In-situ improvement of highly sensitive clays by potassium chloride migration

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Abstract

Highly sensitive, low-saline clays, termed quick clays, represent a risk for large landslides. An in-situ experiment was conducted installing salt wells filled with potassium chloride (*KCl*) in order to study how salt wells can be used to reduce landslide risk. The salt-plume migration and the clay volume surrounding the salt wells were investigated by resistivity cone penetration tests (RCPTU), piston samples, conductivity divers and groundwater samples. Correlating the geotechnical properties to the occurring pore-water compositions, the remolded shear strength (c_{ur}) was improved beyond 1 kPa when the ratio of the sum of potassium, magnesium and calcium over the major cations exceeded 20%. The c_{ur} was improved to about 4-8 kPa 0.5 m from the wells within 3 years, and the liquidity index decreased from more than 3.4 to less than 1.2. A diameter of minimum 1.5 m around the wells was stabilized within 3 years. Thus, it is recommended to install the salt wells with a center-to-center distance of 1.5-2.0 m. The improved post-failure properties (c_{ur} and Atterberg limits) are considered permanent in an engineering time scale due to a lasting pore-water composition inhibiting development of high sensitivity. Salt wells can be installed without substantial disturbance of the soil, and can be used as landslide mitigation in quick-clay areas.

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1 Introduction

Highly sensitive clays, termed quick clays found in Scandinavia, Canada and northern Russia, are defined by a remolded shear strength of less than 0.5 kPa (Norwegian Geotechnical Society 2011), and pose a great risk for large, retrogressive landslides such as the 5-6 million m^3 Rissa quick-clay slide in 1978 (Gregersen 1981). Quick clays were accumulated in seawater during the deglaciation of the northern hemisphere, creating a flocculated structure with large voids originally filled with seawater holding a salt content of 30-35 g/L (Moum et al. 1971). The structure is stable as long as the salt content is high due to the suppressed diffuse double layer (*DDL*). Land heave expose these clays to leaching by meteoric groundwater flow, diluting their pore water, which increases the thickness of the *DDL* around the clay minerals. Thus, the repulsive forces increase and the clays are easy to remold. At sufficiently low salt contents, often less than 2 g/L (Rosenqvist 1977; Torrance 1979), the clays may become quick. The pore-water chemistry greatly influences the geotechnical properties, and knowledge on its impact aids developing effective ground improvement methods.

Laboratory studies carried out in the 1960s and 1970s on Norwegian quick clays, showed that potassium improved the geotechnical properties to a greater extent than ions of higher valence (Moum et al. 1968; Løken 1968, 1970). Re-introducing high salt content by installing salt wells filled with potassium chloride (*KCl*) were used as ground improvement prior to excavation in a quick-clay area at Ulvensplitten, Oslo, Norway in 1972 (Eggestad and Sem 1976). The fall-cone undrained and remolded shear strength, and Atterberg limits were significantly improved, and the clay ceased to be quick. The long-term effect of the method was investigated 40 years after installation, showing that the clay remained non-quick even at low salt contents due to changed pore-water compositions inhibiting quick behavior. Therefore, the improvement using *KCl* wells was suggested as being permanent in an engineering time scale (Helle et al. 2016).

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 at Ulvensplitten. The collected pore-water chemistry data was, however, scarce and inconclusive regarding the determination of when the clay ceased to be quick; vital for estimating the time required to stabilize the quick-clay volume. Furthermore, the installation depths at Ulvensplitten were uncertain due to the drilling methods and the salt wells were not refilled, thus there was no control of the boundary condition. The salt-well method is not in use today due to scarce documentation and insufficient understanding of how and to what extent *KCl* improves the geotechnical properties. Therefore, six salt wells filled with *KCl* were installed in January 2013 in a highly sensitive, low plastic quick-clay deposit at Dragvoll, Trondheim, Norway in order to correlate the changed pore-water chemistry to improved geotechnical properties, and to monitor the salt-plume migration and changed pore-water composition over time while maintaining fully saturated *KCl* solution in the wells. Groundwater samples extracted from filter tips document the changed pore-water composition over time, and resistivity cone penetration tests (RCPTU) were conducted around the wells to map the extent and direction of the salt plumes. Undisturbed samples were extracted around the wells to correlate the improved geotechnical properties to the changed pore-water chemistry. The herein presented correlations between geotechnical properties and pore-water compositions in the salt-treated quick-clay deposit at Dragvoll together with the data from Ulvensplitten, contribute to understand the mechanisms around *KCl* as ground improvement in quick clays and its feasibility, as well as determining at which pore-water composition the clays render to be quick.

2 Background

2.1 Pore-water composition in glaciomarine clays

The geotechnical properties are greatly affected by the electrolyte concentration and ion composition in the pore water due to their impact on the interparticle forces. Especially the post-failure properties, herein defined as the remolded shear strength and Atterberg limits, are crucially dependent on these factors. Leaching and diffusion of the marine deposited, glaciomarine clays has decreased the originally high salt content, and also changed the ion composition in the pore water (Rosenqvist 1946, 1977). According to Bjerrum et al. (1969), leached clays with low salt contents develop high sensitivity. Quick clays often have salt contents of less than 2 g/L (Rosenqvist 1977; Torrance 1979), and the clays may behave as liquids when remolded at salt contents less than 1 g/L (Bjerrum et al. 1969; Moum et al. 1971).

Low salt content does not necessarily imply quick clay as the specific ion composition at low salt contents greatly affects the geotechnical properties due to the impact of the various ions on the diffuse double layer (*DDL*) thickness (Moum et al. 1971; van Olphen 1977; Rosenqvist 1968). At normally occurring pH in Norwegian clays of around 8, the clay mineral surface favors calcium (Ca^{2+}) over magnesium (Mg^{2+}), and potassium (K^+) over sodium (Na^+) due to valence, hydrated radius and available concentrations (Løken 1970; Appelo and Postma 2005; Mitchell and Soga 2005). Na-rich pore water was entrapped in the voids during accumulation of the glaciomarine clays. Consequently, Na^+ dominated the pore-water composition as well as the adsorbed positions on the mineral surfaces. The isostatic uplift allowed leaching of the clay deposits by meteoric groundwater flow, diluting the salt content. The thickness of the *DDL* increases with decreasing salt content. Thus, the repulsive forces increase, and the clays are easier to remold. The ion composition in the groundwater is affected by the background geology, but is normally dominated by Ca^{2+} and Mg^{2+} (Appelo and Postma 2005), both of which are preferred over Na^+ by the clay mineral surfaces. As leaching progress, the pore water is diluted, and the adsorbed Na^+ is replaced by available ions of higher exchange power, such as divalent ions. The pore-water composition in quick clays is still dominated by Na^+, whereas Mg^{2+} and Ca^{2+} dominate the adsorbed positions (Moum et al. 1971). Leaching is an ongoing process, and with time, more and more divalent ions enter the clay-water system, and the concentration of Na^+ in the pore water is depleted. Divalent ions have a greater effect on compressing the *DDL* than Na^+ at same normality; thereby the repulsive forces are reduced. Consequently, the clay minerals will no longer liquefy when remolded, and the clays cease to be quick. Therefore, chemical agents that suppresses the diffuse double layer may be used as ground improvement in highly sensitive quick clays.

2.2 Potassium chloride as a ground improvement agent

Large retrogressive landslides may develop in areas with large volumes of quick clay. Based on historical Canadian and Norwegian quick-clay landslides, a remolded shear strength $c_{ur} < 1$ kPa and a liquidity index $I_L > 1.2$ may be used as an indicator on clays that pose a risk for large retrogressive landslides (Leroueil et al. 1983; Thakur et al. 2014). Re-establishing high salt contents in quick clays improve the c_{ur} so that the clay no longer appear as quick, and at the same time improve the Atterberg limits (Rosenqvist 1946, 1953, 1955; Bjerrum 1955; Løken 1968, 1970; Moum et al. 1968; Quigley 1980; Torrance 1983). Increasing the salt content and changing the ion composition in the pore water by installing *KCl* wells, speeds up the natural ongoing process of changing the clay behavior from quick to non-quick. Introducing high concentrations of K^+, the clay mineral surfaces release Mg^{2+} and Ca^{2+} to the pore water, and adsorb the readily available K^+ (Mitchell and Soga 2005). Potassium has a greater impact than the other major cations (Na^+, Mg^{2+} and Ca^{2+}) on improving the undrained

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and remolded shear strength as well as the Atterberg limits (Moum et al. 1968; Løken 1968, 1970). The reason for this may lie in the fact that K^+ has a larger atomic radius (0.23 nm) than the other cations; 0.19 nm, 0.16 nm and 0.20 nm respectively (Aylward and Findlay 1994). Consequently, 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). Therefore, K^+ has a larger ionic potential, which makes the charge more effective.

