.4 %, whereas it in the KCl-treated clay is increased to the range of 10.0-17.4 %; from low plasticity to medium plasticity.

Figure 7 and 8 present triaxial and oedometer results from 4 m to 5 m depth. The triaxial undrained peak strength for the samples stored in de-aired water increased compared to the reference sample (Figure 7); from 20 kPa to 22.5 kPa. However, the residual strength in this case was decreased to less than the residual strength in the reference sample. By storing the quick clay in KCl, the peak shear strength increased to 25 kPa, which is an increase of 25 % compared to the reference sample. The residual strength increased far beyond the residual strength of the reference sample; from 13.5 kPa to 22 kPa at 5 % strain.

The oedometer modulus (M) is unaltered from the reference sample storing the sample in de-aired water; around 2 MPa (Figure 8a). M increase to around 5 MPa in the sample stored in KCl. The apparent preconsolidation pressure (pc') increase from around 90 kPa to around 120 kPa in the KCl-treated clay. The occurring strains at the same effective stress (σ') show that increased time of storage decrease the stiffness of the specimen (Fig. 8b). However, the stiffness of the KCl-treated clay is increased and the specimen deforms far less at the same σ'.
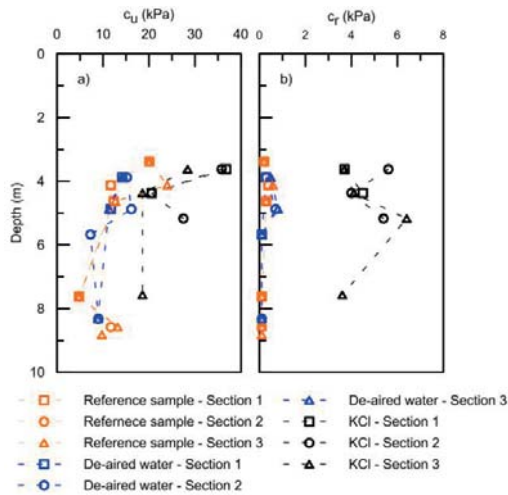
Figure 5. Fall cone a) undrained shear strength and b) remolded shear strength sections 1-3
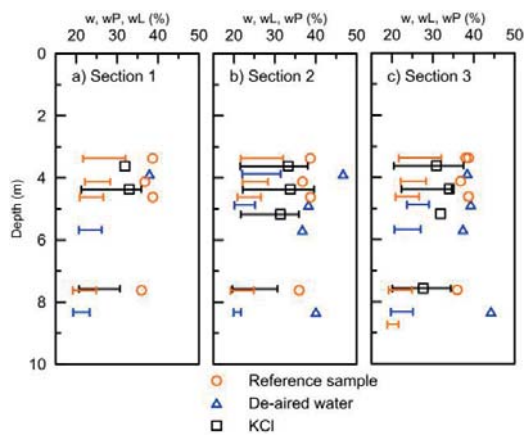
Figure 6. Water content and Atterberg limits sections 1-3
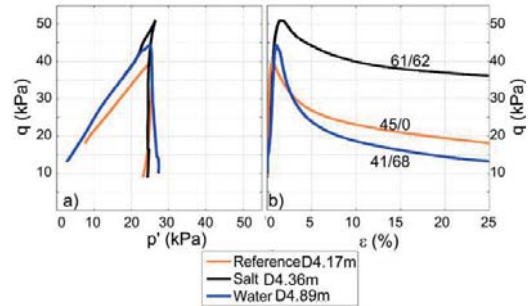
Figure 7. CAU triaxial test on reference sample and samples stored in de-aired water and KCl from 4.17-4.89 m depth. a) Deviatoric (q) versus mean effective stress (pm'), and b) deviatoric stress versus strain (ε). Days stored in clingfilm/days stored in cell is marked in figure b
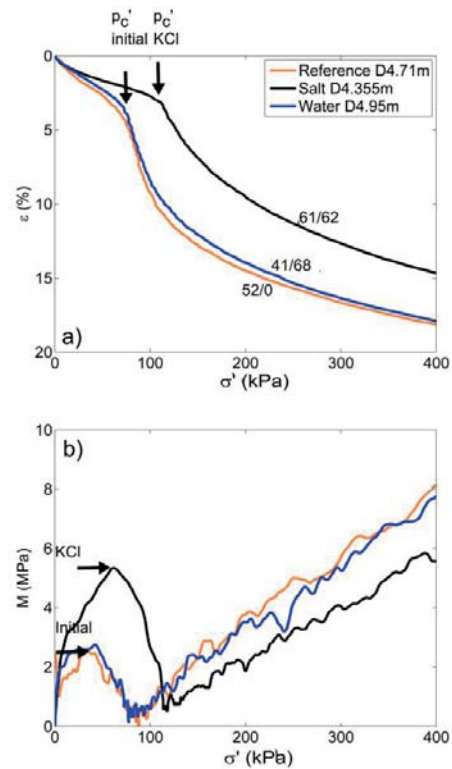
Figure 8. CRS oedometer tests on samples from 4.4-5.0 m depth. a) Strain (ε) versus effective stress (σ'). b) Oedometer modulus (M) versus effective stress. Days stored in clingfilm/days stored in cell is marked in figure a. Preconsolidation pressure (pc') and oedometer modulus is marked by arrow

5 DISCUSSION AND RECOMMENDATIONS

Submerging the whole mini-block sample rather than small specimens in KCl-solution, index, oedometer and triaxial tests can all be carried out on the same block. This includes testing of mineralogy and pore water chemistry. Storing parallel samples submerged in de-aired water and KCl as well as testing one sample from the same depth directly after extraction is necessary to evaluate the improved geotechnical properties as a result of adding KCl. Storing the samples wrapped in clingfilm submerged in de-aired water, the samples seem to retain the index parameters. The pore water chemistry is, however, affected by storage, probably due to oxidation.

The reference samples and the ones wrapped in clingfilm submerged in de-aired water are of low plasticity and highly sensitive with a remolded shear strength of 0.1-0.4 kPa in sections 1-2. The samples stored in KCl have completely changed their behavior to medium plasticity and medium to low sensitivity, with a remolded shear strength of 3.7-5.6 kPa in sections 1-2.

Quick clays retain their water content during leaching (Bjerrum 1967). Re-introducing high salt content by submerging quick clay samples in KCl decreases the water content. However, the samples submerged in KCl has increased density compared to the reference samples. This indicates that the decreased water content may be a result of increased weight of solids which again reduce the porosity. Due to submerging the samples in KCl-slurry, osmoses may have contributed to decreasing the water content.

Losing the in situ overburden pressure, the clay sample expands which greatly affects the parameters determined by triaxial and oedometer testing. Testing the reference samples directly after extraction, may result in higher undrained peak strength. Decreasing time of storage as well as storing the samples at their in situ overburden pressure may result in a larger undrained peak strength increase due to increased concentration of K^+.

Even though storage time clearly affects the triaxial and oedometer parameters determined for the quick clay samples, a clear outcome of storing the samples in KCl is increased undrained peak strength, significantly increased residual strength and significantly reduced compressibility as a result of increased plasticity due to increased salt content. These findings are in agreement with Bjerrum (1967), where clay treated with KCl developed an increased resistance against deformation as the plasticity and shear strength increased.

6 CONCLUSIONS

Quantifying the improved geotechnical properties as a result of treating the clay with KCl is possible using a modification of the described laboratory setup. Determining fall cone undrained and remolded shear strength, water content, density, grain size distribution, Atterberg limits, mineralogy, pore water chemistry, cation exchange capacity (CEC) and exchangeable ions should

be carried out, as well as triaxial and oedoemeter tests. The following laboratory setup is suggested:

a) Determine the initial condition of the clay directly after sample extraction from the ground
b) Store at least one sample from the same depth wrapped in clingfilm, submerged in de-aired water at in situ overburden pressure in a cold storage chamber
c) Store at least one sample from the same depth in supersaturated KCl solution (KCl+de-aired water) at in situ overburden pressure in a cold storage chamber

To delimit undesirable storage effects, the samples in b) and c) should be stored for as short time as possible. Geochemical simulations may provide information on how K^+ is distributed in the soil volume with time, both in the pore water and on the mineral surface. These calculations can be carried out by for instance the computer program PHREEQC. The improved geotechnical behavior found in c) must be evaluated considering the storage effect found in b).

Helle et al. (Submitted 2015) investigated the long-term effect of treating quick clay with KCl. The improved geotechnical properties regarding fall cone undrained and remolded shear strength and Atterberg limits remain 30-40 years after installing salt wells filled with KCl. Due to its beneficial effect on the remolded shear strength, liquid limit and plasticity, it appears to be well suited for stability measures in quick clay areas as well as for settlement reductions under constructions.

REFERENCES

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

Bjerrum, L. 1955. Norske marine leirers geotekniske egenskaper. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication no. 7.

Bjerrum, L. 1967. Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. *Geotechnique*, 17: 81-118.

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

Bozozuk, M. 1971. Effect of sampling, size, and storage on test results for marine clay. *Sampling of Soil and Rock, American Society for Testing and Materials, Special Technical Publication no. 493*: 121-131.

Eggestad. A.. and Sem. H. 1976. Stability of excavations improved by salt diffusion from deep wells. *In proceedings of the European conference on soil mechanics and foundation engineering*, 6, Vienna, March 1976, pp. 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. and Mack, G. 1990. Den postglaciale landskapsutviklingen på Dragvoll universitetsområde, Trondheim. Norks Geografisk Tidsskrift, 44(3): 131-148.

Helle. T.E., Gjengedal. I., Emdal. A., Aagaard. P., and Høydal. Ø. 2013. Potassium chloride as ground improvement in quick clay areas – A preliminary study. *In Landslides in sensitive clays: From Geosciences to risk management*. Edited by J.-S. L'Heureux. A. Locat. S. Lerouil. D. Demers. and J. Locat. Springer Dordrecht Heidelberg New York London. pp. 63-74.

Helle, T.E., Nordal, S., Aagaard, P., and Lied, O.K. Submitted 2015. Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay – Ulvensplitten, Norway. Submitted to *Canadian Geotechnical Journal*.

Henriksson, M., and Carlsten, P. 1994. Lagringstidens inverkan på prøver tagna med standardkolvprotagare. Available from Statens geotekniska institute. Varia 430

Heymann, G. and Clayton, C.R.I. 1999. Block sampling of soil: Some practical considerations. In Geotechnics for Developing Africa. Edited by Wardle, Blight and Fourie. Balkema, Rotterdam. pp. 331-339.

Hvorslev, M.J. 1949. Subsurface exploration and sampling of soils for civil engineering purposes. Waterways Experiment Station, USA.

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

La Rochelle, P., Leroueil, S., and Tavenas, F. 1986. A technique for long-term storage of clay samples. *Canadian Geotechnical Journal*, 23: 602-605.

Lessard, G., and Mitchell, J.K. 1985. The causes and effects of aging in quick clays. *Canadian Geotechnical Journal*, 22: 335-346.

Løken. T. 1968. Kvikkleiredannelse og kjemisk forvitring i norske leirer. Available from Norwegian Geotechnical Institute, Oslo, Norway. *NGI Publication no. 75.*

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

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

Moum, J., Sopp. O.I., and 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., and Torrance, J.K. 1971. A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. *Geotechnique*, 21(4): 329-340.

Quigley, R.M. 1980. Geology, mineralogy and geochemistry of Canadian soft soils: A geotechnical perspective. Canadian Geotechnical Journal 9: 261-285.

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

Rosenqvist, I.T. 1953. Consideration on the sensitivity of Norwegian quick-clays. Geotechnique 3: 195-200.

Rosenqvist, I.T. 1955. Investigations in the clay-electrolyte-water system. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication no. 9.

Torrance, J.K. 1976. Pore water extraction and the effect of sample storage on the pore water chemistry of Leda clay. *Soil Specimen Preparation for Laboratory Testing, American Society for Testing and Materials, Special Technical Publication no. 599*: 147-157.

Torrance, J.K. 1983. Towards a general model of quick clay development. Sedimentology, 30: 547-555

Torrance, J.K. 1988. Mineralogy, pore-water chemistry and geotechnical behaviour of Champlain Sea and related sediments. *In The Late Quaternary development of the Champlain Sea Basin.* Edited by N.R. Gadd. Geological Association of Canada, Special Paper 35: 259–275.

Paper III

Paper III

NRC Research Press

ARTICLE

Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay — Ulvensplitten, Norway

Tonje Eide Helle, Steinar Nordal, Per Aagaard, and Ole Kristian Lied

Abstract: Re-establishing high salt concentration in leached low-saline, highly sensitive clays significantly improves their mechanical properties. Long-term effects on quick clay exposed to diffusion of potassium chloride (KCl) from salt wells installed in 1972 at Ulvensplitten, Oslo, Norway, are investigated. The increased undrained and remolded shear strengths, as well as increased Atterberg limits, remain 30 to 40 years later. The undisturbed shear strength increased from less than 10 to 25–30 kPa, and the remolded shear strength increased from less than 0.5 to more than 6 kPa. The liquid limit increased beyond the natural water content. Adding KCl to quick clay improved the properties to such an extent that it no longer appears as quick. Recent ground investigations in the area suggest a permanent effect on an engineering time scale. Consequently, the method may be suitable to prevent large flow slides in quick clay areas.

Key words: quick clay, ground improvement, diffusion, potassium chloride, geotechnical properties, geochemistry.

Résumé : Le rétablissement de concentrations élevées en sel dans des argiles lessivées très sensibles et peu salines améliore nettement leurs propriétés mécaniques. Le présent article s'intéresse aux effets à long terme de l'exposition d'une argile extrasensible au chlorure de potassium (KCl) provenant de puits de sel construits en 1972 à Ulvensplitten, près d'Oslo, en Norvège. Les valeurs de résistance au cisaillement sans consolidation, de résistance au cisaillement à l'état remanié et les limites d'Atterberg sont restées à des niveaux élevés après 30 ou 40 ans. La résistance au cisaillement à l'état non perturbé a augmenté, passant de valeurs inférieures à 10 kPa à des valeurs comprises entre 25 et 30 kPa. La résistance au cisaillement à l'état remanié a également augmenté, passant de valeurs inférieures à 0,5 kPa à des valeurs supérieures à 6 kPa. La limite de liquidité s'est accrue jusqu'à dépasser la teneur naturelle en eau. On a constaté que l'ajout de KCl à de l'argile extrasensible améliorait ses propriétés à tel point qu'il perdait son extrême sensibilité. Des études menées récemment sur le terrain montrent que cet effet est permanent à l'échelle de la durée de vie d'ouvrage de génie civil. Ainsi, la méthode proposée dans cet article pourrait permettre de prévenir les glissements par liquéfaction de grande ampleur dans les zones comportant de l'argile extrasensible. [Traduit par la Rédaction]

Mots-clés : argile extrasensible, amélioration du sol, diffusion, chlorure de potassium, propriétés géotechniques, géochimie.

Introduction

Highly sensitive post-glacial marine clays, termed quick clays, present a risk for large landslides such as the Kattmarka landslide in Nord-Trøndelag in 2009 (Fig. 1). Landslides may be induced by natural causes such as erosion, but several large landslides have been triggered by human actions. Landslide susceptibility presents great challenges for construction work, even in the construction of landslide mitigation measures. Establishing large counterfills along rivers and creeks is a commonly used method for increasing slope stability, but often results in undesirable changes to the terrain; whereas, ground improvement offers an alternative that avoids this. Knowledge on geochemistry and its impact on the mechanical behavior in clays is needed in developing efficient ground improvement methods.

Quick clays were deposited in seawater during the deglaciation of Scandinavia, Canada, and northern Russia during the Pleistocene–Holocene transition. The high salt content in the seawater caused the clay minerals to flocculate with an edge to edge, or an edge to face orientation, forming an open house of cards structure with large voids accommodating high water content (Rosenqvist 1946). The bonds between the clay minerals are strong as long as the amount of total dissolved solids (TDS) is high. This relates to the amount of salt in the pore water. Post-depositional changes, such as leaching and diffusion, decrease the TDS content and introduce new ions to the clay–water system. Decreased TDS reduces the attracting forces between the clay minerals, whilst the open fabric remains. Consequently, the structure of the clay loses its strength when remolded. The clay develops high sensitivity, i.e., the ratio between undrained and remolded shear strength increases. In Norway, clays with a remolded shear strength equal to or less than 0.5 kPa are defined as quick clays (Norwegian Geotechnical Society 1982). Quick clays often have sensitivity higher than 30 and a liquid limit lower than the natural water content. This enables the clay particles to float in their own pore water when remolded. Re-establishing a high concentration of salts will change the material behavior in quick clay to such an extent that it no longer appears as quick (Rosenqvist 1946, 1953, 1955; Bjerrum 1955; Løken 1968, 1970; Moum et al. 1968; Quigley 1980; Torrance 1983).

T.E. Helle and S. Nordal. Norwegian University of Science and Technology, Department of Civil and Transport Engineering, 7491 Trondheim, Norway.
P. Aagaard. University in Oslo, Department of Geosciences, P.O. Box 1047 Blindern, 0316 Oslo, Norway.
O.K. Lied. Geovita as, Lilleakerveien 4, 0283 Oslo, Norway.
Corresponding author: Tonje Eide Helle (e-mail: tonje.eide.helle@ntnu.no).
A correction was made to the e-First version of this paper on 27 January 2016 prior to the final issue publication. The current online and print versions are identical and both contain the correction.

Fig. 1. 2009 quick clay slide in Kattmarka. (Photo courtesy of Leif Holme, photographer.)

In 1972, 2629 salt wells filled with potassium chloride (KCl) covering an area of 6000 m² were installed in a quick clay at Ulvensplitten, Oslo, Norway (Fig. 2). The site lies at circa 95 m above sea level, 125 m below the post-glacial marine limit. The intention was to improve the mechanical properties in the quick clay prior to excavation. Ground investigations carried out 2 to 3 years after installation revealed a significant increase in undrained and remolded shear strength as well as in the Atterberg limits, as the measured concentration of potassium (K⁺) increased in the soil volume surrounding the wells. Despite these promising results, the method is not used as ground improvement today, mainly due to the fact that it is time consuming and the effects are not fully understood or documented. However, today's equipment may lead to less time consumption than the installation methods used in the 1970s.

In 2013 new samples were extracted from the salt-stabilized clay at Ulvensplitten, providing unique information on the long-term effect of treating quick clay with KCl. The results presented in this paper contribute to the documentation needed to validate the method. Data from ground investigations carried out prior to, and a few years after, installing the salt wells at Ulvensplitten have been collected and compared to ground investigations carried out 30 to 40 years later, to document the long-term effect of KCl treatment on quick clay.

Salinity and ion composition in post-glacial marine clays

The geotechnical properties of clays are greatly influenced by the electrical forces acting between the clay mineral surfaces. These forces are governed by the ion composition and concentration in the pore water and the clay mineral surface chemistry. Changes in their environment such as temperature, pressure, chemical composition and concentration of ions in the pore water, and pH may alter the clay minerals and change the behavior of the clay (Mitchell and Soga 2005). The properties of clays deposited in seawater are dependent on the TDS and ion composition of the environment in which they accumulated. The TDS in the depositional environment of the post-glacial marine clays, and also the ion composition, may have been influenced by the distance from the ice sheet. Moum et al. (1971) assume a TDS in the depositional envi-

ronment for the Drammen clay of around 30 g/L. Today the salt content in seawater is approximately 35 g/L, highly dominated by sodium (Na⁺) and chloride (Cl⁻) (Appelo and Postma 2005).

According to Rosenqvist (1946), subsequent leaching and diffusion in clays deposited in a marine environment leading to dilution of TDS is essential for quick clay development. This occurs when post-glacial isostatic uplift elevates the clay above sea level, exposing them to meteoric groundwater flow. The repulsive forces between the clay mineral surfaces increase by decreasing TDS. At TDS of less than 5–10 g/L, the repulsive forces may increase to such an extent that the remolded shear strength may decrease to less than 0.5 kPa (Bjerrum et al. 1969). Leached clays with a TDS of less than 1 g/L may behave as a liquid when remolded, depending on the ion composition in the pore water (Bjerrum et al. 1969; Moum et al. 1971). As well as diluting TDS, leaching water introduces new ions to the clay–water system. The ion composition in groundwater is particularly influenced by redox reactions, chemical weathering, mineral dissolution, ion exchange reactions, and biological degradation. These processes cause the ion composition in the groundwater to be dominated by Mg²⁺ and Ca²⁺ (Appelo and Postma 2005). Various cations have different impact on the clay behavior. Consequently, low TDS in itself does not necessarily cause clays to become quick. However, at low TDS, the ion composition in the pore water has a great impact on the development of quick clays (Moum et al. 1971). The percentage of monovalent ions in the pore water is then especially relevant.

Sodium (Na⁺), potassium (K⁺), magnesium (Mg²⁺), and calcium (Ca²⁺) are the most common cations occurring in the pore water in clays. The pore water in quick clays is dominated by Na⁺ (Moum et al. 1971; Torrance 1988). The percentage of monovalent cations over the total amount of major ions in the pore water is calculated by eq. (1). All concentrations are given in milliequivalents per litre (meq/L). Seawater has a monovalent percentage of 75% (Mitchell and Soga 2005). Clays with low TDS and a monovalent ion composition in their pore water exceeding this level may develop high sensitivity as seen in the collected data in Moum et al. (1971) and Hilmo (1989).

Fig. 2. Salt-treated area (shaded) at Ulvensplitten showing location of ground investigations. Those presented in Eggestad and Sem (1976) have bold fonts and are marked E&S 1976. Recent investigations carried out in 2013 also have bold fonts. Information on type and year for the other ground investigations is found in Fig. 6. The coordinates are given in UTM 32 EUREF 89.
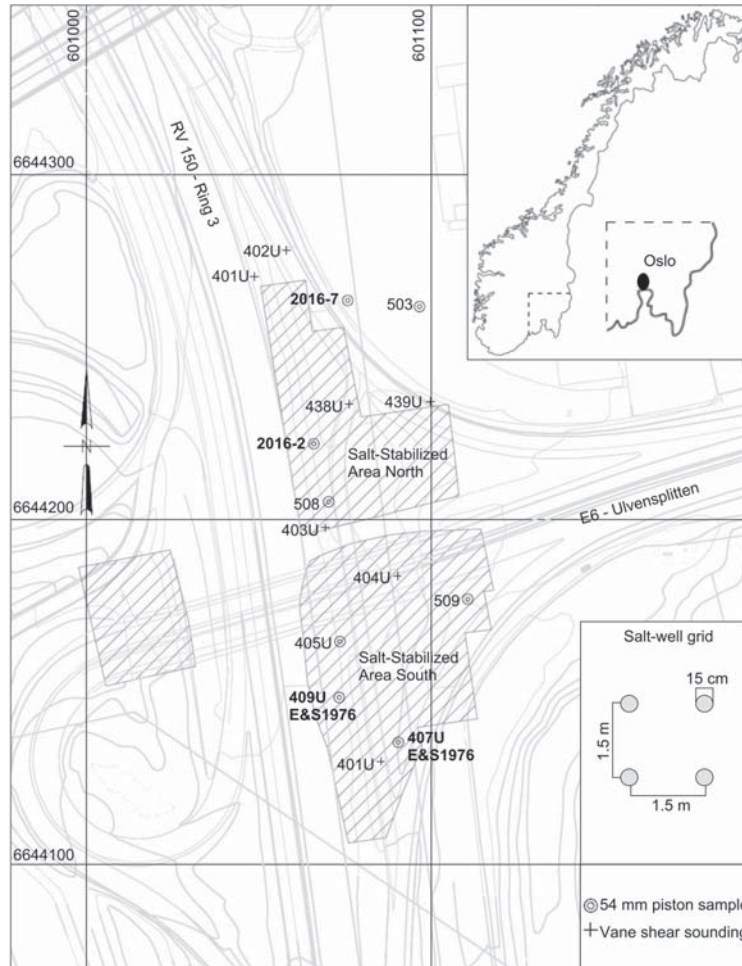
$$(1) \qquad \frac{Na^+ + K^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}} \times 100$$

Leaching and diffusion change the composition of the pore water by introducing weathering products, such as dissolved cations of higher exchange power and valence. Clay minerals are normally negatively charged, attracting cations to their surface. The exchange power increase of the normally occurring ions in clays follows the order: $Na^+ < K^+ < Mg^{2+} < Ca^{2+} <$ aluminum, $Al^{3+} <$ iron, Fe^{3+} (Mitchell and Soga 2005). The adsorbed ions on the clay mineral surface are highly influenced by the ion composition in the pore water. Na^+ is originally abundant in the adsorbed positions in post-glacial marine clays as their pore water composition was dominated by Na^+. In clay–water systems containing both mono- and divalent ions, divalent ions are more abundant on the mineral surface than monovalent. In quick clays, accessible ions in the pore water that have higher affinity than Na^+ to the clay mineral surface are preferentially adsorbed on the

mineral surface, releasing the originally adsorbed Na^+ into the pore water. Consequently, the ion composition in the pore water in quick clays is still dominated by Na^+. Divalent ions may also be removed from the pore water by organic matter, further encouraging quick clay development (Söderblom 1969; Lessard and Mitchell 1985).

After a sufficiently long period, the natural processes of leaching and diffusion will alter a quick clay so that it loses the properties that rendered it quick. As this progresses through the quick clay deposit, the remaining concentration of Na^+ in the pore water will be depleted. The clay will with time be dominated by divalent ions both in the pore water and in the adsorbed positions, inhibiting high sensitivity (Talme et al. 1966; Moum et al. 1971; Andersson-Sköld et al. 2005).

Chemical impact on geotechnical properties

In low permeability clays ($k_h < 1 \times 10^{-10}$ m/s), the migration of salt is dominated by diffusion (Appelo and Postma 2005; Mitchell

and Soga 2005). K^+ has the highest diffusion coefficient of the major ions. Moum et al. (1968) tested how various salts influenced the geotechnical properties in a quick clay from Alna, Oslo. The mineralogy was dominated by illite and chlorite, a normal occurring mineral composition in Norwegian and Swedish glaciomarine clays (Rosenqvist 1955; Løken 1968). The clay samples were kept in their sampling tubes at 7 °C. The upper 12 cm of the clay was removed, and replaced by various types of salt and stored for 85 days. This allowed evaluation of the diffusion coefficient and the impact of the salts on the strength parameters of undisturbed clay samples. Aluminum chloride ($AlCl_3$) showed the largest increase in the remolded shear strength (c_{ur}). However, it also lowered the pH in the clay considerably, inducing clay mineral alteration. Aluminum (Al^{3+}) may form polymeric hydroxy aluminum and precipitate as gels at pH > 5. At high concentrations, these gels may even encapsulate dissolved ions, inhibiting diffusion into the surrounding clay (Bryhn et al. 1985). Among the various salts tested, Moum et al. (1968) concluded that KCl showed the best effect on the geotechnical properties as well as having the highest diffusion coefficient. A concentration of K^+ of only 0.5 g/L was sufficient to increase the remolded shear strength to about 9 kPa (Fig. 3), reducing the sensitivity from more than 100 to 2.2. The maximum increase of undrained shear strength (c_u) was around 60%. Other studies confirm that K^+ has high impact on the remolded as well as the undrained shear strength, and also on the Atterberg limits, especially the liquid limit (w_L) (Løken 1968, 1970; Helle et al. 2013). KCl is readily accessible, cheap and highly soluble in water. Based on these findings, salt wells filled with KCl were installed in a quick clay at Ulvensplitten, Oslo, Norway, in 1972.

Salt stabilization at Ulvensplitten in 1972

A new highway crossing the Ulvensplitten area was constructed in the 1970s. The existing road was lowered by 3–4 m and the project also included a bridge, several ramps, and deep trenches for water supply and sewers. The very sensitive and soft clay in the area caused major challenges for ensuring ground stability (Eggestad and Sem 1976). Salt wells were installed in the period April to June 1972 and filled with solid KCl. The three shaded areas shown in Fig. 2 were treated with KCl to improve the geotechnical properties. A total of 2629 salt wells covering an area of 6000 m² were installed in the areas denoted salt-stabilized area north and south in Fig. 2. The shaded area west of ring 3 was used for a small scale test. No records have been found of ground investigations in this area.

Soil properties

The subsurface in the Ulvensplitten area is well documented. Ground investigations were carried out in the years before and for a couple of years after installation to observe the salt migration and the effect on the mechanical properties. The ground investigations from the 1960s and 1970s include seven vane shear soundings and three boreholes with 54 mm piston samples (Fig. 2 and Table 1).

Underneath the 3 m thick dry crust, soft clay with decreasing shear strength and quick behavior was originally found down to 6 m depth below terrain (Fig. 4). Very soft quick clay was found below this level, from 6 to 15 m depths in the areas later stabilized with salt wells. From 15 m downwards, the clay contained gravel and sand and here a moderate sensitivity (~8) was detected. A typical soil profile for the pre-stabilized clay is presented in Fig. 4, showing data from borehole 409U. Clay of low sensitivity was present at the same depths in the area east of area north. Depth to bedrock in the Ulvensplitten area is between 20 and 35 m (Eggestad and Sem 1970a, 1974). The clay content is 40%–45%. The bulk mineralogy consists of illite (40%–45%), chlorite (15%–20%), quartz (15%–20%), feldspars (15%), and traces of hornblende (<5%) and montmorillonite (<5%) (Eggestad and Sem 1976; Morel-Vulliez

et al. 2013). The clay is 100% saturated with an original void ratio of around 0.91.

Pore pressure measurements in hydraulic piezometers installed next to borehole 508 from January 2004 to June 2006 show pore pressures with depth slightly higher than hydrostatic. The groundwater table is found 2 m below terrain surface. At 13 m depth pore pressure is around 120 kPa, and at 20 m depth it is around 205 kPa, corresponding to a water column fluctuating between the terrain surface and about 0.5 m above the terrain (Stuvøy et al. 2007).

Fig. 3. Impact of increasing concentration of potassium (K^+) on undrained and remolded shear strength (data from Moum et al. 1968).
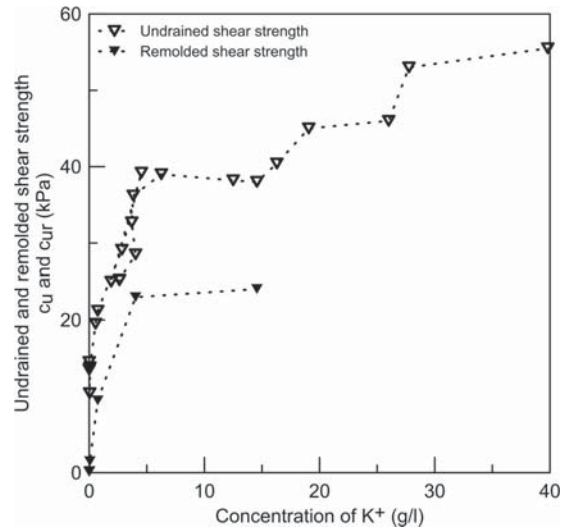
Table 1. Ground investigations sorted by area.

	Borehole No.	Year of investigation
Salt-stabilized area north		
Before stabilization	403U[*]	1970
	438U[†]	1970
After stabilization	508[‡]	2002
	2016-2[§]	2013
Outside salt-stabilized area north		
	401U[*]	1970
	402U[*]	1970
	439U[†]	1970
	503[‡]	2002
	2016-7[§]	2013
Salt-stabilized area south		
Before stabilization	404U[‖]	1967
	409U[‖,¶]	1967
	410U[‖]	1972
After stabilization	405U[‖]	1974
	410U[‖]	1973
	407U[‖,¶]	1974
	509[‡]	2002

[*]Eggestad and Sem 1970a.
[†]Eggestad and Sem 1970b.
[‡]Stuvøy et al. 2007.
[§]Morel-Vulliez et al. 2013.
[‖]Eggestad and Sem 1974.
[¶]Eggestad and Sem 1976.

Fig. 4. Soil profile of pre-stabilized soil. Borehole 409U in area south.

Fig. 5. Concentration of K$^+$, water content, and undrained and remolded shear strength with distance to the well at 5.5 m depth, 21 months after installation. The results are from the part of area south where the salt wells were installed by the wash-boring method. (Reproduced from Eggestad and Sem 1976).
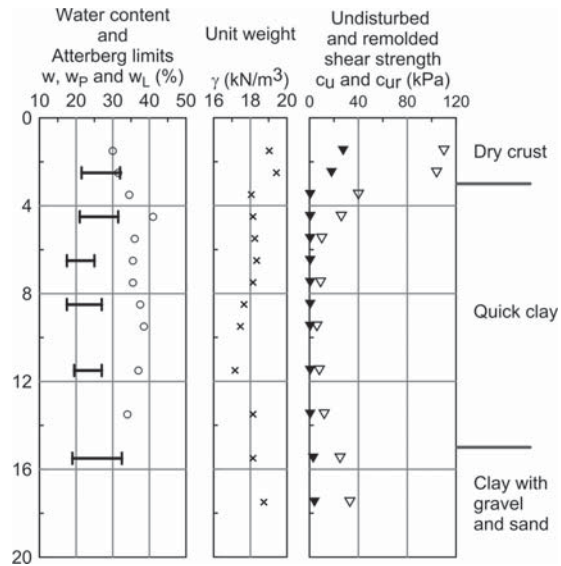
Installation of salt wells

Sand drain technology commonly used at that time was applied for installing the salt wells, employing either wash boring or mandrel drilling. A large amount of water was necessary for the wash-boring method to minimize drilling time. The holes were emptied by compressed air before pouring solid KCl into the holes till it reached the terrain surface. The mandrel method was carried out by steel pipes with a closed lid in the bottom. This may have led to severe disturbance of the clay surrounding the wells. Solid salt was poured directly into the steel pipes before extracting the pipes from the ground. The salt clogged in the pipes as it was extracted from the ground. This was, however, solved by slightly increasing the air pressure in the top of the pipe. The homogeneity of the salt columns is consequently likely to have varied (Eggestad and Sem 1976).

Installation lasted from 4 April to 25 September 1972. The wells had a diameter of 15 cm and were installed to a depth of 15–16 m. They were positioned in a grid pattern with a center to center distance of 1.5 m (Fig. 2). Total salt consumption was 640 t. Using the technology of the day, installation was not without its problems, and some of the clay was remolded in the boreholes, limiting their effective depth. Furthermore, the boreholes made by wash boring may have deformed before salt was poured in. Mud on the ground surface due to the wash-boring method made it difficult to install the wells in the planned grid. Consequently, the distance between the wells may vary (Eggestad and Sem 1972, 1974, 1976). Modern drilling methods may be considerably more efficient.

