PAPER • OPEN ACCESS

Quick-clay landslide mitigation using potassium-chloride wells: Installation procedures and effects

To cite this article: T E Helle *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **710** 012047

IOP Conf. Series: Earth and Environmental Science **710** (2021) 012047 doi:10.1088/1755-1315/710/1/012047

Quick-clay landslide mitigation using potassium-chloride wells: Installation procedures and effects

T E Helle[1,8], M Kvennås[2], O V Kirkevollen[3], B Hamel[4], B K F Bache[2], S A Strand[5], G Svanø[6], A Gylland[1], E Haugen[4], T Wiig[5] and A Horn[7]

[1] Multiconsult AS, PO Box 6230 Torgarden, 7486 Trondheim, Norway
[2] NGI, PO Box 5687 Torgarden, 7485 Trondheim, Norway
3 Viken fylkeskommune, PO Box 220, 1702 Sarpsborg, Norway
[4] Norwegian Public Roads Administration, PO Box 1010 Nordre Ål, 2605 Lillehammer, Norway
[5] Norwegian Water Resources and Energy Directorate, PO Box 5091 Majorstua, 0301 Oslo, Norway
[6] Bane NOR SF, PO Box 4350, 2308 Hamar, Norway
[7] Municipality of Stjørdal, PO Box 133, 7501 Stjørdal, Norway
[8] Corresponding author: tonje.helle@multiconsult.no
[9] The work is funded by the Regional Research Council Mid-Norway R&D project no. 284697

Abstract. Mitigation actions related to quick-clay slopes often induce undesirable changes to the terrain that may have negative impact on developed areas and local biodiversity. Soil improvement may prevent this. Lime-cement piling causes temporarily reduced slope stability and substantial climate-gas emissions. Less climate-gas emissions are associated to the production of potassium chloride (KCl). KCl improves the post-failure properties of quick clay so it renders not quick and may serve as an alternative to current landslide-mitigation. The mechanisms in this chemical process is well documented, but there exist no installation procedures for KCl wells, nor knowledge on cost/benefit or climate-gas emissions. This paper presents two installation procedures of KCl wells, and studies showing that the climate-gas emissions are far less than installing lime-cement piles. Further development of cost-effective installation procedures is needed to justify application of KCl wells in quick-clay areas.

1. Introduction

Conventional quick-clay landslide mitigation includes prevention berms and terrain levelling. Such landslide-mitigation measures cause large damages to the terrain, may come in conflict with buildings, infrastructure, objects and landscape worthy of preservation, and may also destroy the living conditions for fish and animals in the area. Ground improvement may serve as an alternative avoiding such large interventions to the terrain. Installation of the most common ground-improvement method in Scandinavia, lime-cement piles, may however induce excess pore-pressures, temporarily reducing the stability of the slopes. With today's climate-change challenges, the large climate-gas emissions associated with the production of lime and cement also render lime-cement piling less attractive.

Introducing potassium chloride (KCl) to the clay-water system in quick clays changes the ion composition in the pore water and improves the post-failure properties so that the quick clay renders not quick [1][2]. Causing less climate-gas emissions during production, KCl may be a more climate-friendly alternative and less abrasive to the terrain than today's conventional landslide-mitigation measures.

Wells filled with KCl were installed in quick-clay deposits at Ulvensplitten, Oslo, Norway in 1972 [1] and at Dragvoll, Trondheim, Norway in 2013 [2]. Installing wells with a centre-to-centre distance of 1.5 m, the remoulded shear strength, liquid limit and plasticity index (hereafter referred to as post-failure properties) in the quick-clay volume increase to such an extent within about three years that large retrogressive landslides are inhibited and the risk for progressive failures is reduced. The improvement is caused simply by changing the pore-water chemistry.