The salt wells at Ulvensplitten were installed with a center-to-center distance of 1.5 m (Eggestad and Sem 1976). Two years after installation, the remolded 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). Helle et al. (2014) suggest that there might be a limit whereas increased salt content beyond a certain concentration is not followed by further increase in the undrained shear strength, also observed in the investigations of the clays 40 years after the in-situ experiment at Ulvensplitten (Helle et al. 2016). Even though the salt content in the salt-treated clay at Ulvensplitten decreased to its original 0.5 g/L in the deepest part of the salt-treated profile 40 years after installation, the clay was not quick due to favorable changed pore-water composition. The ground investigations carried out thirty to forty years after installation, confirm that the non-quick properties remain in an engineering time scale, making the method current. The effectiveness of KCl wells as a ground-improvement method highly depends on the time it takes to improve the geotechnical properties in the clay volume surrounding the wells.

2.3   Time factors controlling solute transport in clays

No mixing is needed applying KCl as ground improvement in clays, as the migration from the installed wells is self-driven by diffusion due to large concentration gradients between the high-saline well and the low-saline surrounding quick clay. However, the transport mechanisms and coupling between them depend on the hydrogeology on the site. Advective flow is considered to dominate the solute transport in soils with a hydraulic conductivity (k_h) larger than 1 x 10^{-9} m/s, whereas diffusion is considered as the dominating transport mechanism in clays with k_h of less than 2-5 x 10^{-10} m/s as the ions then move faster than the water. Diffusion contributes significantly to the transport in the intermediate soils with k_h up to 1 x 10^{-9} m/s (Shackelford 2014). How fast a solute diffuses in the pore fluid depends on the diffusion coefficients of the various ions. Potassium chloride has a greater diffusion coefficient than for instance calcium chloride ($CaCl_2$) (e.g. Appelo and Postma 2005; Mitchell and Soga 2005), thus changing the pore-water chemistry, increases the salt content and improves the geotechnical properties in the clay volume faster.

When equal concentrations of potassium (K^+) and chloride (Cl^-) are introduced to the clay-water system, where Cl^- as a conservative tracer, travels unhindered through the porous media. Potassium, however, is retarded, i.e. delayed, due to ion exchange reactions on the clay-mineral surfaces. The clay-mineral surfaces release Na^+, Mg^{2+} and Ca^{2+} into the pore water as K^+ enters the adsorbed positions, resulting in increased pore-water concentrations of these cations. The retardation of K^+ highly depends on the cation exchange capacity (CEC) of the soil, the larger CEC, the larger retardation. The CEC is governed by the clay content (particle size < 2 µm), clay-mineral types, organic matter and oxide or hydroxide content (Appelo and Postma 2005). Norwegian glaciomarine clays are normally dominated by the non-expansive clay minerals illite and chlorite (Rosenqvist 1955; Løken 1970), with $CECs$ in the range of 20-50 meq/100 g dry soil and 10-40 meq/100 g dry soil respectively (Appelo and Postma 2005).

In order to investigate at which pore-water compositions quick clays cease to be quick and the required time to do so, mineralogy, CEC, initial pore-water chemistry and geotechnical properties must be determined as well as the hydrogeological conditions at site. The site at Dragvoll

was chosen due its low-plastic and highly sensitive quick clay stretching down to around 16-20 m depth covered with a thin weathered crust ("dry crust") in top (Emdal et al. 2012).

3 Dragvoll research site

3.1 Site description and site installations

The Dragvoll research site is located somewhat 300 m southeast of the site described in Emdal et al. 2012, with the same topography and geological history. The marine limit in the Trondheim area is 175-180 m above present sea level (Kjemperud 1981; Hafsten 1983). The research site is located at 156 m above present sea level, in a relatively flat area used for farmland. Outcropping bedrock is found at distance in the small hills on the northwest- and southeast side of the site. The sediment package is up to 50 m thick. Beach sediments are found in close vicinity to the site at approximately 160 m above present sea level, which may indicate that the sediments are deposited in shallow water (Hafsten and Mack 1990). The site is situated on the south side of a small creek functioning as a drainage path for the surface water in the area.

Six salt wells were installed in the quick-clay deposit at the Dragvoll research site in January 2013 (Fig. 1). The wells were constructed of polyethylene (PE) pipes with an outer diameter of 63 mm. 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. 6 and 7). All wells were installed to a depth of 8 m, with an empty 1 m stand pipe above ground convenient for inspection and refilling of the wells (Fig. 1a). A slotted section from 4 m to 8 m depth allowed the salt to migrate into the quick-clay deposit. A geotextile lashed around the slotted section prevented clay entering the wells. Initially the wells were filled with granular *KCl* to 1 m below the terrain surface. A few liters 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 refilled regularly with granular *KCl* to maintain fully saturated solution 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*, salt well no. 6 (SW6) was monitored using two Schlumberger divers (Eijkelkamp Soil & Water, Giesbeek, The Netherlands) measuring the hydraulic head, temperature and electrical conductivity once a day. These were placed in measuring wells constructed in the same manner as the salt wells with a slotted section from 5.5 m to 6.5 m depth and positioned 0.5 m and 1.0 m from SW6; D2 and D3 respectively in
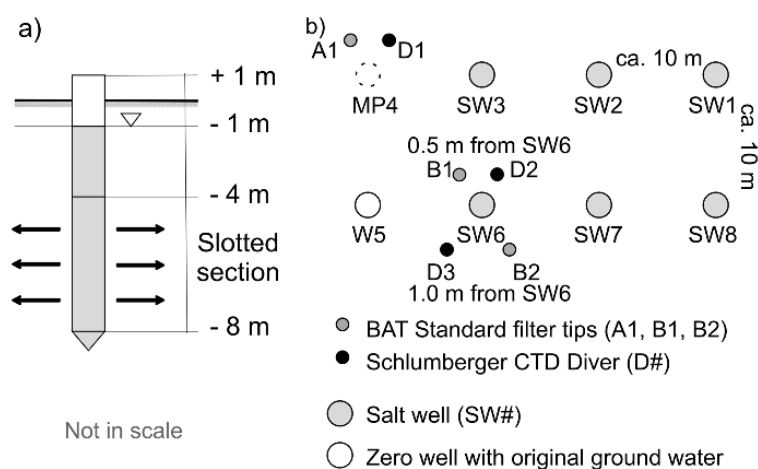

Fig. 1. Installations at the Dragvoll research site. a) Salt-well design. b) Principal sketch of the installations. The salt wells (SW#) are installed with a centre-to-centre distance of approximately 10 m

Fig. 1b. BAT standard filter tips (BAT Geosystems AB, Stockholm, Sweden) connected to 2.55 cm(1 in.) PE pipes were installed at 6 m depth 0.5 m and 1.0 m from SW6; B1 and B2 in Fig. 1b. Groundwater samples were extracted from the BAT filters regularly. Any seasonal changes in the groundwater was monitored by one diver (D1) and BAT standard filter (A1) tip installed in measuring point 4 (MP4) in Fig. 1b.

3.2   Ground investigations and laboratory tests

The initial soil properties were determined on high-quality mini-block samples extracted from 4 m to 8 m depth in the quick clay deposit at Dragvoll. 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 and remolded shear strength, water content, density, Atterberg limits, triaxial and oedometer tests (not presented herein), and pore-water chemistry were determined on all samples. The grain-size distribution was determined by hydrometer tests. X-ray diffraction analysis (*XRD*) were used to determine the bulk and clay mineralogy. The specific surface area was analyzed by nitrogen (N_2) adsorption analysis (*BET*). 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 (10-20 ml) was filtered through 0.45 μm syringe filters, or in some cases 0.20 μm syringe filters, into PE containers and frozen until analysis of the pore-water composition. The cations were analyzed using a Dionex ICS-1000 Ion Chromatography System (ICS-1000) (Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA), and 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 (Metrohm AG, Herisau, Switzerland), and pH was measured in the pore-water samples by Methrom 702 SM Titrono at 25 °C. pH was also determined directly on remolded clay specimens at approximately 25 °C using a Sentix SP electrode (WTW Measurement Systems Inc, Weilheim, Germany).

Table 1. RCPTUs and sampling conducted around the salt wells in the years after installation

RCPTU and sampling 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 extent of the salt plumes around the wells was investigated by resistivity cone penetration tests (RCPTU) carried out with 5 tons GeoTech CPTU Nova (Ingenjörsfirman Geotech AB, Askim, Sweden) and 2 tons Envi CTPU (Environmental Mechanics AB, Alingsås, Sweden) with tip areas of 10 cm². Undisturbed 54 mm piston samples were extracted from 4.0 m to 8.8 m depth in various distances from the salt wells. The investigations around each well was carried out within 1-2 weeks (Table 1). All samples were tested in the geotechnical laboratory within 48 hours after extraction to delimit storage effects. Water content, Atterberg limits, fall cone undrained and

remolded shear strength and density was determined on all samples, as well as pH and the chemical composition of the pore water. The groundwater samples extracted from the BAT filter tips were also filtered through syringe filters and frozen prior to testing in the same manner as the extracted pore water from the clay samples.