Migration of K$^+$ from the salt wells during 1972 to 1974

Prior to installation of salt wells, Eggestad and Sem (1976) reported 350–470 mg/L of Na$^+$ in the pore-water composition in the quick clay in area south. Small amounts of K$^+$ (31–33 mg/L), Mg^{2+} (20–34 mg/L), and Ca^{2+} (13–20 mg/L) were found. After installation, the concentration of K$^+$ in the clay surrounding the salt wells increased rapidly. After 10 months, it was evident that the salt migration influenced the shear strength of the clay to a distance of 50 cm from the well, with a maximum increase of 200% at a distance of 5–25 cm from the well. After 14 months, the salt mi-

gration increased the shear strength over a distance of 60–65 cm (Eggestad and Sem 1974). Figure 5 presents the distribution of K$^+$ and undrained and remolded shear strength with distance from the well 21 months after installation at a depth of 5.5 m. At 60 cm from the well, the concentration of K$^+$ by that time had increased to approximately 50 mg/L. At this concentration, the undrained shear strength had increased from 20 to 28.5 kPa, and the remolded shear strength from less than 0.5 to 3.5 kPa.
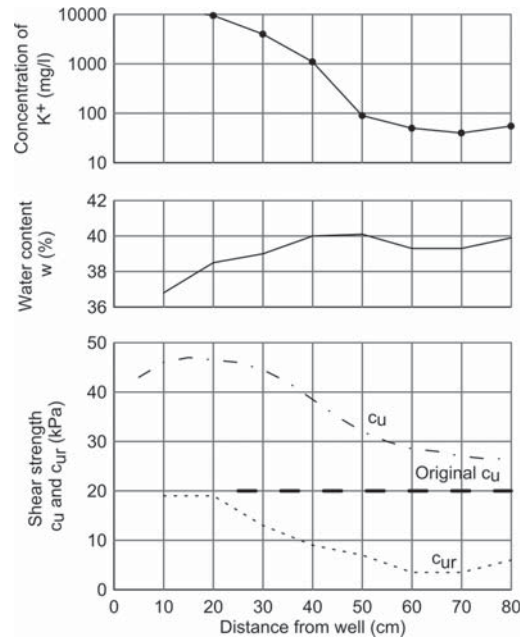
Impact of KCl on geotechnical properties

Eggestad and Sem (1976) presented the results from borehole 409U as the pre-condition (Fig. 6a), and 407U as the condition after stabilization (Fig. 6b). Both boreholes are located within area south (Fig. 2). After 22 months, the introduction of KCl to the quick clay had changed the behavior of the clay completely. An interesting observation is that the salt wells led to a slight decrease of around 5% in the water content and an increase in the density. This is a result of increased dissolved solids in the pore water. Consequently, the porosity and void ratio decreased from around 0.48 to 0.46 and around 0.91 to 0.85, respectively. The undrained shear strength in the quick clay rose from around 10 kPa to the order of 25–45 kPa after 22 months (Figs. 6a and 6b). The remolded shear strength increased greatly, from less than 0.5 kPa to the order of 10–45 kPa, which reduced the sensitivity from 12–80 to 1–3. The considerable variability in the remolded shear strength increase with depth in borehole 407U may be a result of an uneven distribution of the salt column. The clay initially had a liquid limit below the natural water content (Fig. 7a), but with increasing salt content the liquid limit increased beyond the natural water content (Eggestad and Sem 1974, 1976). Eggestad and Sem (1976) concluded that even small amounts of K$^+$ decreased the sensitivity of the clay considerably.

Fig. 6. Undrained (open symbols) and remolded (filled symbols) shear strength with depth in (*a* and *b*) area south and (*c* and *d*) inside and (*e*) outside area north before and after treating the areas with potassium chloride.

a) Area South: before stabilization
b) Area South: after stabilization
c) Area North: before stabilization
d) Area North: after stabilization
e) Outside salt stabilized area North

a) Area South: before stabilization
- 404U Vane (1967)
- 409U Fall cone (1967)
- 410U Vane before (1972)

b) Area South: after stabilization
- 410U Vane after 9 months (1973)
- 405U Fall cone (1974)
- 405U Unconfined (1974)
- 407U Fall cone 22 months after (1974)
- 509 Fall cone (2002)

c) Area North: before stabilization
- 403U Vane (1970)
- 438U Vane (1970)

d) Area North: after stabilization
- 508 Fall cone (2002)
- 2016-2 Fall cone (2013)

e) Outside area North
- 401U Vane (1970)
- 402U Vane (1970)
- 439U Vane (1970)
- 503 Fall cone (2002)
- 2016-7 Fall cone (2013)

Ulvensplitten 30 to 40 years after installation

Three boreholes with 54 mm piston samples, boreholes 503, 508, and 509, were carried out in 2002 and two more boreholes, 2016-2 and 2016-7, in 2013 (Fig. 2 and Table 1). The results from these boreholes are compared to the ground investigation results from the 1960s and 1970s. Undrained and remolded shear strength from vane shear soundings, fall cone and unconfined shear test-ing are compared, as well as water content and Atterberg limits. Chemical data were collected on the samples from the recent investigations in 2013. The concentration of ions in the pore water in cores 2016-2 and 2016-7 was analyzed at the laboratory at the Department for Geosciences at the University in Oslo. The cations were analyzed using a Dionex ICS-1000 Ion Chromatography Sys-tem (ICS-1000), and the anions were analyzed using a Dionex

Fig. 7. Water content and Atterberg limits in (*a*) area south, (*b*) inside salt-stabilized area north, and (*c*) outside salt-stabilized area north.
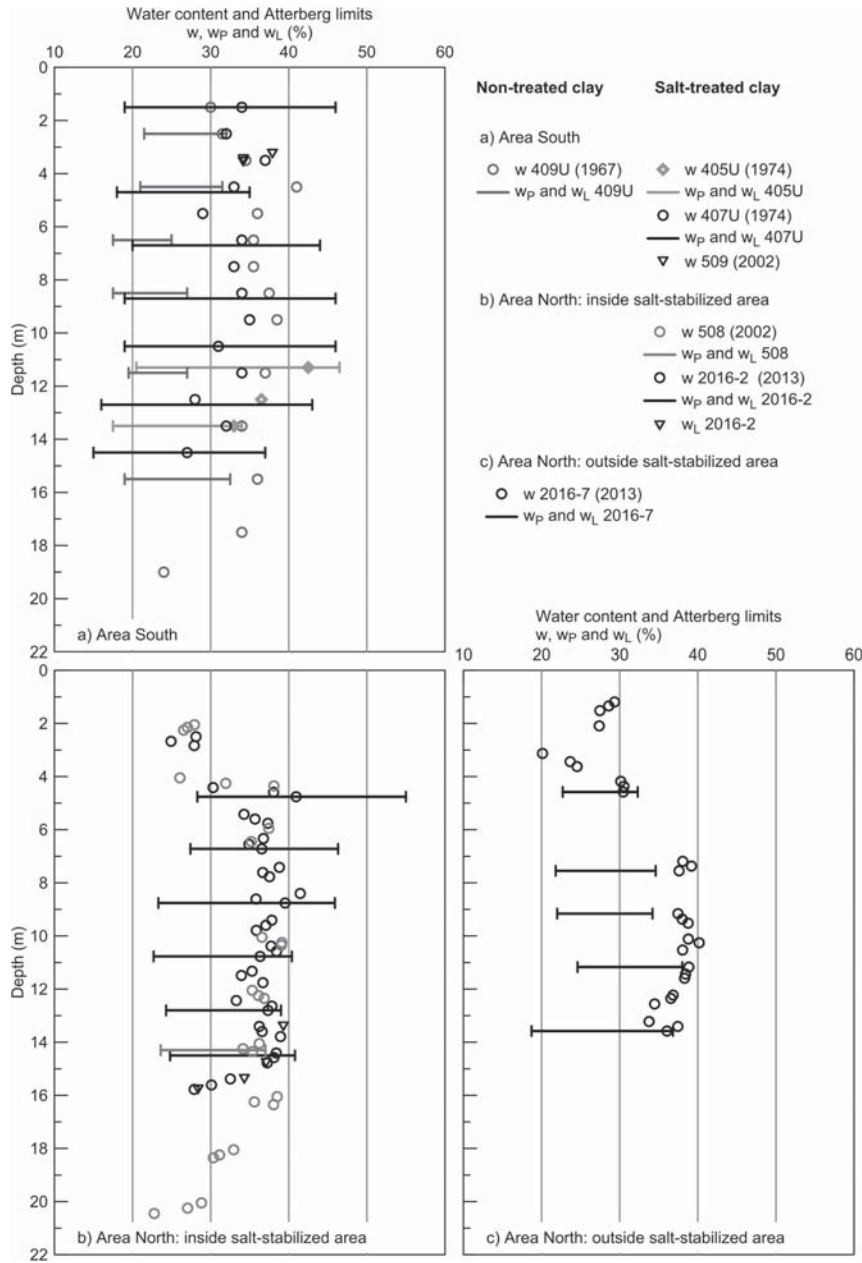
ICS-2000 Ion Chromatography System (ICS-2000). Both machines were calibrated using a standard solution before running the tests. The alkalinity was determined by HCl titration in Metrohm 702 SM Titrino, and pH measured in the pore water by the Methrom 702 SM Titrono at 25 °C.

Geotechnical properties 30 to 40 years after installation

The positioning of borehole 509 in relation to the salt well is unknown. Nevertheless, the undrained shear strength was 39 kPa

and the remolded shear strength, 9 kPa (Stuvøy et al. 2007), which is close to the values found in borehole 407U at the same depths nearly 30 years earlier in 1974 (Fig. 6*b*).

The results from gathering data outside, but in close vicinity to area north, are scattered. Both old and new investigations, except from 401U, are in nonsensitive clay (Fig. 6*e*). However, the natural water content is nevertheless higher than the liquid limit, w_L (Fig. 7*c*). The water content in the clay deposits inside and outside

Fig. 8. Total dissolved solids in the pore water inside (borehole 2016-2) and outside (borehole 2016-7) salt-stabilized area north.
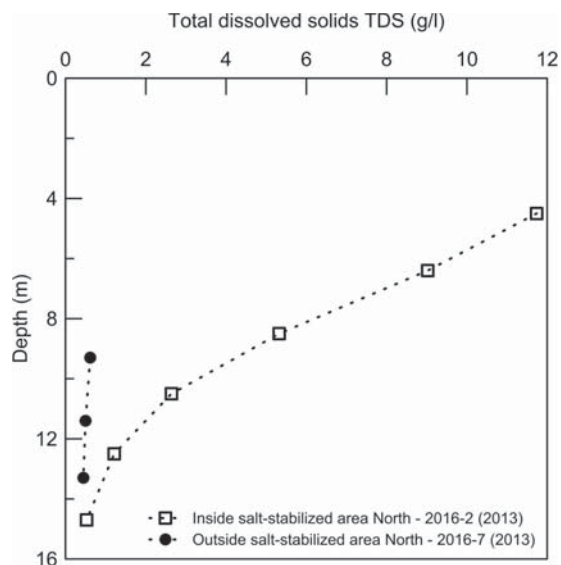
area north is approximately the same (Figs. 7b and 7c). It is evident that introducing KCl to the clay–water system has increased the undrained shear strength significantly (Figs. 6c, 6d, and 6e). Inside the salt-stabilized area, the undrained shear strength has increased to about the same levels as found in the area south in 1974 (Figs. 6c and 6d), i.e., from around 8–9 kPa to 25–30 kPa. The impact on the remolded shear strength is lower in area north (Fig. 6d) than in area south (Fig. 6b). Nevertheless, it increased from less than 0.5 kPa to around 6 kPa, reducing the sensitivity in the quick clay from more than 100 to 3–5.

No Atterberg limits were determined for the clay in area north prior to installation of the salt wells. Quick clays normally have higher natural water content than their liquid limits. Consequently, the increased liquid limits in Fig. 7b are a direct consequence of the increased concentration of K^+. The clay samples from the recent investigations outside the salt-stabilized area north (borehole 2016-7) are characterized by medium plasticity with a liquid limit lower than the natural water content (Fig. 7c). The clay extracted from inside area north (borehole 2016-2) has high plasticity. The clay's plasticity reduces to medium plasticity with decreasing K^+ concentration with depth. The plasticity index (I_P) is not comparable between area south and area north due to deviating plastic limits (Fig. 7). The liquidity index (I_L) in the two salt-stabilized areas is decreased to values below 1 as a result of the increased concentrations of K^+.

Geochemical properties 30 to 40 years after installation

The TDS outside the salt-stabilized area north is in the range 0.44–0.68 g/L (Fig. 8). Inside the salt-stabilized area, the TDS decreases from about 12 g/L at 4.5 m depth to 0.5 g/L at 14.5 m depth. The dilution of TDS with depth may be a result of artesian water bringing dissolved ions upwards in the profile, combined with a downward and outward diffusion towards clay with low TDS. This was also detected in natural clay deposits by Moum et al. (1971) and Torrance (1988). The pore water in the salt-treated clay has been diluted by freshwater over the last 40 years. However, K^+ (Fig. 9b) and chloride, Cl^- (Fig. 9e), are still abundant. As K^+ enters the adsorbed positions on the clay mineral surface, Na^+, Mg^{2+}, and

Ca^{2+} are released into the pore water, increasing their concentrations (Figs. 9a, 9c, and 9d).

The geochemical profiles from the ground investigations carried out in 2013 are from the salt-stabilized area north, whereas the geochemical profile presented by Eggestad and Sem (1976) is from the quick clay deposit in area south before stabilization. The pore-water composition in the nontreated and originally also less sensitive clay outside salt-stabilized area north deviates from the ion composition found in the original quick clay deposit in area south (Fig. 9). This is especially the case for the Na^+ concentration (Fig. 9a) from area south and outside area north (borehole 2016-7). The percentage of monovalent ions of the total amount of major ions is around 85% in the pore water in the pre-stabilized quick clay deposit from area south. In the nonquick clay outside area north (2016-7), it is decreasing from 80% at 5.5 m depth to 44% at 14.5 m depth. This might explain the nonquick behavior even though the natural water content exceeds the w_L.

No change in pH is presently detected in the clay inside or outside the salt-treated area. Consequently, there has been no mineral degradation due to increased KCl concentration. The pH in both boreholes is around 8.4 down to 12.5 m depth. At 14.5 m depth, it is around 8.2. At the prevailing pH the alkalinity is controlled by bicarbonate (HCO_3^-). Carbonate and silicate weathering may release Mg^{2+} and Ca^{2+} to the groundwater. Dissolution of carbonates releases Ca^{2+} and HCO_3^-. The alkalinity outside area north (borehole 2016-7) is higher than inside area north (borehole 2016-2 in Fig. 9f). Consequently, the higher proportion of divalent ions in borehole 2016-7 may be due to the ion composition in the leaching water and to mineral weathering.

Discussion

The collected ground investigation data from the 1970s and during recent years confirm the changes in geotechnical properties as a result of introducing K^+ to quick clay. The soil investigations reported in Eggestad and Sem (1976) are from the mandrel-drilling area in area south, whereas the recent sampling from 2013 was carried out in area north with no reference to distance to individual salt wells. The piston sample 2016-2 from 2013 was extracted within the wash-boring area in area north. While the data from Eggestad and Sem (1976) are not fully comparable with the new investigations, it is clearly evident that the improved clay behavior remains 30 to 40 years after installation.

The planned installation depth of the salt wells was 15 m. The obtained depths, inclination, and distance between the wells may vary within the salt-stabilized areas due to installation challenges, including remolding of the clay and mud on the surface. Even the results from the geotechnical investigations in the years after installation of the salt wells may be affected by the fact that the clay surrounding the wells, especially in the mandrel-drilling area, was remolded. The changed strength properties of the clay thus represent a combination of reconsolidation and diffusion (Eggestad and Sem 1976). Furthermore, the salt columns in the wells dissolved in water. This may have left behind water-filled wells free to deform in the years after installation. The salt columns installed by the mandrel-drilling method may not have been homogenous. This could explain the wide variation with depth in the remolded shear strength increase 22 months after installation (borehole 407U in Fig. 6b). With time, diffusion has evened out the differences in TDSs in the soil volume. The geotechnical investigations carried out in 2013 show increased undrained and remolded shear strength in the whole profile, as well as increased liquid limits.

Moum et al. (1968) calculated the time of an effective diffusion distance of K^+ from a well with a diameter of 15 cm. The effective diffusion distance is defined in their study by the concentration front of 0.5 g K^+/L. They concluded that a soil volume with a radius of 75 cm out from the well will be stabilized after 22 months. At a

Fig. 9. Ion concentrations in the pore water inside and outside the salt-stabilized area north and in the original pore water of the quick clay prior to installation of salt wells in area south, as presented by Eggestad and Sem (1976): (*a*) Na⁺; (*b*) K⁺; (*c*) Mg²⁺; (*d*) Ca²⁺; (*e*) Cl⁻; (*f*) alkalinity.
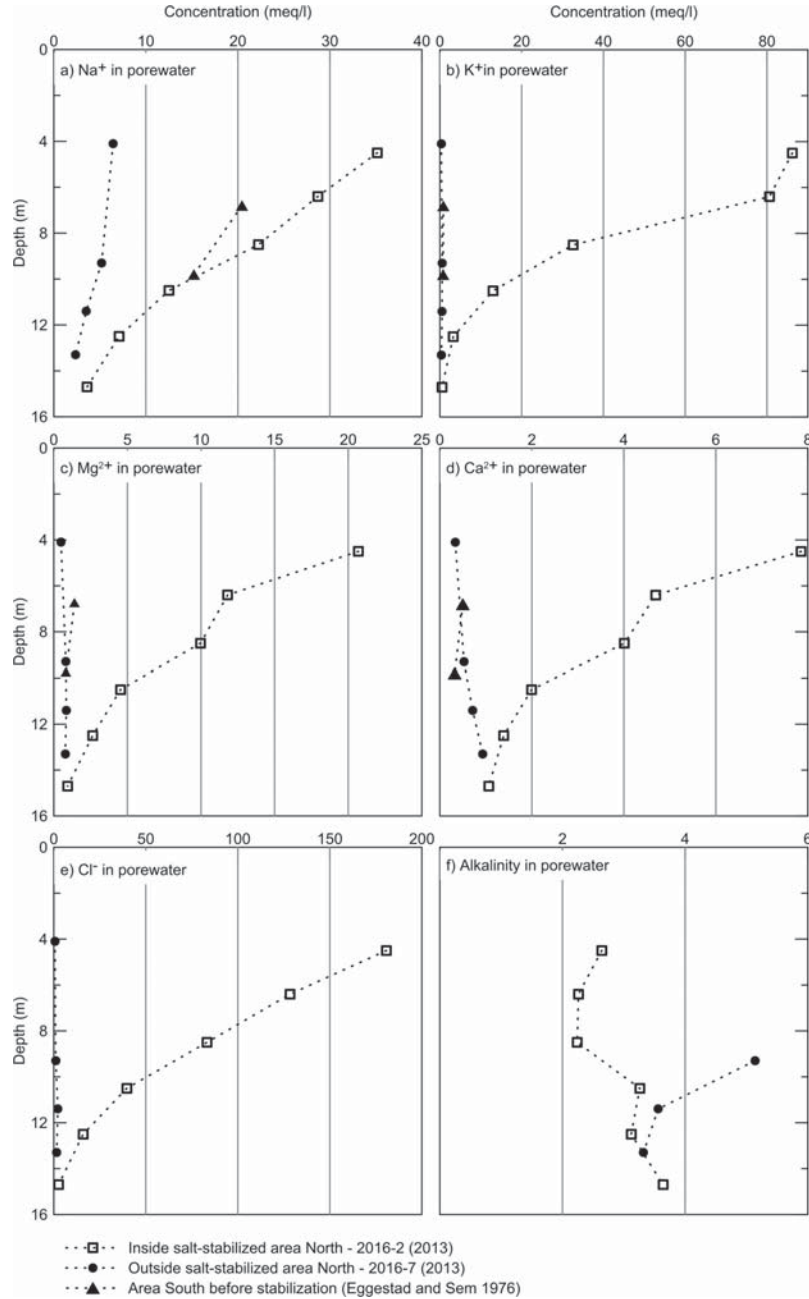
concentration of 0.7 g K⁺/L, they found that shear strength had increased approximately 60%, and sensitivity had fallen dramatically from greater than 100 down to 2.2. Twenty-one months after installation of the salt wells at Ulvensplitten, the concentration of K⁺ 75 cm from the salt well was around 0.5 g/L (Fig. 5). A shear

strength increase of 35% was found. Even though the Ulvensplitten clay had a lower percentage shear strength increase, the clay had a higher shear strength originally than the Alna clay used in the study by Moum et al. (1968). The laboratory study by Helle et al. (2013) indicates that there is an upper limit, with further increase

in solute concentration not necessarily leading to further increases in the undrained and remolded shear strengths. This is also seen in the recent sampling at Ulvensplitten from 2013. The higher TDS in the upper part of the profile in borehole 2016-2 (Fig. 8) has not induced higher shear strength than in the deeper soil with lower TDS (Fig. 6d). The higher TDS may, however, still provide a reservoir keeping TDS high over time in the treated soil volume.

The present ion composition in the pore water in area north (borehole 2016-2) is dominated by K^+ decreasing towards 14.5 m depth, likewise the percentage of monovalent cations over the total amount of major ions decreases (Fig. 10c). This decrease with depth might be due to a shallower installation depth than anticipated in combination with leaching of freshwater into the clay–water system, and diffusion to the surrounding clay volume. The increased concentrations of Na^+, Mg^{2+}, and Ca^{2+} (Figs. 9a, 9c, and 9d) in the pore water may indicate that K^+ has entered the adsorbed positions on the clay mineral surface.

Considering TDS versus increased undisturbed and remolded shear strength from 6.5 m depth downwards, the undrained fall cone shear strength seems almost unaffected by the TDS (Fig. 10a). The remolded shear strength, however, increases with increasing TDS (shaded area in Fig. 10a). Eggestad and Sem (1976) found an increase in the remolded shear strength up to the original undrained shear strength in the wash-boring area (Fig. 5). The liquidity index increases with decreasing TDS (Fig. 10b). Nevertheless, it is lower than 1.2. According to Leroueil et al. (1983), sensitive clays with a liquidity index of higher than 1.2 may be susceptible to flow slides. Considering the percentage of monovalent cations over the total amount of major ions (eq. (1)), it is lower than 75% at a TDS of less than 5 g/L (Fig. 10c). A higher proportion of divalent ions has entered the pore water, maintaining the increased undrained shear strength and inhibiting quick behavior (Fig. 10e).

According to van Olphen (1977), the higher the ion concentration is in the pore water, the thinner the diffuse double layer is. Furthermore, the thickness of the double layer is decreased by a factor of 2 in a divalent solute compared to a monovalent solute at the same normality. In the salt-stabilized clay in area north at Ulvensplitten, the pore water at around 6.5 m depth is dominated by monovalent ions. The TDS is 9 g/L. The calculated thickness of the diffuse double layer is only 0.8 nm (Fig. 10d). At 14.5 m depth, the pore water is dominated by divalent ions having a TDS of 0.5 g/L and the diffuse double layer is 3 nm thick. Even though the undrained shear strength is the same, the remolded shear strength has decreased from 11 kPa to around 3 kPa. The increased thickness of the diffuse double layer, increasing the repulsive forces, may account for this. The clay at 13.5 m depth in the clay outside of the salt-stabilized area north has equivalent undrained and remolded shear strength as well as calculated thickness of the diffuse double layer similar to the clay within the salt-stabilized area north. The thickness of the diffuse double layer seems to affect the remolded shear strength more than the undrained shear strength. The remolded shear strength increases with decreasing thickness of the diffuse double layer, as seen in the shaded area in Fig. 10d.

The yield stress, remolded shear strength, and Atterberg limits increase with increasing TDS due to its impact on depressing the diffuse double layer. Consequently, at high TDS the composition of ions in the pore water is of less importance (Bjerrum 1954; Rosenqvist 1955; Bjerrum and Rosenqvist 1956; Bjerrum et al. 1969; Løken 1970; Torrance 1975, 1999; Quigley 1980; Locat and Demers 1988). However, as the pore water salinity decreases towards 5 g/L, the composition of ions plays a major role in the soil's behavior (Bjerrum et al. 1969; Torrance 1999). The adsorbed cations' ability to increase the remolded shear strength follows the order: $Na^+ < Fe^{2+} \leq Mg^{2+} \leq Ca^{2+} < Fe^{3+} < K^+ < Al^{3+}$ (Løken 1968). The Atterberg limits are increased by adsorbed cations in the following order: $Na^+ < Fe^{2+} = Mg^{2+} = Ca^{2+} < Fe^{3+} < Al^{3+} = K^+$ (Løken 1970).

Løken (1970) presents results showing that the remolded shear strength is increased far less by adding $MgCl_2$ or $CaCl_2$ than KCl at the same normality. However, the remolded shear strength was increased compared to the clay treated with NaCl. Torrance (1999) reports results on Ca-saturated clay compared to Na-saturated clay at the same water contents. The yield stress is much higher in the Ca-saturated clay even at lower concentrations than of Na^+. This is due to the fact that divalent ions have a greater effect on suppressing the electric diffuse double layer.

Forty years after installation of the salt wells, the concentration of K^+ remains high in borehole 2016-2 located in salt-stabilized area north. Even though the salt content decreases, the salt-treated quick clay has significantly changed properties compared to untreated quick clay. The beneficial change in properties remains unaltered at the present time. The clay–water system at Ulvensplitten is slowly changing as leaching water enters the system. The leaching water will contain higher proportions of divalent ions than the originally Na^+-dominated pore water. With time, leaching and diffusion will decrease TDS and remove Na^+ and K^+ from the system. Assuming constant TDS of 0.5 g/L with an ion composition consisting only of Ca^{2+} and HCO_3^-, the calculated thickness of the diffuse double layer is 2.8 nm. This corresponds to a remolded shear strength of around 4 kPa (Fig. 10d) as found for the double layer thickness in the Ulvensplitten clay. As the pore water with time will have a larger fraction of divalent ions, the remolded shear strength will increase as the thickness of the diffuse double layer decreases, weakening the repulsive forces.

Divalent ions have higher affinity than monovalent ions, and will replace the adsorbed Na^+ and K^+ on the mineral surface. The yield stress, remolded shear strength, and the Atterberg limits in the salt-stabilized areas may be changed as the proportion of Mg^{2+} and (or) Ca^{2+} with time increases in the pore water. Even though the improved properties of the clay in the beginning are caused by the high TDS, the improvement will most likely remain as cations of higher affinity and ability to maintain the changed behavior will dominate the clay–water system. Small amounts of iron and (or) aluminum compounds may be present at the prevailing pH as coatings on the particles. These compounds may form cementing bonds that increase the undrained shear strength of the clay. Increasing amounts of iron and (or) aluminum may also with time increase the remolded shear strength (Torrance 1990). More research is needed on how various cations affect the geotechnical parameters and to what extent. However, it seems to be a valid conclusion that clay treated with KCl will remain nonquick, and not regain its high sensitivity within the lifetime of normal engineering works.

The shear strength increase as a result of treating the quick clay with KCl is low compared to for instance lime-cement piles. Thus the method may not be applicable in projects that demand high undrained shear strength. Nevertheless, the clay changes its behavior completely with respect to increased remolded shear strength and liquid limit. The method appears to be applicable as safety mitigation in slide-prone quick clay slopes. A slope failure in clay slopes treated with KCl will not develop into large slides as the movement of the slide debris will be moderate due to high remolded shear strength and increased viscosity. By installing salt wells with a smaller center to center distance and maintaining a high concentration of KCl in the wells, the time necessary to improve the geotechnical properties may be reduced. The time it takes for KCl to diffuse into the clay volume depends on the clay content, mineral composition, permeability, water-filled porosity, initial ion composition in the pore water, and the cation exchange capacity of the soil. Thus thorough investigations prior to installation to define these factors are necessary to achieve good results. Changing the soil–water environment activates processes that go on until the soil–water system regains equilibrium. Consideration of which salt to use for ground improvement to limit the effect on the physiochemical environment is necessary, espe-

Fig. 10. The impact of total dissolved solids (TDS) 40 years after salt well installation on (*a*) undrained and remolded shear strength and (*b*) liquidity index. (*c*) Correlation between TDS and percentage of monovalent cations over total amount of major cations. (*d*) Impact of the thickness of diffuse double layer on undrained and remolded shear strength. Dashed line shows a calculated TDS of 0.5 g/L solely consisting of Ca^{2+} and HCO_3^-. (*e*) Impact of percentage of monovalent cations over total amount of major cations on undrained and remolded shear strength.
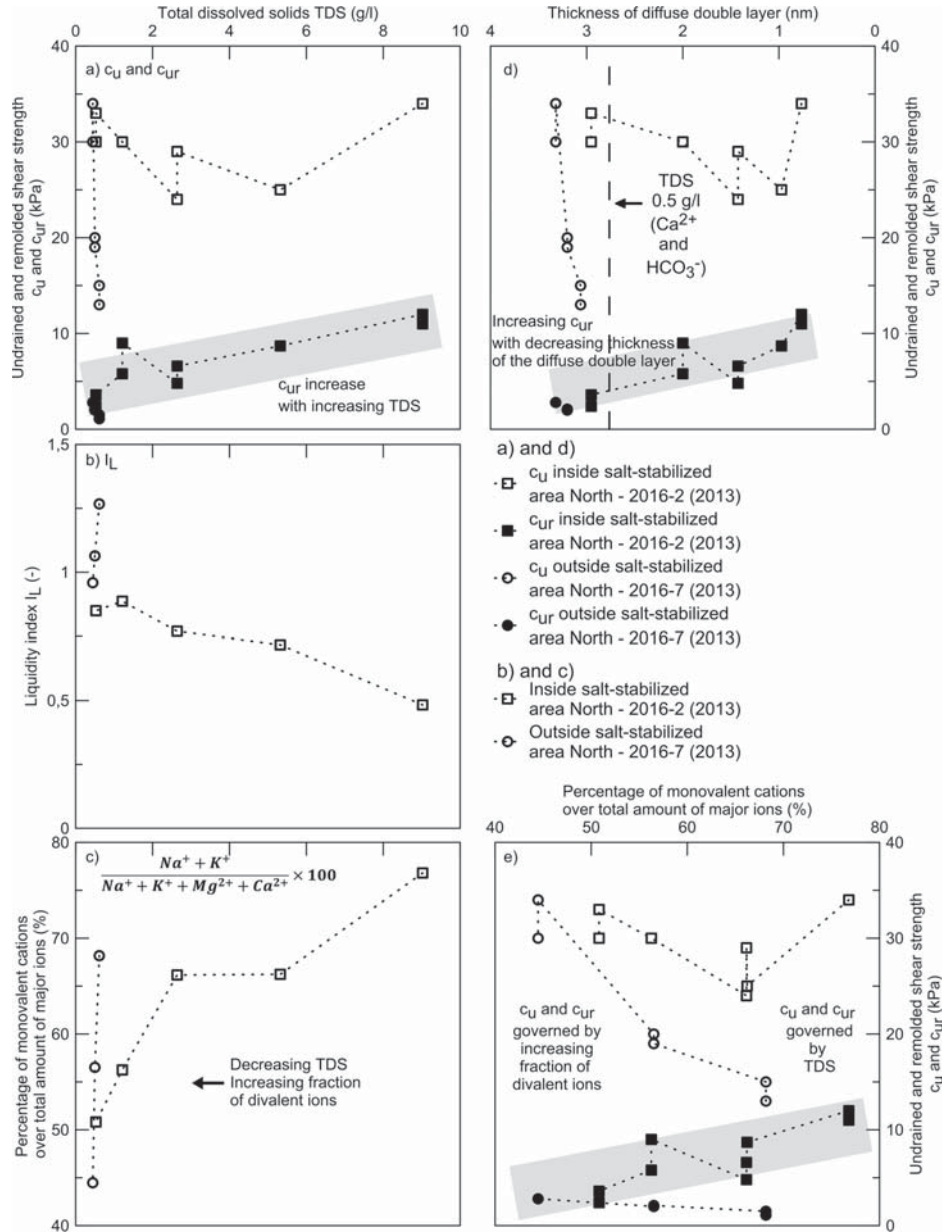
cially with regards to pH. Post-glacial clays normally have high pH (~8) (Løken 1970; Mitchell and Soga 2005). Introducing chemicals that create an acidic environment will degrade less stable minerals, such as chlorite and carbonates. In the worst case, it may give a drastic drop in the undrained yield strength in materials containing carbonates due to the loss of cementing properties (Moum et al. 1968; Torrance and Pirnat 1984; Torrance 1999; Appelo and Postma 2005; Mitchell and Soga 2005). Using KCl at Ulvensplitten showed no changes in the pH inside the salt-treated area. Consequently, the change in the clay behavior is found not to be influ-

enced by pH. Chloride has a negative effect on drinking water, so salt wells should not be installed in areas close to groundwater reservoirs used for drinking water.

Conclusions

Moum et al. (1968) concluded that a concentration of K$^+$ of only 0.5 g/L is sufficient to increase the remolded shear strength above 0.5 kPa. The results from Ulvensplitten confirm that even though TDS and the concentration of K$^+$ decrease over time from initially high levels, the clay will no longer behave as quick. At low TDS, the geotechnical properties are governed by the ion composition in the pore water and adsorbed ions on the mineral surface. A low-saline, K$^+$-dominated clay will have much higher yield stress, remolded shear strength, and Atterberg limits than a low-saline, Na$^+$-dominated clay with the same water content, due to the greater impact on suppressing the diffuse double layer.

The results presented herein show that the improved geotechnical properties remains 30 to 40 years after installation of salt wells in a quick clay deposit in Oslo, Norway. The liquidity index in the salt-treated quick clay is decreased to below 1.2. The clay is considered not to be susceptible for flow slides as the clay particles will no longer float in their own pore water if remolded. The clay is thus no longer characterized as quick, and therefore the salt-well method may be suitable to prevent large flow slides in quick clay areas.

More research is needed on how the clay behavior changes as a result of divalent cations entering the pore water over time (decades or centuries) replacing K$^+$ at the adsorbed positions on the mineral surface. However, changing the clay from a Na$^+$-saturated state to a K$^+$-saturated or divalent-saturated state implies that it will actually never revert to its former quick behavior.

Acknowledgements

References

Andersson-Sköld, Y., Torrance, J.K., Lind, B., Odén, K., Stevens, R.L., and Rankka, K. 2005. Quick clay – a case study of chemical perspective in Southwest Sweden. Engineering Geology, **82**(2): 107–118. doi:10.1016/j.enggeo.2005.09.014.

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

Bjerrum, L. 1954. Geotechnical properties of Norwegian marine clays. Géotechnique, **4**: 49–69. doi:10.1680/geot.1954.4.2.49.

Bjerrum, L. 1955. Norske marine leirers geotekniske egenskaper. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication No. 7.

Bjerrum, L., and Rosenqvist, I.T. 1956. Some experiments with artificially sedimented clays. Géotechnique, **6**: 124–136. doi:10.1680/geot.1956.6.3.124.