The low-saline pore water in quick clays is dominated by sodium and bicarbonate. By installing wells with KCl, the salt content in the clay volume around the salt wells increases during the first years. The increased salt content leads to improved post-failure properties. With time the salt-treated clays will be exposed to leaching, and the low salt content in the pore water will reoccur. However, as a result of introducing KCl to the clay-water system, the composition of cations in the pore water and on the clay mineral surfaces is changed. With as little as 20% of the cations in the pore water consisting of potassium, magnesium and calcium, even at salt contents of less than 2 g/L, the remoulded shear strength increases beyond 1 kPa, the liquidity index decreases below 1.2, and the clay changes from being of low to medium plasticity with a plasticity index exceeding 10% [2]. As a result of sodium being "washed" out of the clay-water system, the improvement is irreversible due to permanently favourable changed pore-water chemistry.

Whereas the mechanisms in this chemical process and KCl's impact on the geotechnical properties in quick clays is well documented elsewhere i.e. [2], there exist no installation procedures for KCl wells, nor knowledge on cost/benefit or climate-gas emissions compared to conventional landslide-mitigation measures. Therefore, the R&D project "Salt stabilisation of quick clays (SAK)" (2018-2019) was initiated, intending to test various procedures for KCl-well installation and monitor the installation effects (i.e. pore pressure). Cost-benefit analyses of these procedures compared to conventional landslide-mitigation measures are performed, and the climate-gas emissions related to various landslide-mitigation measures are compared. Two installation procedures using conventional geotechnical drill-rigs together with their influence on the pore-pressure response, and results from cost-benefit analysis and calculated climate-gas emissions are reported in this paper. For supplementary information, see [3] and [4].

2. Site installations and installation procedures

Twenty-one KCl wells (Figure 1) were installed at National GeoTest Sites' quick-clay site NGTS Tiller-Flotten (Norwegian Research Council project no. 24650). Four different installation procedures were applied (Table 1), using drilling equipment readily available on the market. Several issues appeared applying all four methods. Severe problems with clogging and termination of installation occurred applying Method A. The Sonic rig used for Method D was not as easy to navigate on site as a conventional drill rig. In addition, it was more difficult to have control of water supply and rotation during drilling using the Sonic rig. Due to practical challenges on site and time consumption, Methods B and C were considered the most applicable out of the four procedures. Therefore, installation procedures and results from four wells installed by these two methods are reported herein (Figure 1 and 2).

Quick clay is found from about 7.5 m depth to minimum 20 m depth at the site. Fourteen piezometers with memory were installed in the quick clay in seven stations, each with two piezometers at 8 m and 12 m depth. In order to monitor the pore-pressure response in close vicinity to the wells, the piezometers were installed with a horizontal distance of only 0.5 m and 1.0 m in each station. The groundwater table is found at 1 m depth, and the pore-pressure distribution is under hydrostatic with a pore pressure of about 41 kPa at 8 m depth, and about 53 kPa at 12 m depth.

The salt wells were installed in distances of 0.5 m and 1.0 m from the piezometers. The pore-pressure was logged every minute during installation and the first 24 hours after installation, and once an hour over the following couple of days.

Pre-drilling of the salt-wells (Figure 2) presented herein was carried out by using the total sounding equipment (Norwegian sounding method) replacing the drill bit with a 90 mm diameter drill bit for clays with 19 mm flush holes (Figure 3a). The boreholes were drilled to 25 m depth while flushing with water (1000 l of water per well) applying a penetration rate of 155-160 cm/min and rotation of 125-128 rpm. To ensure backflow of the drilling mud along the drill string and to avoid cavitating of the partially drained topsoil, a casing was installed in the upper 3 m. Pre-drilling the boreholes down to 25 m depth took about 1 hour.