4 The effect of KCl on geochemical and geotechnical properties

4.1 Initial soil properties in the Dragvoll quick clay

The present groundwater table at Dragvoll fluctuates between the terrain surface and 1 m below. The weathered zone (or the "dry crust") stretches down to 1-2 m below surface. Clay with gravel/rock fragments is found down to approximately 4 m. Between 3 m and 4 m, the remolded shear strength in the clay gradually decreases below 0.5 kPa (Bryntesen 2013). The clay deposit at Dragvoll is interbedded with millimeter thick silt/sand layers, increasing to 1-2 cm thickness at 7-8 m depth. From 4.2 m to 5.8 m, the hydraulic conductivities in the constant rate of strain oedometer tests are in the range of $1.3\text{-}1.5 \times 10^{-9}$ m/s. The hydraulic conductivity determined by the inflow test in the BAT filters at 6 m depth is of 2.3×10^{-10} m/s. The clay content (< 2 µm) is of 34-41%. The bulk mineralogy is dominated by the non-clay minerals quartz and albite, whereas the clay mineralogy is dominated by illite (Table 2). The specific surface area is of only 18.3-27.8 m^2/g, typical for post-glacial clays originating from grounded rock flour (Quigley 1980). The determined cation exchange capacity (*CEC*) is around 25 meq/100 g dry soil in the Dragvoll quick clay; within the range of *CEC* often found in text books for illites and chlorites of 20-50 meq/100 g dry soil and 10-40 meq/100 g dry soil, respectively (Appelo and Postma 2005). According to Grim (1968), the specific surface area for illites is in the range of 65-100 m^2/g; much larger 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. Kenney (1967) and Locat and St-Gelais (2014) report *CEC* in illitic-chloritic Norwegian and Canadian chloritic-illitic Quebec clastic clays in the range of 6-17 meq/100 g dry soil in clays with similar clay mineralogy, specific surface areas and clay content as in the Dragvoll clay. The presence of calcite in the clay from Dragvoll is sensitive to dissolution and may have given too high *CEC* values (Jackson 1979). Estimating the *CEC* based on mineralogy, clay content and the lowest *CEC* ranges for illite and chlorite of 20 meq/100 g dry soil and 10 meq/100 g dry soil, the Dragvoll clay have *CEC* in the range of 5.7-6.8 meq/100 g dry soil. Back calculations of the changing pore-water chemistry by the geochemical computer program PHREEQC (Parkhurst and Appelo 2013) around salt-well no. 6, correspond well with the estimated *CEC*.

Table 2. Bulk and clay mineralogy in the Dragvoll clay

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

The water content (*w*) in the Dragvoll quick clay is in the range of 33.0-40.6% (Table 3), which is normal for Norwegian clay deposits. The clay has an average volumetric porosity (ε_w) of 0.51, average bulk density (ρ) of 1.87 g/cm^3, and dry bulk density (ρ_d) of 1.36 g/cm^3. The liquid

limit (w_L) is lower than the natural water content, a typical feature in quick clays. Both the plastic limit (w_P) and w_L decrease with depth, and the clay is of low plasticity, with a liquidity index (IL) well above 1.2. The clay is highly sensitive, with a remolded shear strength of 0.5 kPa at 4 m depth, decreasing to less than 0.1 kPa from around 5 m depth downwards. The fall-cone undrained shear strength is much lower than the peak undrained shear strength of around 27 kPa found in anisotropically consolidated undrained compression tests (CAU$_c$). The total salt content is of only 0.60-0.72 g/L, with a sum of cations and anions in the pore water of only 15-18 meq/L. The cation composition in the pore water consists of 85-92% sodium (Na^+), with slightly higher concentrations of magnesium (Mg^{2+}) and calcium (Ca^{2+}) in the upper part of the soil profile than deeper down, possibly explaining the decreasing remolded shear strength with depth.

Table 3. Geotechnical properties in the Dragvoll quick clay

Geotechnical properties	
Fall cone undrained shear strength (c_u)	8-16 kPa
Fall cone remolded shear strength (c_{ur})	<0.1-0.5 kPa
Water content (w)	33.0-40.6%
Plastic limit (w_P)	15-19%
Liquid limit (w_L)	21-24%
Plasticity index (IP)	4.4-6.3%
Liquidity index (IL)	3.4-4.3

4.2 Salt-plume extent

Resistivity cone penetration tests (RCPTU) around the salt wells, revealed variations in the salt-plume extent in different directions from the wells, also with depth, implying that the salt migrated slightly unsymmetrical around the wells (Fig. 2). The direction of fastest migration varied from one
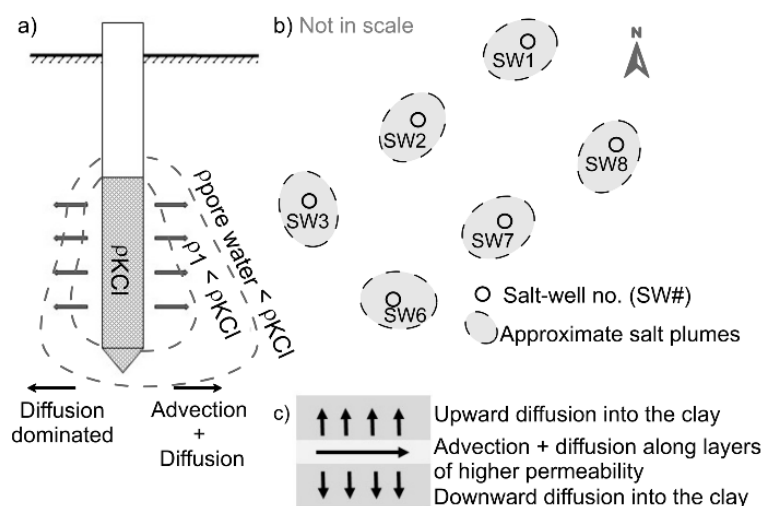

Fig. 2 (a) Diffusion dominates the salt migration around the wells, with contribution from some advection due to density (ρ) gradients between the well and the pore water in the quick clay. The plumes migrate faster in predominant directions and also with depth; (b) the fastest direction of the salt migration varies from one well to the other; (c) the plume is forced horizontally along layers of higher permeability, possibly facilitating vertical diffusion

well to the other, indicating that there is no dominating groundwater flow on the site. Also confirmed by measuring the hydraulic head in the salt wells; a hydraulic gradient of maximum 0.01 was found in various directions over the site. The density of the *KCl* solute in the wells is higher than in the low-saline pore water in the quick clay. The detected coarser layers aid some advective flow due to density gradients combined with horizontal and possibly vertical diffusion (Fig. 2c).
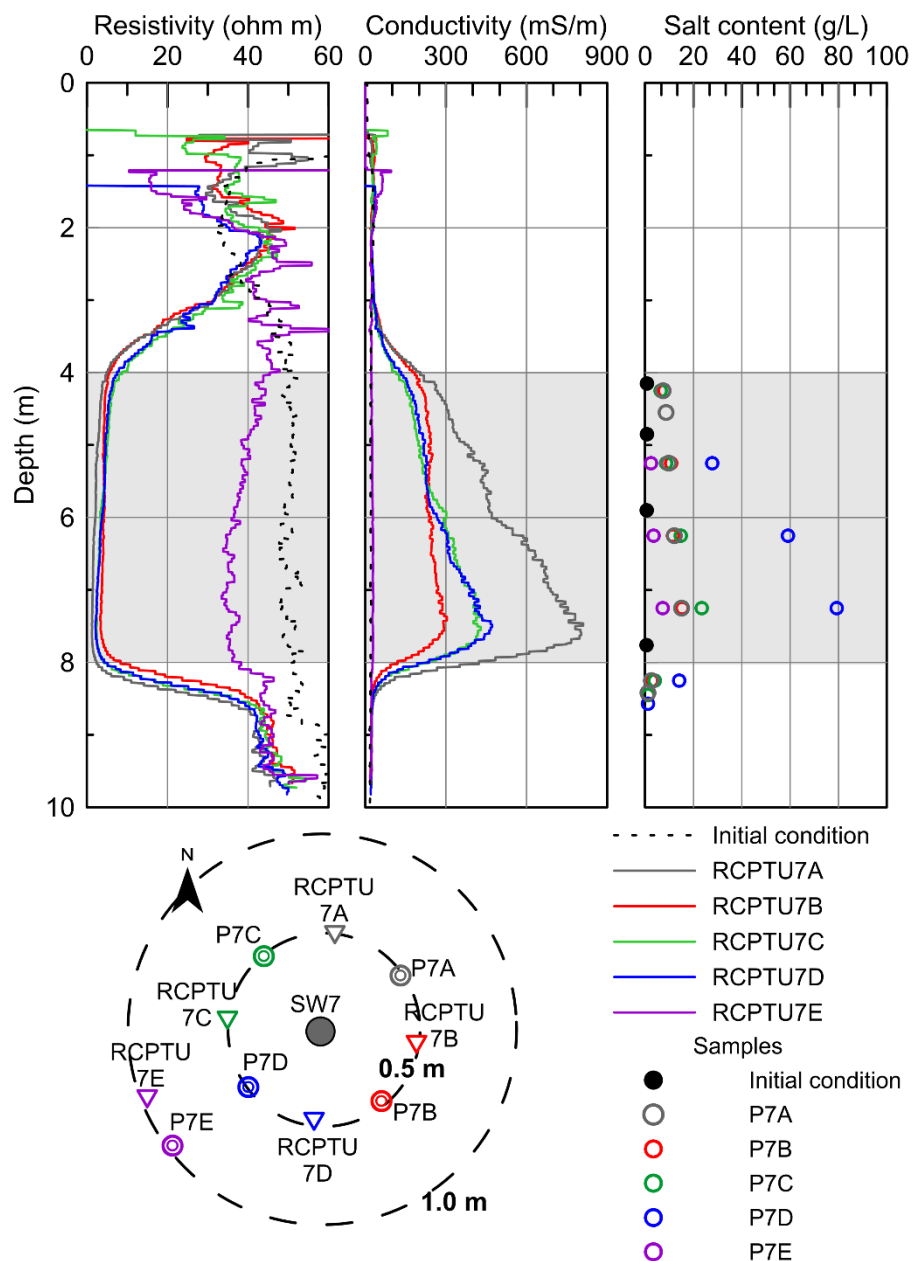