Bjerrum, L., Løken, T., Heiberg, S., and Foster, R. 1969. A field study of factors responsible for quick clay slides. In Proceedings of 7th International Conference in Soil Mechanics and Foundation Engineering, Mexico 1969. International Society for Soil Mechanics and Geotechnical Engineering. pp. 531–540.

Bryhn, O.R., Løken, T., and Reed, M.G. 1985. Stabilization of sensitive clays (quick clays) using Al(OH)$_{2.5}$Cl$_{0.5}$. In Proceedings of the International Clay Conference, Denver 1985. The Clay Minerals Society. pp. 427–435.

Eggestad, A., and Sem. H. 1970a. Haslelinjen mellom Strømsvn. og Store Ringvei: Stabilitetsforholdene langs Store Ringvei. Report No. R-894. Oslo municipality, Norway.

Eggestad, A., and Sem. H. 1970b. Kraftledningsmaster v/Store Ringvei x Hasleslplitten. Report No. R-996. Oslo municipality, Norway.

Eggestad, A., and Sem. H. 1972. Haslelinjen: Markforsterkning ved saltdiffusjon i krysset Haslelinjen – Store Ringvei. Report No. R-894 part 7. Oslo municipality, Norway.

Eggestad, A., and Sem. H. 1974. Haslelinjen: Resultatet av markforsterkingen i krysset Haslelinjen – Store Ringvei. Report No. R-894 part 8. Oslo municipality, Norway.

Eggestad, A., and Sem. H. 1976. Stability of excavations improved by salt diffusion from deep wells. In Proceedings of the 6th European Conference on Soil Mechanics and Foundation Engineering, Vienna, March 1976. International Society for Soil Mechanics and Geotechnical Engineering. pp. 211–216.

Helle, T.E., Gjengedal, I., Emdal, A., Aagaard, P., and Høydal, Ø. 2013. Potassium chloride as ground improvement in quick clay areas – a preliminary study. In Landslides in sensitive clays: From Geosciences to risk management. Edited by J.-S. L'Heureux, A, Locat, S. Leroueil, D. Demers, and J. Locat. Springer Dordrecht Heidelberg, New York, London. pp. 63–74.

Hilmo, B.O. 1989. Marine sensitive leirers mineralsammensetning, kolloidkjemi og mekaniske egenskaper. Doctoral thesis, Department of geology and rock mechanics, Norwegian University of Science and Technology, Trondheim, Norway.

Leroueil, S., Tavenas, F., and Le, Bihan, J.-P. 1983. Propriétés caractéristiqués des argiles de l'est du Canada. Canadian Geotechnical Journal, **20**(4): 681–705. doi:10.1139/t83-076.

Lessard, G., and Mitchell, J.K. 1985. The causes and effects of aging in quick clays. Canadian Geotechnical Journal, **22**(3): 335–346. doi:10.1139/t85-046.

Locat, J., and Demers, D. 1988. Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays. Canadian Geotechnical Journal, **25**(4): 799–806. doi:10.1139/t88-088.

Løken, T. 1968. Kvikkleiredannelse og kjemisk forvitring i norske leirer. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication No. 75.

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

Mitchell, J.K., and Soga, K. 2005. Fundamentals of soil behavior. 3rd ed. John Wiley & Sons Inc., New Jersey.

Morel-Vulliez, G., Ørbech, T., and Fürst. C. 2013. E31-Ulvensplitten – Geotekniske undersøkelse. Report No. 124691/1. Multiconsult AS, Oslo, Norway.

Moum, J., Sopp, O.I., and 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., and Torrance, J.K. 1971. A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Géotechnique, **21**(4): 329–340. doi:10.1680/geot.1971.21.4.329.

Norwegian Geotechnical Society. 1982. Veiledning for symboler og definisjoner i geoteknikk: Identifisering og klassifisering av jord. Available from Norwegian Geotechnical Society, Oslo, Norway. NGF notification No. 2.

Quigley, R.M. 1980. Geology, mineralogy, and geochemistry of Canadian soft soils: a geotechnical perspective. Canadian Geotechnical Journal, **17**(2): 261–285. doi:10.1139/t80-026.

Rosenqvist, I.T. 1946. Om leirers kvikkaktighet. Available from the Norwegian Public Road Administrations, Oslo, Norway. Meddelelsen fra Vegdirektøren No. 3. pp. 29–36.

Rosenqvist, I.T. 1953. Considerations on the sensitivity of Norwegian quick-clays. Géotechnique, **3**: 195–200. doi:10.1680/geot.1953.3.5.195.

Rosenqvist, I.T. 1955. Investigations in the clay-electrolyte-water system. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication No. 9.

Söderblom, R. 1969. Salt in Swedish clays and its importance for quick clay formation. Available from Swedish Geotechnical Institute, Linköping, Sweden. SGI Proceedings No. 22.

Stuvøy, A., Gunnes, I., and Føyn, T. 2007. Rv 150 Ring 3 Ulven-Sinsen Entreprise 3: Geoteknisk datarapport. Report No. 3717200-GEO-07. Norconsult AS, Oslo, Norway.

Talme, O., Pajuste, M., and Wenner, C.-G. 1966. Secondary changes in the strength of clay layers and the origin of sensitive clay. Available from the National Swedish Institute for Building Research. Byggforskningsrådet report No. 46.

Torrance, J.K. 1975. On the role of chemistry in the development and behavior of the sensitive marine clays of Canada and Scandinavia. Canadian Geotechnical Journal, **12**(3): 326–335. doi:10.1139/t75-037.

Torrance, J.K. 1983. Towards a general model of quick clay development. Sedimentology, **30**: 547–555. doi:10.1111/j.1365-3091.1983.tb00692.x.

Torrance, J.K. 1988. Mineralogy, pore-water chemistry and geotechnical behaviour of Champlain Sea and related sediments. In The Late Quaternary development of the Champlain Sea Basin. Edited by N.R. Gadd. Geological Association of Canada. Special Paper 35, pp. 259–275.

Torrance, J.K. 1990. Oxide minerals in the sensitive post-glacial marine clays. Applied Clay Science, **5**: 307–323. doi:10.1016/0169-1317(90)90027-M.

Torrance, J.K. 1999. Physical, chemical and mineralogical influences on the rheology of remoulded low-activity sensitive marine clay. Applied Clay Science, **14**: 199–223. doi:10.1016/S0169-1317(98)00057-X.

Torrance, J.K., and Pirnat, M. 1984. Effect of pH on the rheology of marine clay

from the site of the South Nation River, Canada, landslide of 1971. Clays and Clay Minerals, **32**(5): 384–390. doi:10.1346/CCMN.1984.0320506.

van Olphen, H. 1977. Clay colloid chemistry. 2nd ed. J. Wiley, New York.

List of symbols

c_u undrained shear strength (kPa)
c_{ur} remolded shear strength (kPa)
I_L liquidity index
I_P plasticity index (%)
k_h horizontal hydraulic conductivity (m/s)
TDS   total dissolved solids (ppm ≈ mg/L)
w water content (%)
w_L liquid limit (%)
w_P plastic limit (%)
γ unit weight (kN/m³)

Paper IV

Paper IV

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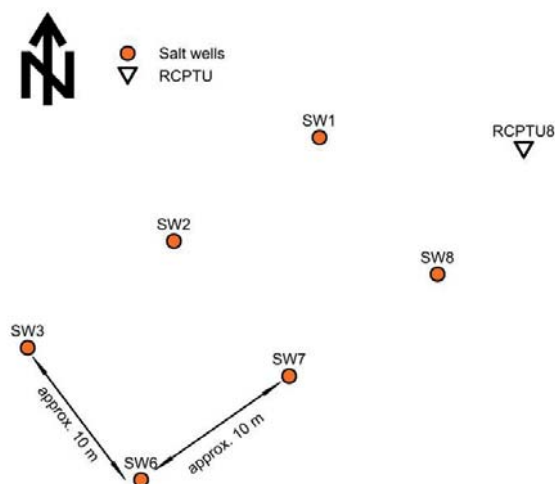
Figure 1. The salt wells are positioned with ~10 m spacing. RCTU8 is located in the outskirt of the test site.

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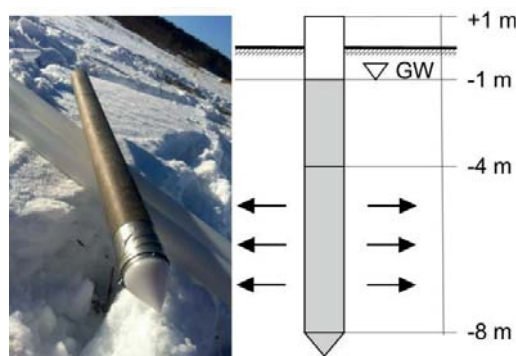
Figure 2. The salt wells are constructed using PE- pipes with an outer diameter of 63 mm. The pipes have slits covered with a geotextile in the depth interval 4-8 m.

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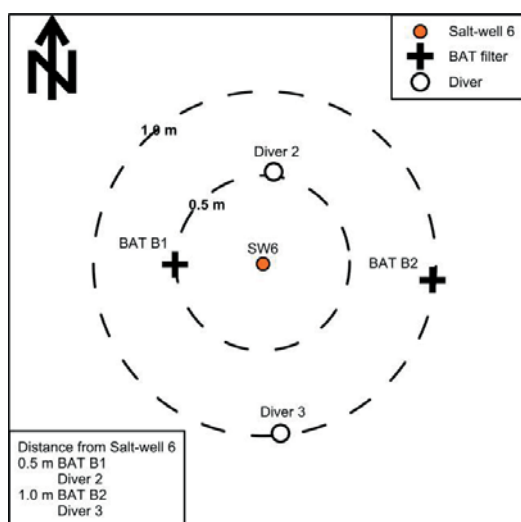
Figure 3. Positioning of BAT filter tips and divers used for monitoring the salt plume arrival over time.

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.
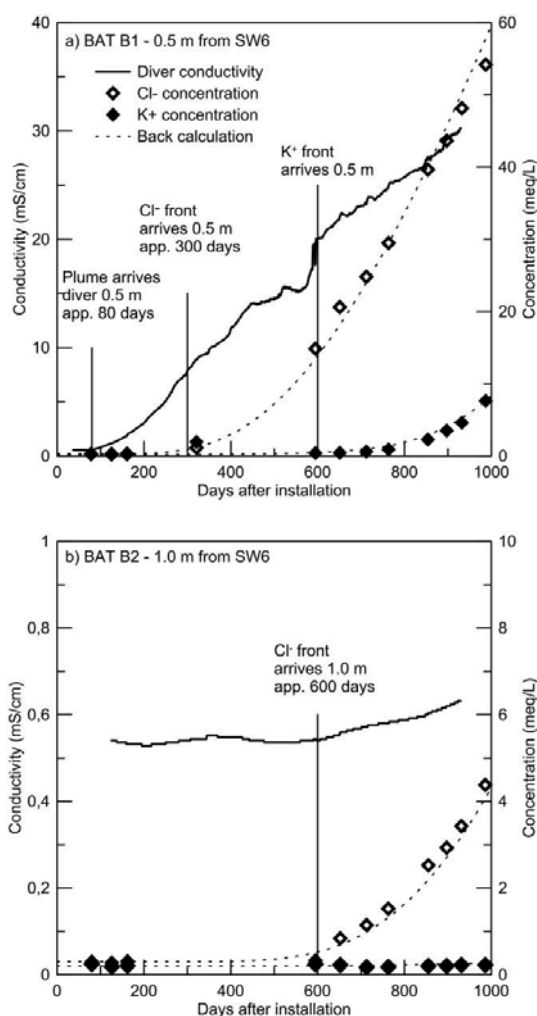
Figure 4. Diver conductivity and concentration of potassium (K^+) and chloride (Cl^-) in the extracted pore water in the BAT filters positioned a) 0.5 m and b) 1.0 m from salt-well no. 6.
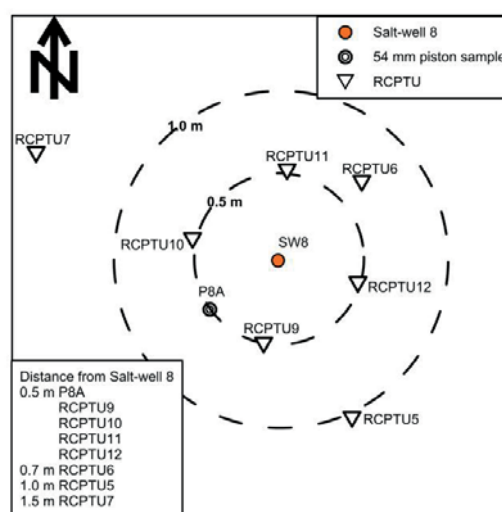
Figure 5. Ground investigations carried out around salt-well no. 8 2 years and 9 months after installation.
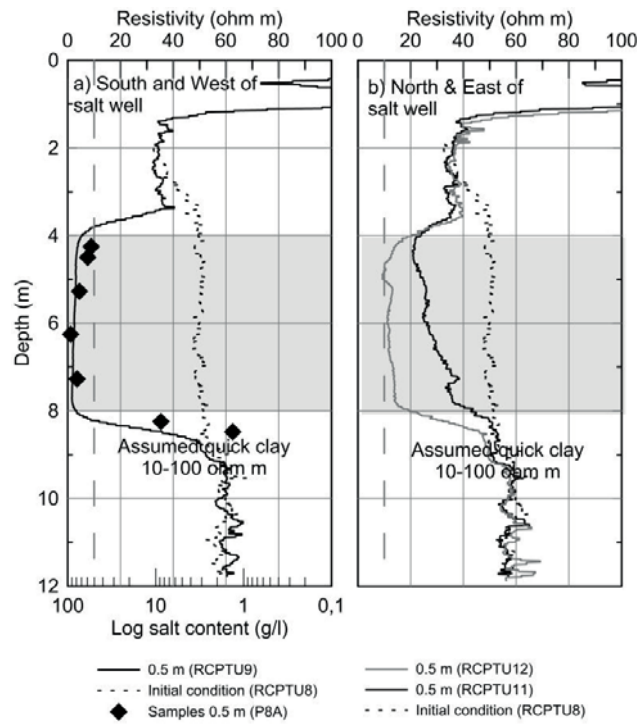
Figure 6. Resistivity profiles 0.5 m from salt-well no. 8. The initial condition is shown by dotted line. a) RCPTU9 and salt content 0.5 m west of salt-well no. 8. Note that the axis for the salt content is in log scale and reverse order. b) RCPTU11 and 12 north and east of the well.
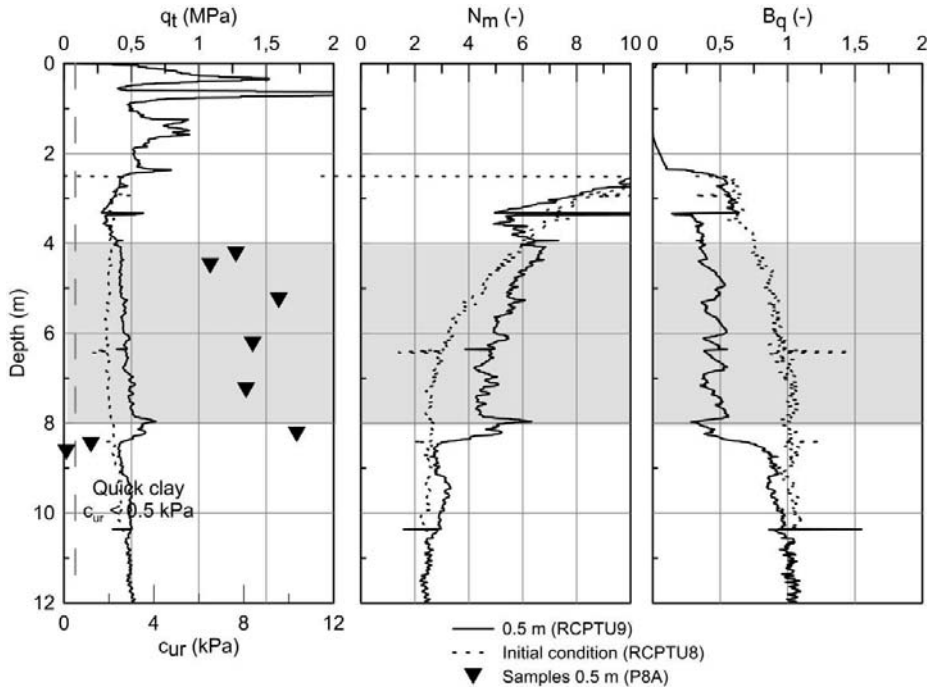
Figure 7. Corrected tip resistance (q_t), normalised tip resistance (N_m) and pore pressure parameter (B_q) in RCTPU, 2 years and 9 months after installation of salt well no. 8 The remoulded shear strength (c_{ur}) found in the samples extracted 0.5 m from the well is shown with black triangles. The 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 east-ward 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).
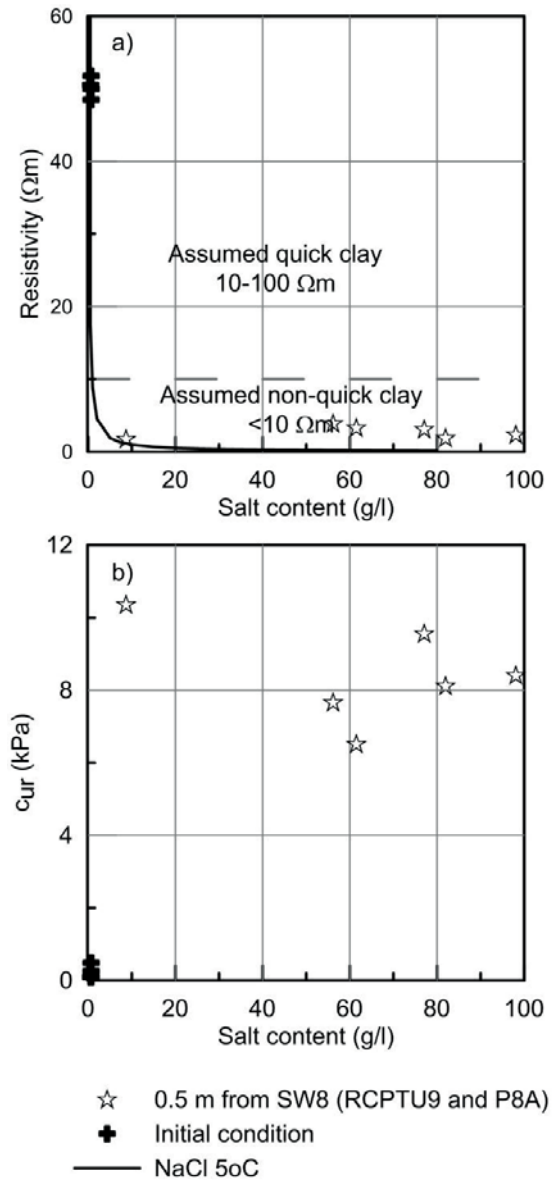
Figure 8. a) RCPTU resistivity correlated to salt content found in nearby samples. The dashed line shows the limit where the resistivity may indicate quick clay (10-100 Ωm) and non-quick clay (<10 Ωm) (Solberg et al. 2012). The black line shows PHREEQC calculated resistivity versus TDS equivalent to NaCl solutions at 5°C. b) Remoulded shear strength correlated to salt content found in nearby samples.

5 ACKNOWLEDGMENTS

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.

Paper V

Paper V

Paper VI

Paper VI

Predicting required time stabilising quick clays by potassium chloride

Tonje Eide Helle[1,2], and Per Aagaard[3]

Abstract

Salt-wells filled with potassium chloride (KCl) were installed in a highly sensitive, low saline, glaciomarine quick clay at Dragvoll, Trondheim, Norway, to investigate the improvement of geotechnical properties and the required time to stabilise the clay volume sufficiently to inhibit retrogressive landslide development. Improving the remoulded shear strength (c_{ur}) beyond 1 kPa reduces the risk for successive back-scarp failures. When more than 20% of the cations in the pore water consist of K^+, Mg^{2+} and Ca^{2+}, c_{ur} is improved beyond 1 kPa. Optimisation of the well grid is necessary prior to installation to ensure $c_{ur} > 1$ kPa within 2-3 years. PHREEQC simulations predicted a diameter of stabilised clay of minimum 1.5 m within 3.3 years after installation, which fits reasonably with observed pore-water compositions and improved geotechnical properties in-situ. Salt wells may be used as landslide mitigation preventing backwards successive, retrogressive development, and PHREEQC can be used to give a rough estimate of the required time to stabilise the quick clay volume around the wells.

Keywords: Geochemistry; Landslides;

[1] Norwegian University of Science and Technology, Department of Civil and Environmental Engineering, 7491 Trondheim, Norway
[2] The Directorate for Public Roads, P.O. box 8142 Dep, 0033 Oslo, Norway
[3] University of Oslo, Department of Geosciences, P.O. box 1047 Blindern, 0316 Oslo, Norway

1 Introduction

Highly sensitive quick clays are often found in inhabited areas in Norway. Erosion or construction work pose a serious risk for triggering quick-clay landslides even in relatively flat terrain with slope inclinations as low as 1:15 (Gregersen, 2001). Initial slides in the foot of slopes comprising quick clay may flow out of the initial slide-pit, triggering further remoulding and successive backwards retrogression or progression of the landslide. Quick-clay landslides may stretch several hundred meters backwards from the initial back scarp. The well-documented Rissa quick-clay landslide in 1978 stretched catastrophically 1.5 km backwards from the initial slide in a relatively flat area (inclination app. 1:10), covering an area of 330 000 m^2 with a total volume of slide debris of 5-6 million m^3 (Gregersen, 1981). Prevention berms of soils or rocks in the foot of the slope balancing out the driving forces in a potential landslide and protect against erosion, are commonly used to increase the marginal safety in quick-clay slopes. A method not always feasible due to terrain constraints. Conventional methods such as sheet-pile walls and lime/cement piles may be too expensive, or create excess pore pressures in the slopes during installation, temporarily reducing the stability. Clays are electrochemically very active, and chemical agents improving the geotechnical properties may serve as an alternative to conventional landslide mitigation methods.

Quick clays are low saline, highly sensitive glaciomarine clays, originally deposited in saline environment during the Pleistocene-Holocene transition causing the clay particles to flocculate in a fabric with large water-filled voids (Rosenqvist, 1946). Isostatic uplift exposed these clays to leaching, diluting the pore water and changed its ion composition. The clay structure is strong as long as the salt content is high. Decreasing salt content increases the thickness of the diffuse double layer around the clay minerals, which increases the repulsive forces between the clay particles. The structure becomes weaker, and at salt contents of less than 2 g/L with pore-water compositions dominated by sodium (Na$^+$), the clays may liquefy when remoulded (Penner, 1965; Moum et al., 1971; Rosenqvist, 1977; Torrance, 1979, 1983; Mitchell and Soga, 2005).

Re-establishing high salt concentrations in leached low-saline quick clays decrease the repulsive forces and significantly improve their mechanical properties (Rosenqvist, 1946, 1953, 1955; Bjerrum, 1955; Løken, 1968, 1970; Moum et al., 1968; Eggestad and Sem, 1976; Quigley, 1980; Torrance, 1983; Helle et al., 2016, 2017). A liquidity index (IL) larger than 1.2 and a remoulded shear strength (c$_{ur}$) of less than 1 kPa may indicate susceptibility for large retrogressive landslides (Leroueil et al., 1983; Thakur et al., 2014). Therefore, changing the ion composition so that c$_{ur}$ > 1 kPa and IL < 1.2, may prevent retrogressive landslide development.

Laboratory studies treating quick clays with various salts proved that potassium (K$^+$) improved the remoulded shear strength and Atterberg limits to a greater extent than sodium (Na$^+$), magnesium (Mg^{2+}) and calcium (Ca^{2+}) at same normality (Moum et al., 1968). Even though K$^+$ is monovalent, the hydrated radius is much smaller than of Na$^+$. The ionic potential is therefore higher, and the charge is more effective. Thus, the diffuse double layer is greatly suppressed with K$^+$ present in the pore water, significantly improving the geotechnical properties (van Olphen, 1963; Løken, 1968, 1970; Torrance, 1999; Helle et al. 2016).

In 1972, wells filled with potassium chloride (KCl) were installed with a centre-to-centre distance of 1.5 m in a quick-clay deposit at Ulvensplitten, Oslo, Norway (Eggestad and Sem, 1976). Significantly increased c$_{ur}$ and Atterberg limits were observed with increasing concentration of potassium (K$^+$) in the clay volume within the following 2-3 years. Recent ground investigations in the salt-treated area prove that the clay remain non-quick 40 years

after installation due to favourable changed ion composition in the pore water (Helle et al., 2016).

The KCl-well method is not used as ground improvement today due to limited documentation on how the pore-water chemistry affects the geotechnical properties of quick clays, and at what velocity the salt plume migrates through low-permeable clay deposits. Therefore, wells filled with KCl were installed in January 2013 at the Dragvoll research site, Trondheim, Norway to investigate the required time to improve the c_{ur} beyond 1 kPa, sufficient to inhibit retrogressive landslide development. As KCl migrates in the clay volume, Ca^{2+} and Mg^{2+} are released from the clay mineral surfaces into the pore water. Both of which suppress the diffuse double layer to a greater extent than Na^+. Thereby, together with increasing concentrations of K^+, the released Ca^{2+} and Mg^{2+} contribute to improve the geotechnical properties. Both the Dragvoll and Ulvensplitten quick clays gained c_{ur} > 1 kPa when the KMgCa-ratio in Equation 1 exceeded 20%, applying the normality (meq/L) of each element (Helle et al., 2017).

$$\frac{K^+ + Mg^{2+} + Ca^{2+}}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}} \tag{1}$$

Time is essential evaluating the applicability of using KCl in landslide mitigation. A minimum diameter of 1 m around the wells at Dragvoll was stabilised within 2.2 years, and a minimum diameter of 1.5 m within 3 years. The wells at Dragvoll were installed with an internal spacing of around 10 m to avoid interaction of the salt plumes. Installing salt wells for landslide mitigation requires a denser grid. Simulation tools may be used in optimising the well grid, minimizing the time needed to improve c_{ur} beyond 1 kPa by applying the criterion KMgCa-ratio > 20%.

PHREEQC version 3 (Parkhurst and Appelo, 2013) is one of the available and widely used computer programs that offers computations of chemical reactions between aqueous solutions and exchangers such as clay minerals, as well as modelling 1D solute transport. PHREEQC dates back to 1980 (Parkhurst et al. 1980), and can be freely downloaded at www.usgs.gov. The transport modelling includes advection, dispersion and diffusion, and provides results on how the chemical composition changes with time both in the pore water and in the adsorbed positions on the clay-mineral surface. PHREEQC is used in the following to estimate the velocity of the observed salt migration at the Dragvoll research site, aiding prediction of the required time to improve the quick clay volume so that retrogressive landslide development is inhibited.

2 Solute transport in clays

Diffusion of KCl from salt wells is a slow process driven by concentration gradients between the wells and the low-saline surrounding clay. Of the major cations, potassium (K^+) has the highest diffusion coefficient in free water (D_f) at 25 °C of 1.96 x 10^{-9} m²/s (1.11 x 10^{-9} m²/s at 6 °C) (Appelo and Postma, 2005). Chloride (Cl^-) is the fastest of the common anions in groundwater with a D_f of 2.03 x 10^{-9} m²/s (1.15 x 10^{-9} m²/s at 6 °C). The 'slower' ion impedes the faster co-travelling ion. In multi-component solutions, such as in groundwater, an average D_f of 1.3 x 10^{-9} m²/s (7.38 x 10^{-10} m²/s at 6 °C) may be applied. Diffusion dominates the solute transport in clayey soils with low hydraulic conductivity (k_h < 2-5 x 10^{-10} m/s), and contributes

greatly in clays with $k_h < 1$ x 10^{-9} m/s. At $k_h > 1$ x 10^{-9} m/s, advection dominates the solute transport (Shackelford, 2014).

In porous media, the solute transport takes place in the available pore space, which reduces the diffusive mass flux compared to that of chemical diffusion in aqueous solutions (Shackelford and Moore, 2013; Malusis et al., 2015). In saturated soils with fully interconnected pores, the entire pores are available for solute transport. In soils with entrapped pores not available for advective transport, the pores may be available for molecular diffusion (Huysmans and Dassargues, 2004; Hendry et al., 2009; Shackelford and Moore, 2013). However, in the following, the whole porosity is considered available for diffusion, and is referred to as the water-filled effective porosity (ε_w). Including tortuosity (θ^2) in Fick's first law accounts for the porous media. Tortuosity is the ratio of the length the pore-fluid has to travel around the grains from a point A to B to the straight-line distance between A and B. Often, the effective diffusion coefficient (D_e) is applied directly into Fick's first law, including the tortuosity by Equation 2. The tortuosity (Equation 3) is related to the formation factor (F) and ε_w. In non-cohesive soils, F may be determined from Archie's law (Equation 4). The formation factor describes the geometry of the pores, defined as the ratio between the electrical pore-water conductivity (σ_w) and the electrical soil conductivity (σ_t) as the electrical current travels along the same path as the pore-fluid.

$$D_e = \frac{D_f}{\theta^2} \tag{2}$$

$$\theta^2 = F \cdot \varepsilon_w = \varepsilon_w^{1-m} \tag{3}$$

$$F = \frac{\sigma_w}{\sigma_t} = \varepsilon_w^{-m} \tag{4}$$

Clay minerals are net negatively charged and are therefore conductive, and the bulk electrical conductivity is the sum of the electrical conductivity of the clay minerals and the electrical pore-water conductivity (Waxman and Smit, 1968). The conductivity of the clay minerals depend on the number of charges. Therefore, the cation exchange capacity (CEC) may influence F (Manheim and Waterman, 1974), and F cannot be determined applying Equation 4. Nevertheless, several authors do suggest that Archie's law also applies in clays using a rather high exponent m; 2.5-5.4 (Atlan et al., 1968), 1.8-3.0 (Jackson et al. 1978; Campanella and Weemees, 1990), or 3.2 (Kelly et al., 2016). The larger m, the less spherical are the grains (Atkins and Smith, 1961).

Clay minerals have a fixed net negative charge, attracting cations from the pore fluid to balance the charge. Valence, hydrated radius and availability determine which cations the clay minerals adsorb. The cations exchange power depends on valence and hydrated ion radius (the smaller radius, the higher exchange power), and increases in the following order: $Na^+ < K^+ < Mg^{2+} < Ca^{2+} <$ aluminium (Al^{3+}) < iron (Fe^{3+}) (Mitchell and Soga, 2005). Introducing high concentrations of KCl, the clays adsorb the readily available K^+ and release Mg^{2+} and Ca^{2+} into the pore water. Chloride (Cl^-) travels unhindered through the clay volume (conservative tracer), whereas ion exchange reactions delay (retards) the K^+ front. The delay depends on the cation exchange capacity (CEC) of the clays. Ions travel through the soil volume in an overall charge balance. Thus, available cations in the pore water accompany Cl^-. Na^+ has the lowest exchange power, and is the dominating cation in the pore water in quick clays (Moum et al. 1971).

4

Therefore, the Na-front will arrive at a distance X simultaneously as the Cl-front, followed by the Mg-front and the Ca-front (Appelo and Postma, 2005). As more and more K^+ is adsorbed on the mineral surfaces, the excess K^+ is free to migrate in the soil volume, and will arrive as the last major cation at distance X.

3   Material and methods

3.1   Site description and soil properties

The Dragvoll research site is relatively flat with a groundwater table fluctuating between the surface and down to about 1 m depth, sensitive to weather and seasonal changes. The sediment package is up to 50 m thick (Hafsten and Mack, 1990), with a thin dry crust stretching down to about 2 m depth. Quick clay is encountered from 3-4 m depth (Bryntesen, 2014), and is found in the area down to 16-20 m depth (Emdal et al., 2012). The c_{ur} decreases from 0.5 kPa to less than 0.1 kPa at 5 m depth downwards. The liquid limit (w_L) is far less than the natural water content, and the IL is of 3.4-4.3. The quick clay is lean consisting of 34-41% clay (< 2 μm) and is intersected with millimetre thick silt and/or sand layers with a few cm spacing. At 7.5-8.0 m depth, the silt/sand layers increase to a thickness of 1-2 cm. The hydraulic conductivity (k_h) measured in BAT filters (www.bat-gms.com) installed at 6 m depth was of 2.3 x 10^{-10} m/s, and of 1.3-1.5 x 10^{-9} m/s determined by constant rate of strain oedometer tests on samples extracted from 4.2-5.8 m depth. The average volumetric porosity is 0.51, the average bulk density is 1.87 g/cm^3 and the average dry bulk density 1.36 g/cm^3.

The bulk mineralogy is dominated by quartz (24-31%), followed by albite (21-23%), illite (15-17%) and chlorite (12-13%), with less than 3% calcite (Bryntesen, 2014). The clay mineralogy is dominated by low-active illite (67%) and chlorite (33%). The specific surface area at 4.0-5.9 m depth is 18.3-27.8 m^2/g, and the x-ray fluorescence (XRF) determined cation exchange capacity (CEC) on samples saturated with strontium is around 25 meq/100 g dry soil. Sodium (Na^+) dominates the composition of cations in the pore-water in the pre-stabilised quick clay (Table 1).

In January 2013, six salt wells were installed at the Dragvoll research site (Figure 1). An internal spacing between the wells of approximately 10 m prevented neighbouring effects during the whole project period of 3 years and 5 months. The salt wells were 8 m deep, with a

Table 1 Initial ion composition in the Dragvoll quick clay

	Concentration (mmol/l)
Sodium Na^+	9.00
Potassium K^+	0.20
Magnesium Mg^{2+}	0.12
Calcium Ca^{2+}	0.12
Chloride Cl^-	0.30
Alkalinity (as HCO_3^-)	8.10
Fluoride F^-	0.20
Sulfate SO_4^{2-}	0.00
Bromide Br^-	0.00
pH	8.8
Temp (ºC)	6
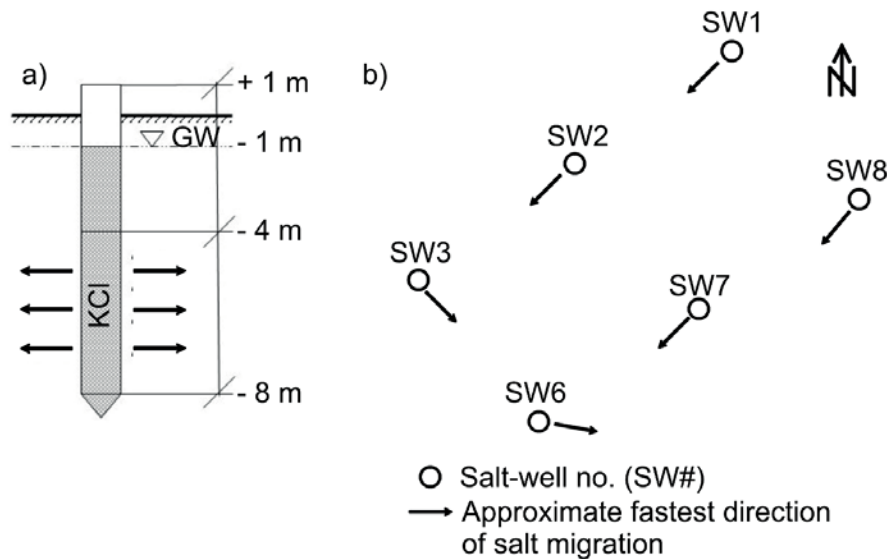
Figure 1 a) The salt wells were constructed of polyethylene (PE) pipes with a slotted section from 4 m to 8 m depth allowing migration of KCl into the clay volume. b) The salt wells were installed with an internal spacing of 10 m. The arrows indicate the approximate fastest direction of the salt migration from the wells.

slotted section from 4 m to 8 m depth, deep enough to avoid KCl damaging the vegetation and allowing KCl to migrate into the quick-clay volume. Fully saturated KCl solution was maintained in the wells during the whole project period. In total approximately 66-80 kg of granular KCl was consumed in each well.