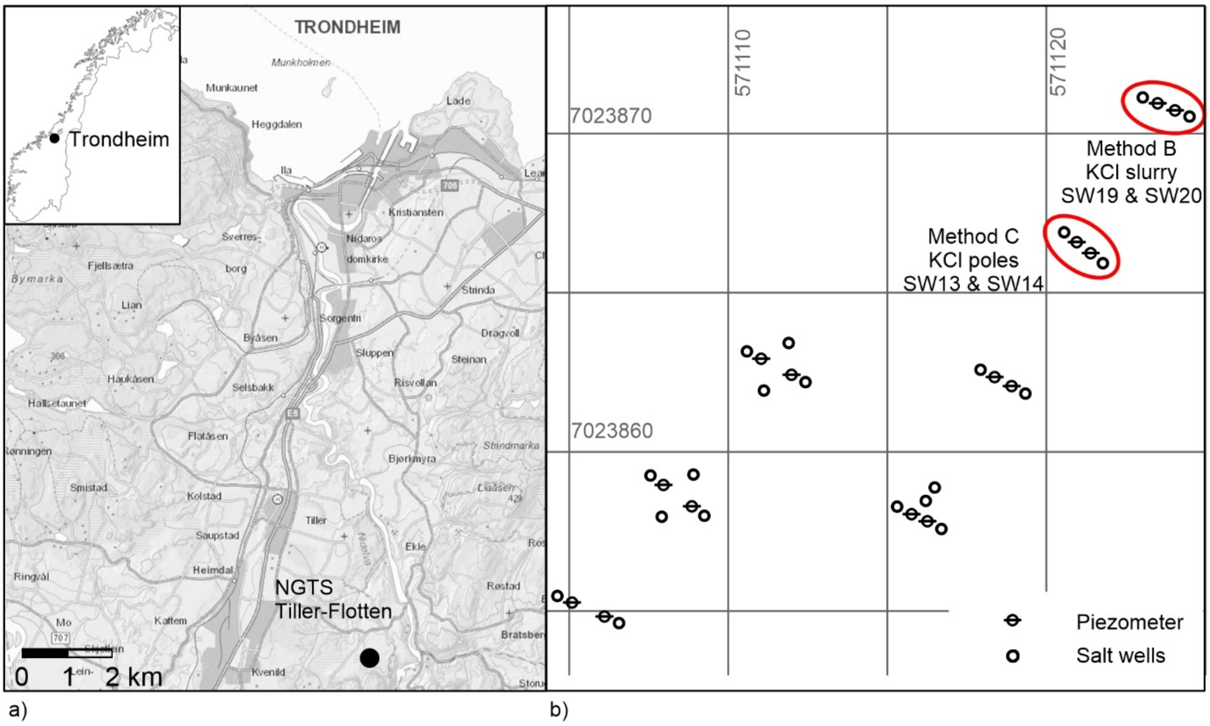

Figure 1. a) Location of NGTS Tiller-Flotten. b) Installed piezometers and salt wells. The location of installation procedures Method B and C are marked with red ellipses. Euref 89 Utm 32, 10 m grid.

Table 1. Installation procedures

	Method A	Method B	Method C	Method D
Drill rig	Conventional geotech. rig	Conventional geotech. rig	Conventional geotech. Rig	Sonic
Drill bit	90 mm with 19 mm flush holes	90 mm with 19 mm flush holes	90 mm with 19 mm flush holes	85 mm ring bit, drag bit and PDC bit
Rods	Titan drill drain 40/27	Total sounding drill rods 45 mm	Total sounding drill rods 45 mm	Sonic drill rods 75 mm
Salt	KCl-slurry	KCl-slurry	KCl-poles	KCl-slurry
Installation of salt	Flushed through the drill rods positioned at18-25 m depth	Flushed into the predrilled borehole through 32 mm reinforced hose	KCl-poles were lowered into the predrilled borehole	Flushed into the predrilled borehole through 32 mm reinforced hose