Fig. 3. In-situ soil resistivity and conductivity measured with resistivity cone penetration tests (RCPTU), and salt content in the pore water extracted from the 54 mm piston samples (P#) around salt-well no. 7 (SW7)

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The RCPTU soundings carried out 2.4-3.2 years after installation show a distinct drop in electrical resistivity from around 50 Ωm in the original quick clay, to below 10 Ωm in the salt-treated clay 0.5 m from the salt wells (Fig. 3). The decrease in resistivity is less pronounced one meter from the wells, nevertheless indicating salt-plume arrival. The electrical conductivity is the inverse of the electrical resistivity, providing better visualization of the salt plume with depth. The conductivity is lower in top of the salt-stabilized clays than deeper down, implying that the salt contents increase with depth. At 8.5 m depth, the conductivity decreases to the original conductivity in the quick clay layer below the wells, which indicates that the salt plumes extend to around 0.5 m below the salt wells.

Considering the measured conductivity around salt-well no. 7 (SW7), the salt plume seem to migrate in a northern direction, between piston sample P7A and P7C. The salt contents in the extracted pore water from piston samples, however, evidently show that the salt plume is migrating non-symmetrically moderately off-centered from the well, with the fastest velocity in direction of piston sample P7D. The salt contents and ion concentrations were lower, but quite similar in the piston samples extracted from boreholes P7A, P7B and P7C, indicating that diffusion dominates the transport mechanism around the wells. Sediment heterogeneity aids slightly faster migration by some advection along coarser layers in predominant directions from the wells.

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 (BAT B1 in Fig. 4 and 5a). In the opposite direction, one meter from the well (BAT B2) (Fig. 4 and 5b), the salt plume arrived approximately 600 days after installation. Sodium (Na^+) balanced by the alkalinity, here considered to be dominated by bicarbonate (HCO_3^-), is the abundant cation in the pore-water composition in the initial groundwater samples extracted from the BAT filter tips (Fig. 5). The increasing concentration of Cl^- was accompanied with increasing concentration of Na^+ and
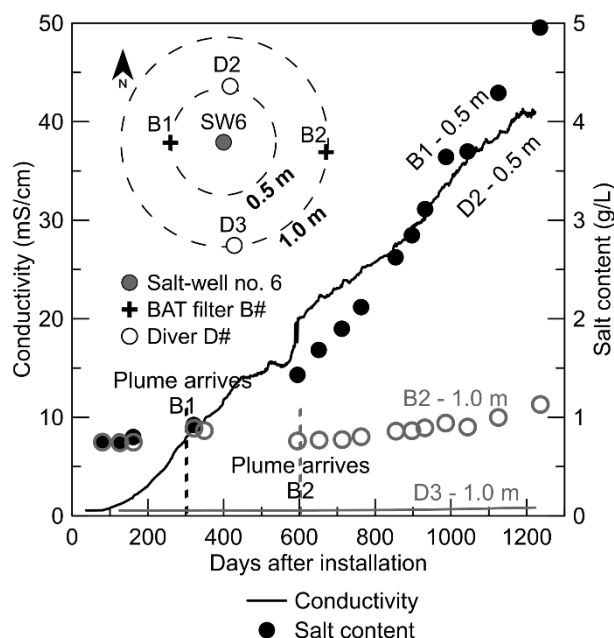

Fig. 4. Diver conductivity (D2 and D3) and total salt contents found in ground-water samples extracted from the BAT filter tips (B1 and B2) installed 0.5 m (black line and symbols) and 1.0 m (grey line and symbols) from salt-well no. 6 (SW6)

decreased alkalinity (Fig. 5a). The K-, Mg- and Ca-fronts arrived approximately simultaneously, around 600 days after installation. The Na-concentration seemed to flatten out around 1000 days after installation, indicating that most of the Na^+ was released by the clay mineral surfaces, and was on its way out of the clay-water system closest to the well. The concentrations of Mg^{2+} and Ca^{2+} were still increasing, indicating ongoing ion exchange. The concentration of the delayed K^+ was also increasing, implying that more and more of the adsorbed positions were dominated by K^+ in the clay volume closest to the well. The Cl-front arrived the BAT filter 1 m from the well approximately 600 days after installation, accompanied by increased Na-concentration and decreased alkalinity (Fig. 5b). The K-, Mg- and Ca-fronts were not yet arrived in the last extracted groundwater sample.
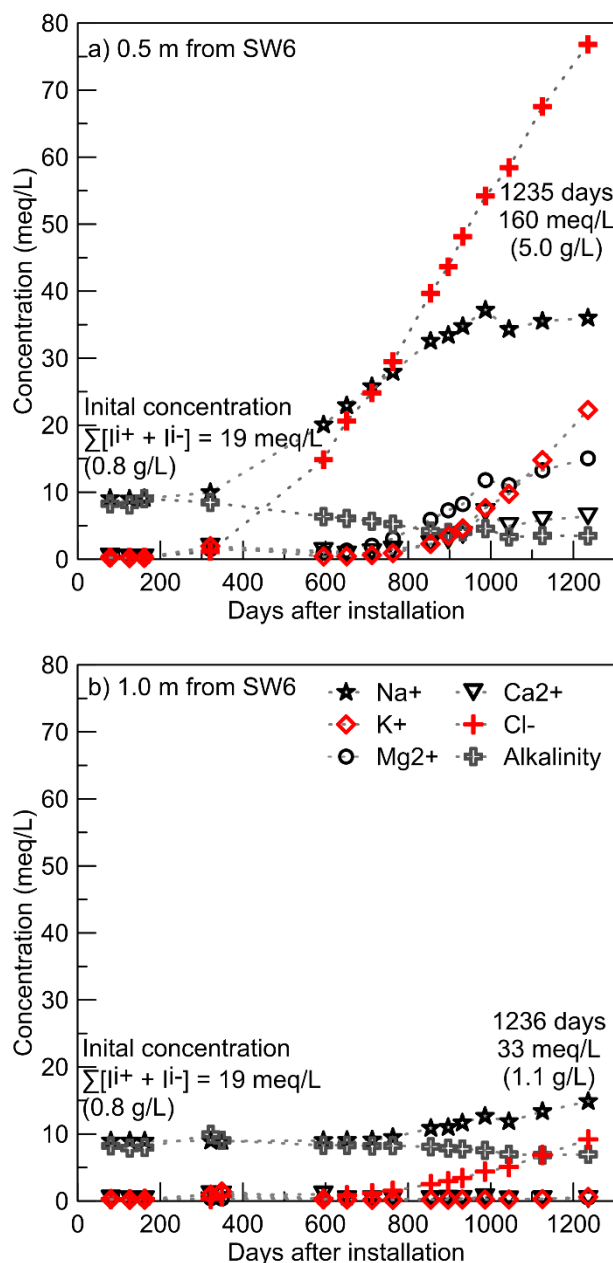

Fig. 5. Concentration of major cations, chloride and alkalinity found in ground-water samples extracted from the BAT filter tips installed a) 0.5 m from salt-well no. 6 (SW6) and b) 1.0 m from SW6. The arrival of K^+ is retarded compared to the arrival of Cl^-, both in red

RCPTU soundings around SW6 indicated that the direction of the fastest migration was towards BAT B2. This may explain why the diver conductivity 0.5 m from the salt well indicated

salt-plume arrival already 80 days after installation (Diver 2 in Fig. 4). 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, even though this might not be easy to see from Fig. 4 due to the scale on the axis.

The groundwater samples extracted from the BAT filter tips provide valuable information on how fast *KCl* migrates in the clay deposit, and how it affects the migration and concentrations of the other major cations with distance and time from the salt well. Undisturbed clay samples were extracted around salt-well no. 7, and in the directions of fastest migration from salt-wells no. 2, 3 and 8 to correlate geotechnical properties to the occurring pore-water compositions.