BAT filter-tips were installed at 6 m depth on opposite sides of the well in a distance of 0.5 m (BAT B1) and 1 m (BAT B2) from the well (Figure 2). Groundwater samples were collected approximately every third month, and sent for chemical analysis at the Department of Geosciences at the University of Oslo. For further description of installations, ground investigations, laboratory tests and results, see Helle et al. (2017).
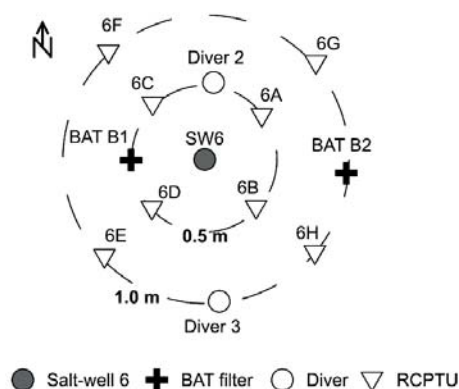
Figure 2 Installations and resistivity cone penetration tests (RCPTU) around salt-well no. 6 (SW6)

3.2   PHREEQC model and input

PHREEQC version 3 (Parkhurst and Appelo 2013) was used for estimating the velocity of salt migration from the wells at Dragvoll. Diffusion was considered the dominant transport mechanism as the in-situ measured hydraulic conductivity was low and there was no apparent hydraulic gradient (based on groundwater readings) over the site. 1D chemical diffusion in PHREEQC is simulated either by applying an effective diffusion coefficient (D_e), or by simulating multi-component diffusion (MCD) by applying the diffusion coefficient in free water (D_f) at 25 °C for the conservative tracer, in this case chloride (Cl^-). The diffusion coefficients for the other species are given in the database (phreeqc.dat). The solute transport is simulated along a column split into cells of equal volume and equal length. The salt around the wells diffuses radially, thus the plumes migrate slower along a straight line than would be the case in a laboratory column. Radial diffusion is accounted for by decreasing length of the cells with distance from the well (Figure 3) according to Equations 5 (cell no. 1) and 6 (cell no. n) (Appelo and Postma, 2005). Radial 1D simulations in PHREEQC are not applicable for advective flow due to unequal length of the cells. The dispersivity was therefore set to zero, and the applied D_e is in reality the apparent diffusion coefficient (D^*) which includes effective diffusion and any advection.

$$length(1) = total\ length/\sqrt{n_{tot}} \tag{5}$$

$$length(n) = length(1) \cdot (\sqrt{n} - \sqrt{n-1}) \tag{6}$$
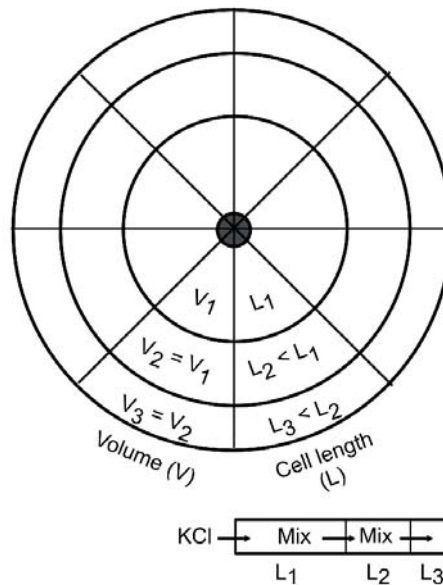
Figure 3 Illustration of decreasing cell length (L) with distance from the well in radial diffusion simulations

The altering pore-water chemistry around salt-well no. 6 was used for calibrating the model. The electrical resistivity profiles around SW6 indicated that the salt plume migrated faster towards BAT B2 than BAT B1 (Figure 4), possibly due to density gradients between the high-saline solute in the well and the low-saline surrounding clays, aiding some advective flow along coarser layers. The PHREEQC simulations were carried in the following sequence:

1) D* was estimated by fitting the simulated chloride (Cl^-) concentration to the observed concentrations in the BAT filters around salt-well no. 6
2) CEC was fitted so that the simulated potassium (K^+) and sodium (Na^+) concentrations gave a close fit to the observed concentrations in the BAT filters
3) MCD simulations were carried out to find any deviations between D* and D_e around SW6
4) Validate the above simulations by comparing the simulation results to the pore-water composition found in extracted clay samples from 6 m depth around salt-wells no. 2, 3, 7 and 8
5) The simulated pore-water chemistry was used for prediction of the extent of stabilised clay volume and the required time to do so, applying the criterion KMgCa-ratio > 20%
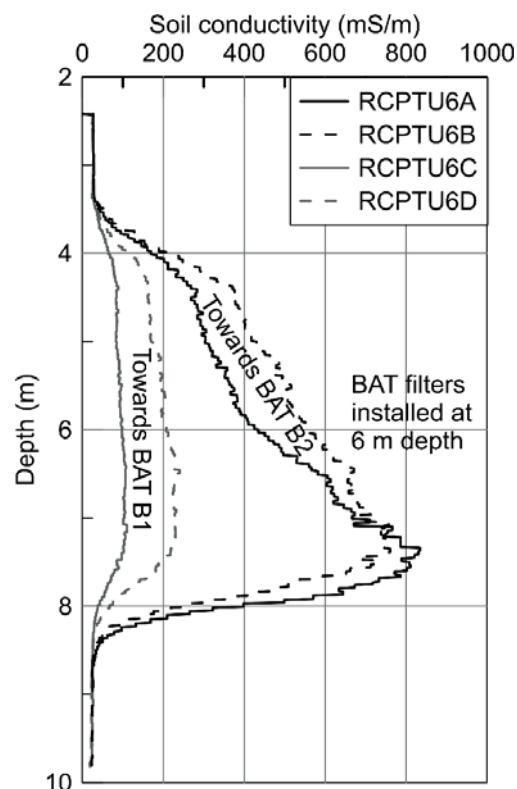
Figure 4 RCPTU conductivities around the well 41 months after installation

Radial diffusion and ion exchange was simulated along a 2 m long column split into 240 cells (n_{tot}) of equal volume. The salt wells were modelled by applying a constant concentration of KCl of 4 mol/kgw at the inlet of the column. The simulations were run with a time step of 30 days. In each step, the solution in the cells was "shifted forward" and mixed with the solution already there. The cation exchange was simulated by equilibrating the mixed solution in the cell with the exchanger using the Gaines Thomas convention (Appelo and Postma, 2005). All simulations were run at in-situ soil-temperature of 6 ºC.

Tortuosity is included in the MCD simulations assuming that Archie's law is valid for all soil types, and D_e is thereby determined applying Equation 7. The water-filled porosity (ε_w), and the exponent n = (m - 1) must be defined in the input file.

$$D_e = D_f \cdot \varepsilon_w^{(m-1)} = D_f \cdot \varepsilon_w^n \tag{7}$$
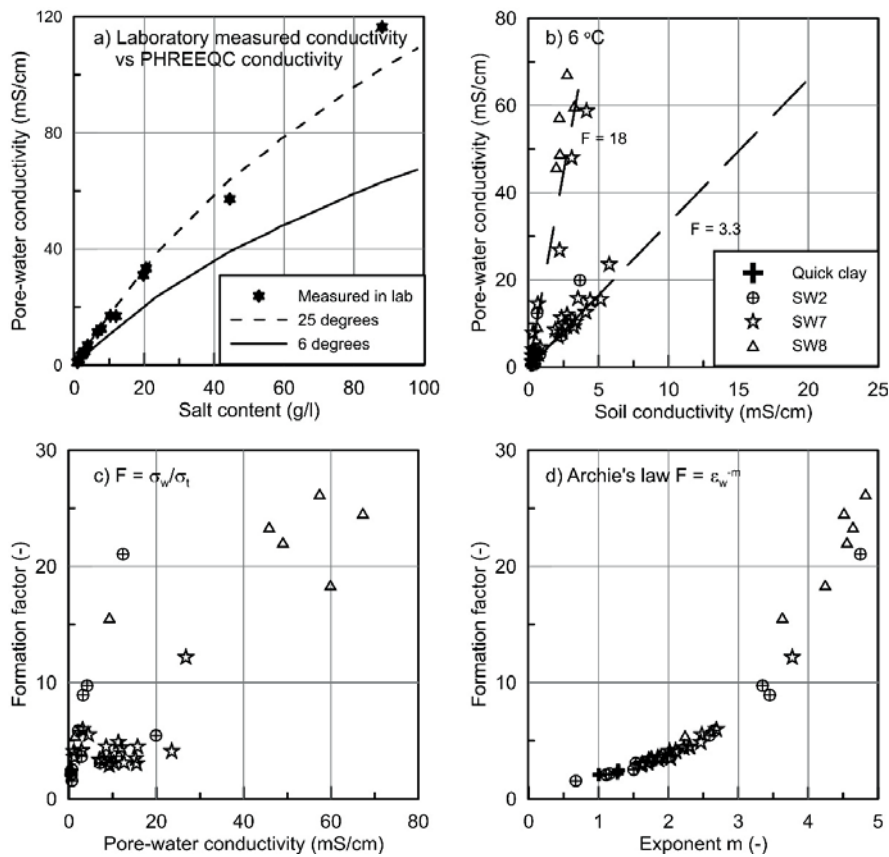
Figure 5 a) Electrical conductivity in the pore-water measured in the laboratory versus salt content, and PHREEQC simulated electrical conductivity at 6 ºC and 25 ºC. b) Electrical soil conductivity measured by RCPTU and PHREEQC simulated electrical conductivity at 6 ºC. c) The formation factor (F) with increasing electrical conductivity in the pore-water. d) Exponent m determined by Archie's law

9

Pore-water samples were extracted by centrifuge from undisturbed clay samples from the original quick clay and the salt-treated clay around the salt wells. The σ_w was measured on samples extracted around salt-wells no. 2 and 3 in the laboratory at a temperature of around 25 °C. The chemical composition was analysed in all the pore-water samples, and the electrical conductivity was estimated by PHREEQC. The estimated PHREEQC pore-water conductivities at 25 °C corresponded well with the laboratory-measured conductivities (Figure 5a). PHREEQC was therefore used for estimating σ_w for all pore-water samples at in-situ soil temperature of 6 °C. The σ_t was measured by resistivity cone penetration tests (RCPTU) conducted less than 0.5 m from the piston samples, at same distance from the salt wells.

An average F found directly from the slope between σ_w and σ_t (Figure 5b) was between 3.3 and 18.0. The formation factor F increased with increasing salt content (Figure 5c). Applying Archie's law (Equation 4), the exponent m increased exponentially with increasing F (Figure 5d). It was therefore not possible to determine the exponent m in the Dragvoll clay by F and Archie's law directly. Knowing the propagation of the Cl⁻ front around SW6 and ε_w, the exponent n may be fitted by PHREEQC simulations and thereby determine the Archie's exponent $m = n + 1$. According to Taylor-Smith (1971), the exponent m in clays with a porosity greater than 0.6 is 2 (n = 1). The MCD simulations were in the first round carried out with Archie's exponent m in the range of 2-3, corresponding to the findings of Taylor-Smith (1971), Jackson et al. (1978), Campanella and Weemees (1990), and Kelly et al. (2016).

4 Simulation results

4.1 Altering pore-water composition around Salt-well no. 6

4.1.1 Apparent diffusion coefficient

The PHREEQC simulations confirmed that the salt plume migrated faster towards BAT B1 and BAT B2 indicated by the in-situ measured soil conductivity (Figure 4). The apparent diffusion coefficient (D*) was more than two times larger towards BAT B2 than BAT B1; 6.6×10^{-10} m²/s and 3.1×10^{-10} m²/s respectively (Figure 6). Applying the laboratory-
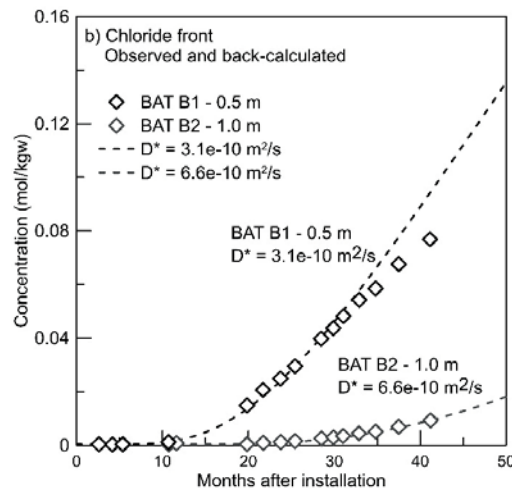
Figure 6 Chloride concentration over time in BAT B1 (black symbols) and BAT B2 (grey symbols), 0.5 m and 1.0 m from the well respectively, and back calculated values of the apparent diffusion coefficient (D)*

determined CEC of 0.659 moles (25 meq/100 g dry soil), the retardation of K^+ was greatly overestimated. The simulations also overestimated the released cations from the mineral surfaces. Consequently, the concentration of sodium (Na^+) was much too high (Figure 7). Applying a much lower CEC of 0.180 moles (6.8 meq/100 g dry soil), the simulated concentrations coincided well with the observed increase in K^+ and Na^+ concentrations with time. Stempwoort and van der Kamp (2003), also experienced that the laboratory determined CEC by conventional ammonium acetate method was too high compared to the one estimated by PHREEQC simulations on a Saskatchewan shale core also containing some calcite (amounts not stated). The glaciomarine clays originating from grinded rock flour have small specific surface areas, thus a small CEC (e.g. Quigley, 1980). Grim (1968) report specific surface areas of 65-100 m^2/g in illites of diagenetic origin related to a CEC of 10-40 meq/100 g dry soil. The specific surface area of the detrital Dragvoll clay is much smaller, 18.3-27.8 m^2/g. Therefore, it is thought that the analysed CEC was too high. Calcite is sensitive to dissolution, and may therefore cause too high CEC values (Jackson, 1979).
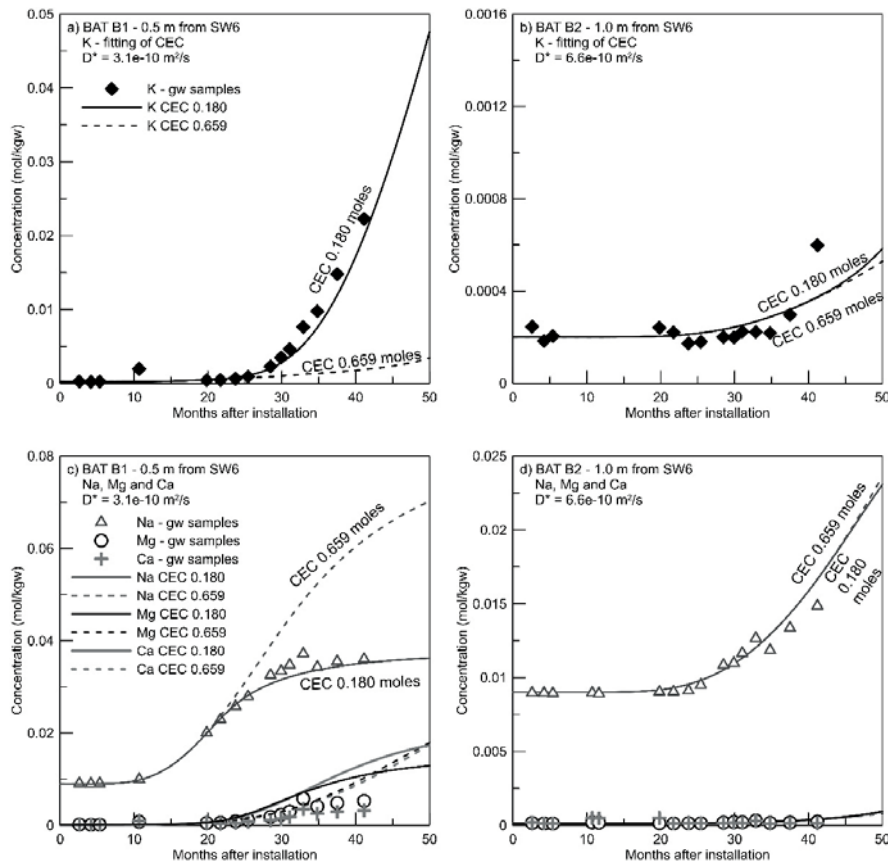
Figure 7 Simulations of the concentrations over time of potassium (K^+) in BAT B1 (a) and BAT B2 (b), and sodium (Na^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) in BAT B1 (c) and BAT B2 (d) applying apparent diffusion coefficients (D^*) of 3.1 x 10^{-10} m^2/s and 6.6 x 10^{-10} m^2/s. The observation data are included in Table 4 and Table 5

The clay content in the Dragvoll clay is 34-41%, consisting of 67% illite and 33% chlorite. Various mineral types have great ranges of CEC that can be found in the literature (e.g. Grim, 1968; Appelo and Postma, 2005). According to Appelo and Postma (2005), illite is in the range of 20-50 meq/100 g dry soil, and chlorite of 10-40 meq/100 g dry soil. Applying the lowest value in the CEC range (CEC$_{low\ range}$) for illites and chlorites in Equation 8, CEC in the Dragvoll clay was estimated to 5.7-6.8 meq/100 g dry soil (CEC estimated in Table 2).

$$CEC = \sum \frac{\% < 2\mu m}{100} \cdot \frac{\%\ mineral\ type}{100} \cdot CEC_{low\ range} \tag{8}$$

Kenney (1967) reported CEC of three Norwegian very sensitive clays saturated with Ca^{2+} of 9-11 meq/100 g dry soil at clay contents of 42-44%. Locat and St-Gelais (2014) reported specific surface areas in chloritic-illitic Quebec clays in the order of 10-36 m^2/g and a CEC of 6-17 meq/100 g dry soil in clays with clay contents of 30-83%. Therefore, the CEC estimated in the PHREEQC simulations was considered credible.

Table 2 Cation exchange capacity (CEC) analyzed by x-ray fluorescence (XRF), PHREEQC fitted, found empirically, and determined from clay mineralogy (CEC estimated). All in meq/100 g dry soil. The lowest CEC for illites and chlorites found in Appelo and Postma (2005) are applied, 20 meq/100 g dry soil and 10 meq/100 g dry soil respectively

	Analyzed	Simulated	34% clay	41% clay
XRF analysis	25			
CEC simulated		6.8		
CEC estimated			5.7	6.8

4.1.2 Multi-component diffusion simulations

The applied exponent n greatly affected the results in the multi-component diffusion (MCD) simulations (Figure 8). The MCD simulations fit well with the Cl$^-$ concentrations in
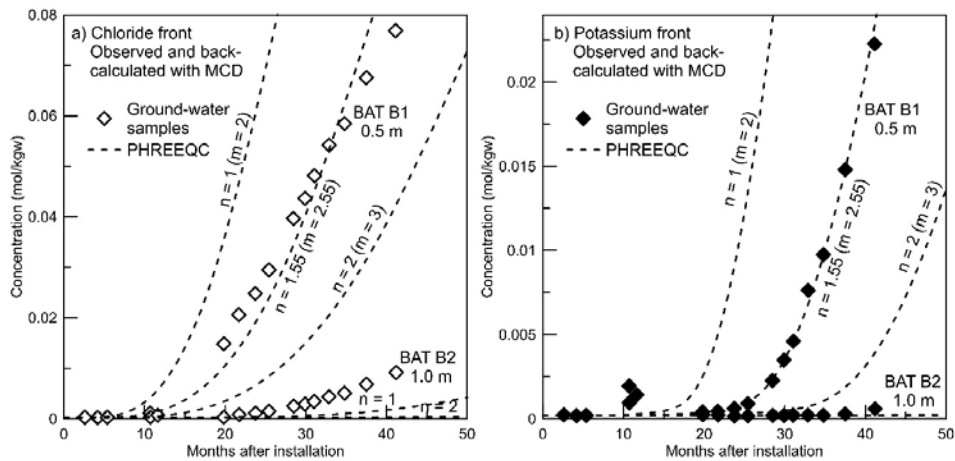
Figure 8 Simulations of the chloride (a) and potassium (b) concentrations in BAT B1 (0.5 m distance) and BAT B2 (1.0 m distance) over time using multi-component diffusion (MCD) with a porosity 0.51 and an exponent n of 1, 1.55 and 2

BAT B1 applying an exponent n of 1.55. This corresponded to an Archie's exponent m of 2.55, within the range of 2-3 based on previous studies on clays. The Cl⁻ concentrations in BAT B2 increased faster than the simulated concentrations carried out with Archie's exponent of 2-3, confirming that some advection was involved in the salt migration towards BAT B2.

4.2   Validation of the back calculations

Clay samples were extracted from 4 m to 8 m depth around salt-wells no. 2, 3, 7 and 8, and the analysed pore-water compositions were in the following compared to the PHREEQC-simulations to investigate the validity of the above findings. The clay samples extracted around salt-wells no. 2, 3 and 8 (1181 days, 1185 days and 995 days after installation respectively), were all positioned in or close to the direction of the fastest salt migration from the wells. Around salt-well no. 7 (1140 days after installation), four boreholes were positioned in a distance of 0.5 m from the well to determine the direction of the fastest salt migration (boreholes P7A, B, C and D). In addition, one borehole 1.0 m from the well was positioned in the direction of fastest salt migration (borehole P7E).

The pore-water compositions found in the clay samples at 6 m depth along the directions of fastest migration from salt-wells no. 2, 3, 7 and 8 exceeded the simulated concentrations applying the largest apparent diffusion coefficient (D*) of 6.6×10^{-10} m²/s (Figure 9 and Figure 10). The pore-water compositions in the samples P7A, B and C at 6 m depth around salt-well no. 7 fit within the range of simulated pore-water concentrations from the multi-component diffusion (MCD) simulations and in simulations applying the largest D* (Figure 10). This confirms that diffusion dominated the transport mechanism around the wells, with some advective flow in predominant directions.

The electrical conductivity profiles retrieved by resistivity cone penetration tests (RCPTU) clearly showed that the salt plumes migrated faster with depth in all directions. This may imply local variations of permeability, continuity and inclinations of permeable layers around the wells, enhancing some advection along coarser layers in preferred directions The thickness of the coarse layers increased from being millimetre thick to occasionally 1-2 cm thick at around 7.5 m depth. Thus, the density gradients between the well and the surrounding
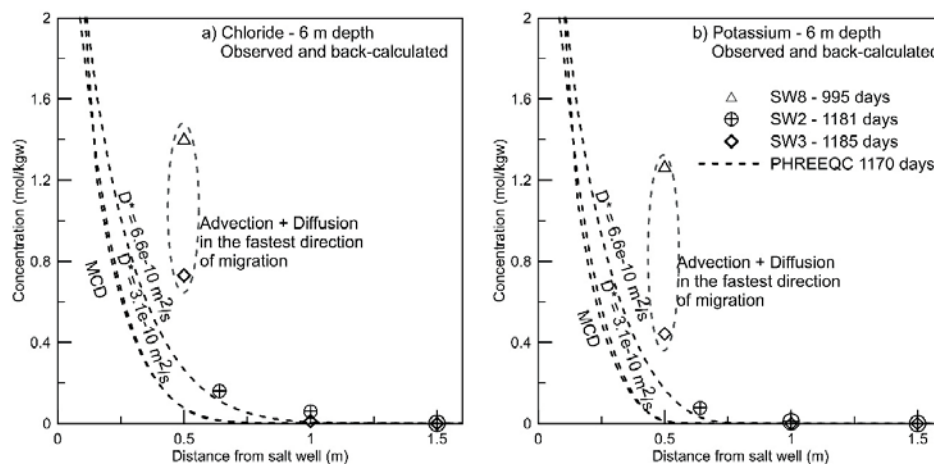
Figure 9 Simulations (a) and potassium (b) concentrations in pore-water samples extracted from clay samples at 6 m depth along the fastest direction of the salt migration from salt-wells no. 2, 3 and 8 compared to the PHREEQC simulations
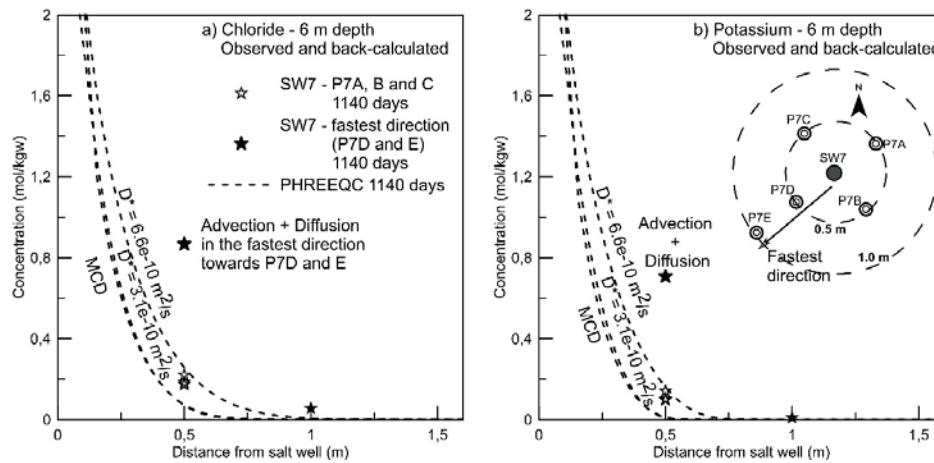
Figure 10 Chloride (a) and potassium (b) concentrations in pore-water samples extracted from clay samples at 6 m depth around salt-wells no. 7 compared to the PHREEQC simulations. The orange symbols are from P7A, B and C, and the red symbols are in the fastest direction of migration, towards P7D and E

groundwater may have forced the salt horizontally along these coarser layers with higher permeability causing variety in the salt-plume extent with depth, and the direction of fastest migration from one well to the other.

5   Predicting required time to stabilise the quick-clay volume

The observed changes in the pore-water composition with time in the clay at Dragvoll was fitted in the simulations both by applying an apparent diffusion coefficient (D*) and by multi-component diffusion (MCD). The simulations applying a D* of 3.1 x 10^{-10} m^2/s corresponded well with the MCD results applying an exponent n of 1.55 (Archie's exponent m = 2.55). This implies that D* and D_e corresponded well. Thus, diffusion dominated the transport mechanism towards BAT B1. In the opposite direction, towards BAT B2, D^* was larger, 6.6 x 10^{-10} m^2/s.

The effective diffusion coefficient (D_e) in soils is greatly affected by the tortuosity (θ^2), and may be determined by Equation 2. The formation factor (F) is related to the tortuosity (θ^2) and the water-filled porosity (ε_w) by Equation 4, and can be used for determination of Archie's exponent m assuming that Archie's law is valid. Both the minerals and the pore water affect the electrical soil conductivity in clays. Thus, F cannot be determined directly from the measured pore-water and soil conductivities. According to Boudreau (1996), the tortuosity (θ^2) in fine-grained, unlithified sediments can be determined by Equation 9 for a wide range of porosity values (0.3-1.0). Applying Equation 9, the tortuosity in the Dragvoll clay was estimated to 2.35. Thus, F is 4.6 and Archie's exponent m is 2.27 (Table 3), which corresponds well with the exponent m of 2.55 estimated in the MCD simulations.

$$\theta^2 = 1 - 2 \cdot \ln(\varepsilon_w) \tag{9}$$

14

Table 3 Effective diffusion coefficients for potassium (K⁺), chloride (Cl⁻), KCl and the average of a multi-component solution. The tortuosity is determined by either using the m from the PHREEQC simulations, and from θ² = 1-2ln(εw)

	K⁺	Cl⁻	KCl	Average
D_f at 6 °C (m²/s)	1.11×10^{-9}	1.15×10^{-9}	1.13×10^{-9}	7.38×10^{-9}
m from PHREEQC	2.55	2.55	2.55	2.55
$F = \varepsilon_w^{-m}$	5.57	5.57	5.57	5.57
$\theta^2 = F \cdot \varepsilon_w$	2.84	2.84	2.84	2.84
$D_e = D_f/\theta^2$ (m²/s)	3.91×10^{-10}	4.05×10^{-10}	3.98×10^{-10}	2.60×10^{-10}
$\theta^2 = 1-2ln(\varepsilon_w)$	2.35	2.35	2.35	2.35
$F = \theta^2/\varepsilon_w$	4.60	4.60	4.60	4.60
$m = ln(F)/ln(\varepsilon_w)$	2.27	2.27	2.27	2.27
$D_e = D_f/\theta^2$ (m²/s)	4.73×10^{-10}	4.90×10^{-10}	4.82×10^{-10}	3.14×10^{-10}

The effective diffusion coefficient (D_e) is found by Equation 2. The diffusion coefficient in free water (D_f) for a multi-component solution at 6 °C is 7.38×10^{-10} m²/s. Applying the tortuosity determined by the expression suggested by Boudreau (1996) of 2.35, D_e is about the same as the lowest D^* of 3.1×10^{-10} m²/s determined for the direction towards BAT B1. This confirms the above findings that diffusion dominated the solute transport around the well. The D_e is also in agreement with the findings of Hendry et al. (2009), who determined a D_e of 2.5- 3.5×10^{-10} m²/s at 5 °C in their in-situ experiment applying a chloride isotope in a
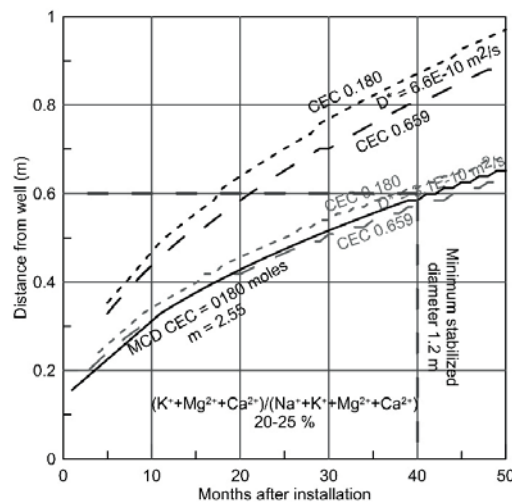
Figure 11 Time needed to stabilise the quick clay in a distance from the salt well. The Dragvoll quick clay ceases to be quick at a ratio between the sum of potassium (K⁺), magnesium (Mg²⁺) and calcium (Ca²⁺) over the sum of major cations (sodium (Na⁺), K⁺, Mg²⁺ and Ca²⁺), all in meq/l, exceeding 20 %. The simulations are carried out with apparent diffusion coefficients (D*) of 3.1 x 10⁻¹⁰ m²/s (grey dotted lines) and 6.6 · 10⁻¹⁰ m²/s (black dotted lines). Forty months after installation, the quick clay is stabilised within a radius of 0.6 m, and a minimum diameter of 1.2 m around the well is stabilised

clay-rich aquitard with a porosity of 0.31. Therefore, it is suggested that diffusion in clays may be estimated by PHREEQC applying a D_e based on D_f for a multicomponent solute and the tortuosity determined by Equation 9.

The simulations gave a rough estimate of the time required to achieve a KMgCa-ratio > 20% inhibiting retrogressive landslide development. Only diffusion was modelled in the MCD simulations, whereas the simulations applying the largest apparent diffusion coefficient (D*) found towards BAT B2 of 6.6 x 10^{-10} m^2/s, also included a small advective component. The concentrations of K^+ and Cl^- in the extracted clay samples around salt-wells no. 2, 3, 7 and 8 exceeded the simulation results applying the largest D*, indicating faster salt migration, and thereby larger D* than estimated towards BAT B2. Applying D* of 6.6 x 10^{-10} m^2/s towards BAT B2, the maximum extent of stabilised quick clay with a remoulded shear strength (c_{ur}) > 1 kPa was therefore conservatively estimated. Sorting the simulated data by a KMgCa-ratio of 20-25%, the Dragvoll quick clay was stabilised over a diameter of minimum 1.2 m within 40 months (3.3 years) assuming only diffusion (MCD simulations) around the entire well (Figure 11). Including advection in one direction from the well, the diameter extended to about 1.5 m within 40 months. This fit well with the in-situ improved geotechnical properties found around the wells around 3 years after installation.

6   Conclusions

Diffusion was the dominant transport mechanism around the wells, with an effective diffusion coefficient of 3.1 x 10^{-10} m^2/s. In the direction of fastest salt migration, density gradients forced the plume horizontally along coarser layers. The minimum apparent diffusion coefficient (D*) in direction of fastest migration was 6.6 x 10^{-10} m^2/s. At pore-water compositions with a KMgCa-ratio exceeding 20% the remoulded shear strength (c_{ur}) is improved beyond 1 kPa, which is thought to be sufficient to inhibit retrogressive landslide development. Sorting the simulated pore-water chemistry by a KMgCa-ratio of 20-25%, PHREEQC can be used for predicting the required time to improve c_{ur} beyond 1 kPa. Considering only diffusion, c_{ur} > 1 kPa in a clay volume with a simulated diameter of approximately 1.2 m within 40 months (3.3 years). Including advection in one predominant direction by applying D* of 6.6 x 10^{-10} m^2/s, the diameter increased to minimum 1.5 m within 40 months (3.3 years). The simulated extent of the stabilised clay volume fit reasonably with observed changed pore-water chemistry and improved geotechnical properties around the salt wells at Dragvoll 3 years after installation.

The cation exchange capacity (CEC) determines the delay (retardation) of the cations involved in the ion-exchange reactions; the higher CEC the greater retardation and the longer time is required before improvement of the geotechnical properties commences. The smaller CEC, the less K^+ is retarded due to ion exchange reactions. Compared to the simulated pore-water compositions, the laboratory determined CEC of 25 meq/100 g dry soil (0.659 moles) was too high. The PHREEQC estimated CEC of 6.8 meq/100 g dry soil (0.180 moles) was considered credible based on findings in previous studies on CECs in Norwegian and Canadian glaciomarine clays (Kenney, 1967; Locat and St-Gelais, 2014).

