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Complete List of Authors:	Helle, Tonje; Norwegian University of Science and Technology, ; The Norwegian Public Roads Administration, Nordal, S.; Norwegian University of Science and Technology Aagaard, Per; University in Oslo, Department of Geosciences Lied, Ole; Geovita AS,
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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

Tonje Eide Helle (corresponding author)

Postal adress: NTNU. Institutt for bygg, anlegg og transport, 7491 Trondheim, Norway

E-mail: tonje.eide.helle@ntnu.no

Phone: +47 959 67 746

Steinar Nordal

Postal adress: NTNU, Institutt for bygg, anlegg og transport, 7491 Trondheim, Norway

E-mail: steinar.nordal@ntnu.no

Per Aagaard

Postal adress: University in Oslo, Department of Geosciences, P.O box 1047 Blindern, 0316 Oslo, Norway

E-mail: per.aagaard@geo.uio.no

Ole Kristian Lied

Postal address: Geovita as, Lilleakerveien 4, 0283 Oslo, Norway

E-mail: okl@geovita.no

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 thirty to forty years later. The undisturbed shear strength increased from less than 10 kPa to 25–30 kPa, and the remolded shear strength increased from less than 0.5 kPa 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

Draft

Introduction

Highly sensitive postglacial 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; ground improvement offers an alternative which 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 porewater. 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 porewater 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; Rosenqvist 1953; Bjerrum 1955; Rosenqvist 1955; Løken 1968; Moum et al. 1968; Løken 1970; Quigley 1980; Torrance 1983).

In 1972, 2 629 salt wells filled with potassium chloride (KCl) covering an area of 6 000 m² were installed in a quick clay at Ulvensplitten, Oslo, Norway (Fig. 2). The site lies at c. 95 m above sea level, 125 m below the postglacial marine limit. The intention was to improve the mechanical properties in the quick clay prior to excavation. Ground investigations carried out two to three 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 seventies.

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 thirty to forty 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 porewater and the clay mineral surface chemistry. Changes in their environment such as temperature, pressure, chemical composition and concentration of ions in the porewater 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 total dissolved solids (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 environment 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 postglacial isostatic uplift elevates the clay above sealevel, 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 porewater (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 Mg^{2+} and Ca^{2+} (Appelo and Postma 2005). Various cations have different impact on the clay behaviour. Consequently, low TDS in itself does not necessarily cause clays to become quick. However, at low TDS, the ion composition in the porewater has a great impact on the development of quick clays (Moum et al. 1971). The percentage of monovalent ions in the porewater is then especially relevant.

Sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) are the most common cations occurring in the porewater in clays. The porewater 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 porewater is calculated by equation (1). All concentrations are given in milli-equivalents per liter. Seawater has a monovalent percentage of 75 % (Mitchell and Soga 2005). Clays with low TDS and a monovalent ion composition in their porewater exceeding this level may develop high sensitivity as seen in the collected data in Moum et al. (1971) and Hilmo (1989).

$$(1) \quad \frac{Na^+ + K^+}{Na^+ + K^+ + Mg^{2+} + Ca^{2+}} \times 100$$

Leaching and diffusion change the composition of the porewater 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: $Na^+ < K^+ < Mg^{2+} < Ca^{2+} < Al^{3+} < Fe^{3+}$ (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 postglacial marine clays as their porewater 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 porewater 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 porewater. Consequently, the ion composition in the porewater in quick clays is still dominated by Na^+ . Divalent ions may also be removed from the porewater 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 which rendered it quick. As this progresses through the quick clay deposit, the remaining

concentration of Na^+ in the porewater will be depleted. The clay will with time be dominated by divalent ions both in the porewater and in the adsorbed positions, inhibiting high sensitivity (Talme et al. 1966; Moum et al. 1971; Andersson-Sköld et al. 2005).