4.3 Pore-water chemistry in the salt-treated clay

In general, the salt content 1.5 m from the wells was unaltered from its original 0.7 g/L at time of investigations (Table 1). 0.5 m from salt-well no. 7 (SW7), in the directions where diffusion dominated the solute transport (boreholes P7A, B and C), the salt content was around 7 g/L at 4.3 m depth, increasing to around 19 g/L at 7.3 m depth (Table 4). In the directions of fastest migration, the salt content was much higher, around 24 g/L at 5.3 m depth, increasing to around 84 g/L at 7.3 m depth 0.5 m from salt-wells no. 3 and 7. One meter from salt-wells no. 2, 3 and 7, the salt contents were much lower, but still, the highest salt contents were found at 7.3 m depth. The salt plumes extended to around 8.5 m depth, 0.5 m below the wells, also detected in the electrical conductivity profiles in Fig. 3. The highest salt contents were found in the clays around salt-well no. 8 (in parentheses in Table 4), even though the samples were extracted half a year before the samples around salt-wells no. 2, 3 and 7. Two samples were extracted 10 cm from salt-well no. 8, having salt contents up to 170 g/L, whereas 0.5 m from the well the salt content was up to 98.1 g/L at 6.3 m depth.

Table 4. *Salt contents and remolded 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 parentheses*

	Diffusion		Advection and diffusion			
	0.5 m		0.5 m		1.0 m	
	Salt content	c_{ur}	Salt content	c_{ur}	Salt content	c_{ur}
Depth	g/L	kPa	g/L	kPa	g/L	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

Potassium (K^+) and chloride (Cl^-) were abundant in the pore water closest to the wells, decreasing with increasing distance from the wells (Fig. 6 symbols showing results from 6.3 m depth, dotted black lines show the maximum and minimum concentrations found in the clay samples). Ion exchange reactions with the mineral surfaces retarded K^+ relative to Cl^- (grey dotted line in Fig. 6 show the concentration at 6.3 m depth). The clay mineral surfaces release sodium (Na^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) to the pore water as the concentration of K^+ increases in the clay-water

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system. The concentrations of all the ions peak at around 7 m depth 0.5 m and 1.0 m from the wells due to higher velocity of the salt plume at around these depths. The concentrations of the various cations have some variation from one well to the other. Possibly caused by slightly deviating positions of the boreholes relative to the directions of fastest salt migration.

The pH measurements conducted on clay specimens (Fig. 7a), were lower than pH measured in the pore-water extract. However, both measurements show decreasing pH with increasing salinity. Changes in the physiochemical environment may either dissolve or precipitate calcite ($CaCO_3$), following the chemical reactions in (1).
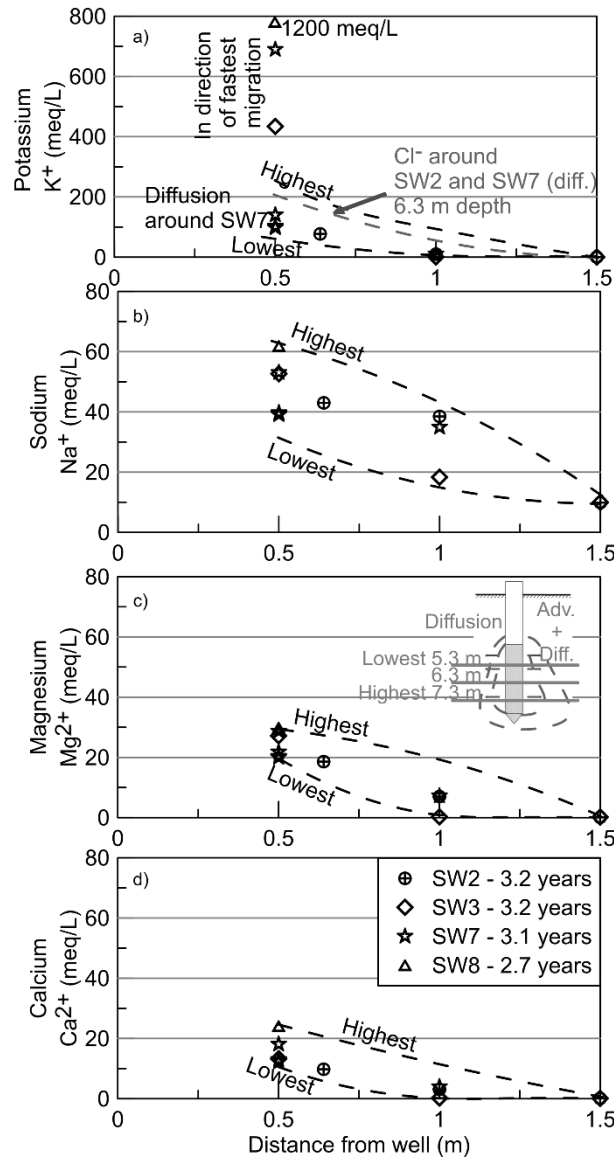
Fig. 6. Concentrations of a) potassium (K^+), b) sodium (Na^+), c) magnesium (Mg^{2+}) and d) calcium (Ca^{2+}) with distance from the salt wells (SW#). The symbols show the concentrations at 6.3 m depth, and the black dashed lines show the highest (7.3 m depth) and lowest (5.3 m depth) obtained concentrations around the wells. The grey dotted line in a) illustrates the chloride (Cl^-) concentration found in samples P7A, B and C 0.5 m from SW7, P2A 0.6 m from SW2 and 1.5 m from all the salt wells

$$CaCO_3(s) \leftrightarrow Ca^{2+} + CO_3^{2-}$$
$$\underline{CO_3^{2-} + H^+ \leftrightarrow HCO_3^-}$$
$$CaCO_3(s) + H^+ \leftrightarrow Ca^{2+} + HCO_3^- \hspace{3cm} (1)$$
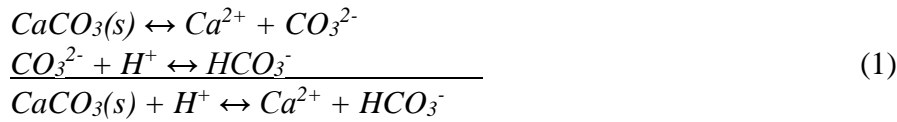
Small amounts of calcite (2-3%) were found in the bulk mineralogy. The geochemical computer program PHREEQC (www.usgs.gov) applying the Pitzer database for solutions of high activity was used to determine the saturation indexes in order to investigate if some of the increased concentration of Ca^{2+} in the pore water was caused by calcite dissolution. The saturation index of calcite is higher than zero, increasing with increasing salt content. At super saturation, no dissolution of calcite takes place. Consequently, the increased concentration of Ca^{2+} in the pore water is solely caused by ion
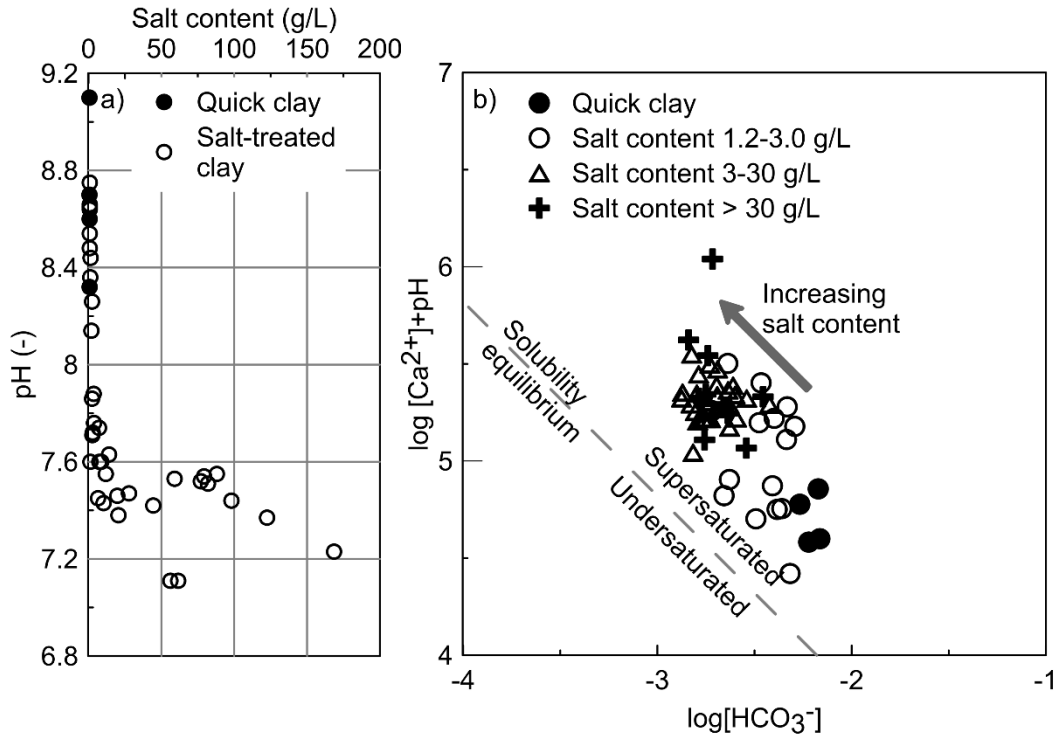
Fig. 7. a) pH measured on remolded clay specimens, and b) stability chart of calcite in the pore water showing the activity of bicarbonate (log[HCO$_3^-$]) towards the activity of calcium (log[Ca^{2+}]) and pH of the solution

exchange reactions on the mineral surfaces. Decreasing HCO_3^- and pH will keep the pore water close to calcite saturation (Fig. 7b).