The MCD simulation-results were greatly affected by Archie's exponent m. Preferably the initial pore-water composition, CEC and m should be determined in order to estimate the required time to stabilise the quick clay sufficiently to inhibit retrogressive landslide development. The results in the present study does however imply that both CEC and Archie's

exponent m can be estimated by PHREEQC simulations if the propagation of the concentration fronts is known.

Potassium-chloride treated quick clays will inhibit successive back-scarp failures. The well grid must be optimised to ensure that c_{ur} is improved beyond 1 kPa within reasonable time; 2-3 years in quick-clay slopes not in immediate risk of failure. The simulation results presented herein suggest that PHREEQC estimates the time it takes to stabilise the clay volume around the wells with reasonable accuracy, valuable when planning the internal distance between the wells for landslide mitigation measures.

7 Acknowledgments

8 References

Appelo CAJ and Postma D (2005) Geochemistry, groundwater and pollution. 2nd edn. Balkema, Leiden, The Netherlands.

Atkins ER and Smith GH (1961) The Significance of Particle Shape in Formation Resistivity Factor - Porosity Relationships. Journal of Petroleum Technology **13(3)**: 285-291, http://dx.doi.org/10.2118/1560-G-PA.

Atlan Y, Bardon C, Minssieux L, Quint M and Delvaux P (1968) Conductivite en milieu poreux argileux. Interpretation des diagraphies. Troisieme colloque de Fassociation de recherche sur les techniques de forage et de production, 10-14 June, 1968, Pau. Comm. No. 31 (in French).

Bjerrum L (1954) Geotechnical properties of Norwegian marine clays. Géotechnique **4(2)**: 49 -65. http://dx.doi.org/10.1680/geot.1954.4.2.49.

Bjerrum L (1955) Norske marine leirers geotekniske egenskaper. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 7 (in Norwegian).

Bjerrum L and Rosenqvist IT (1956) Some experiments with artificially sedimented clays. Géotechnique **6(3)**: 124-136. http://dx.doi.org/10.1680/geot.1956.6.3.124.

Bjerrum L, Løken T, Heiberg S and Foster R (1969) A field study of factors responsible for quick clay slides. In *Proceedings of 7th International Conference on Soil Mechanics and Foundation Engineering (ICSMFE)*. Sociedad Mexicana de Mecanica, Mexico City, Mexico, vol. 2, pp. 531-540.

Boudreau BP (1996) The diffusive tortuosity of fine-grained unlithified sediments. Geochimica et Cosmochimica Acta **60(16)**: 3139-3142, https://doi.org/10.1016/0016-7037(96)00158-5.

Bryntesen RN (2014) Laboratory investigation on salt migration and its effect on the geotechnical strength parameters in quick clay mini-block samples from Dragvoll. Master's thesis, Norwegian University of Science and Technology, Trondheim, Norway, pp. 1-105.

Campanella RG and Weemees I (1990) Development and use of an electrical resistivity cone for groundwater contaminant studies. Canadian Geotechnical Journal **27(5)**: 557-567.

Eggestad A and Sem H (1976) Stability of excavations improved by salt diffusion from deep wells. In *Proceedings of the 6th European conference on soil mechanics and foundation engineering*, Vienna, Austria. ISSMFE Austrian National Committee, Vienna, Austria, pp. 211-216.

Emdal A, Long M, Bihs A, Gylland AS and Boylan N (2012) Characterisation of quick clay at Dragvoll, Trondheim, Norway. Southeast Asian Geotechnical Society Geotechnical Engineering Journal of the SEAGS & AGSSEA **43(4)**: 11-23.

Gregersen O (1981) The quick clay landslide in Rissa, Norway. In *Proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering*, 3, Stockholm, Sweden. A.A. Balkema, Rotterdam, the Netherlands, pp. 421-426.

Gregersen O (2001) Program for økt sikkerhet mot leirskred - Metode for kartlegging og klassifisering av faresoner, kvikkleire. Norwegian Geotechnical Institute, Oslo, Norway, NGI-report no. 20001008-2, Revision no. 3. pp. 1-22.

Grim RE (1968) Clay mineralogy. McGraw-Hill Book Company, Inc., New York, USA.

Hafsten U and Mack G (1990) Den postglaciale landskapsutviklingen på Dragvoll universitetsområde, Trondheim. Norsk Geografisk Tidsskrift – Norwegian Journal of Geography **44(3)**: 131-148.

Helle TE, Nordal S, Aagaard P and Lied OK (2016) Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay — Ulvensplitten, Norway. Canadian Geotechnical Journal **53(3)**: 410-422. http://dx.doi.org/10.1139/cgj-2015-0077.

Helle TE, Aagaard P and Nordal S (2017) In-situ improvement of highly sensitive clays by potassium chloride migration. Journal of Geotechnical and Geoenvironmental Engineering ASCE **143(10)**, https://doi.org/10.1061/(ASCE)GT.1943-5606.0001774.

Hendry MJ, Barbour SL, Boldt-Leppin BEJ, Reifferscheid LJ and Wassenaar LI (2009) A comparison of laboratory and field based determinations of molecular diffusion coefficients in a low permeability geologic medium. Environmental Science and Technology **43(17)**: 6730-6736, http://dx.doi.org/10.1021/es901036p.

Huysmans M and Dassargues A (2004) Review of the use of Péclet numbers to determine the relative importance of advection and diffusion in low permeability environments. Hydrogeology Journal **13(5)**: 895-904, http://dx.doi.org/10.1007/s10040-004-0387-4.

Jackson ML (1979) Soil chemical analysis – Advanced course. Published by the author, Madison, Wisconsin, USA.

Jackson PD, Taylor-Smith D and Stanford PN (1978) Resistivity-porosity-shape relationships for marine sands. Geophysics **43(6)**: 1250-1268, http://dx.doi.org/10.1190/1.1440891.

Kelly R, Pineda JA and Suwal L (2016) A comparison of in-situ and laboratory resistivity measurements in soft clay. In *Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterization (ISC'5),* Gold Coast, Australia (Lehane BM, Acosta-Martinez HE and Kelly R (eds)).Australian Geomechanics Society, Sydney, Australia, vol. 2, pp. 883-886

Kenney TC (1967) The influence of mineral composition on the residual strength of natural soils. . In *Proceedings of the Geotechnical Conference*, Oslo, Norway. Norwegian Geotechnical Institute, Oslo, Norway, pp. 123-129.

Leroueil S, Tavenas F and Le Bihan JP (1983) Proprietes caracteristiques des argiles de l'est du Canada. Canadian Geotechnical Journal **20(4)**: 681–705, http://dx.doi.org/10.1139/t83-076.

Locat J and Demers D (1988) Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays. Canadian Geotechnical Journal **25(4)**: 799-806. http://dx.doi.org/10.1139/t88-088.

Locat J and St-Gelais D (2014) Nature of sensitive clays from Quebec. In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer, Dordrecth, The Netherlands, pp. 25-37

Løken, T (1968) Kvikkleiredannelse og kjemisk forvitring i norske leirer. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 75, pp. 1-9 (in Norwegian).

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

Malusis MA, Kang JB and Shackelford CD (2015) Restricted salt diffusion in a geosynthetic clay liner. Environmental Geotechnics **2(2)**: 68-77. https://doi.org/10.1680/envgeo.13.00080.

Manheim FT and Waterman LS (1974) Diffusimetry (diffusion constant estimation) on sediment cores by resistivity probe. Contribution No. 2784 of the Woods Hole Oceanographic Institution. Publication approved by the Director, United States Geological Survey.

Mitchell JK and Soga K (2005) Fundamentals of soil behaviour. 3rd edition. John Wiley & Sons Inc. New Jersey, USA.

Moum J, Sopp OI and Løken T (1968) Stabilization of undisturbed quick clay by salt wells. Väg- och vattenbyggaren no. 8. Reprinted in Norwegian Geotechnical Institute, Oslo, Norway, NGI publication no. 81, pp. 1-7.

Moum J, Løken T and Torrance JK (1971) A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. Géotechnique 21(4): 329-340, http://dx.doi.org/ 10.1680/geot.1971.21.4.329.

Norwegian Geotechnical Society (2011) Veiledning for symboler og definisjoner i geoteknikk: Identifisering og klassifisering i jord. Norwegian Geotechnical Society, Oslo, Norway, NGF-notification no. 2 2nd revision, first published in 1982. pp. 1-54 (in Norwegian).

Parkhurst DL, Thorstenson DC and Plummer LN (1980) PHREEQE – a computer program for geochemical calculations. U.S. Geological Survey Water-Resources, Denver, CO, USA. Investigations Report 80-96. pp. 1-195.

Parkhurst DL and Appelo CAJ (2013) Description of Input and Examples for PHREEQC Version 3—A Computer Program for Speciation, Batch-Reaction, One-Dimensional Transport, and Inverse Geochemical Calculations. U.S. Geological Survey, Denver, CO, USA. pp. 1-49.

Quigley RM (1980) Geology, mineralogy, and geochemistry of Canadian soft soils: a geotechnical perspective. Canadian Geotechnical Journal **17(2)**: 261–285, http://dx.doi.org/10.1139/t80-026.

Rosenqvist IT (1946) Om leirers kvikkaktighet. Norwegian Public Road Administrations, Oslo, Norway (in Norwegian).

Rosenqvist IT (1953) Considerations on the sensitivity of Norwegian quick-clays. Géotechnique **3(5)**: 195–200. http://dx.doi.org/10.1680/geot.1953.3.5.195.

Rosenqvist IT (1955) Investigations in the clay-electrolyte-water system. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 9, pp. 1-125.

Shackelford, C.D., Moore, S.M., 2013 Fickian diffusion of radionuclides for engineered containment barriers: Diffusion coefficients, porosities, and complicating issues. Engineering Geology, **152(1)**: 133-147. 10.1016/j.enggeo.2012.10.014

Shackelford CD (2014) The ISSMGE Kerry Rowe Lecture: The role of diffusion in environmental geotechnics. Canadian Geotechnical Journal **51(11)**: 1219-1242, http://dx.doi.org/10.1139/cgj-2013-0277.

Taylor Smith D (1971) Acoustic and electric techniques for sea-floor sediment identification. In *Proceedings of the International Symposium On Engineering Properties of Sea-Floor Soils and their Geophysical Identification.* University of Washington, Seattle, Washington, USA. pp. 253-267.

Thakur V, Degago SA, Oset F, Aabøe R, Dolva BK, Aunaas K, Nyheim T, Lyche E, Jensen OA, Sæter MB, Robsrud A, Viklund M, Nigussie D and L'Heureux JS (2014) Characterisation of post-failure movements of landslides in soft sensitive clays. . In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, The Netherlands, pp.91-104.

Torrance JK (1975) On the role of chemistry in the development and behavior of the sensitive marine clays of Canada and Scandinavia. Canadian Geotechnical Journal **12(3)**: 326-335. http://dx.doi.org/10.1139/t75-037.

Torrance JK (1979) Post-depositional changes in the pore water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. Engineering Geology **114(2-3)**, 135-147, http://dx.doi.org/10.1016/0013-7952(79)90081-4

Torrance JK (1983) Towards a general model of quick clay development. Sedimentology **30(4)**: 547-555, http://dx.doi.org/10.1111/j.1365-3091.1983.tb00692.x

Torrance JK (1999) Physical, chemical and mineralogical influences on the rheology of remoulded low-activity sensitive marine clay. Applied Clay Science **14(4)**: 199–223, http://dx.doi.org/10.1016/S0169-1317(98)00057-X.

Torrance JK (2012) Landslides in quick clay. In *Landslides: Types, Mechanisms and Modeling* (Clague JJ and Stead D (eds)). Cambridge University Press, Cambridge, UK, pp. 83-94.

van Olphen H (1963) An introduction to clay colloid chemistry. John Wiley & Sons, Inc, New York, NY, USA.

van Olphen H (1977) Theories of the stability of lyophobic colloidal systems. In Physical Chemistry: Enriching topics from colloid and surface science 2nd edt. Edited by van Olphen, H. and Mysels, K.J., THEOREX, California, USA. pp. 5-15

van Stempvoort DR and van der Kamp G (2003) Modeling of hydrogeochemistry of aquitards using minimally disturbed samples in radial diffusion cells. Applied Geochemestry **18(4)**: 551-565, http://dx.doi.org/10.1016/S0883-2927(02)00152-X.

Waxman MH and Smits LJM (1968) Electrical conductivities in oil-bearing shaly sands. Society of Petroleum Engineers Journal **243(2)**: 107–122, http://dx.doi.org/10.2118/1863-A.

List of notations

CEC	cation exchange capacity (meq/100 g dry soil)
c_{ur}	remoulded shear strength (kPa)
D_e	effective diffusion coefficient (m^2/s)
D_f	diffusion coefficient in free water (m^2/s)
D^*	apparent diffusion coefficient (m^2/s)
ε_w	water-filled porosity (-)

F	formation factor (F)
IL	liquidity index (-)
IP	plasticity index (%)
k_h	horizontal hydraulic conductivity (m/s)
m	Archie's exponent (-)
n	exponent used in MCD simulations in PHREEQC
n_{tot}	total number of cells in PHREEQC model
σ_t	electrical soil conductivity
σ_w	electrical pore-water conductivity
θ^2	tortuosity (-)

Table 4 Pore-water chemistry in ground-water samples extracted from BAT B1 0.5 m from salt-well no. 6

Days after installation	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	F^-	Br^-	SO_4^{2-}	PO_4^{3-}	NO_3^-	Alkalinity	EB	Salt content	KMgCa-ratio
	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	%	g/L	%
78	9.06	0.24	0.31	0.38	0.29	0.22	0.05	0.06	0.11	0.00	8.26	5.32	0.76	9.30
125	8.99	0.19	0.25	0.24	0.28	0.17	0.00	0.08	0.50	0.10	8.10	2.30	0.75	6.98
161	9.08	0.21	0.24	0.26	0.30	0.17	0.00	0.08	0.00	0.10	9.04	0.48	0.80	7.22
321	9.95	1.95	1.52	1.88	1.15	0.06	0.02	0.01	0.00	0.00	8.48	22.31	0.92	34.95
595	20.05	0.41	0.98	1.22	14.86	0.01	0.02	0.00	0.00	0.00	6.36	3.22	1.43	11.53
651	22.92	0.45	1.29	0.68	20.62	0.10	0.05	0.00	0.00	0.00	6.10	-2.92	1.68	9.57
712	25.77	0.61	2.02	1.03	24.82	0.08	0.06	0.00	0.02	0.07	5.66	-2.12	1.90	12.45
763	27.90	0.91	3.08	1.43	29.48	0.07	0.06	0.00	0.00	0.07	5.24	-2.34	2.12	16.24
854	32.54	2.28	5.89	2.25	39.67	0.05	0.07	0.00	0.00	0.00	4.21	-1.21	2.62	24.24
897	33.40	3.49	7.29	2.80	43.64	0.05	0.07	0.00	0.00	0.00	4.01	-0.82	2.85	28.92
932	34.75	4.61	8.23	3.62	48.14	0.05	0.06	0.00	0.00	0.00	4.08	-1.09	3.11	32.14
987	37.17	7.63	11.79	7.02	54.18	0.04	0.06	0.00	0.00	0.00	4.56	3.89	3.64	41.57
1044	34.30	9.75	11.04	4.97	58.44	0.04	0.08	0.00	0.35	0.00	3.33	-1.78	3.70	42.89
1125	35.53	14.80	13.26	5.85	67.55	0.04	0.09	0.00	0.00	0.03	3.51	-1.26	4.29	48.84
1235	35.99	22.27	15.05	6.41	76.83	0.03	0.09	0.00	0.00	0.00	3.49	-0.45	4.95	54.86

Na^+ sodium, K^+ potassium, Mg^{2+} magnesium, Ca^{2+} calcium, Cl^- chloride, F^- fluoride, Br^- bromide, SO_4^{2-} sulphate, PO_4^{3-} phosphate, NO_3^- nitrate, EB electric charge balance, KMgCa –ratio $(K^++Mg^{2+}+Ca^{2+})/(Na^++K^++Mg^{2+}+Ca^{2+}) \cdot 100\%$

Table 5 Pore-water chemistry in ground-water samples extracted from BAT B2 1.0 m from salt-well no. 6

Days after installation	Na⁺	K⁺	Mg²⁺	Ca²⁺	Cl⁻	F⁻	Br⁻	SO₄²⁻	PO₄³⁻	NO₃⁻	Alkalinity	EB	Salt content	KMgCa-ratio
	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	meq/l	%	g/L	%
80	8.96	0.25	0.30	0.35	0.30	0.23	0.00	0.05	0.11	0.00	8.22	5.13	0.75	9.16
126	8.95	0.18	0.24	0.24	0.27	0.18	0.00	0.08	0.49	0.10	7.90	3.23	0.74	6.93
162	8.93	0.20	0.23	0.24	0.31	0.17	0.00	0.08	0.49	0.10	7.98	2.56	0.75	7.00
322*	8.97	0.96	0.39	1.01	0.31	0.06	0.02	0.00	0.00	0.01	9.93	4.57	0.89	
349*	8.92	1.42	0.36	0.95	0.72	0.07	0.02	0.00	0.00	0.02	9.05	8.27	0.87	
595	9.03	0.24	0.29	0.99	0.33	0.06	0.00	0.00	0.00	0.00	8.31	9.59	0.76	14.36
652	9.05	0.22	0.24	0.24	0.84	0.19	0.04	0.00	0.02	0.00	8.32	1.77	0.77	7.22
713	9.12	0.17	0.28	0.25	1.14	0.19	0.05	0.00	0.02	0.00	8.20	1.18	0.77	7.20
763	9.51	0.18	0.27	0.27	1.52	0.19	0.04	0.00	0.00	0.07	8.24	0.86	0.80	7.11
855	10.85	0.20	0.38	0.28	2.53	0.18	0.04	0.00	0.00	0.04	8.09	3.73	0.86	7.35
897	10.98	0.20	0.43	0.34	2.93	0.17	0.04	0.00	0.00	0.00	7.87	4.11	0.86	8.13
931	11.66	0.22	0.40	0.33	3.43	0.17	0.04	0.05	0.00	0.00	7.77	4.75	0.89	7.56
986	12.66	0.22	0.65	0.57	4.38	0.20	0.02	0.00	0.00	0.00	7.57	7.35	0.94	10.22
1044	11.86	0.22	0.32	0.23	5.08	0.17	0.04	0.00	0.00	0.00	6.97	1.49	0.90	6.12
1125	13.36	0.30	0.39	0.26	6.87	0.16	0.04	0.00	0.00	0.03	6.86	1.23	1.00	6.60
1236	14.85	0.60	0.49	0.30	9.18	0.14	0.01	0.00	0.00	0.00	6.96	-0.12	1.13	8.58

* Results not included in Figure 4b due to unlikely high concentration of K⁺

Paper VII

Helle TE, Aagaard P and Nordal S (2017) **Improving the post-failure properties in quick clays by treatment with potassium chloride.** In: *Landslides in sensitive clays: From research to implementation*. Advances in Natural and Technological Hazards Research 46, Springer. 2nd International Workshop on Landslides in Sensitive Clays, Trondheim, Norway, June 2017: 45-55. http://dx.doi.org/10.1007/978-3-319-56487-6_4

Paper VII

Paper VIII

Paper VIII

Effectiveness of resistivity cone penetration tests in salt-treated highly sensitive clay

1 **Tonje Eide Helle** MSc
PhD candidate, Department of Civil and Environmental Engineering,
Norwegian University of Science and Technology, Trondheim, Norway;
Head Engineer, Directorate of Public Roads, Trondheim, Norway
(corresponding author: tonje.helle@vegvesen.no)
(Orcid:0000-0003-3527-7600)

2 **Michael Long** BE, MEngSc, PhD, CEng, MICE
Associate Professor, School of Civil Engineering, University College
Dublin, Dublin, Ireland

3 **Steinar Nordal** MSc, PhD
Professor, Department of Civil and Environmental Engineering,
Norwegian University of Science and Technology, Trondheim, Norway

4 **Per Aagaard** MSc, PhD
Professor Emeritus, Department of Geosciences, University of Oslo,
Oslo, Norway

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.

Notation

a	attraction
B_q	pore-pressure parameter
c_{ur}	remoulded shear strength
F	formation factor
f_s	uncorrected sleeve friction
N_m	normalised tip resistance
q_c	uncorrected tip resistance
q_n	net tip resistance
q_t	corrected tip resistance
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
α	area factor of the cone penetration test cone
σ_t	soil conductivity
σ_{v0}	total overburden stress
σ'_{v0}	effective overburden stress
σ_w	pore water conductivity

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 (Moum *et al.*, 1971; Rosenqvist, 1946). 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 liquid when remoulded. Clays are characterised as quick clays at remoulded shear strengths of <0·5 kPa (NGF, 2011; Rosenqvist, 1946). Sodium (Na^+) is the dominant cation in the pore water in quick clays often having salt contents of <2 g/l (Torrance, 1979), and the clays may even behave as liquids at a salt content <1 g/l (Moum *et al.*, 1971). Re-introducing a high salt content in these clays decreases the repulsive forces and renders the clays not quick (e.g. Bjerrum, 1955; Quigley, 1980; Rosenqvist, 1946; Torrance, 1983).

In January 2013, six salt wells filled with potassium chloride were installed in a quick-clay deposit at Dragvoll, Trondheim, Norway, in order to investigate the feasibility of potassium

Ground Improvement
Volume 170 Issue GI3

**Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay**
Helle, Long, Nordal and Aagaard

chloride as ground improvement. In situ tests are widely used to investigate the subsurface and to determine the geotechnical properties effectively and relatively cheaply without the necessity of sampling. Resistivity cone penetration tests (RCPTus) were conducted around all the salt wells to investigate their applicability in detecting the improved geotechnical properties in the salt-treated clay, distinguishing when the clay ceases to be quick based on the criteria for detecting highly sensitive quick clays developed over the last decades (e.g. Sandven *et al.*, 2015; Solberg *et al.*, 2012). 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 two decades (e.g. Dahlin *et al.*, 2004; Donohue *et al.*, 2012; Lundström *et al.*, 2009; Sauvin *et al.*, 2011; 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 (Long *et al.*, 2012; Solberg *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 (Helle *et al.*, 2016, 2017; Moum *et al.*, 1971; Penner, 1965; Rosenqvist, 1968; Torrance, 1983; van Olphen, 1963). Clays with low-saline pore-water compositions dominated by sodium (Na^+) may develop high sensitivity (Mitchell and Soga, 2005; Penner, 1965; Torrance, 1983), 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 as 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. Löfroth *et al.*, 2011; Rømoen *et al.*, 2010; 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 (Glover *et al.*, 2000; Waxman and Smits, 1968). Nevertheless, the salt content also greatly influences the soil conductivity. RCPTu is not extensively used in mapping highly sensitive quick clays due to the fact that conductivity measurements in clays do not

necessarily distinguish highly sensitive, low-saline quick clay from non-quick low-saline clays. Combining the conventional CPTu data with the conductivity measurements facilitates interpretation.

Very low tip resistance (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 (NGF, 2010)

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

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. $\qquad N_m = q_n/(\sigma'_{v0} + a)$

3. $\qquad B_q = (u_2 - u_0)/q_n$

Combining the soil conductivity with the normalised parameters N_m and B_q may simplify distinguishing highly sensitive, low-saline – that is, 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 histories, the investigation presented herein is restricted to the Dragvoll research site with its specific geological history. The improved geotechnical properties are only due to the changed chemistry in the pore water and in the adsorbed positions on the mineral surfaces. This paper presents the challenges in distinguishing the improved clay properties of quick clays based on the 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 by combining soil conductivity and normalised parameters at the same time as mapping the extent of the salt plume and the improved geotechnical properties

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay
Helle, Long, Nordal and Aagaard

around salt wells. The correlations between salt content, 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. The Dragvoll research site

2.1 Site description and soil properties

The Dragvoll research site is located at 156 m above the current sea level, in close vicinity to the marine limit at around 175–180 m above the current sea level (Hafsten, 1983; Kjemperud, 1981). The groundwater table fluctuates 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 depths. Clay, gravel, shells and shell fragments are commonly found down to about 4 m depth and occasionally at deeper levels. The investigated quick clay encountered at 3–4 m depth (Bryntesen, 2013) is interbedded with millimetre-thick silt and sand layers with a few centimetres 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 causes high repulsion between the

clay particles, and the clay therefore easily remoulds. The remoulded shear strength (c_{ur}) is 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 (ILs) of 3·4–4·3, and plasticity indexes (IPs) of 4·4–6·3%.

Six salt wells were installed with a centre-to-centre distance of about 10 m. The wells were constructed of 63 mm polyethylene pipes, allowing the salt to be in contact with the clay through slotted sections from 4 to 8 m depth. The wells were refilled regularly to ensure fully saturated potassium chloride 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 number 1 (M1) and one of the probes is from manufacturer number 2 (M2). Both of the probe types allow an electrical resistivity
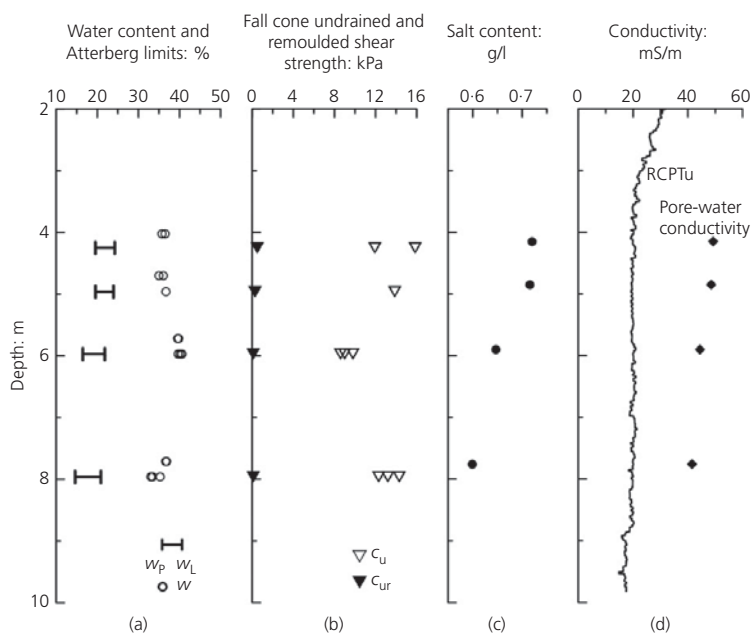

Figure 1. (a) Water content (w) and Atterberg limits (w_P and w_L), (b) fall cone undrained (c_u) and remoulded shear strength (c_{ur}), (c) salt content and (d) soil and pore-water conductivity in the quick clay at Dragvoll

Ground Improvement
Volume 170 Issue GI3

**Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay**
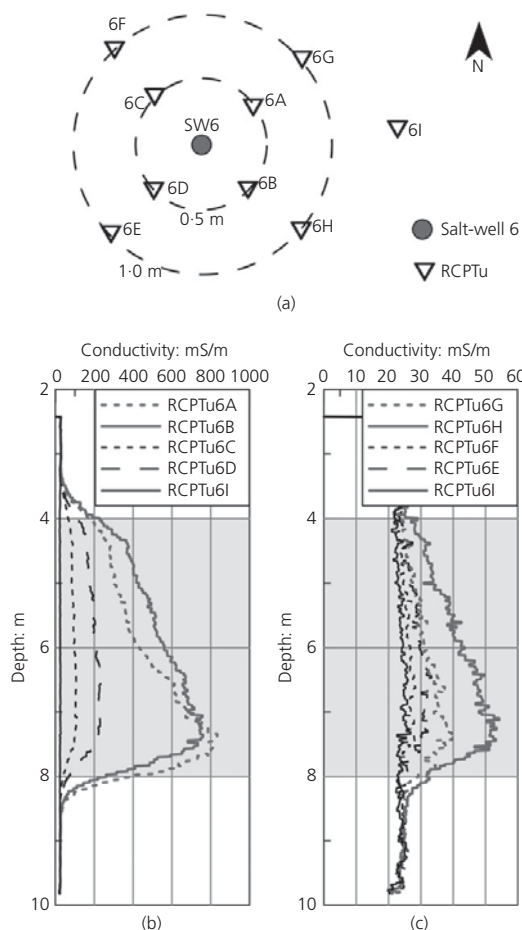Helle, Long, Nordal and Aagaard

Figure 2. (a) RCPTus conducted around salt-well number 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 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 to 1·0 m

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, the 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), represents 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). Of the 18 soundings conducted with the probe from M2, 11 are classified as application class number 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 it was filled with groundwater. Soundings 0·5 and 1·0 m from this well showed that the well installations had a moderate, but measurable, effect on the pore-pressure measurements in the top of the soil, down to ∼6 m depth. Some of the soundings in the original quick clay and the salt-treated clay, using a porous-bronze filter with anti-freeze as the 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 ∼6 m depth, and in the 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 as opposed to porous-bronze filters in the CPTu equipment for measuring u_2 was investigated both in the

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

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay
Helle, Long, Nordal and Aagaard

original quick clay and around the dummy well. In general, there was no difference in using the two filter types, except that the sounding results using the slot filter with grease and oil as saturation fluids were not affected by the loss of saturation. According to Robertson and Campanella (1983), when there is loss of saturation in the 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 at a distance of 0·5, 1·0 and 1·5 m from the salt wells. The conductivity measurements revealed that the extents of the salt plumes were non-symmetrical around the wells (Helle *et al.*, 2017), with salt migrating to further distances in predominant directions (Figures 2(b) and 2(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 potassium chloride 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, ERT was conducted on the site (Bazin *et al.*, 2016) in an attempt to map the directions and extents 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 electrode spacings of 0·25, 0·50 and 1·00 m over lengths of 20, 40 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 conductivities
The conductivity in soils is greatly influenced by the salt content in the pore fluid. The pore-water conductivities in the extracted pore water in the clay samples from around salt-well numbers 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-well numbers 2 and 3. The in situ soil temperature at Dragvoll is around 6°C. As conductivity is influenced by temperature, the pore-water conductivity should be correlated to the in situ soil conductivity at the corresponding temperatures. The pore-water conductivities in the samples from around salt-well numbers 2 and 3 were determined at a laboratory temperature of around 25°C. The pore-water conductivities for all the pore-water compositions were therefore adjusted to 6°C by the geochemical computer program PHREEQC, which are 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 3(a)), whereas the soil conductivities measured with the RCPTu increase 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 3(b)), 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 (Glover *et al.*, 2000; Waxman and Smits, 1968), 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 conductivities 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 content in clays surrounding salt wells, and thus effectively map the salt-plume extent. Correlation 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.

3.3 Conductivity and improved geotechnical properties
Quick clays are defined in Norway by a remoulded shear strength (c_{ur}) of <0·5 kPa (NGF, 2011), often having an IL above 1·2 (Leroueil *et al.*, 1983), and salt content <2 g/l (Torrance, 1979). Both the pore-water and soil conductivities are low in quick clays. Increased salt content above 2 g/l – that is, pore-water conductivity >200 mS/m – improves the remoulded shear strength beyond 0·5 kPa (Figure 4(a)) and the IP increases beyond 10% (Figure 4(e)); the Dragvoll clay
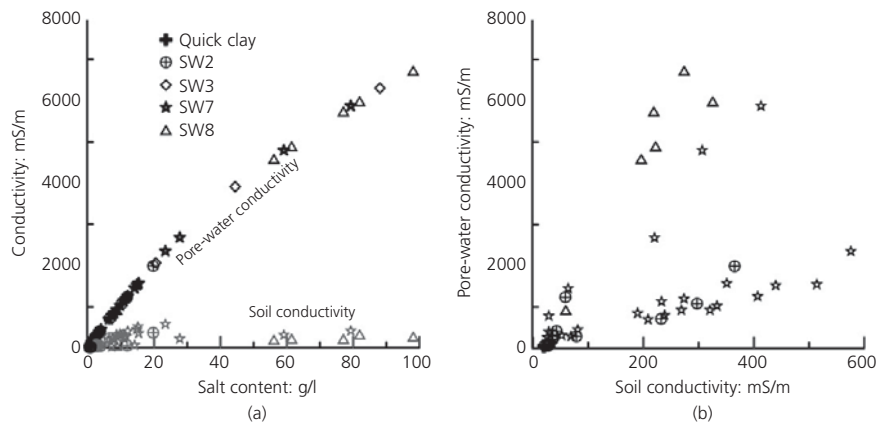
Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay
Helle, Long, Nordal and Aagaard

Figure 3. (a) Soil conductivity from RCPTus (grey symbols) and PHREEQC-estimated pore-water conductivity (black symbols) at 6°C correlated to salt content; (b) pore-water conductivity correlated to soil conductivity

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 4(c)).

According to Long *et al*. (2012) and Solberg *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 (Figures 4(b), 4(d) and 4(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 5(a)). For these cases, a 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 4(b), the improved properties begin at soil conductivity values exceeding only 30 mS/m, corresponding to a salt content exceeding 1 g/l. At soil conductivities exceeding 200 mS/m, the salt content in nearby clay samples exceeds 6 g/l (Figure 5(a)), c_{ur} is improved beyond 3·5 kPa, IL decreased below 1·2 and the clay is of medium plasticity (Figures 4(b), 4(d) and 4(f)).

The pore-water conductivity is directly correlated to the salt content. However, at low salt content the pore-water composition determines whether the clay is quick or not (e.g. Helle *et al*., 2016, 2017; Moum *et al*., 1971; Penner, 1965; Torrance, 1983). Correlating the soil conductivity to the pore-water composition in nearby clay samples clearly illustrates the challenge in distinguishing quick from non-quick clay based solely on soil conductivity (Figure 5(b)). 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 a low salt content (Helle *et al*., 2017). Therefore, clays with a low salt content (< 2 g/l), and in the case at Dragvoll actually up to 14 g/l, with a pore-water composition that inhibits the 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/m³, a groundwater 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 to 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 6(a)), increasing towards and beyond 4 as the geotechnical properties are improved (Figure 6(b)). At low conductivity, B_q is both above and below 1 (Figure 6(c)), decreasing below 1 as the geotechnical properties are improved (Figure 6(d)). Using an N_m value of 4 as an 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 6(b)). The B_q is both below and above 1 in the quick clays, but in general lower than 1 at c_{ur} higher than ∼1 kPa (Figure 6(d)).