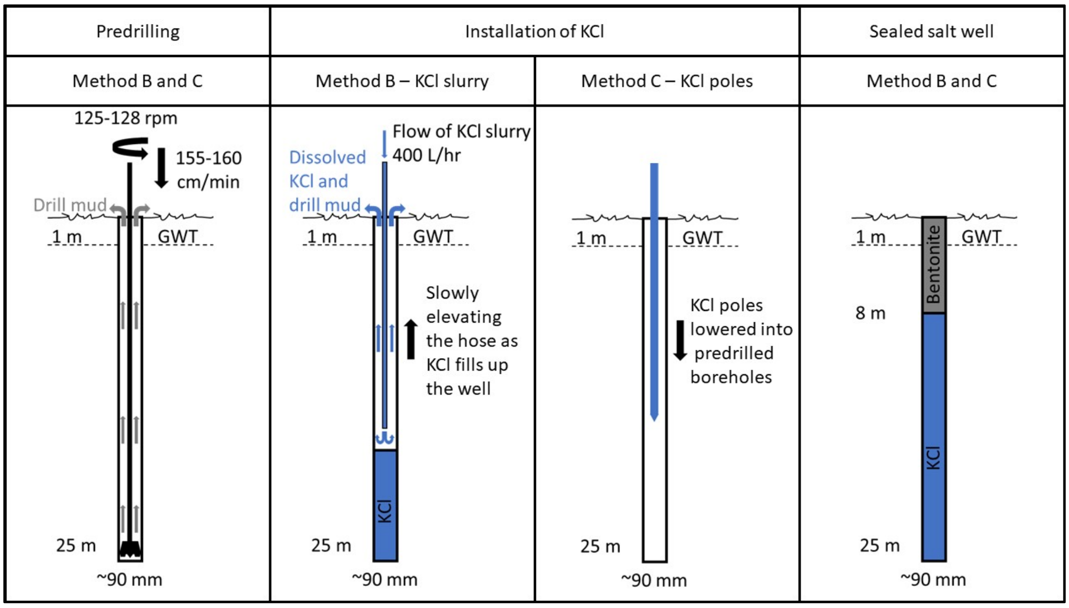

Figure 2. Installation procedures of Methods B and C. The groundwater table (GWT) is indicated at around 1 m depth.

KCl were filled in the pre-drilled boreholes from 8 m till 25 m depth either as a KCl-slurry (Method B in Figure 2), or as compressed KCl cubes (5x5x5 cm, weight 250 g) produced for the project by K+S Aktiengesellschaft (Method C in Figure 2). The slurry was mixed on site of granular KCl and water aiming to maintain as high KCl to water ratio as possible to ensure long-lasting supersaturated conditions in the wells.

In salt-wells no. 19 (SW19) and SW20 (Figure 1b), KCl slurry was pumped through a 32 mm in diameter reinforced hose (Figure 3b). To avoid KCl slurry clogging the system, the slurry was pumped through a screw pump (MAI pump NT400) with a flow of 400 L/hr attempting to maintain continuous circulation in the slurry. The hose was initially lowered in level with the bottom of the pre-drilled water-filled borehole, and slowly elevated as the well was filled with KCl slurry (Method B in Figure 2). A procedure which turned out to cause some practical challenges such as difficulties in balancing the mix of dry, granular KCl and as little water as possible without clogging the system. If the circulation stopped due to clogging, and the drillers were unable to resume circulation, pressure build-up in the system would cause the hose to burst even though the hose was reinforced. Furthermore, during filling some of the KCl was flushed out from the well and spilt out on the terrain surface. It was not possible to keep track of how much of the added KCl would remain in the well, and how much was spilt out. The KCl slurry was mixed as thick as possible, so even though KCl is highly soluble, solid KCl grains remained in the water. Pumping the KCl slurry into the well whirled up the KCl grains, and in some of the wells it took several hours for the KCl grains to settle as solid columns in the boreholes. Therefore, a few kilos of dry KCl was poured directly into the boreholes from the terrain surface to ensure a solid KCl column from the bottom of the well up to about 8 m depth. Uncertainties remain on the homogeneity of the KCl columns along the whole depth.

KCl poles (Figure 3c) were produced by drilling holes in the compressed KCl cubes and mount them on 10-mm hydraulic steel-pipes (1.5 mm wall thickness) in 1 m long sections with grooves on the ends. A piston was mounted on the bottom pole. The 1 m long sections were easily assembled on site and lowered into SW13 and SW14 using a wire (Method C in Figure 2 and Figure 3d). In total, it took about 10-15 mins to install 17 m of KCl poles.