4.4   The impact of KCl on geotechnical properties

Risk of large retrogressive landslides increases in clays with a remolded shear strength (c_{ur}) of less than 1 kPa, and a liquidity index (IL) larger than 1.2 (Leroueil et al. 1983; Thakur et al. 2014). Therefore, these criteria are used in the following to define stabilized quick clay rather than the Norwegian quick-clay definition of $c_{ur} < 0.5$ kPa (Norwegian Geotechnical Society 2011). In the direction of fastest migration, 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 7-8 m depth 1 m from salt-well no. 3 (Table 4). An improvement of the c_{ur} to more than 1 kPa was also found 0.5 m underneath the salt wells, within the investigated distance of 50 cm. Both the fall-cone undrained and remolded shear strength increased significantly with increasing salt contents up to 10 g/L by adding *KCl* (Fig. 8a). The
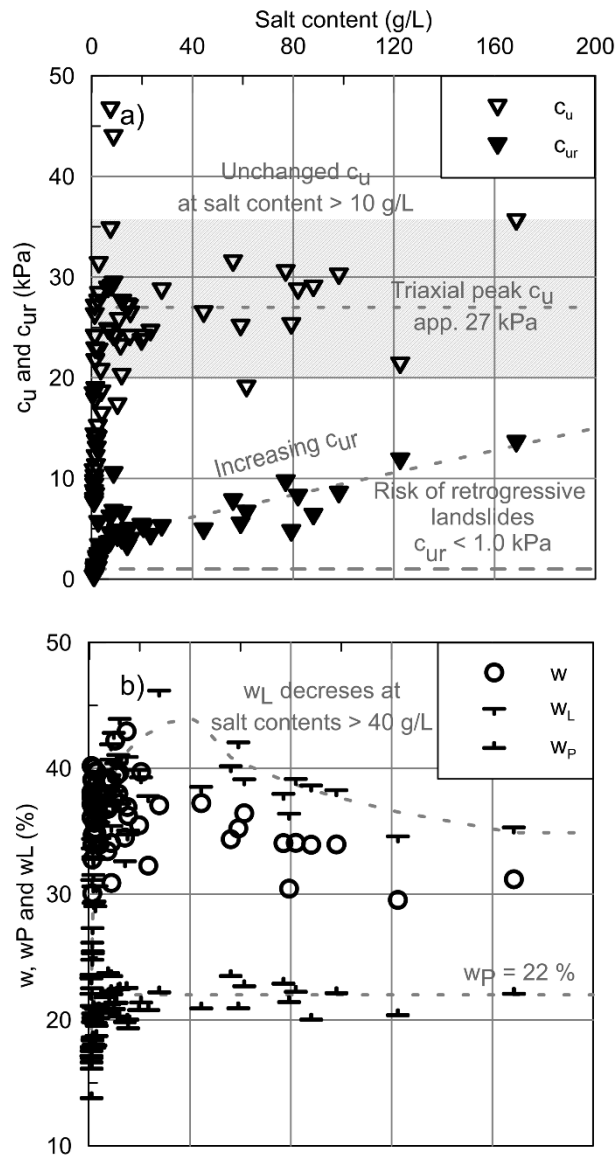
Fig. 8. a) Fall-cone undrained and remolded shear strength. The peak undrained shear strength from an-isotropically consolidated, undrained compression triaxial tests (CAU$_c$) on original quick clay is around 27 kPa (dashed line). b) Natural water content (w), plastic (w$_P$) and liquid limit (w$_L$) correlated to salt content in original quick clay and KCl-treated clay from the research site Dragvoll

undrained fall-cone shear strength (c_u) increased from 7.5-13.9 kPa to 25-30 kPa, close to peak shear strength found in the triaxial compression tests on original quick clay. 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 remolded shear strength increased up to as much as 9.6 kPa 0.5 m from salt-well no. 8 (SW8), and 13.5 kPa 10 cm from SW8. Solutes of such high salt contents as found around SW8 have greater densities than water, and therefore the bulk density increased from 1.87-1.90 g/cm³ in the original quick clay to 1.97 g/cm³ in the salt-treated clay 10 cm from SW8. This may have affected the geotechnical properties in the clay around SW8.

The water content (*w*) was around 37% in the original quick clay (Fig. 8b), and was unaffected 0.5 m from salt wells no. 3 and 7. In the samples extracted 10 cm from SW8, however, the water content was decreased to around 30%. The increased salt contents increased the total solids in the soil volume, and consequently decreased the water content. At 4 m depth, 54% of the reduction

in water content may be 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.

The liquid limit (w_L) reached the natural water content at salt contents of around 3-4 g/L. The w_L increased further with increasing salt contents up to around 40 g/L, from where it started to decrease with increasing salt content (Fig. 8b). Nevertheless, still beyond the natural water content. The plastic limit (w_P) increased from 15-19% and averaged 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 original quick clay, to less than 1.2 in the salt-treated clay 0.5 m from the salt wells. At c_{ur} slightly above 1 kPa IL was not necessarily below 1.2, which was seen at certain depths 1 m from the wells in the direction of fastest migration.

5 Discussion

5.1 Improved geotechnical properties due to changed pore-water chemistry

Clay deposits with a remolded shear strength (c_{ur}) of less than 1 kPa, or a liquidity index (IL) exceeding 1.2, pose a risk to develop into successive retrogressive landslides if remolded (Leroueil et al. 1983; Thakur et al. 2014). The salt content in the pore water has a great impact on the remolded shear strength, and quick clays normally have salt contents of less than 2 g/L (Torrance 1979). However, low salt content does not necessarily imply quick clay as a high ratio of divalent to monovalent ions after leaching inhibits low remolded shear strength (Penner 1965; Torrance 1983). Low-saline, non-quick clays were found outside the salt-treated area at Ulvensplitten in Oslo, Norway. The relatively high remolded shear strength even at salt contents of less than 0.6 g/L, is explained by the increasing amount of divalent ions in the pore water (Fig. 9). The ion composition in the pore water greatly influences the diffuse double layer (DDL) thickness, and consequently the geotechnical properties. According to Mitchell and Soga (2005), quick behavior may develop in clays where the sum of sodium (Na^+) and potassium (K^+) over the sum of major cations (all in meq/L) in the pore water exceeds 75%. However, K^+ has a much greater impact on suppressing the DDL than Na^+ due to smaller hydrated radius and a more effective charge. The authors therefore suggest that rather than considering the ratio of Na^+ and K^+ over the sum of major cations, quick or non-quick behavior in clays is governed by the ratio of the sum of K^+, Mg^{2+} and Ca^{2+} over the sum of major cations in the pore water (all concentrations in meq/L), in the following referred to as the KMgCa-ratio. The remolded shear strength in both the low-saline, non-quick Ulvensplitten clay and the salt-treated Dragvoll clay, exceeds 1 kPa when the KMgCa-ratio exceeds 20% (Fig. 9b). The IL is also reduced from 3.4 to less than 1.2 (Fig. 10b and e), and change from being of low to medium plasticity (Fig. 10c and f) at KMgCa-ratios exceeding 20%.

The particle interaction governs the rheology in clays, and the interparticle repulsion is greatly influenced by the electrolyte concentration (van Olphen 1963). Clay minerals flocculate in an edge-to-edge or an edge-to-face orientation when they are accumulated in seawater at salt contents of around 30-35 g/L. At very high salt contents, the DDL is suppressed to such an extent that the only remaining repulsion is due to the electron clouds surrounding the ions in the DDL. In these cases, clay particles may move closer together before the $DDLs$ overlap, and in suspension the particles may form aggregates, referred to as rapid coagulation (van Olphen 1963). In rapid coagulation, the particles are accumulated in both edge-to-face and face-to-face orientations, creating a fabric with smaller voids. The increase in liquid limit (w_L) with increasing salt content up to 40 g/L may be explained by decreasing double layer repulsion between the clay minerals. The

decrease in w_L at salt contents exceeding 40 g/L, may be caused by rapid coagulation of the suspension due to the high electrolyte concentration (van Olphen 1963), changing the rheology.