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay
Helle, Long, Nordal and Aagaard
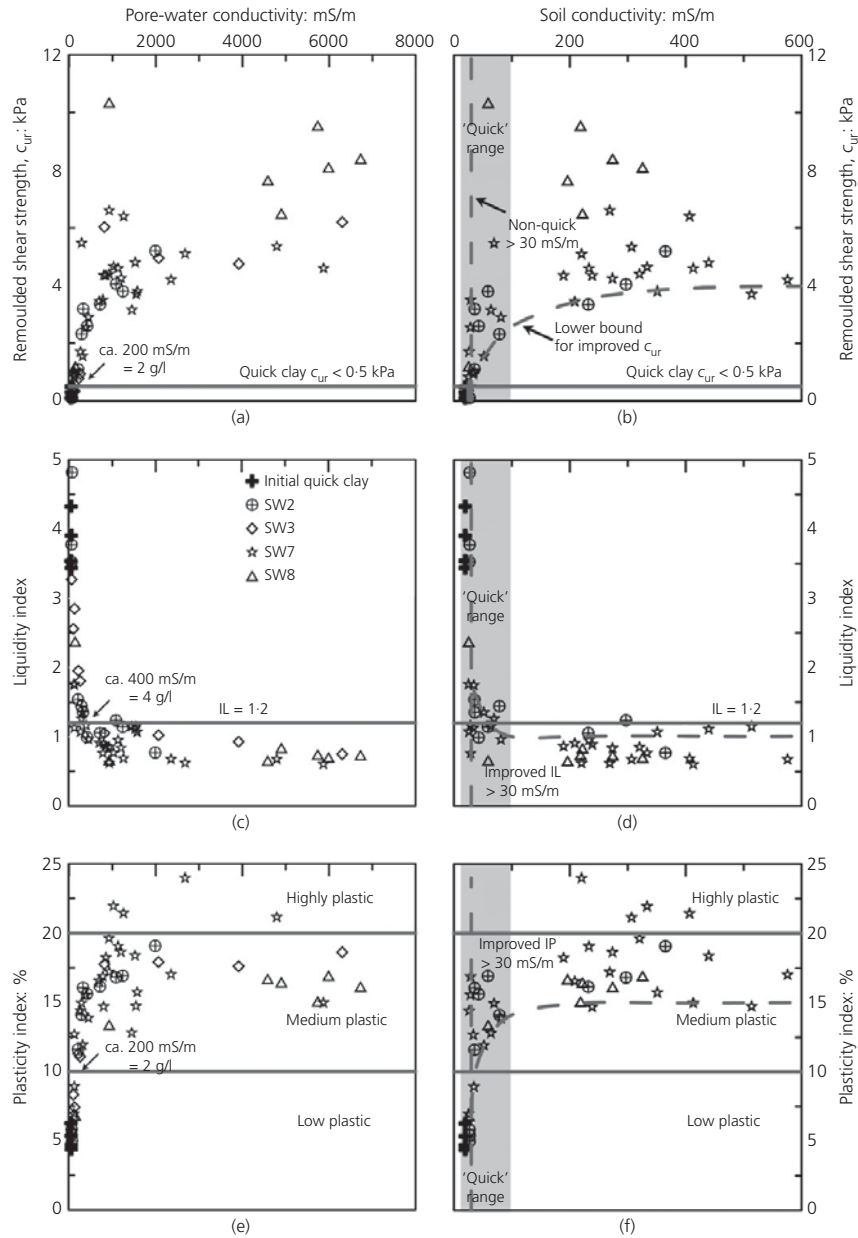
Figure 4. Pore-water and soil conductivity correlated to (a) and (b) remoulded shear strength (c_{ur}), (c) and (d) IL, and (e) and (f) IP. Soil conductivity in the range 10–100 mS/m (grey shading) may indicate possible quick clay. Improved geotechnical properties are detected within the dashed grey lines in (b), (d) and (e) having soil conductivities exceeding 30 mS/m

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

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone penetration tests in salt-treated highly sensitive clay
Helle, Long, Nordal and Aagaard
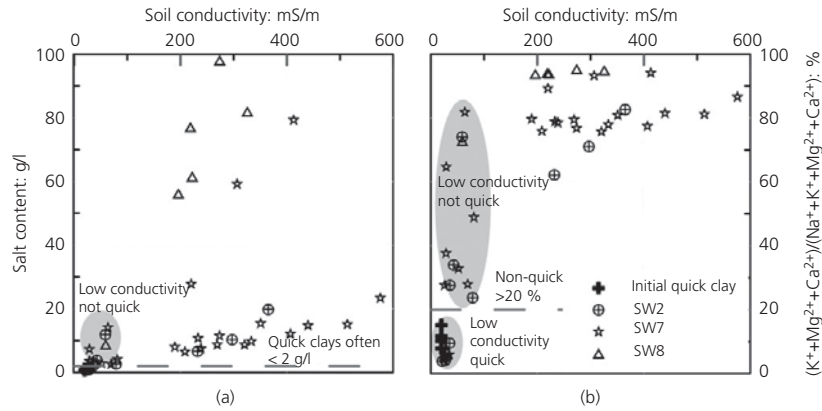
Figure 5. Soil conductivity correlated to (a) salt content and (b) the ratio of the sum of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) over the sum of sodium (Na^+), K^+, Mg^{2+} and Ca^{2+} (all concentrations in meq/l). Quick clays often have a salt content of <2 g/l, and a ratio of K^+, Mg^{2+} and Ca^{2+} over the major cations of <20%
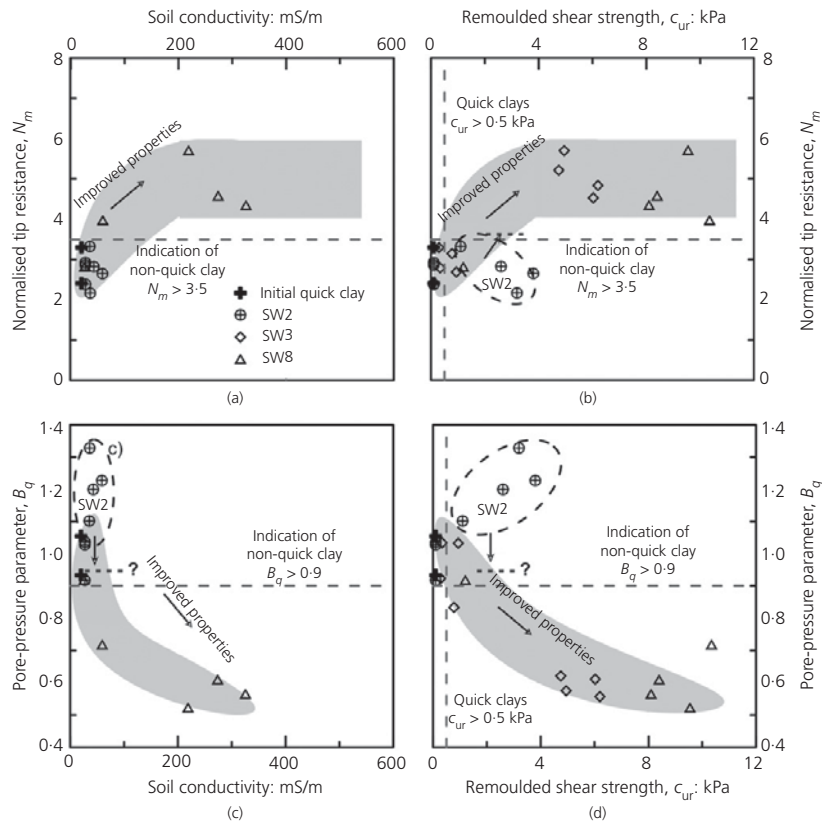
Figure 6. Normalised tip resistance correlated to (a) soil conductivity and (b) remoulded shear strength, and pore-pressure parameter correlated to (c) soil conductivity and (d) remoulded shear strength. The N_m and B_q values within the dotted circles may be moved in the direction of the arrow. All data are from 5 to 8 m depth

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone penetration tests in salt-treated highly sensitive clay
Helle, Long, Nordal and Aagaard
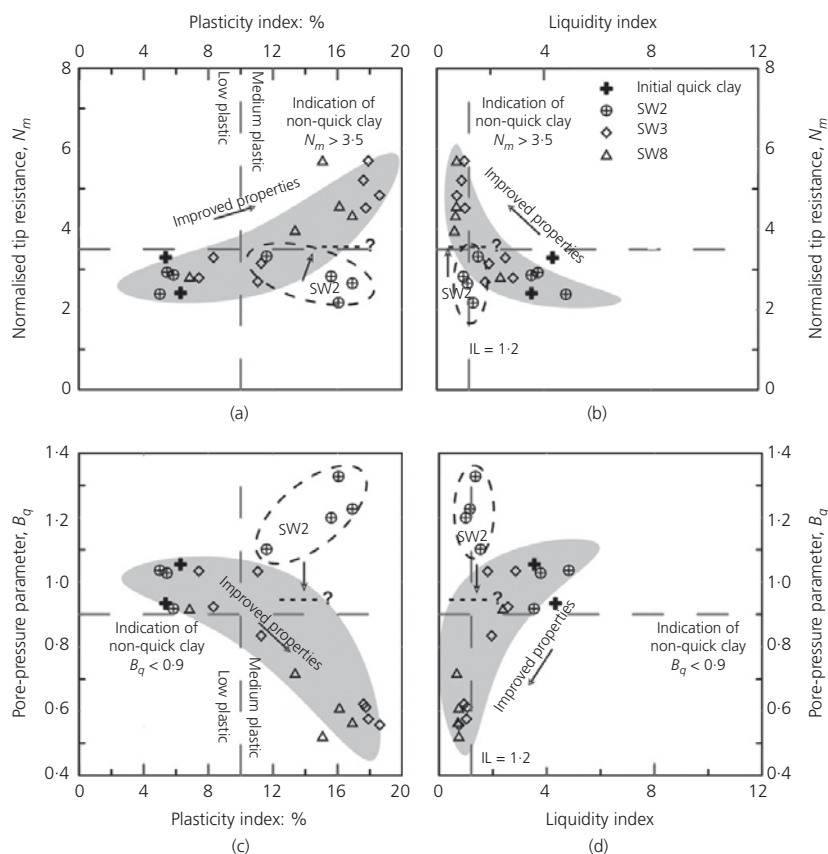
Figure 7. Normalised tip resistance (N_m) and pore-pressure parameter (B_q) correlated to (a) and (c) IP, and (b) and (d) IL. The N_m and B_q values within the dotted circles may be moved in the direction of the arrow. All data are from 5 to 8 m depth

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 values from the RCPTus around salt-well number 2, differing slightly from the remainder of the data points. The conductivities 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 the dotted line and '?' in Figures 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 content decreases the IL and increases the IP in the clays. The N_m increases towards 3·5 as the clay changes from being of low plasticity to medium plasticity (Figure 7(a)), and the B_q decreases below 0·9 in the salt-treated clay as it changes to medium plasticity (Figure 7(c)). According to Leroueil *et al.* (1983), clays with IL > 1·2 may pose a risk of developing into large retrogressive quick-clay landslides when remoulded. The N_m increases towards and beyond 3·5, and B_q less than ∼0·9 as the IL decreases below 1·2 (Figures 7(b) and 7(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 (Figures 6(b) and 6(d)). A site-specific correlation model by correlating the geotechnical properties from the site to the RCPTu results can be used in determining improved geotechnical properties based on the CPTu data.

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay
Helle, Long, Nordal and Aagaard

4.   Discussion and conclusions

Introducing a high salt content into the clay–water system increases the remoulded shear strength (c_{ur}) beyond 0·5 kPa, decreases the IL below 1·2 and increases the plasticity from low to medium and high. The pore water in quick clays has a 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 illustrate the challenges in distinguishing low-saline quick clay from non-quick clay at salt contents <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} exists for measured soil conductivity. The results from Dragvoll illustrate that low soil conductivity (<100 mS/m) does not necessarily imply quick clay. This emphasises the importance of establishing a site-specific interpretation model for distinguishing quick clay from non-quick clay, which is 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-plume extent and direction.

The CPTu tip resistance increased in the salt-treated clay compared with the soundings conducted in the original quick clay. Quick clays are strain-softening materials with a dramatic reduction in post-peak strength at strains exceeding the strain at failure. Penetrating CPTu probes remould the soil. Therefore, the tip resistance is affected by both the peak and the c_{ur}. The CPTu tip resistance increases with decreasing compressibility – that is, 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 decrease when the IP increases (Bjerrum, 1967). Adding large concentrations of potassium chloride to quick clays increases the peak as well as post-peak undrained shear strength and the apparent pre-consolidation stress, and reduces the deformations due to increasing loads (Helle *et al.*, 2015; Torrance, 1974). The plasticity and the c_{ur} in the salt-treated clay at Dragvoll is improved. The constant rate of strain oedometer tests conducted on the salt-treated clay at Dragvoll showed decreased deformations due to increasing loads with increasing salt content and IP. Therefore, increasing tip resistance may detect the improved geotechnical properties in salt-treated clay, and interpretation models based on normalised 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 <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 of <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 the 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 begins at N_m exceeding 3·5 and B_q lower than 0·9.

REFERENCES

Bazin S, Anschütz H, Sauvin G *et al.* (2016) Geophysical characterisation of marine and quick clay sites: field and laboratory tests. In *Proceedings of the 5th International Conference on Geotechnical and Geophysical Site Characterization (ISC'5), Gold Coast, Australia* (Lehane BM, Acosta-Martinez HE and Kelly R (eds)). Australian Geomechanics Society, Sydney, Australia, vol. 2, pp. 831–836.

Bjerrum L (1955) *Norske Marine Leirers Geotekniske Egenskaper.* Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 7 (in Norwegian).

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone
penetration tests in salt-treated highly
sensitive clay
Helle, Long, Nordal and Aagaard

Bjerrum L (1967) Engineering geology of Norwegian
normally-consolidated marine clays as related to settlements of
buildings. *Géotechnique* **17(2)**: 83–118, http://dx.doi.org/10.1680/
geot.1967.17.2.83.

Bo MW, Chu J and Choa V (2005) The Changi East reclamation project
in Singapore. In *Ground Improvement – Case Histories*
(Indraratna B and Chu J (eds)). Elsevier, Amsterdam, the
Netherlands, vol. 3, pp. 247–276.

Bryntesen RN (2013) *Block Sample Testing at Dragvoll*. Project thesis,
Norwegian University of Science and Technology, Trondheim,
Norway.

Bryntesen RN (2014) *Laboratory Investigation on Salt Migration and
Its Effect on the Geotechnical Strength Parameters in Quick Clay
Mini-Block Samples from Dragvoll*. Master's thesis, Norwegian
University of Science and Technology, Trondheim, Norway.

Campanella RG and Weemees I (1990) Development and use of an
electrical resistivity cone for groundwater contaminant studies.
Canadian Geotechnical Journal **27(5)**: 557–567.

Dahlin T, Palm M and Garin H (2004) Combined resistivity imaging
and RCPT for geotechnical preinvestigation. In *Proceedings
of the 14th NGM, Nordic Geotechnical Meeting, Ystad, Sweden*
(Garin H (ed.)). Swedish Geotechnical Society, Linköping,
Sweden, pp. C81.

de Ruiter J (1982) The static cone penetration test. State of the art
report. In *Proceedings of the 2nd European Symposium of
Penetration Testing (ESOPT-II), Amsterdam, the Netherlands*
(Verruijt A, Beringen FL and de Leeuw EH (eds)). Balkema,
Rotterdam, the Netherlands, pp. 389–405.

Donohue S, Long M, O'Connor P et al. (2012) Multi-method
geophysical mapping of quick clay. *Near Surface Geophysics*
10(3): 207–219.

Glover PWJ, Hole MJ and Pous J (2000) A modified Archie's law for
two conducting phases. *Earth and Planetary Science Letters*
180(3–4): 369–383.

Hafsten U (1983) Shore-level changes in South Norway during the
last 13,000 years, traced by biostratigraphical methods and
radiometric datings. *Norsk Geografisk Tidsskrift – Norwegian
Journal of Geography* **37(2)**: 63–79.

Helle TE, Bryntesen RN, Amundsen HA et al. (2015) Laboratory setup
to evaluate the improvement of geotechnical properties from
potassium chloride saturation of a quick clay from Dragvoll,
Norway. In *Proceedings of 68th Canadian Geotechnical Conference
GeoQuebec 2015, Quebec, Canada* (Côté J and Allard M (eds)).
Agora Communication Inc., Quebec, QC, Canada.

Helle TE, Nordal S, Aagaard P and Lied OK (2016) Long-term effect
of potassium chloride treatment on improving the soil behavior
of highly sensitive clay – Ulvensplitten, Norway. *Canadian
Geotechnical Journal* **53(3)**: 410–422.

Helle TE, Aagaard P and Nordal S (2017) In-situ improvement of highly
sensitive clays by potassium chloride migration. *Journal of
Geotechnical and Geoenvironmental Engineering ASCE*,
https://doi.org/10.1061/(ASCE)GT.1943-5606.0001774.

ISO (International Organization for Standardization) (2012) ISO
22476-1:2012: Geotechnical investigation and testing – field
testing – part 1: electrical cone and piezocone penetration test.
ISO, Geneva, Switzerland.

Kjemperud A (1981) A shoreline displacement investigation from
Frosta in Trondheimsfjorden, Nord-Trøndelag, Norway.
Norsk Geologisk Tidsskrift **61**: 1–15 (in Norwegian).

Lerouueil S, Tavenas F and Le Bihan JP (1983) Propriétés caractéristiques
des argiles de l'est du Canada. *Canadian Geotechnical Journal*
20(4): 681–705 (in French).

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*. Swedish Geotechnical Institute, Linköping, Sweden.

Long M, Donohue S, L'Heureux JS et al. (2012) Relationship between
electrical resistivity and basic geotechnical parameters for marine
clays. *Canadian Geotechnical Journal* **49(10)**: 1158–1168.

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

Lunne T, Eidsmoen T, Gillespie D and Howland JD (1986) Laboratory
and field evaluation of cone penetrometers. In *Proceedings of
the ASCE Specialty Conference In Situ'86: Use of In-Situ Tests
in Geotechnical Engineering, Blacksburg, VA, USA* (Clemence SP
(ed.)). American Society of Civil Engineers (ASCE), New York,
NY, USA, GSP 6, pp. 714–729.

Lunne T, Robertsson PK and Powell JJM (1997) *Cone Penetration Testing
in Geotechnical Practice*. Spon Press, London, UK.

Mitchell JK and Soga K (2005) *Fundamentals of Soil Behaviour*,
3rd edn. John Wiley & Sons Inc., Hoboken, NJ, USA.

Moum J, Løken T and Torrance JK (1971) A geochemical investigation
of the sensitivity of a normally consolidated clay from Drammen,
Norway. *Géotechnique* **21(4)**: 329–340, https://doi.org/10.1680/geot.
1971.21.4.329.

NGF (Norwegian Geotechnical Society) (2010) *Veiledning for utførelse
av trykksondering*, 3rd revision. Norwegian Geotechnical Society,
Oslo, Norway, NGS-notification no. 2 (in Norwegian).

NGF (2011) *Veiledning for symboler og definisjoner i geoteknikk:
Identifisering og klassifisering i jord*, 2nd revision. Norwegian
Geotechnical Society, Oslo, Norway, NGF-notification no. 2
(in Norwegian).

Parkhurst DL and Appelo CAJ (2013) *Description of Input and Examples
for PHREEQC Version 3–A Computer Program for Speciation,
Batch-Reaction, One-Dimensional Transport, and Inverse
Geochemical Calculations*. U.S. Geological Survey, Denver, CO,
USA, pp. 1–49.

Penner E (1965) A study of sensitivity in Leda clay. *Canadian Journal
of Earth Science* **2(5)**: 425–441.

Pfaffhuber AA, Bazin S and Helle TE (2014) An integrated approach
to quick-clay mapping based on resistivity measurements and
geotechnical investigations. In *Landslides in Sensitive Clays:
From Geoscience to Risk Management* (L'Heureux JS, Locat A,
Lerouueil S, Demers D and Locat J (eds)). Springer, Dordrecht,
the Netherlands, pp. 63–74.

Quigley RM (1980) Geology, mineralogy, and geochemistry of
Canadian soft soils: a geotechnical perspective. *Canadian
Geotechnical Journal* **17(2)**: 261–285.

Robertson PK and Campanella RG (1983) Interpretation of cone
penetration tests. Part II: clay. *Canadian Geotechnical
Journal* **20(4)**: 734–745.

Rømoen M, Pfaffhuber AA, Karlsrud K and Helle TE (2010). Resistivity
on marine sediments retrieved from RCPTU soundings:
a Norwegian case study. In *Proceedings of the 2nd International
Symposium on Cone Penetrating Testing (CPT'10), Huntington
Beach, CA, USA* (Robertson PK and Mayne PW (eds)).
Omnipress, Madison, WI, USA, pp. 289–296.

Rosenqvist IT (1946) *Om leirers kvikkaktighet*. Norwegian Public
Road Administrations, Oslo, Norway (in Norwegian).

Rosenqvist IT (1968) *Mechanical Properties of Soils from a
Mineralogical–Physical–Chemical Viewpoint*.
Communication from Institutt for Geologi, University in Oslo,
Oslo, Norway.

Sandven R, Montafia A, Gylland AS et al. (2015) *Detection of Brittle
Materials. Summary Report with Recommendations*. Naturfare:
infrastruktur, flom og skred (NIFS), Oslo, Norway, pp. 1–149,
final report, report no. 126/2015.

Sandven R, Gylland A, Montafia A et al. (2016a) In situ detection
of sensitive clays – part I: selected test methods. In
*Proceedings of the 17th Nordic Geotechnical Meeting: Challenges
in Nordic Geotechnics, Reykjavik, Iceland* (Ingimarsdóttir A,

Ground Improvement
Volume 170 Issue GI3

Effectiveness of resistivity cone penetration tests in salt-treated highly sensitive clay
Helle, Long, Nordal and Aagaard

Jónsson A, Sigtryggsdóttir FG *et al.* (eds)). The Icelandic Geotechnical Society, Reykjavik, Iceland, pp. 123–132.

Sandven R, Gylland A, Montafia A *et al.* (2016b) In situ detection of sensitive clays – part II: results. In *Proceedings of the 17th Nordic Geotechnical Meeting: Challenges in Nordic Geotechnics, Reykjavik, Iceland* (Ingimarsdóttir A, Jónsson A, Sigtryggsdóttir FG *et al.* (eds)). The Icelandic Geotechnical Society, Reykjavik, Iceland, pp. 133–142.

Sauvin G, Bazin S, Vanneste M, Lecomte I and Pfaffhuber AA (2011) Towards joint inversion/interpretation for landslide-prone areas in Norway – integrating geophysics and geotechnique. *Proceedings of Near Surface 2011 – 17th European Meeting of Environmental and Engineering Geophysics, Leicester, UK*, Paper E11.

Solberg IL, Hansen L, Rønning JS *et al.* (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 JK (1974) A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. *Géotechnique* **24(2)**: 155–173, https://doi.org/10.1680/geot.1974.24.2.155.

Torrance JK (1979) Post-depositional changes in the pore water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. *Engineering Geology* **114(2–3)**: 135–147.

Torrance JK (1983) Towards a general model of quick clay development. *Sedimentology* **30(4)**: 547–555.

van Olphen H (1963) *An Introduction to Clay Colloid Chemistry.* John Wiley & Sons, Inc, New York, NY, USA.

Waxman MH and Smits LJM (1968) Electrical conductivities in oil-bearing shaly sands. *Society of Petroleum Engineers Journal* **243(2)**: 107–122.

Paper IX

Paper IX

Improved geotechnical properties in salt-treated highly sensitive landslide-prone clays

Tonje Eide Helle[1,2], Steinar Nordal[1], and Per Aagaard[3]

Abstract

Retrogressive or progressive landslides in slopes with highly sensitive quick clay may stretch several hundred meters from where the slide was initiated. Re-introducing high salt contents in the pore water of the leached low-saline quick clays may inhibit development of such large landslides. Wells filled with potassium chloride were installed in a quick clay deposit at Dragvoll, Trondheim, Norway, to investigate the impact of changed pore-water chemistry on the geotechnical properties. The clay ceased to be quick due to favourable changed ion composition in the pore water even at low salt contents, inhibiting retrogressive development. The apparent pre-consolidation stresses (p_c') increased with increasing salt contents, and the immediate collapse in structure typically seen in quick clays was avoided at loads beyond p_c' by changing the pore-water chemistry. Potassium chloride treated quick clay may therefore work as a barrier against retrogressive development, and reduce the risk for initiating progressive landslides.

Keywords: Geotechnical engineering; Site investigation; Slopes – stabilisation; Strength & testing of materials

[1] Norwegian University of Science and Technology, Department of Civil and Environmental Engineering, 7491 Trondheim, Norway
[2] The Directorate for Public Roads, P.O. box 8142 Dep, 0033 Oslo, Norway
[3] University of Oslo, Department of Geosciences, P.O. box 1047 Blindern, 0316 Oslo, Norway

1 Introduction

The geotechnical properties of post-glacial marine clays are greatly influenced by their depositional environment and post-depositional conditions including weathering and leaching. The forces acting between the clay particles are determined by the stress history and by the pore-water chemistry and mineralogy (Rosenqvist, 1955; Torrance, 1983; Mitchell and Soga, 2005). The concentration and composition of ions in the pore fluid have significant impact on the geotechnical properties, as clays are electrochemically very active (van Olphen, 1963). It is essential to understand the impact of the clay-water system on the behaviour of clays when using chemical additions as ground improvement in highly sensitive clays.

Most clays on the mainland of Norway were deposited in seawater during the deglaciation. The clay particles flocculated and entrapped highly saline water with salt contents of 30-35 g/L in their large voids. The structure in clays with high salt contents is stable as the repulsive forces are small due to the suppressed diffuse double layer surrounding the clay minerals. The isostatic uplift has exposed these clays to meteoric groundwater flow, diluting the salt content in their pore water (Rosenqvist, 1946, 1977). Decreasing salt-content increases the thickness of the diffuse double layer around the clay minerals (Figure 1a), increasing the repulsive forces between the clay particles. Thus, the structure may collapse during loading and the clays may behave as a liquid when remoulded. Highly sensitive, leached marine clays, termed quick clays, are defined by a remoulded shear strength (c_{ur}) of less than 0.5 kPa (Norwegian Geotechnical Society, 2011). Quick clays often have liquid limits less than the natural water content, a liquidity index larger than 1.2 (Leroueil et al., 1983) and salt contents of less than 2 g/L (Rosenqvist, 1977; Torrance, 1979). As quick clays becomes liquid when remoulded, these clays pose a serious risk for catastrophic landslides in inhabited areas especially in Mid-Norway and in the Southeast part of Norway. Re-introducing high salt contents in these highly sensitive, leached marine clays reduce the repulsive forces to such an extent that they no longer appear as quick (Rosenqvist, 1946, 1953, 1955; Bjerrum, 1955; Løken, 1968, 1970; Moum et al., 1968; Eggestad and Sem, 1976; Quigley, 1980; Torrance, 1983). Therefore, introducing salt to the clay-water system may reduce the risk of large quick clay landslides.

Laboratory studies adding various types of salts to quick clays showed that potassium chloride (KCl) has a greater impact on the remoulded shear strength and Atterberg limits than other salts at same normalities (Moum et al., 1968; Løken, 1968, 1970). Therefore, salt wells filled with KCl were installed in a quick clay deposit at Ulvensplitten, Oslo, Norway in 1972. This successfully improved the geotechnical properties prior to excavation 18-21 months later (Eggestad and Sem, 1976). Ground investigations carried out 40 years after installation revealed that the salt-treated clay maintained its non-quick behaviour (Helle et al., 2016). In spite of the encouraging results from 1972, the salt-well method is not used as a ground-improvement today due to limited experience and documentation on the effect of the method.

In order to investigate the potential of using KCl as landslide mitigation in quick clay areas, wells filled with KCl were in January 2013 installed in a quick clay deposit at Dragvoll, Trondheim, Norway. The recent in-situ experiment at Dragvoll provides unique documentation of improvement of geotechnical properties caused by the changed pore-water chemistry. Previous studies carried out in the laboratory as well as the in-situ experiment at Ulvensplitten, mainly focused on the properties in remoulded state; c_{ur} and Atterberg limits (post-failure properties). Some laboratory studies are also carried out to investigate the impact of both removing and adding salt on the compressibility of clays. All studies show that the apparent
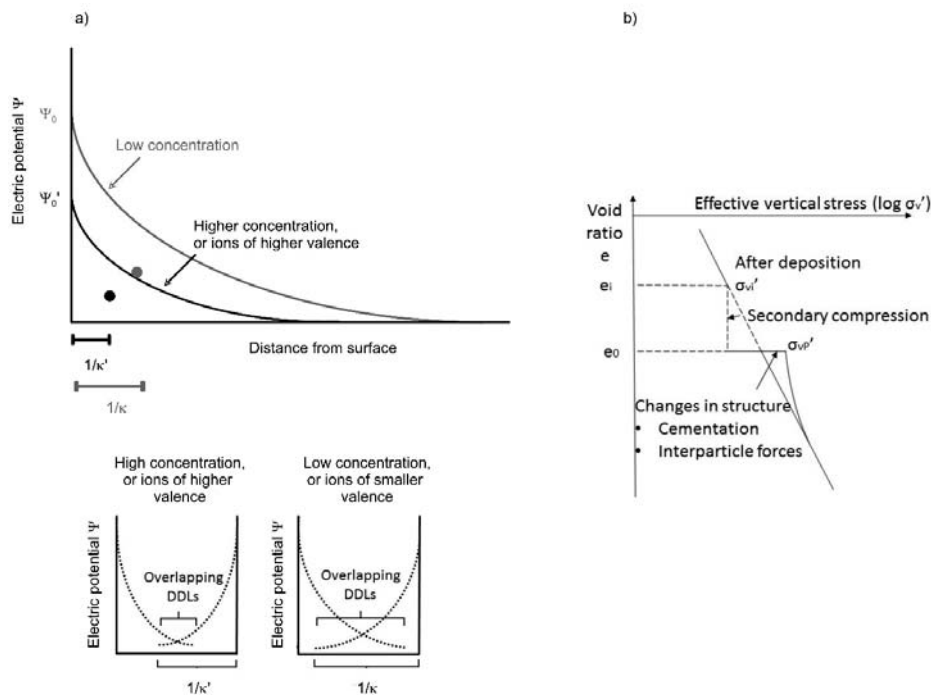
Figure 1 a) The decay of electric potential with distance from the mineral surface. The surface potential (ψ_0) is higher at low electrolyte concentrations (grey line) than at high concentrations (ψ_0') (black line). Of two electrolytes of same concentration, the surface potential is lower for the electrolyte consisting of ions of higher valence. Thus, the thickness of the diffuse double layer is smaller (1/κ). The overlap of the diffuse double layers (DDL) determines the repulsion between the clay particles. Adapted from van Olphen (1963) and Moore and Reynolds Jr. (1997). b) Vertical effective stress (σ_{vi}') and void ratio (e_i) after deposition of the clay. Secondary compression decreases the void ratio (e_0). With time, and without any excess loading or changes in the void ratio, changes in the structure may result in a further apparent increase of the vertical pre-consolidation stress (σ_{vP}'). Modified from Leroueil, S. and Vaughan, P.R. (1990)

pre-consolidation stress increases and the volume change at increasing loads decreases (decreased compressibility) with increasing salt contents (e.g. Bjerrum, 1967; Kenney et al., 1967; Torrance, 1974; Gjengedal, 2012; Bryntesen, 2014; Helle et al., 2015). Quick clays have a very brittle behaviour with significantly reduced post-peak strength due to the rapid collapse of the structure. Decreasing this brittleness may prevent large quick clay landslides. To the authors' knowledge, no studies on in-situ KCl improvement of the apparent pre-consolidation stress, compressibility and brittleness in quick clays have been carried out in the past. The improved geotechnical properties correlated to the pore-water chemistry, and their effect on reducing risk of retrogressive and progressive quick clay landslides (Figure 2) are presented and discussed herein.

In order to discuss the results it is necessary to look back at the geochemical history of quick clays. The pore-water chemistry in post-glacial Norwegian marine clays is affected by the ion composition in the seawater at time of deposition (Na^+, K^+, Mg^{2+}, Ca^{2+}), microfossils
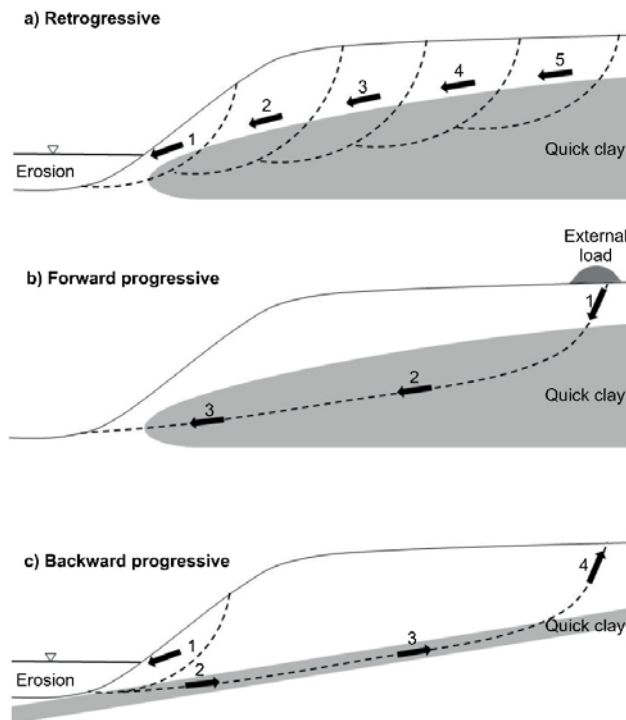
Figure 2 a) Retrogressive quick clay landslide with successive back-scarp failures. b) Forward progressive quick clay landslide due to external loading. c) Backward progressive development along a thin quick-clay layer

such as shells (Ca^{2+}), and weathering of minerals such as chlorite (Mg^{2+}, Al^{3+}, Fe^{2+}, Fe^{3+}), feldspar (K^+, Al^{3+}) and mica (K^+). The plasticity index (IP) and c_{ur} increase with the cations at same normality (eq/L) in the following order: $Na^+ < Ca^{2+} < Mg^{2+} < Al^{3+} < Fe^{2+}$ and $Fe^{3+} < K^+$ (Bjerrum 1967). The cations in the pore water and in the adsorbed positions in clays accumulated in seawater is dominated by sodium (Na^+) (Penner, 1965; Moum et al., 1971; Torrance, 1979; Mitchell and Soga, 2005). Leaching by meteoric groundwater flow dilutes the salt content in the pore water, and introduces cations of higher exchange power and higher effect on suppressing the diffuse double layer (Figure 1a) to the clay-water system such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). Thus, the clay mineral surfaces release Na^+ into the pore water, replacing it by ions of higher exchange power (higher valence, smaller hydrated radius). Therefore, Na^+ is still after significant leaching the abundant cation in the pore water in quick clays (Moum et al., 1971). As long as more than 80% of the normality of cations in the pore water consist of Na^+, the clay remains quick. As seen, adding KCl in quick clays has a beneficial effect on the geotechnical properties. Even though K^+ is of same valence as Na^+, it has a greater ionic potential, and a smaller hydrated radius. Thus, it has a more "effective" charge and greater ability to suppress the diffuse double layer. This explains why K^+ is a more effective agent on improving the post-failure properties than the other major cations (Na^+, Mg^{2+} and Ca^{2+}) at same normalities (Moum et al., 1968; Løken, 1968, 1970). In the studies at Ulvensplitten and Dragvoll, the clays ceased to be quick when the sum of the normalities of

4

K^+, Mg^{2+} and Ca^{2+} over the sum of major cations exceeded 20% (Helle et al., Submitted), in the following referred to as the KMgCa-ratio.