Chemical impact on the 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 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 potassium chloride (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; Løken 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 2 629 salt wells covering an area of 6 000 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 sixties and seventies 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 m 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 (Fig. 6e). Depth to bedrock in the Ulvensplitten area is between 20 m and 35 m (Eggestad and Sem 1970a; Eggestad and Sem 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).

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 4th April to 25th 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 tons. 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; Eggestad and Sem 1974; Eggestad and Sem 1976). Modern drilling methods may be considerable 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 porewater composition in the quick clay in area South. Small amounts of K⁺ (31-33 mg/l), Mg²⁺ (20-34 mg/l) and Ca²⁺ (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 migration increased the shear strength over a distance of 60-65 cm (Eggestad and Sem 1974). Fig. 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. 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 kPa to 28.5 kPa, and the remolded shear strength from less than 0.5 kPa to 3.5 kPa.

The impact of KCl on the 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 porewater. 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 (Fig. 6a and b). 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; Eggestad and Sem 1976). Eggestad and Sem (1976) concluded that even small amounts of K^+ decreased the sensitivity of the clay considerably.

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 testing 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 porewater 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 System (ICS-1000), and the anions were analyzed 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 HCl-titration in Metrohm 702 SM Titrino, and pH measured in the porewater 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. 6b).

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 non-sensitive clay (Fig. 6e). However, the natural water content is nevertheless higher than the liquid limit (Fig. 7c). The water content in the clay deposits inside and outside area North is approximately the same (Figs. 7b and c). It is evident that introducing KCl to the clay-water system has increased the undrained shear strength significantly (Figs. 6c, d and e). 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 d), 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 total dissolved solids (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 porewater in the salt-treated clay has been diluted by freshwater over the last forty 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 porewater, increasing their concentrations (Figs. 9a, c and d).

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 porewater composition in the non-treated 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 porewater in the pre-stabilized quick clay deposit from area South. In the non-quick 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 non-quick behavior even though the natural water content exceeds the liquid limit.

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 the recent years confirms 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 thirty to forty 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 total dissolved solids (TDS) 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 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. 21 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 porewater 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, c and d) in the porewater 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 (Equation 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 porewater, 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 porewater, the thinner is the diffuse double layer. Furthermore, the thickness of the double layer is decreased by a factor of two in a divalent solute compared to a monovalent solute at the same normality. In the salt-stabilized clay in area North at Ulvensplitten, the porewater 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 porewater 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 porewater is of less importance (Bjerrum 1954; Rosenqvist 1955; Bjerrum and Rosenqvist 1956; Bjerrum et al. 1969; Løken 1970; Torrance 1975; Quigley 1980; Locat and Demers 1988; Torrance 1999). However, as the porewater salinity decrease towards 5 g/l, the composition of ions plays a major role on the soil's behavior (Bjerrum et al. 1969; Torrance 1999). The adsorbed cations' ability to increase the remolded shear strength follows the order: $\text{Na}^+ < \text{Fe}^{2+} \leq \text{Mg}^{2+} \leq \text{Ca}^{2+} < \text{Fe}^{3+} < \text{K}^+ < \text{Al}^{3+}$ (Løken 1968). The Atterberg limits are increased by adsorbed cations in the following order: $\text{Na}^+ < \text{Fe}^{2+} = \text{Mg}^{2+} = \text{Ca}^{2+} < \text{Fe}^{3+} < \text{Al}^{3+} = \text{K}^+$ (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 porewater. 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 only 0.9 nm. This corresponds to a remolded shear strength of around 10 kPa (Fig 10d) as found for the double layer thickness in the Ulvensplitten clay. As the porewater 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 porewater. 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 non-quick, 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 porewater 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, especially 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 influenced 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 total dissolved solids (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 porewater 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 thirty to forty 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 porewater 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 porewater 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.