Increasing salt content beyond a certain concentration seem not to be followed by further increase in the fall-cone undrained shear strength. This may be caused by a decrease in the *DDL* thickness to such an extent that the long-range van der Waals attraction forces, which are practically independent of electrolyte concentration, dominate the surface forces acting between the clay particles.
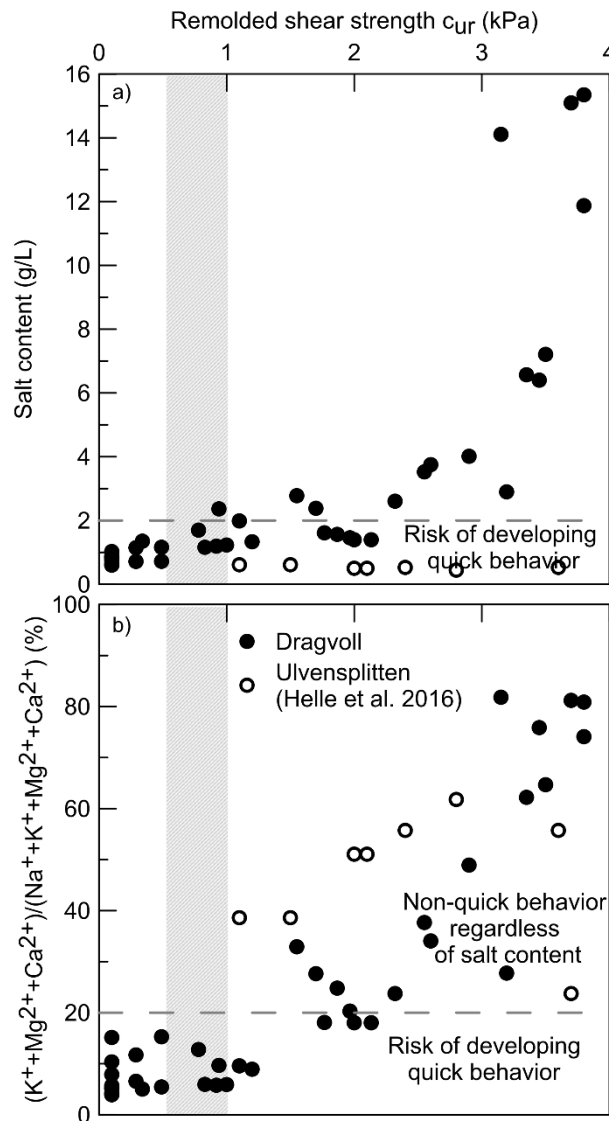
Fig. 9. Remolded shear strength correlated to a) salt content and b) ratio of the sum of K^+, Mg^{2+} and Ca^{2+} over the sum of major cations. The shaded area shows the transition between quick clay with a $c_{ur} < 0.5$ kPa and clay that pose a risk for retrogressive landslides ($c_{ur} < 1$ kPa). The Ulvensplitten data are from the non-treated, non-quick area
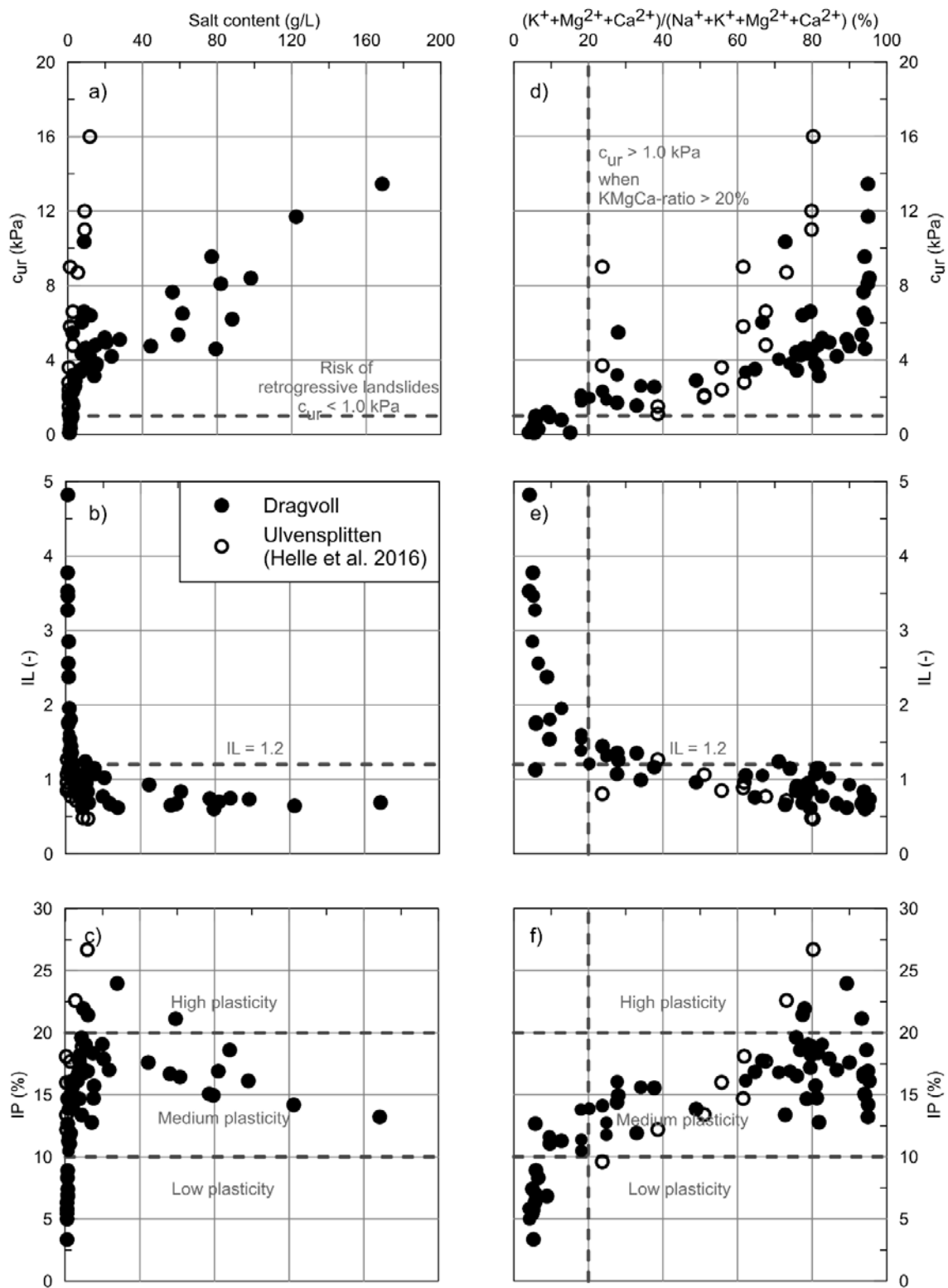
Fig. 10. Salt content correlated to a) remolded shear strength (c_{ur}), b) liquidity index (IL) and c) plasticity index (IP). Ratio of the sum of K^+, Mg^{2+} and Ca^{2+} over the sum of major cations correlated to d) c_{ur}, e) IL and f) IP. The Ulvensplitten data are from both the salt treated and the low-saline, non-quick area

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5.2   Time requirement and stabilized clay volume

In the following, the effective salt plume extent is defined as the extent of clays with a KMgCa-ratio exceeding 20% improving the remolded shear strength (c_{ur}) beyond 1 kPa. Even though the site is geotechnical homogenous, the resistivity cone penetration tests (RCPTU) showed that the salt plumes migrated non-symmetrically moderately off-centered from the wells. The non-symmetry also varied with depth. The fact that the fastest direction of migration varied almost randomly from one well to the other, indicate that there is no dominating direction of groundwater flow in the area. The salt plume migrating from the wells is similar to what is seen in saltwater intrusion in fresh water aquifers, where the salt plume migrates to further distances with depth under the fresh groundwater plume (e.g. Robinson et al. 2006). The salt plume has higher density than 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 RCPTUs and pore-water compositions revealed that the plumes migrated at greater distances with depth, which may indicate that the plumes sink. The plumes stop, however, at around 8.5 m depth; 0.5 m below the wells. Due to the low permeability in the clay and no dominating groundwater flow,
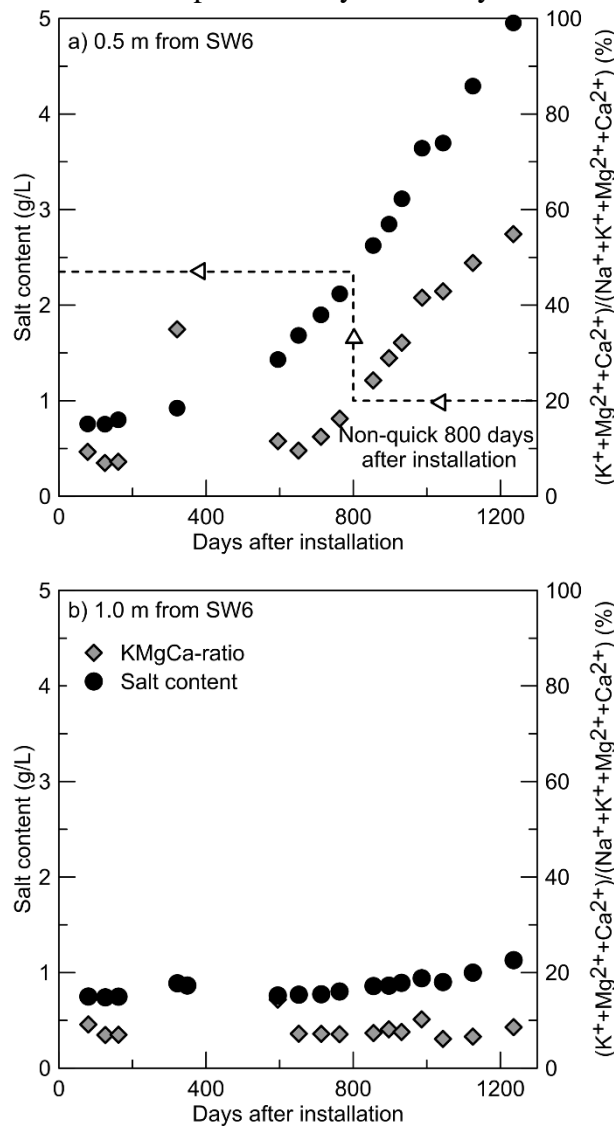

Fig. 11. Alteration of salt content and the ratio of K^+, Mg^{2+} and Ca^{2+} over the sum of major cations. a) 0.5 m and b) 1.0 m from salt-well no. 6 (SW6)

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the clay inhibits the plume from sinking further below the well, forcing it to migrate horizontally along coarser layers of higher permeability. In soils of higher permeability than found at Dragvoll, a salt plume like this would sink considerably deeper.