Today, in natural state, the concentration of K^+ is normally higher in the weathered dry crust and upper clay profiles than in the deeper part of the sediments, inhibiting quick behaviour in the top soil (Rosenqvist, 1955). In normally consolidated clay profiles, the top soil may have an over-consolidation ratio larger than 1 due to capillary suction in the unsaturated dry crust, and due to weathering and percolating of fresh water that over centuries have fed the clay-water system with stabilising cations. Pore-water compositions dominated by cations of higher valence or smaller hydrated radius than Na^+ have a greater impact on suppressing the diffuse double layer around the clay particles, as do high salt contents (Figure 1a). The decreased repulsion between the clay particles allows the particles to move closer together before the structure breaks down, increasing the apparent pre-consolidation stress (p_c') (Figure 1b). Thus, the clay may take higher loads before large deformation occurs when the diffuse double layer thickness decreases, and the shear strength increases (Kenney et al., 1967; Santamarina, 2002). The shear strength is related to the p_c' and increases with increasing plasticity index, and the compressibility decreases with increasing shear strength and plasticity (Bjerrum and Rosenqvist, 1956; Bjerrum, 1967). The plasticity index in clays normally increases with increasing salt content (Løken, 1968). Therefore, increased salt content should also induce less deformation during loading, and increased p_c' and shear strength. However, it is not known at what plasticity index, salt content or pore-water composition the improvement commences, which will be discussed in the following.

2   Improved geotechnical properties

2.1   Ground investigations and laboratory tests

High quality mini-block samples (downsized Sherbrooke block samples) were extracted from the quick clay deposit at Dragvoll to determine the original geotechnical properties before the salt wells were installed. The fall-cone undrained and remoulded shear strength (c_u and c_{ur}), water content (w), Atterberg limits and pore-water chemistry were determined. Constant rate of strain oedometer tests (CRS) and an-isotropically consolidated, undrained compression triaxial tests (CAU$_c$) were conducted to determine the apparent pre-consolidation stress (p_c'), over-consolidation ratio (OCR), deformations at applied loads and peak undrained shear strength (c_{uc}). The constant rate of strain oedometer tests (CRS) were conducted with a strain rate of 0.75%/hr. The CAU$_c$ tests were an-isotropically consolidated to the effective overburden stresses (σ_{v0}') applying a coefficient at rest (K_0') of 0.7. The samples were consolidated for approximately 16 hrs before applying a backpressure of 250 kPa and left to rest prior to shearing at a strain rate of 1.5%/hr.

The salt from the wells were allowed to migrate into the clay thorough slotted sections from 4 m to 8 m depth. The migration was self-driven by diffusion, with a small advective component due to density gradients between the high-saline wells and the surrounding low-saline clays. Pockets and discontinuous layers of slightly coarser material (more silt) caused a moderately non-symmetric salt-migration around the wells, mainly dominated by diffusion. For further description of the site and installations, see Helle et al. (Submitted). Two years and five months after salt-well installation, a mini-block sample was extracted in one borehole 0.5 m from salt-well no. 1 (SW1) at 4.4-4.8 m depth. Undisturbed 54 mm piston samples were extracted 3 years and 2 months after installation from 4.0-8.8 m depth in four boreholes (P7A, B, C and D) positioned 0.5 m from salt-well no. 7 (SW7), and from 5.0-7.8 m depth in one

borehole positioned 1.0 m (P7E) from SW7 (Figure 3). All samples except from the mini-block 0.5 m from SW1 were tested in the laboratory at the same day as they were extracted from the ground to minimize storage effects on the results. The mini-block 0.5 m from SW1 was tested within 48 hours after extraction. Fall-cone undrained and remoulded shear strength, Atterberg limits and pore-water chemistry were determined on all samples, whereas CAU_c and CRS tests were conducted on the salt-treated clay at 4.4-4.8 m depth 0.5 m from SW1, and CRS tests were conducted on the samples extracted from 5.0-5.8 m depth around salt-well no. 7. The CRS data from boreholes P7B, C and E showed poor quality, and are not included herein. In addition to the in-situ experiment, mini-block samples extracted from the quick clay deposit at Dragvoll research site and stored in KCl slurry for a couple of months to study the impact of high concentrations of KCl on the geotechnical properties (Bryntesen, 2014; Helle, et al. 2015). Parallel samples were stored wrapped in cling-film submerged in de-aired water to account for the storage effect. Index testing, CAU_c and CRS tests, as well as determining the pore water composition, were carried out on all samples stored in the containers.
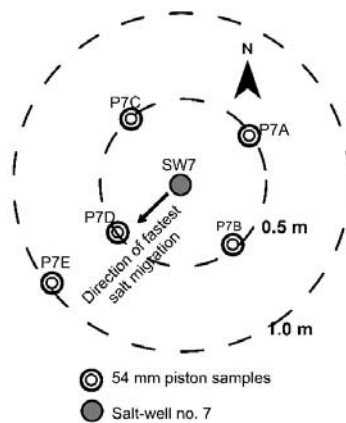
Figure 3 Undisturbed 54 mm piston samples were extracted 0.5 m and 1.0 m from salt-well no. 7 (SW7) 3 years and 2 months after installation. The direction of the fastest salt migration is indicated by the arrow in direction of boreholes P7D and P7E

2.2   Changed pore-water chemistry and improved geotechnical properties

The salt content in the original quick clay is of only 0.6-0.7 g/L, sodium (Na^+) constituting approximately 85-92% of the major cations in the pore water (Table 1). Initially the quick clay had a remoulded shear strength (c_{ur}) of < 0.1 kPa to 0.5 kPa, a plasticity index (IP) of 4.4-6.3%, and a liquidity index (IL) of 3.4-4.3. The fall cone undrained shear strength (c_u) is much lower than the peak undrained shear strength (c_{uc}) determined from the CAU_c tests; 8-16 kPa and around 27.5 kPa respectively (Figure 4). The apparent pre-consolidation stress (p_c') in the original quick clay is of 85 kPa at 4.78 m depth, and 67 kPa at 5.78 m depth with corresponding over-consolidation ratios (OCR) of 1.8 and 1.2. The oedometer modulus (M_{OC}) at stresses below p_c' is of around 5 MPa (Figure 5).

Table 1 Pore-water chemistry in the original quick clay and salt-treated clays

		Quick clay 4.7-5.0 m	Salt treated SW1 4.4-4.8 m	Quick clay 5.7-6.0 m	Salt treated P7A 5.0-5.8 m	Salt treated P7D 5.0-5.8 m
Salt content	g/L	0.7	1.6	0.6	9.7	27.7
Sodium (Na^+)	meq/L	7.83	20.59	7.50	32.81	40.85
Potassium (K^+)	meq/L	0.30	1.09	0.24	79.33	291.29
Magnesium (Mg^{2+})	meq/L	0.41	4.14	0.18	25.14	33.74
Calcium (Ca^{2+})	meq/L	0.33	1.56	0.22	11.41	15.77
Chloride (Cl^-)	meq/L	0.27	17.91	0.27	144.75	407.17
Alkalinity	meq/L	8.07	5.28	7.16	2.76	3.52
pH pore water	-	8.60	8.62	8.76	8.03	8.08
$\dfrac{K^+ + Mg^{2+} + Ca^{2+}}{Na^+ + K^+ + Mg^{2+} + Ca^2}$	%	12	25	8	78	89
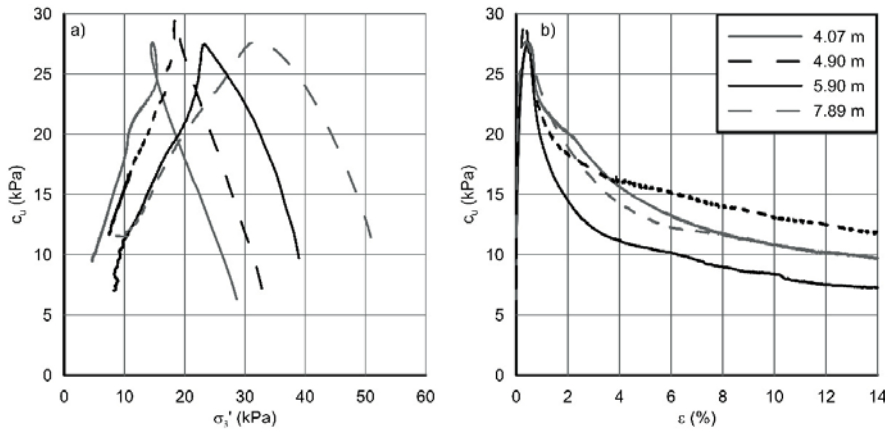
Figure 4 Triaxial testing of original quick clay. Undrained shear strength (c_u) versus a) horizontal effective stresses (σ_3'), and b) vertical strain (ε)

The total salt content in the clay extracted 0.5 m from salt-well no. 1 (SW1) was after 2 years and 5 months increased from 0.7 g/L to 1.6 g/L, and the pore-water composition was changed compared to the quick clay, having a KMgCa-ratio of 25% (all concentrations in meq/L) (Table 1). The clay was no longer quick, having a c_{ur} of 1.8 kPa, an IL of 1.6 (still higher than 1.2 due to a liquid limit lower than the natural water content) and an IP of 12.8% (Table 2). Even though, the index parameters were improved, the p_c' was the same as in the quick clay; 85 kPa (Figure 5a), and there was no improvement of c_{uc} or post-peak strength in the CAU_c test.
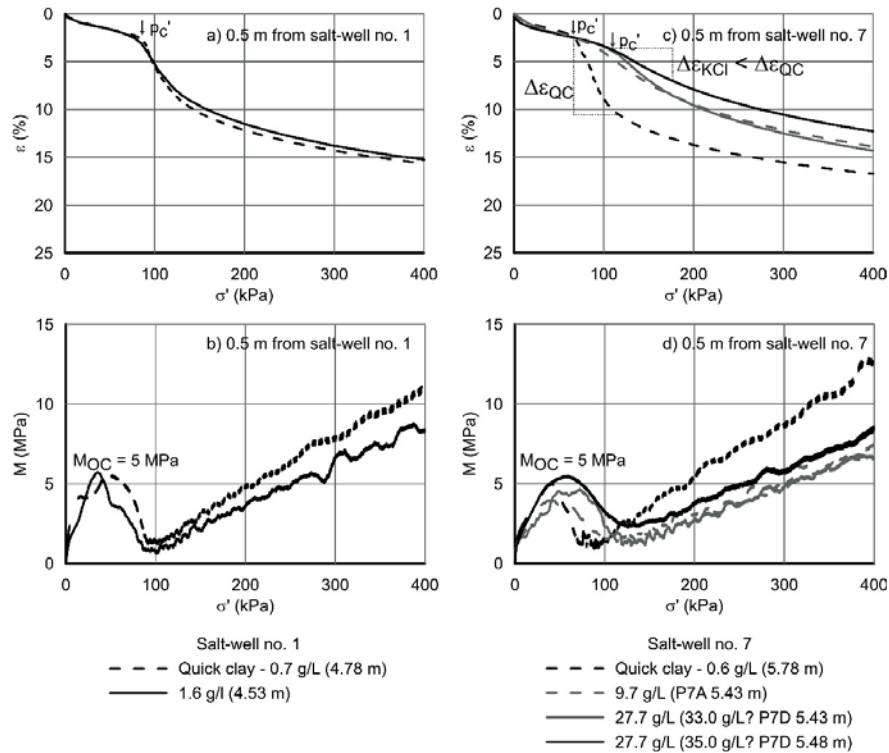
Figure 5 Oedometer results from original quick clay and salt-treated clay. a) strains (ε) and b) oedometer stiffness (M) versus effective vertical stress (σ') on mini-block sample extracted 0.5 m from salt-well no. 1 at 4.5-4.8 m depth. c) ε and d) M versus σ' on 54 mm samples extracted 0.5 m from salt-well no. 7 at 5.4-5.8 m depths. The apparent pre-consolidation stress (pc') is indicated in a) and b). The immediate collapse of the structure at loads beyond pc' is decreased in the KCl-treated clay (ΔεKCl) compared to the original quick clay (ΔεQC) in b)

The salt content in the pore water from the clay samples around salt-well no. 7 (SW7) showed that the salt migrated faster in direction of boreholes P7D and P7E (Figure 3), also migrating faster with depth in all directions (Figure 6c). At 5.25 m depth, the salt contents were 9.7 g/L (P7A) and 27.7 g/L (P7D). The sodium (Na^+) was depleted, and the KMgCa-ratios was of 78% and 89% respectively (Table 1). The increased salt contents and concentrations of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) improved the c_{ur} way beyond what is considered to be quick; to around 5 kPa (Figure 6a). The fall-cone c_u increased up to around 25 kPa, close to c_{uc} found in the CAU_c of around 27.5 kPa implying that the 54 mm piston samples extracted from the salt-treated clay is less disturbed. The plasticity index (IP) of the clay was improved from low to medium and high (Figure 7a), and the IL in the salt treated clay decreased to 0.6-0.8 in the samples used for CRS tests (Figure 7b and Table 2). The p_c' increased from 67 kPa in the quick clay to 90 kPa at a salt content of 9.7 g/L and 110 kPa at a salt content of 27.7 g/L, with a corresponding increase of the OCR from 1.2 to 1.7-2.1. The oedometer modulus (M_{OC}) is practically unchanged (Figure 5d). The observed decrease in M_{OC}

in two of the salt-treated clay specimens at 5.43 m depth is most likely due to the fact that the 54 mm piston samples may be of poorer quality than the mini-block samples extracted in the quick clay. The immediate deformation at loads exceeding p_c' is far less in the salt-treated clay ($\Delta\varepsilon_{KCl}$ in Figure 5c) than in the quick clay ($\Delta\varepsilon_{QC}$). There is a difference in the compressibility at loads beyond p_c' in the specimens with salt content of 27.7 g/L ("P7D 5.43 m" and "P7D 5.48 m"). The salt content increases with depth, and the above described pore-water composition is from 5.25 m depth, whereas the oedometer tests were conducted on samples from 5.43 m and 5.48 m depth. The salt content at 6.25 m depth was 59.1 g/L. Assuming a linear increase of the salt content with depth, the salt contents in the oedometer specimens may have been higher; approximately 33 g/L and 35 g/L. The difference in the salt content is small, and does not explain the difference in compressibility. Therefore, the difference in the compressibility after p_c' between the two specimens with salt contents of around 30 g/L may be due to poorer quality of the specimen from 5.43 m depth (33 g/L) leading to higher compressibility (Figure 5c).

Table 2 Geotechnical properties in the original quick clay and salt treated clays. The depths relate to the CRS tests within the samples extracted from depths given in Table 1

|		Quick clay 4.78 m	Salt treated SW1 4.53 m	Quick clay 5.78 m	Salt-treated P7A 5.43 m	Salt treated P7D 5.43 m	Salt treated P7D 5.48 m
Salt content	g/L	0.7	1.6	0.6	9.7	27.7 (33?)	27.7 (35?)
Water content (w)	%	37.7	38.2	36.6	37.8	37.7	37.5
Bulk density (ρ)	g/cm^3	1.89	1.88	1.89	1.88	1.87	1.87
Plasticity index (IP)	%	4.4	12.8	5.4	21.9	24.0	24.0
Liquidity index (IL)	-	3.9	1.6	4.3	0.8	0.6	0.6
Fall cone undr. shear strength (c_u)	kPa	13.9	11.1	8.6	24.0	28.6	28.6
Remoulded shear Strength (c_{ur})	kPa	0.3	1.8	0.1	4.7	5.1	5.1
Peak undrained shear strength (c_{uc})	kPa	27.5	26.6	27.5			
Effective over-burden stress (σ_{v0}')	kPa	46.6	44.4	55.3	52.2	52.2	52.7
Pre-consolidation stress (p_c')	kPa	85.0	85.0	67.0	90.0	110.0	110.0
Over-consolidation ratio (OCR)	-	1.8	1.9	1.2	1.7	2.1	2.1
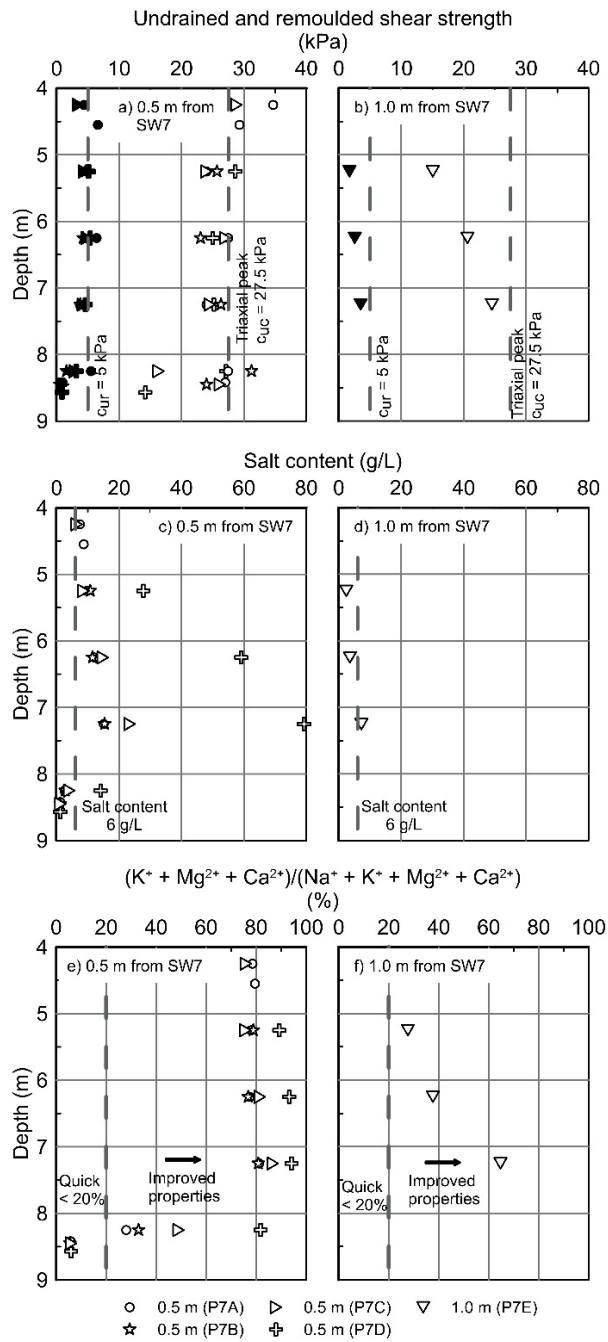
Figure 6 a) Fall cone undrained (open symbols) and remoulded (filled symbols) shear strength in samples P7A, B, C and D 0.5 m and b) P7E 1.0 m from salt-well no. 7 (SW7). c) Salt contents 0.5 m and d) 1.0 m from SW7. e) Ratio of the sum of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) over the sum of major cations 0.5 m and f) 1.0 m from SW7
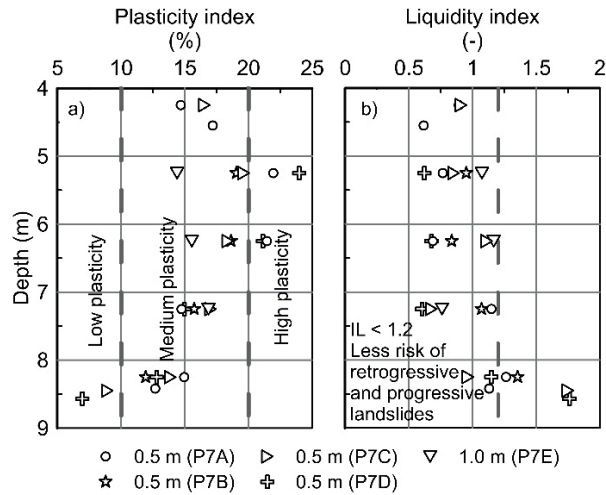
10

Figure 7 a) Plasticity and b) liquidity index in boreholes P7A, B, C and D 0.5 m), and P7E 1.0 m from salt-well no. 7

3 Discussions

Salt-wells filled with potassium chloride (KCl) were installed in a highly sensitive quick clay deposit to study the impact of changed pore-water chemistry on the geotechnical properties in order to validate KCl wells as a landslide mitigation method. The most common quick clay landslide types are either retrogressive or progressive. Retrogressive development may be inhibited by a remoulded shear strength (c_{ur}) larger than 1 kPa and a liquidity index lower than 1.2 (Leroueil et al. 1983; Thakur et al. 2014a), as the slide debris will not flow out of the slide pit which reduces the risk for successive back-scarp failures. The c_{ur} determined on the clay samples extracted around salt-well no. 7 (SW7) seem to stabilise at around 5 kPa and the fall-cone shear strength (c_u) at around 25 kPa at salt contents exceeding 6 g/L and a KMgCa-ratio exceeding 80% (Figure 6). According to Helle et al. (Submitted), the clays cease to be quick and obtains $c_{ur} > 1$ kPa, IL < 1.2, and the clay changes from having low to medium plasticity when the KMgCa-ratio in the pore water exceeds 20%, inhibiting retrogressive development and reduces the post-failure movement of progressive landslides. The initiating of progressive landslides depends, however, on the strain-softening behaviour of the clay around peak shear strength.

Re-introducing high salt contents increases the apparent pre-consolidation stress (p_c'), thus also the over-consolidation ratio (OCR) in the highly sensitive quick clays at Dragvoll. At salt contents of 9.7 g/L and 27.7 g/L the salt-treated clays had a c_{ur} of 4.7-5.1 kPa, IL of 0.6-0.8 and the clays were of high plasticity. The p_c' increased from 67 kPa to 90 kPa and 110 kPa respectively. Loading the samples beyond p_c', the deformations in the in-situ salt treated clay samples were significantly reduced compared to the rapid structure collapse and immediate large deformations seen in the original quick clay. Highly sensitive quick clays have a characteristic strain-softening behaviour with a distinct peak undrained shear strength (c_{uc}), and a rapid collapse of the structure after peak dramatically reducing the post-peak strength (Figure

11

4). The slower collapse of the structure and decreased deformations at loads exceeding p_c' seen in the CRS tests on the salt-treated clay may imply that the brittleness (softening after peak) is reduced, and that the clay may have a higher post-peak strength at deformations exceeding strains at failure. At a KMgCa-ratio of 25%, the c_{ur} increased from 0.3 kPa to 1.8 kPa. The post-failure properties (c_{ur} and Atterberg limits) are improved even at low salt contents due to the favourable pore-water composition. However, at low salt content the deformations for increasing loads are the same as in the quick clay and p_c' and c_{uc} are unchanged.

The salt content in the mini-block samples stored in KCl slurry were much higher than found in the in-situ experiment at Dragvoll (170-260 g/L), increasing the bulk and dry density of the clay due to introduction of more solids. The bulk and dry density in the samples extracted around SW7 with salt contents up to 27.7 g/L was, however, unaltered. Thus, for the samples stored in KCl slurry, some of the effect on the decreased deformation at loads beyond p_c', may at very high salt contents ($> \sim 80$ g/L) be induced by increased solids in the voids in addition to a maximum suppression of the diffuse double layer. Nevertheless, the oedometer stress-strain curves for the samples stored in KCl slurry and in the in-situ treated clays corresponded quite well. In addition to decreased deformation and improved p_c' and OCR in the oedometer tests, the peak and post-peak undrained shear strength both increased in the samples stored in KCl slurry compared to the samples stored in de-aired water (Figure 8) which may reduce the risk for progressive landslides.

Progressive development of landslides in highly sensitive quick clays may be explained by a process consisting of two parts (Jostad and Grimstad, 2011). The first part is where the progressive failure is initiated along a shear band, and the second part comprises the post-failure movement. At initiation of failure along a failure plane, peak strength is mobilised. A progressive landslide may be initiated if the post-peak strength thereafter is sufficiently reduced leading to a domino effect with subsequent deformations beyond strains at failure along a shear plane (Fornes, 2014; Gylland, 2014; Thakur et al., 2014b). Many
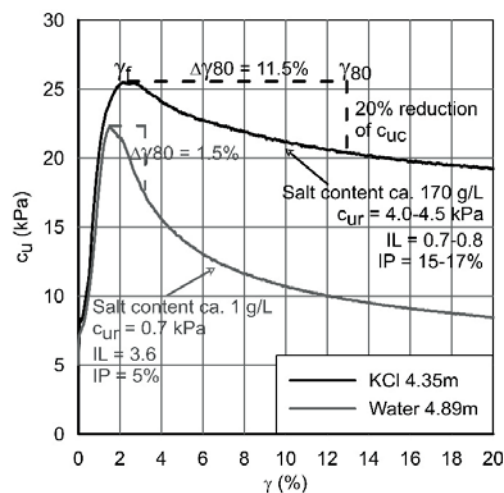
Figure 8 Triaxial test results on samples stored in KCl slurry (black line) compared to samples stored in de-aired water (grey line). The brittleness parameter ($\Delta\gamma_{80}$) is found from subtracting the shear strain at failure (γ_f) from the shear strain (γ_{80}) found at 20% reduction of peak-strength (c_{uc}). The $\Delta\gamma_{80}$ increased from 1.5% in the sample stored in de-aired water to 11.5% in the sample stored in KCl slurry

authors suggest that the peak undrained shear strength is correlated to the OCR (e.g. Bjerrum, 1967; Ladd and Foot, 1974; Karlsrud and Hernandez-Martinez, 2013). Therefore, it is likely to believe that the increased OCR in the in-situ salt-treated clays is related to an increased peak-undrained shear strength (c_{uc}), thereby reducing the risk for initiating progressive failures.

The degree of softening after peak describes the brittleness of the clay. Fornes (2014) introduces the brittleness parameter $\Delta\gamma_{80}$ where values in the range of 0-2% may indicate high brittleness, 2-5% medium brittleness and > 5% low brittleness. The $\Delta\gamma_{80}$ is defined as the difference between the shear strain (γ_{80}) at 20% reduction of the c_{uc} after peak and the shear strain at failure (γ_f). The peak undrained shear strength was improved and the post-peak undrained shear strength was significantly improved in the mini-block sample stored in KCl slurry having an OCR of 2.7. Furthermore, $\Delta\gamma_{80}$ increased from 1.5% in the sample stored in de-aired water, to 11.5% in the sample stored in KCl slurry, significantly reducing the brittleness (Figure 8). The decreased collapse of the structure seen at loads exceeding p_c' in the oedometer tests on the in-situ salt-treated clay, may be related to a reduced brittleness of the clay. Thus, installing KCl wells in quick clay slopes may reduce the risk for initiating progressive failures, and reduce potential post-failure movements. The reduced risk for initiating progressive failures commence at larger salt contents and different KMgCa-ratios than for inhibiting retrogressive landslide development.

The leaching tests conducted on clay samples presented by Torrance (1974), reveals larger compressibility, i.e. volume change as a response to loading, and a reduction in p_c' in leached clays with Na-dominated pore fluids with salt contents of less than 2 g/L than in clays with higher salt contents. The results from the in-situ treated Dragvoll clay imply that improved p_c' and decreased compressibility commence at salt contents less than 9 g/L. This may imply that the deformations due to loading are decreased and p_c', c_{uc}, post-peak strength and $\Delta\gamma_{80}$ are increased at salt contents exceeding somewhere between 2 g/L and 9 g/L.

The compressibility of the clay influences the measured tip-resistance in cone penetration tests (CPTU) as decreased compressibility increases the resistance against deformation, thus penetration (Lunne et al., 1997). Both Bjerrum (1967) and Sridharan and Nagaraj (2000) relate decreasing compressibility to increasing plasticity. The in-situ treated samples with increased p_c' and decreased deformations at loads beyond p_c' was of high plasticity; IP in the range of 21.9-24.0%. In the samples stored in KCl slurry, the IP was in the range of 10.0-17.4%. Correlations between the in-situ test results at Dragvoll and laboratory-determined geotechnical properties showed that the measured tip resistance increased significantly at a c_{ur} of around 3.5 kPa, corresponding to an IP of around 15%, which is obtained at salt contents exceeding around 6 g/L, or at a KMgCa-ratio exceeding 60%, even at low salt contents (Figure 9). This may indicate that that the immediate deformations at loads exceeding p_c' decrease, and the post-peak shear strength improves at a KMgCa-ratio exceeding 60% at low salt contents, or at salt contents larger than 6 g/L due to significantly improved c_{ur} and IP.

The changed pore-water chemistry due to diffusion from the KCl wells has a great impact on improving c_{ur}, IL and IP, also improving p_c' and OCR and decreasing the immediate deformations and rapid de-structuring of the clays at loads exceeding p_c'. The samples stored in KCl slurry showed a modest effect on the increase in peak shear strength. Nevertheless, the brittleness as observed from the steepness of the stress-strain curve after peak was significantly reduced. Therefore, changing the pore-water chemistry by installing KCl wells in quick clay slopes inhibit retrogressive landslide development, and may also reduce the risk for initiating progressive landslides.
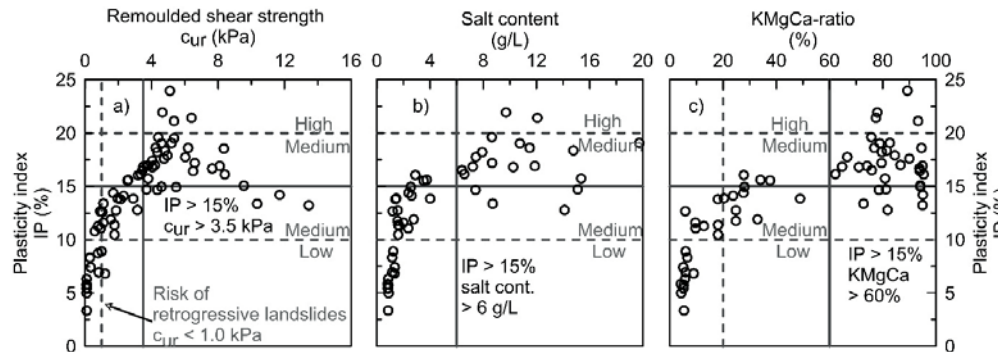
Figure 9 Plasticity index (IP) versus a) remoulded shear strength (c_{ur}), b) salt content (shown up to 20 g/L) and, c) KMgCa-ratio. The clay has low plasticity at IP < 10%, medium plasticity in the range of 10-20% and high plasticity at IP > 20%. Note that the salt contents are only shown up to 20 g/L even though salt contents are found up to 98 g/L. The data suggest that IP > 15% at c_{ur} > 3.5 kPa, at salt contents > 6 g/L and/or KMgCa-ratio > 60%

4   Conclusions

Diffusion of potassium chloride (KCl) from wells into quick clays changes the pore-water chemistry so that the geotechnical properties are improved. The remoulded shear strength (c_{ur}) improves beyond 1 kPa, the liquidity index (IL) decreases below 1.2 and the plasticity of the clay changes from low to medium at a KMgCa-ratio exceeding 20%; inhibiting retrogressive landslide development. The apparent pre-consolidation stress (p_c') increases and the immediate deformations at loads exceeding p_c' decreases with increasing salt contents. The increased p_c' and over-consolidation ratio (OCR) imply increased peak undrained shear strength. Decreased immediate deformation at loads exceeding p_c' indicate that the structure in the salt-treated clay does not collapse as rapid as seen in quick clays. This imply that the brittleness of the salt-treated clays is decreased which may reduce the risk for initiating progressive landslides in quick clay areas. The brittleness may be sufficiently reduced when salt treatment provides c_{ur} > 3.5 kPa and IP > 15%, which commence at a KMgCa-ratio exceeding 60%, or at salt contents exceeding 6 g/L. Leaching of the salt-treated clay by groundwater will with time after salt-well installation again decrease the salt content in the pore water. However, groundwater is dominated by calcium and/or magnesium both of which having a favourable impact on the geotechnical properties. Clays treated with KCl will therefore maintain a non-quick behaviour and improved plasticity even at future low salt contents.

Initial slides triggered in quick clay slopes stabilised with KCl wells will not develop into large retrogressive landslides as the salt-treated clay barrier will not flow out of the area when the c_{ur} > 1 kPa. The obtained reduced collapse of the structure in the salt-treated clays implies reduced brittleness, which may reduce the risk for progressive landslide development.

5   Acknowledgments

6 References

Appelo CAJ and Postma D (2005) Geochemistry, groundwater and pollution. 2nd edn. Balkema, Leiden, Netherlands.

Bjerrum L (1955) Norske marine leirers geotekniske egenskaper. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication no. 7.

Bjerrum L (1967) Engineering Geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. Géotechnique **17(2)**: 83-118, http://dx.doi.org/10.1680/geot.1967.17.2.83.

Bjerrum L and Rosenqvist IT (1956) Some experiments with artificially sedimented clays. Géotechnique **6(3)**: 124-136. http://dx.doi.org/10.1680/geot.1956.6.3.124.

Bryntesen RN (2014) Laboratory investigation on salt migration and its effect on the geotechnical strength parameters in quick clay mini-block samples from Dragvoll. Master's thesis, Norwegian University of Science and Technology, Trondheim, Norway, pp. 1-105.

Eggestad A and Sem H (1976) Stability of excavations improved by salt diffusion from deep wells. In *Proceedings of the 6th European conference on soil mechanics and foundation engineering*, Vienna, Austria, pp. 211-216.

Fornes P (2014) NGIs anbefalinger for krav til effekt av sprøbruddoppførsel. Naturfare: infrastruktur, flom og skred (NIFS), report no. 88/2014, pp. 1-15.

Gjengedal I (2012) Laboratoriestudie av saltdiffusjon i kvikkleire. Master's thesis, Norwegian University of Science and Technology, Trondheim, Norway, pp. 1-73.

Gylland AS (2014) The effect of deformation rate in progressive slope failure. In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J. (eds)). Springer Dordrecht, pp. 267-277.

Helle TE, Bryntesen RN, Amundsen HA, Emdal A, Nordal S and Aagaard P (2015) Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway. In *Proceedings of 68th Canadian Geotechnical Conference GeoQuebec 2015, Quebec*. Agora Communication Inc., Canada. 8 pp.

Helle TE, Nordal S, Aagaard P and Lied OK (2016) Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay — Ulvensplitten, Norway. Canadian Geotechnical Journal **53(3)**: 410-422. http://dx.doi.org/10.1139/cgj-2015-0077.

Helle TE, Aagaard P and Nordal S (Submitted) In-situ improvement of highly sensitive clays by potassium chloride migration. Submitted for re-review in Journal of Geotechnical and Geoenvironmental Engineering ASCE in March 2017.

Jostad HP, Fornes P and Thakur V (2014) Effect of Strain-Softening in Design of Fills on Gently Inclined Areas with Soft Sensitive Clays. . In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, pp.305-316.