Due to the under hydrostatic pore-pressure distribution with depth, the puncturing of the impermeable clay layers between the hanging ground-water table at 1 m depth and the deeper layers at 8 m depth, would cause a water column in the open well. This water column introduced an excess pore-pressure to the deeper layers. Therefore, the water above the KCl columns was pumped out of the wells, and bentonite pellets were poured into the wells sealing off the KCl column from the top layers (Figure 2).

3. Pore-pressure response

The piezometers from which results are presented herein, were installed with an internal distance of 0.5 m. SW13 and SW14 (Method C) were installed 0.5 m from piezometer no. PZ15039 (8 m depth)

Figure 3. a) 90 mm drill bit used for pre-drilling. b) 32 mm reinforced hose for pumping KCl slurry into the pre-drilled borehole. c) KCl poles in 1 m sections ready for installation. d) Installation of KCl poles.

and PZ15040 (12 m depth) respectively (Figure 4a), and SW19 and SW20 (Method B) were installed in a distance of 0.5 m from PZ15038 (12 m depth) and PZ15004 (8 m depth) respectively (Figure 4b). The salt wells were installed only hours apart. Due to the closely spaced installations, any excess pore-pressures in the clay volume caused by installing the first salt well would not have time to dissipate before installing the second salt well. Therefore, the pore-pressure response (Δu) in Figure 4 is calculated relative to the pore pressure at start of installation and presented along a timeline from start of installation of each well at t = 0. No neighbouring effect was detected during installation of SW13 and SW14 (Figure 4c). However, such neighbouring effect is visible in Figure 4d, where the installation of SW20 affects the pore-pressure measurements presented for installation of SW19 (about 19 hours after start of installation in Figure 4d).

Predrilling and filling the wells with KCl were considered the most critical steps of the installation procedures regarding the pore-pressure build-up. These operations took about 1.5-2.0 hours for each well. Excess pore-pressures were not detected in the piezometers during this time period. Maximum excess pore-pressures (Δu_{max}) were observed in the piezometers a few hours after the first critical steps were finalized (Table 2). For instance, for the salt wells installed by applying Method C, SW13 was installed first of the two wells and was located 0.5 m from the piezometer installed at 8 m depth and 1.0 m from the piezometer at 12 m depth. The Δu_{max} appeared 5.5 hours after start of installation of SW13 in the piezometer 0.5 m from SW13, and 7.9 hours after start of installation in the piezometer 1.0 m from SW13 (Table 2). For the four wells presented herein, Δu_{max} was observed 0.5 m from the wells within 3.5-5.5 hours, and 1.0 m from the wells within 6.2-9.6 hours (neglecting SW14 in Table 2).

Installation of KCl poles (Method C) created less Δu_{max} than KCl slurry (Method B) (Figure 4c and d and Table 2); 0.6-4.0 kPa towards 0.0-8.7 kPa. The enhanced pore-pressure lasted for 1.7-9.8 hours in the piezometer station where Method C was applied, and 7.9-8.7 hours in the piezometer station where Method B was applied. The higher Δu_{max} applying Method B may be a result of not sealing the wells off with bentonite immediately after filling the wells with KCl slurry. These wells were sealed off 7-14 hours after finishing pumping salt into the wells to ensure that the KCl grains were settled and solid salt-columns were obtained from 8 m to 25 m depth in the wells. SW13 and SW14 (Method C) were sealed off within one hour after the KCl poles were installed.