The groundwater samples extracted from the BAT filter tips around salt-well no. 6 provide valuable information on the migration and ion-exchange reactions. Considering the KMgCa-ratio, the clays cease to be quick 0.5 m from the salt-well in the westward direction, approximately 2.2 years (800 days) after installation (Fig. 11a). In the eastward direction, the clay was still quick at the end of the project (Fig. 11b). However, the chloride front was arrived, and the clay behavior is expected to change to non-quick as soon as the KMgCa-ratio exceeds 20%. Knowing that the salt plume migrates faster towards BAT B2 than BAT B1, a clay volume with a minimum diameter of 1.0 m around the well is stabilized within 2.2 years after installation.

The salt migration around the wells is dominated by diffusion. However, the small advective flow component changes the pore-water composition also improving the geotechnical properties at greater distances in predominant directions (Fig. 12). The c_{ur}, salt contents and KMgCa-ratios plotted towards distance in Fig. 12 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 stretches over a radius of 0.5 m in the directions dominated by diffusion, increasing to 1.0 m in the directions of fastest migration (shaded in Fig. 12a). Thus, a clay volume with a diameter of around 1.5 m is stabilized 2.9-3.3 years after installation. However, considering KMgCa-ratio (Fig. 12c) obtaining a $c_{ur} > 1$ kPa, the effective salt plume extents has a radius of around 0.75 m around the wells even at the lowest concentrations at 5.3 m depth (dashed black lines in Fig. 12). The greatest effective salt plume radius seem to be around 1.4 m at 7.3 m depth in the direction of fastest migration.

5.3 Recommendations

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. 2014), such as the Rissa quick-clay landslide (Gregersen 1981). Improving the c_{ur} in clays to more than 1 kPa, the slide debris will not flow out of the initial slide pit, thereby preventing successive back-scarp failures. The in-situ experiments at Dragvoll and Ulvensplitten show that salt wells filled with *KCl* with a center-to-center distance of 1.5-2.0 m improve the post-failure properties of the clay, and reduce the risk of retrogressive landslides within three years.

The salt plume will continue to migrate in the years to come, improving the geotechnical properties in a larger soil volume surrounding the wells. 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, which tend to equalize the concentration differences and the geotechnical properties in the soil 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 favorable changed pore-water chemistry even though the salt contents in the salt-treated clay was in the range of 0.5-12.0 g/L (Helle et al. 2016).

Chloride (*Cl⁻*) being a conservative tracer will travel unhindered through the clay volume. Chloride has a negative impact on drinking water, and at large concentrations on the vegetation. One must ensure that salt wells are installed in great distances from groundwater or drinking water reservoirs. The release of *Cl⁻* from the salt-treated clay in the subsurface to the surface in for instance a clay slope is time consuming. Thus, only small amounts of *Cl⁻* will be released at the time, and will probably be washed away by precipitation before it damages the vegetation.
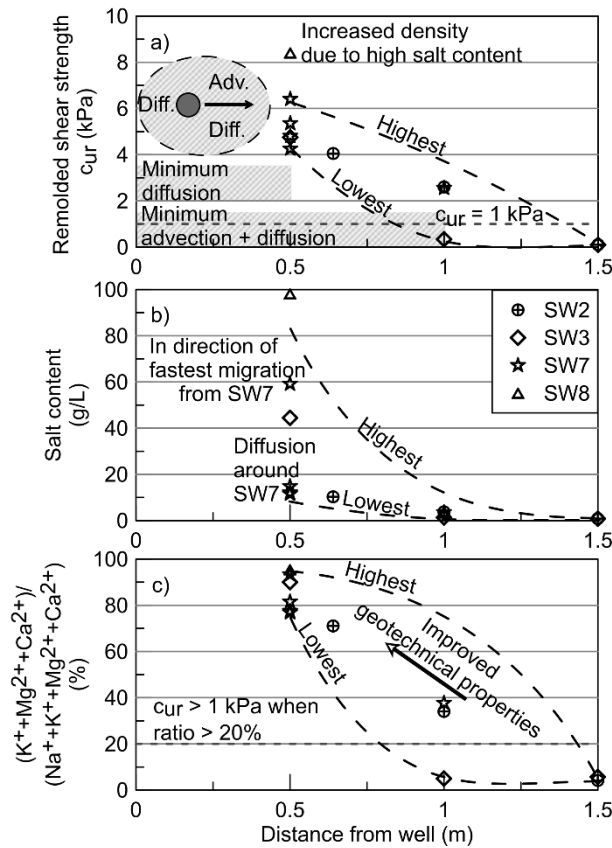
Fig. 12. a) Remolded shear strength (c_{ur}), b) salt content and c) ratio of the sum of K^+, Mg^{2+} and Ca^{2+} over the sum of major cations with distance from the well. The symbols show the results from 6.3 m depth, and the lowest and highest concentrations and cur at 5.3 m and 7.3 m depth are indicated with black dashed lines. The shaded oval in a) indicates the variation of the salt plume around the well, indicating influence zones with stabilized clays to a $c_{ur} > 1$ kPa around 3 years after installation

The soil properties and hydrogeology of the site greatly affects the time required in order to stabilize the quick clay. The clay deposit at Dragvoll is interbedded with coarser layers of higher permeability, aiding some advective flow. Salt migration in clay deposits without such stratification may be restricted to diffusion, impeding the velocity of the salt plume and increase the time it takes to stabilize the clay volume. Glaciomarine clays of low activity (non-swelling) have small specific surface areas, thus low cation exchange capacities (*CEC*) (Quigley 1980). The retardation of potassium (K^+) on its path through the soil volume is highly affected by the *CEC*. Due to the presence of calcite, and the *CEC* method used (Sr-saturated samples with analyses by X-ray fluorescence (XRF)) in the Dragvoll clay gives probably a too high value. Estimating the *CEC* by clay content, clay mineralogy and the lowest value in the range of *CEC* for illite and chlorite found in Appelo and Postma (2005) of 20 meq/100 g dry soil and 10 meq/100 g dry soil respectively, the *CEC* at Dragvoll is in the range of 5.7-6.8 meq/100 g dry soil. The K-front will migrate at a slower rate in soils consisting of minerals of larger specific surface areas and *CEC* than found in the Dragvoll clay due to larger retardation. Quick clays have varying pore-water compositions, but are all dominated by sodium (Na^+). At Dragvoll, the quick clay consisted of 85-92% Na^+. Quick clays with larger fractions of Na^+ may need greater addition of K^+ to achieve a KMgCa-ratio of 20%. This may also increase the time it takes to stabilize the clay volume.

The Dragvoll clay consists of non-expansive clay minerals, dominated by illite and chlorite. Detrital illite and chlorite consist of tens to hundred unit cell layers. Consequently, the thickness of

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the clay particles may be large compared to the thickness of the *DDL*, and the attractive forces between the particles may be of greater importance (Mitchell and Soga 2005). Larger specific surface areas may indicate that the *DDL* has a greater impact on the surface forces than the long-range van der Waals attraction forces, and the improvement of the geotechnical properties may be greater.

Lime/cement piles clearly have the advantage of increasing the undrained shear strength of the soil rapidly and to much greater values than using *KCl*. However, the increase is restricted solely to the piles, with only small amounts of Ca^{2+} diffusing a few cm into the surrounding soil. Furthermore, the mixing induces excess pore pressures, temporarily reducing the undrained shear strength. Potassium chloride may be used as ground improvement without the necessity of mixing as the diffusion into the surrounding clay volume is driven by the concentration gradients. Excess pore pressures, can be avoided by careful installation of the salt wells.

6 Conclusions

Installing salt wells filled with potassium chloride (*KCl*) significantly improve the post-failure properties in quick clays. Improving the c_{ur} in clays to more than 1 kPa, the slide debris will not flow out of the initial slide pit, preventing 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 results from the in-situ experiment at Dragvoll together with data from Ulvensplitten, suggest that quick or non-quick behavior in clays is to a large extent determined by the ratio of the sum of the normality of potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) over the sum of major cations in the pore water. The c_{ur} is improved beyond 1 kPa at KMgCa-ratios exceeding 20%. Therefore, leached salt-treated clay with low salt contents, will maintain improved c_{ur} and Atterberg limits 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 *KCl*-well method is therefore considered to have a permanent effect on improving the clay behavior in an engineering time scale.

In order to stabilize the quick-clay volume within 3 years it is recommended to install the salt wells with a center-to-center distance of 1.5-2.0 m. The time required to stabilise the quick-clay volume is greatly dependent on the cation exchange capacity (*CEC*) affected by the mineral type and specific surface area, 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 post-failure properties significantly improve in *KCl*-treated clays, and the clay will no longer liquefy when remolded. 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.

7 Acknowledgments

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