Jostad HP and Grimstad G (2011) Comparison of distribution functions for the nonlocal strain approach. *In Proceedings of the 2nd international symposium on computational geomechanics*, Cavtat-Dubrovnik, Croatia.

Karlsrud K and Hernandez-Martinez FG (2013) Strength and deformation properties of Norwegian clays from laboratory tests on high-quality block samples. Canadian Geotechnical Journal **50**: 1273-1293. dx.doi.org/10.1139/cgj-2013-0298.

Kenney TC, Moum J and Berre T (1967) An experimental study of bonds in natural clay. In *Proceedings of the Geotechnical Conference*, Oslo, Norway. pp. 65-69.

Ladd CC and Foott R (1974) New design procedure for stability of soft clays. Journal of the Geotechnical Engineering Division (ASCE) **100(7)**: 763-786.

Leroueil S and Vaughan PR. (1990).The general and congruent effects of structure in natural soils and weak rocks. Géotechnique **40(3)**: 467-488.

Leroueil S, Tavenas F and Le Bihan JP (1983) Proprietes caracteristiques des argiles de l'est du Canada. Canadian Geotechnical Journal **20(4)**: 681–705, http://dx.doi.org/10.1139/t83-076.

Lunne T, Robertson PK and Powell JJM (1997) Cone penetration testing in geotechnical practice. Spon Press.

Løken, T (1968) Kvikkleiredannelse og kjemisk forvitring i norske leirer. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 75, pp. 1-9.

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

Mitchell JK and Soga K (2005) Fundamentals of soil behaviour. 3rd edition. John Wiley & Sons Inc. New Jersey, USA.

Moore DM and Reynolds Jr. RC (1997) X-ray diffraction and the identification and analysis of clay minerals. 2nd edition. Oxford University Press, Inc., New York.

Moum J, Sopp OI and Løken T (1968) Stabilization of undisturbed quick clay by salt wells. Väg- och vattenbyggaren no. 8. Reprinted in Norwegian Geotechnical Institute, Oslo, Norway, NGI publication no. 81, pp. 1-7.

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

Norwegian Geotechnical Society (2010) Veiledning for utførelse av trykksondering. Norwegian Geotechnical Society, Oslo, Norway, NGF-notification no. 5 3rd revision, first published in 1982. pp. 1-38.

Norwegian Geotechnical Society (2011) Veiledning for symboler og definisjoner i geoteknikk: Identifisering og klassifisering i jord. Norwegian Geotechnical Society, Oslo, Norway, NGF-notification no. 2 2nd revision, first published in 1982. pp. 1-54.

Penner E (1965) A study of sensitivity in Leda clay. Canadian Journal of Earth Science **2(5)**: 425-441.

Quigley RM (1980) Geology, mineralogy, and geochemistry of Canadian soft soils: a geotechnical perspective. Canadian Geotechnical Journal **17(2)**: 261–285. http://dx.doi.org/10.1139/t80-026.

Rosenqvist IT (1946) Om leirers kvikkaktighet. Available from the Norwegian Public Road Administrations, Oslo, Norway. Meddelelsen fra Vegdirektøren No. 3. pp. 29–36.

Rosenqvist IT (1953) Considerations on the sensitivity of Norwegian quick-clays. Géotechnique **3**: 195–200. http://dx.doi.org/10.1680/geot.1953.3.5.195.

Rosenqvist IT (1955) Investigations in the clay-electrolyte-water system. Norwegian Geotechnical Institute, Oslo, Norway, NGI Publication no. 9, pp. 1-125.

Rosenqvist IT (1977) A general theory for quick clay properties. In *Proceedings of the 3rd European Clay Conference*, Oslo, Norway, pp. 215-228.

Santamarina JC, Klein KA, Palomino A and Guimaraes MS (2002) Micro-scale aspects of chemical-mechanical coupling: Interparticle forces and fabric. In *Chemo-Mechanical Coupling in Clays: From nano-scale to engineering applications* (Di Maio C, Hueckel T and Loret B (eds)). Swets & Zeitlinger, Lisse. pp. 47-63.

Sridharan A and Nagaraj HB (2000) Compressibility behaviour of remoulded, finegrained soils and correlation with index properties. Canadian Geotechnical Journal **37**: 712–722.

Thakur V, Degago SA, Oset F, Aabøe R, Dolva BK, Aunaas K, Nyheim T, Lyche E, Jensen OA, Sæter MB, Robsrud A, Viklund M, Nigussie D and L'Heureux JS (2014a) Characterisation of post-failure movements of landslides in soft sensitive clays. In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, pp.91-104.

Thakur V, Jostad HP, Kornbrekke HA and Degago SA (2014b) How Well Do We Understand the Undrained Strain Softening Response in Soft Sensitive Clays? In *Landslides in sensitive clays: From geoscience to risk management* (L'Heureux JS, Locat A, Leroueil S, Demers D and Locat J (eds)). Springer Dordrecht, pp.291-302.

Torrance JK (1974) A laboratory investigation of the effect of leaching on the compressibility and shear strength of Norwegian marine clays. Géotechnique **24(2)**: 155-173.

Torrance JK (1979) Post-depositional changes in the pore water chemistry of the sensitive marine clays of the Ottawa area, eastern Canada. Engineering Geology **114**, 135-147.

Torrance JK (1983) Towards a general model of quick clay development. Sedimentology **30**: 547-555.

van Olphen H (1963) An introduction to clay colloid chemistry. John Wiley & Sons, Inc.

List of notations

c_u is the undrained shear strength

c_{uc} is the peak undrained shear strength

c_{ur} is the remoulded shear strength

$\Delta\varepsilon_{KCl}$ is the strain during the immediate collapse of the structure at loads beyond p_c' in KCl-treated clay

$\Delta\varepsilon_{QC}$ is the strain during the immediate collapse of the structure at loads beyond p_c' in the original quick clay

$\Delta\gamma_{80}$ is the brittleness parameter

ε is the vertical strain

γ is the shear strain

γ_{80} is the shear strain at 20% reduction of the c_{uc} after peak

γ_f is the shear strain at failure

IL   is the liquidity index

IP   is the plasticity index
K_0'   is the coefficient at rest
M_{OC} is the oedometer modulus at stresses below p_c'
OCR   is the over-consolidation ratio
p_c'   is the apparent pre-consolidation stress
ρ is the bulk density
σ'   is the effective vertical stress
σ_{v0}'   is the effective overburden stress
σ_3'   is the effective horizontal stress
w   is the natural water content
w_L is the liquid limit
w_P is the plastic limit

A Pilot study: Mineralogy, pore-water chemistry and post-failure properties in Norwegian clays

A.1 Background and motivation

The geotechnical properties in clays are greatly affected by mineralogy and pore-water chemistry. Clay specimens were collected to get a better understanding on how these factors affect the post-failure properties in Norwegian leached, highly sensitive clays originally accumulated in a marine environment. Post-failure properties are herein defined as the remoulded shear strength (c_{ur}), liquidity (IL) and plasticity index (IP). The clay specimens were collected from ongoing projects throughout Norway from January until April 2013. The geotechnical parameters were determined at several geotechnical laboratories. Due to limited access to clay samples, data from the PhD thesis by Hilmo (1989) are included.

A.2 Laboratory tests

A.2.1 Mineralogy

Master student Fredrikke S.G. Syversen at University of Oslo (UiO) prepared the clay samples for X-ray diffraction (XRD). Both the bulk and clay mineralogy were determined. For more details around the sample preparation, equipment description, qualitative and quantitative analyses of the mineralogy, see Syversen (2013)[1]. The XRD was run by Maarten Aerts at UiO. PhD Candidate Beyene Girma Haile and Professor Emeritus Per Aagaard at UiO analysed the XRD-data for the samples included herein, fall 2016. The XRD software Diffrac.Suite (www.bruker.com) was used for bulk mineralogy identification and quantification. Difrac.Eva was used for identification of the occurring mineral types, and Diffrac.Topas was used for quantification of the bulk mineralogy. The clay mineralogy was quantified using the software NEWMOD II (www.newmod-for-clays.com).

A.2.2 Pore-water composition

The geotechnical laboratories were instructed to wrap the clay samples tightly with cling-film, surround them with wet paper, put them in sealed plastic bags, and send them to the geotechnical laboratory at NTNU within a week. The pore water was extracted by centrifuging the clay specimens at 4000 rpm for 15-150 minutes to make sure that the pore-water volume exceeded 10 ml. The pore water was filtered through a 0.45 μm syringe filter to remove any remaining particles from the solute. In total 42 pore-water samples were sent to the laboratory at the Department of Geosciences at University of Oslo for analyses of sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), calcium (Ca^{2+}), chloride (Cl^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), phosphate (PO_4^{3-}) and alkalinity (Alk).

The cations were analysed using a Dionex ICS-1000 Ion Chromatography System (ICS-1000), and the anions were analysed using a Dionex ICS-2000 Ion Chromatography System (ICS-2000). Both machines were calibrated using a standard solution before running the tests. The alkalinity was determined by hydrochloric acid (HCl) titration in Metrohm 702 SM Titrino,

---

[1] Syversen, SG (2013) Et studie av den mineralogiske sammensetningen i norske sensitive leirer. Master's thesis, University of Oslo, Norway, pp. 1-77.

and pH measured in the pore water by the Metrohm 702 SM Titrino at 25 °C. The pore-water analyses were carried out by laboratory technician Mufak Naoroz.

Alkalinity is defined as the acid neutralizing capacity where bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) normally are the main neutralizing constituents. Appelo and Postma (2005) states that at pH below 8.3, less than 1% of the total carbonic acid is present as CO_3^{2-}. Even though some of the samples in this project has pH exceeding 8.3, the bicarbonate concentrations are set equal to the alkalinity. The salt content is equivalent to the total dissolved solids (*TDS*), and is calculated as the sum of cations and anions. The concentrations of the ions are reported in ppm, which in dilute fresh water is equivalent to mg/L.

A.2.3 Geotechnical parameters

The geotechnical parameters were determined at several geotechnical laboratories, both with experienced technicians and students. The control of procedures and quality of the techniques are not investigated in this PhD work.

A.2.4 Data quality

The data collection is very scarce, and the gathered and analysed data contains numerous sources of errors such as sample handling and storage prior to pore-water extraction, handling and storage of the pore-water samples amongst others. Some of the pore-water samples were difficult to filtrate through the 0.45 μm syringe filters. In cases where the pressure got too high during filtration, hyper filtration may have occurred. If this has been the case for some of the samples in this data collection, the concentration of both cations and anions may be too low (Appelo and Postma 2005). In order to rule out as many of the errors as possible to increase the reliability of the dataset for the pore-water composition, the following criteria were used for exclusion of test results:

1) clay samples that were opened in a geotechnical laboratory more than 7 days prior to pore-water extraction
2) samples that were not tightly wrapped in cling-film
3) samples from shallower depths than 4 m
4) samples that were centrifuged for less than 30 minutes, or more than 60 minutes
5) pore-water analyses that did not include analysis of alkalinity (or bicarbonate)
6) pore-water analyses where the electric charge balance (*EB*) exceeded 10%

The volume of extracted pore water may often be very small. Therefore, achieving a full set of analyses of both cations and anions, especially the analyses of bicarbonate, may be difficult. At the laboratory at UiO, a minimum of 10 ml pore water is necessary to be able to analyse all the major cations and anions in the pore water. Three datasets are included in this appendix:

- Dataset with all collected data
- Dataset excluding results based on criteria 1-4, but includes those pore-water compositions where bicarbonate was not analysed. Consequently, the *EB* is unknown and may exceed 10%
- Dataset fulfilling all the criteria for exclusion listed above

The results of the XRD may be altered if the sample is inadequately prepared. The samples must be adequately long and thick, flat with a smooth surface, and be mineralogical homogenous throughout the depth. The samples prepared for bulk mineralogy shall have as little orientation as possible. Overestimated quantification of illite may occur in samples that mistakenly have some degree of orientation. The quantification of the mineralogy depends on the identification of mineral types in the qualitative analyses, and also on the available mineralogy database used in the software.

A.3 Post-failure properties in Norwegian clays

The full data sets from the pilot study and Hilmo (1989) are included in the correlations of geotechnical properties in Figure A-1-Figure A-3. The clay content was found by hydrometer tests. Hydrometer tests were not conducted for all the samples, but for those data available the clay content (grain size < 2 μm) was in the range of 25-67%. The clay content may have an impact on the geotechnical properties. However, no coherent pattern was found in the correlations between clay content and the post-failure properties (Figure A-1).

Clays and a c_{ur} of < 1 kPa and an IL > 1.2, may develop into large retrogressive quick-clay landslides (Leroueil et al. 1983; Thakur et al. 2014a). The IL in the collected data decreased non-linearly with increasing c_{ur} (Figure A-2a), also found by Leroueil et al. (1983) and Locat and Demers (1988). According to the correlation between IL and c_{ur} established by Leroueil et al. (1983), the IL is of around 1.2 at a c_{ur} of 1 kPa which was also detected in the collected clay samples (Figure A-2a). The IP seemed to increase with increasing c_{ur} (Figure A-2b). The general trend showed that clays with a larger IL than 1.2 were of low plasticity (Figure A-3), whereas the clays with a liquidity index lower than 1.2 were of medium plasticity.

The geotechnical properties are affected by the salt content and the ion composition in the pore water. The total dissolved solids (*TDS*) were found in the samples that fits all the criteria listed in section A.2.4. According to Torrance (1979), quick clays often have a salt content of less than 2 g/L; equivalent to *TDS* of 2000 ppm. Even though the salt content is less than 2 g/L in many of the collected samples, the clays were not necessarily quick (Figure A-1). The impact of the pore-water chemistry on the geotechnical properties in the collected data will be discussed in the following sections.

A.4 Correlations of pore water chemistry and geotechnical properties

Clays accumulated in a marine environment during and after the last ice age may develop high sensitivity when leached by fresh water, as the reduced salt content increases the electrostatic repulsion (Rosenqvist 1946; van Olphen 1967). The entrapped seawater in the clays' pores is originally dominated by sodium (Na^+) and chloride (Cl^-). Isostatic uplift has exposed these sediments to leaching by meteoric groundwater flow, diluting the salt content and changing the ion composition both in the pore water and in the adsorbed positions on the clay-mineral surfaces. The salt content in quick clays is often less than 2 g/L; still dominated by Na^+ (Moum et al. 1971; Torrance 1979). The cations in the leaching groundwater, however, is normally dominated by calcium (Ca^{2+}) and/or (Mg^{2+}) which have a greater effect on decreasing the repulsive forces between the clay particles than Na^+ at same normality (Appelo and Postma 2005). The pore-water composition and the geotechnical properties will change with time as leaching progress. According to Mitchell and Soga (2005), clays with a remaining ratio of monovalent cations over the sum of the major cations (Equation A-1 all concentrations in meq/L) exceeding 75% in the pore water, may develop high sensitivity.

$$\frac{Na^+ + K^+}{Na^+ + K^+ + Mg^{2+}Ca^{2+}}$$

Eq. A-1

The geotechnical properties are in the following sections correlated to the ratio in Equation A-1 including all collected data (section A.4.1), the data set excluding data according to criteria 1-4 (section A.4.2), and only adequate quality data (A.4.3).
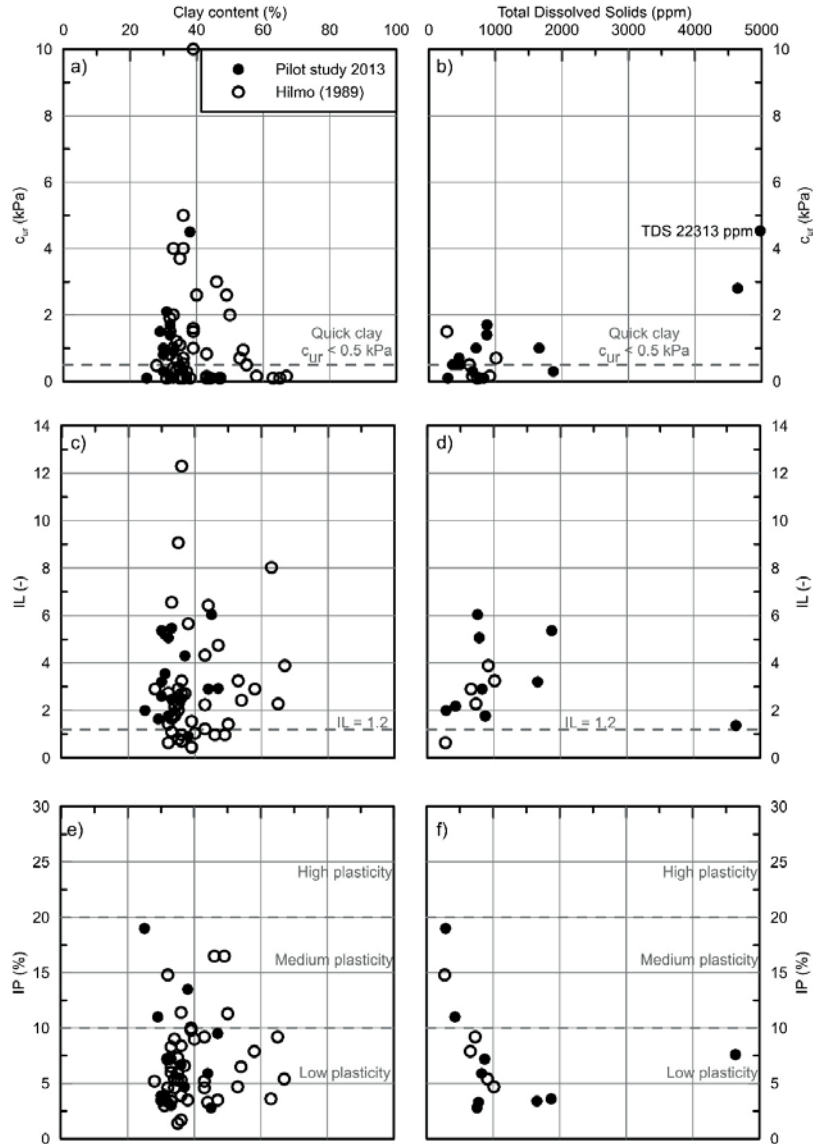

Figure A-1 Results from the recent pilot study (filled symbols) and Hilmo (1989) (open symbols). Clay content and total dissolved solids (TDS) correlated to a) and b) remoulded shear strength (c_{ur}), c) and d) liquidity index (IL), and e) and f) plasticity index (IP)
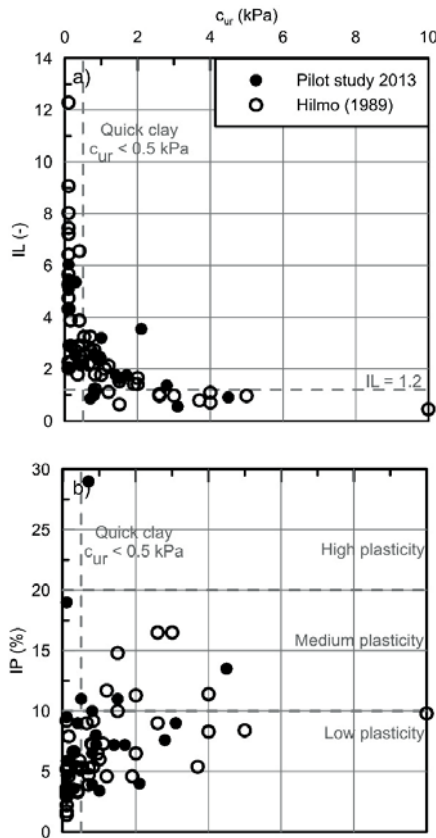
Figure A-2 Remoulded shear strength (c_ur) correlated to a) liquidity index (IL) and b) plasticity index (IP)
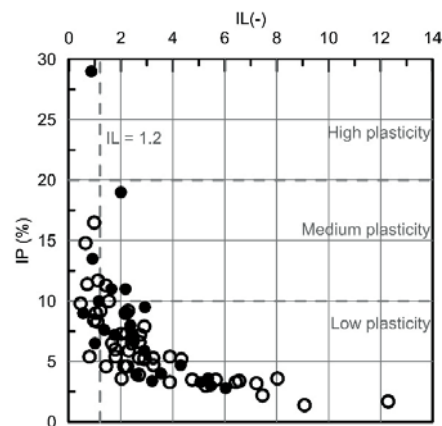

Figure A-3 Correlation between liquidity (IL) and plasticity index (IP). The legend is the same as in Figure A-1and A-2

A.4.1 All collected data

All the collected data are presented in this section (Figure A-4). The electric charge balance (EB) and salt content cannot be calculated without knowing the alkalinity in the pore water. Correlations between the ratios given in Equation A-1, and the remoulded shear strength (c_{ur}), liquidity (IL) and plasticity (IP) index are included herein. Most of the data clustered at a c_{ur} of less than 2 kPa when the ratio in Equation A-1 exceeded 75%. Furthermore, most of the IL was above 1.2, and most of the clays were of low plasticity. However, many data points differed from the lot. Some of the clays had c_{ur} below 0.5 kPa and were of low plasticity even though the pore-water compositions were below the suggested ratio. The in-consistency in the data may be caused by the numerous sources of error.

A.4.2 Correlations of data also including those without analyses of bicarbonate

In this section, some of the results are excluded based on criteria 1-4 in section A.2.3 (Figure A-5). The scatter in the data set is still wide, and the trends are the same as when including all the results. Therefore, no conclusions are drawn based on the correlations between the pore water compositions and the geotechnical properties in Figure A-5.

A.4.3 Data that fit all the criteria

Out of the 42 specimens collected in 2013, 16 remain when excluding results according to all the criteria described in section A.2.4 (Figure A-6). Out of Hilmo's data set of in total 55 specimens, only 7 are included. The included data are from 10 different sites:

- Eastern part of Norway:
    - Holm
    - Rakkestad municipality
    - Kleppe bridge
- Mid-Norway
    - Dragvoll
    - Esp
    - Lade
    - Leira
    - Klett
    - Tiller
- Northern part of Norway
    - Furubakken

The scatter in the data set was reduced including only the results that were considered of adequate quality. The scatter in the remoulded shear strength (c_{ur}) correlated to the ratio in Equation A-1 is still wide, with the majority of results below 2 kPa. The majority of the IL clustered above 1.2 at ratios exceeding 75%.

The pore water composition in the samples from Kleppe Bridge, Rakkestad municipality (7.7 m depth) and Esp (9.7 m depth), differed from the lot considering c_{ur}, IL and IP. The pore-water composition in the sample from Esp at 9.7 m depth deviated from the other samples. The amount of K^+ in the clay samples from 7.7-8.8 m depth in the same borehole had concentrations of K^+ of 0.7 meq/L. At 9.7 m depth, however, the concentration of K^+ was 11.4 meq/L. In the

Figure A-4 The ratios of the sum of sodium (Na⁺) and potassium (K⁺) over the sum of major cations (Na⁺, K⁺, magnesium (Mg²⁺) and calcium (Ca²⁺)), and K⁺ over the major cations correlated to the remoulded shear strength (a and d), liquidity index (b and e), and plasticity index (c and f). All the collected data are included and contains numerous sources of errors
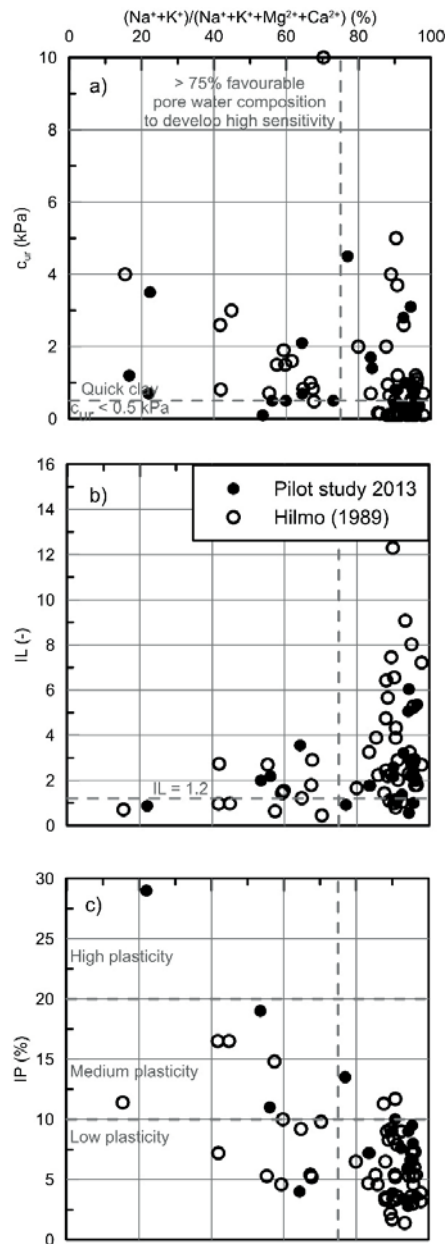
Figure A-5 The ratios of the sum of sodium (Na$^+$) and potassium (K$^+$) over the sum of major cations (Na$^+$, K$^+$, magnesium (Mg^{2+}) and calcium (Ca^{2+})), and K$^+$ over the major cations correlated to the remoulded shear strength (a and d), liquidity index (b and e), and plasticity index (c and f). The alkalinity in these samples are not determined, therefore the electric charge balance and salt content is not known
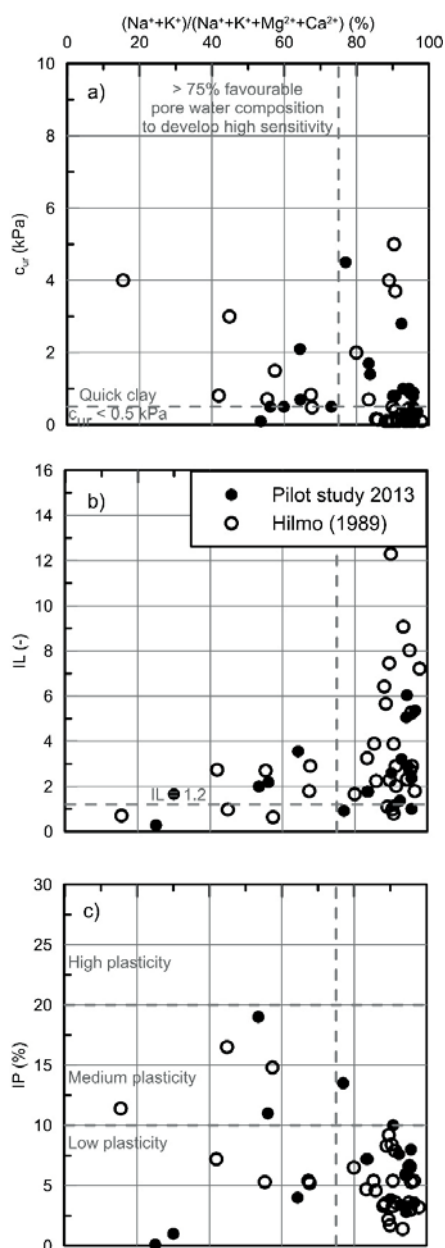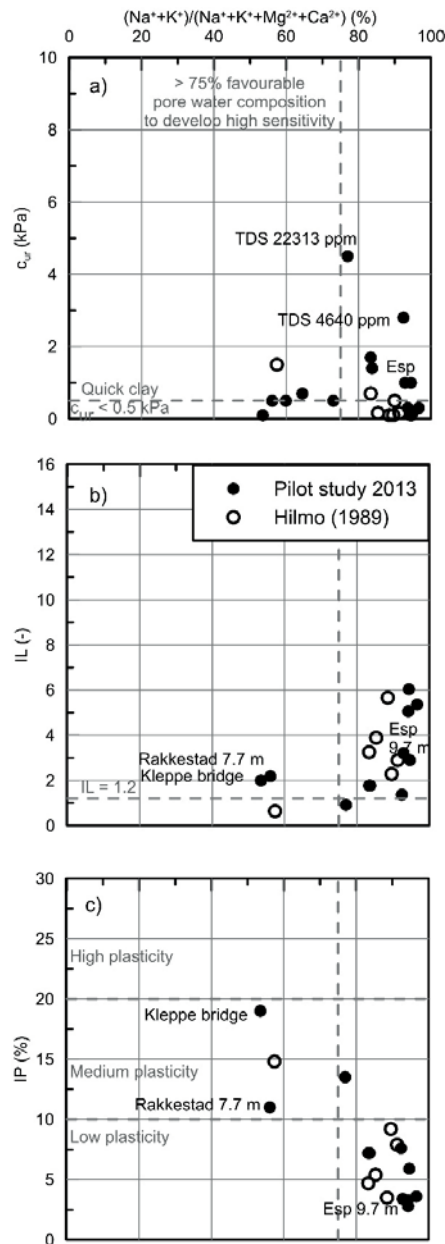
Figure A-6 The ratios of the sum of sodium (Na^+) and potassium (K^+) over the sum of major cations (Na^+, K^+, magnesium (Mg^{2+}) and calcium (Ca^{2+})), and K^+ over the major cations correlated to the remoulded shear strength (a and d), liquidity index (b and e), and plasticity index (c and f). Data that did not fit the criteria are ruled out

rest of the collected samples the concentration of K^+ was in the range 0.3-4.3 meq/L. An increase in the concentration of K^+ of this size at this depth is unlikely. The concentration of Cl^- increased from 0.9-1.4 meq/L to unlikely 12.7 meq/L at 9.7 m depth. It is therefore believed that this pore water sample was contaminated.

Both the clay samples from Rakkestad and Kleppe bridge had lower c_{ur} than 0.5 kPa and higher IL than 1.2 at pore-water compositions not favouring development of high sensitivity. The clays were, however, of medium plasticity. The alkalinity in the pore water from the sample from Kleppe bridge was very low, only 1.6 meq/L. In the rest of the samples, the alkalinity was in the range of 3.4-17.9 meq/L. However, this does not explain the deviations in the geotechnical properties correlated to the pore-water composition, and the impact of mineralogy on the geotechnical properties is investigated in the following section.

A.5   Mineralogy

The bulk mineralogy was quantified for 11 of the collected samples, and the clay mineralogy for 12 of the samples. All of which were from the collected samples of adequate quality regards to pore-water chemistry. The bulk mineralogy consisted of in average 24.8% muscovite/illite, 24.7% plagioclase/albite, 22.5 % quartz, 9.1% amphibole, 9.1% K-feldspar/microcline, 6.8% chlorite, and 3.4% calcite (Table A-1). The clay mineralogy (Table A-2) consisted of in average 71.7% illite, 27.5% chlorite and 2.7% mixed-layer of chlorite-smectite. The quantified mineralogy did not vary to a great extent, and no coherent pattern was seen correlating the geotechnical properties to the various mineral types. There were some deviations from the average bulk mineralogy (Furubakken and Kleppe bridge), but the deviations in the geotechnical properties correlated to the pore-water compositions in the clays from Rakkestad and Kleppe cannot be explained by differing mineralogical contents due to the limited data.

Table A-1 Bulk mineralogy

Site	Depth	Qtz[a] %	Ms/Ill[b] %	Kfs/Mc[c] %	Pl/Ab[d] %	Am/Hbl[e] %	Cal[f] %	Chl[g] %
Rakkestad	7.7	23.1	23.8	12.6	28.1	4.9	2.1	5.4
Kleppe bridge	4.25	17.1	22.3	15.1	32.5	6.5		6.5
Dragvoll	4.6[h]	20.5	14.2	9.8	27.2	16.4	4.5	7.4
Dragvoll	5.6[h]	22.8	25.8	7.7	23.6	8.6	3.4	8.1
Esp	8.4	21.7	32.7	8.5	18.9	7.0	2.1	9.1
Esp	8.8	23.6	31.1	10.7	19.5	5.5	3.2	6.4
Esp	9.7	28.6	17.8	5.1	30.6	9.1	3.5	5.4
Klett	11.3	24.5	36.4	9.3	15.1	6.5		8.2
Lade	9.5	21.6	21.1	11.4	24.3	8.6	5.9	7.2
Leira	29.4	29.6	13.8	8.3	32.9	8.5	3.3	3.7
Leira	31.5	26.5	29.1	8.3	24.0	6.3		5.9
Furubakken	11.4	9.5	37.6	5.3	23.9	21.0		2.7

[a]quartz, [b]muscovite/illite, [c]K-feldspar/microcline, [d]plagioclase/albite, [e]amphibole/hornblende, [f]calcite, [g]chlorite. [h] not from the same depths as the analysed pore-water chemistry.

Table A-2 Clay mineralogy

Site	Depth	Chlorite %	Illite[a] %	Mixed layers[b] %
Rakkestad	4.7	27.8	72.3	
Rakkestad	7.7	21.2	78.8	
Kleppe bridge	4.25	30.7	69.3	
Dragvoll	4.6[c]	37.4	62.7	
Dragvoll	5.6[c]	33.2	66.8	
Esp	8.4	30.5	69.5	
Esp	8.8	34.4	65.6	
Esp	9.7	39.4	60.7	
Klett	11.3	10.4	88.8	0.8
Lade	9.5	25.8	72.6	1.6
Leira	29.4	23.7	74.9	1.5
Leira	31.5	26.7	73.3	
Furubakken	11.4	15.9	77.2	6.9

[a]Dioctahedral mica of Muscovite type + Trioctahedral mica of biotite type, [b]Chlorite-smectite.
[c] not from the same depths as the analysed pore-water chemistry.

A.6   Discussions and Conclusions

The bulk mineralogy was dominated by quartz, illite and plagioclase. The clay mineralogy was dominated by illite, followed by chlorite with small amounts of mixed-layers of chlorite-smectite which agrees well with earlier findings in Norwegian clays (Løken 1968; Rosenqvist 1955; Rosenqvist 1975; Berry and Jørgensen 1971). Swelling minerals may prevent developing highly sensitive clays. However, they may appear under reduced conditions (personal communication, Torrance 2013). Only traces of swelling minerals were found in a few of the specimens in the collected data.

The quick clays in the herein presented collection of Norwegian clays, all had salt contents of less than 2 g/L, corresponding to total dissolved solids of 2000 ppm. However, not all of them were quick. The variations in mineralogy did not explain their variation in the geotechnical properties. Correlating the remoulded shear strength, liquidity and plasticity index to the pore-water compositions, the ratio of monovalent over the major cations in most of the quick clays exceeded 75%, which favours development of high sensitivity (Mitchell and Soga 2005). Some of the clays had a remoulded shear strength equal to or less than 0.5 kPa and a liquidity index larger than 1.2, but a ratio below 75% and salt contents of less than 0.5 g/L. However, these clays were of medium plasticity rather than of low plasticity as the remainder data points. According to Penner (1965), low plasticity index may be a result of higher content of coarser material, or it may be caused by the ratio of monovalent over divalent cations in the pore water. As the clay content in the collected data did not explain the deviating plasticity, it is likely to believe that in this case the pore-water composition did not impede high sensitivity, but may have improved the plasticity index.