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List of symbols

Al^{3+}	Aluminum
Cl^-	Chloride
c_u	Undrained shear strength (kPa)
c_{ur}	Remolded shear strength (kPa)
Ca^{2+}	Calcium
Fe^{3+}	Iron
HCO_3^-	Bicarbonate
I_L	Liquidity index (-)
I_p	Plasticity index (%)
K^+	Potassium
Mg^{2+}	Magnesium
mg/l	milligram per liter
meq/l	milliequivalent per liter
Na^+	Sodium
TDS	Total dissolved solids (ppm $\approx$ mg/l)
w	Water content (%)
w_L	Liquid limit (%)
w_p	Plastic limit (%)

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 1974; †Eggestad and Sem 1976;

‡Morel-Vulliez et al. 2013; §Stuvøy et al. 2007;

||Eggestad and Sem 1970b; ¶Eggestad and Sem 1970a;

Figure captions

Fig. 1 The quick clay slide in Kattmarka 2009. Photo: Holme

Fig. 2 Salt-treated area (shaded) at Ulvensplitten showing the location of the ground investigations. Those presented in Eggstad and Sem (1976) have bold fonts and are marked E&S 1976. The 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.

Fig. 3 The impact of increasing concentration of potassium (K^+) on the undrained and remolded shear strength. Data from Moum et al. (1968).

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

Fig. 5 Concentration of potassium (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 Eggstad and Sem (1976).

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

Fig. 7 Water content and Atterberg limits in a) area South, b) inside salt-stabilized area North and c) outside salt-stabilized area North.

Fig. 8 Total dissolved solids in the porewater inside (borehole 2016-2) and outside (borehole 2016-7) salt-stabilized area North.

Fig. 9 Ion concentrations in the porewater inside and outside the salt-stabilized area North and in the original porewater of the quick clay prior to installation of salt wells in area South, as presented by Eggstad and Sem (1976).

Fig. 10 The impact of total dissolved solids (TDS) forty 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 the total amount of major cations. d) The impact of the thickness of diffuse double layer on the undrained and remolded shear strength. The dashed line shows a calculated TDS of 0.5 g/l solely consisting of calcium and bicarbonate. e) The impact of the percentage of monovalent cations over total amount of major cations on the undrained and remolded shear strength.

Fig. 1 The quick clay slide in Kattmarka 2009. Photo: Holme
57x38mm (600 x 600 DPI)

Fig. 2 Salt-treated area (shaded) at Ulvensplitten showing the location of the ground investigations. Those presented in Eggestad and Sem (1976) have bold fonts and are marked E&S 1976. The 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.

152x198mm (600 x 600 DPI)

Fig. 3 The impact of increasing concentration of potassium (K^+) on the undrained and remolded shear strength. Data from Moum et al. (1968).
82x78mm (600 x 600 DPI)

Fig. 4 Soil profile of pre-stabilized soil. Borehole 409U in area South.
195x201mm (300 x 300 DPI)

Fig. 5 Concentration of potassium (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 Eggstad and Sem (1976). 226x281mm (300 x 300 DPI)

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

518x775mm (300 x 300 DPI)

Fig. 7 Water content and Atterberg limits in a) area South, b) inside salt-stabilized area North and c) outside salt-stabilized area North.
492x726mm (300 x 300 DPI)

Fig. 8 Total dissolved solids in the porewater inside (borehole 2016-2) and outside (borehole 2016-7) salt-stabilized area North.
87x89mm (600 x 600 DPI)

Fig. 9 Ion concentrations in the porewater inside and outside the salt-stabilized area North and in the original porewater of the quick clay prior to installation of salt wells in area South, as presented by Eggestad and Sem (1976).
540x878mm (300 x 300 DPI)

Fig. 10 The impact of total dissolved solids (TDS) forty 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 the total amount of major cations. d) The impact of the thickness of diffuse double layer on the undrained and remolded shear strength. The dashed line shows a calculated TDS of 0.5 g/l solely consisting of calcium and bicarbonate. e) The impact of the percentage of monovalent cations over total amount of major cations on the undrained and remolded shear strength.

489x643mm (300 x 300 DPI)