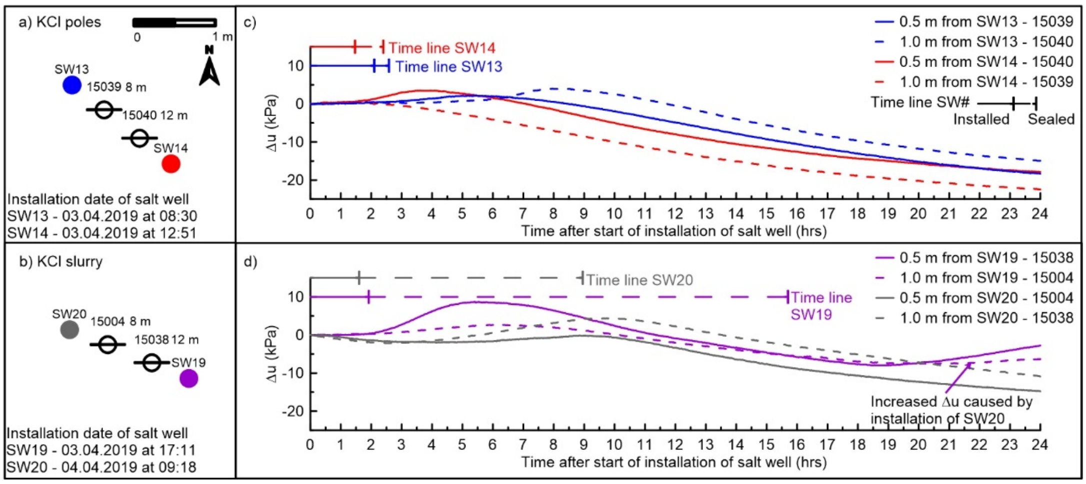

Figure 4. a) Salt-wells (SW) no. 13 and 14 (Method C) are installed 0.5 m from piezometer (PZ) no. 15039 and 15040 respectively. b) SW19 and SW20 (Method B) are installed 0.5 m from PZ15038 and PZ15004. The piezometers in a) and b) are installed with an internal distance of 0.5 m. c) Pore-pressure response (Δu) the first 24 hours after installing KCl poles. d) Δu the first 24 hours after installing KCl slurry.

For all the wells, the pore-pressure response decreased and turned negative after reaching its original in-situ pore pressure. Large amounts of solid KCl were installed in the wells. Thus, water may have been drawn towards the wells do dissolve the salt. In the last reading 10th September 2019, the pore pressures were still much lower than original in the wells with KCl poles (Method C), and slightly lower than original in the wells filled with KCl slurry (Method B).

Table 2. Maximum excess pore-pressures (Δu_{max}) measured in the piezometers at time t_l after installation of the salt wells. The pore pressures are measured at 8 m and 12 m depth in distances of 0.5 m and 1.0 m from the salt wells (SW#).

		0.5 m from SW#		1.0 m from SW#	
Method	*SW#*	*Δu_{max} (kPa)*	*t_l (hrs)*	*Δu_{max} (kPa)*	*t_l (hrs)*
C - KCl poles	13	2.3 kPa at 8 m	5.5	4.0 kPa at 12 m	7.9
	14	3.5 kPa at 12 m	3.5	0.6 kPa at 8 m	1.1
B - KCl slurry	19	8.7 kPa at 12 m	5.4	2.7 kPa at 8 m	6.2
	20	0.0 kPa at 8 m	-	4.4 kPa at 12 m	9.6

4. Cost-benefit and climate-gas emissions

The quick-clay hazard zone Hegramo in Stjørdal municipality, Norway, is classified in the highest risk class no. 5. Debris from a landslide triggered within the hazard zone may flow into the centre of Hegramo. Therefore, restrictions are made inhibiting further development of this area. To overcome these restrictions, quick-clay landslide-mitigation measures are needed. KCl-wells, lime-cement piling and conventional topographic measures (terrain levelling and prevention berm) are all methods that can be suitable in this area. Cost-benefit and emission of CO_2-equivalents (CO_2eq) are calculated for these three mitigation measures based on achieving a 15% improvement of the slope stability [5][6].

The calculations are based on an amount of lime and cement of 100 kg/m^3 soil. With a coverage of 25%, lime and cement amounts to 12.5 tons per m slope. In the calculations of CO_2-eq for KCl slurry, a consumption of 15 kg KCl per m well is used as input. In total, Method B amounts to 9.2 tons of KCl per m slope. The dimensions of the KCl poles in Method C, are increased to a diameter of 8 cm in the calculations. Consequently, Method C amounts to 10 kg KCl per m well, and in total 6.1 tons per m slope. Costs of installation of KCl wells is obtained from NGTS Tiller-Flotten (Methods B and C). Costs of topographic measures and lime-cement piling are obtained from quick-clay landslide mitigation projects and road projects in Norway.

Calculations of cost-benefit are based on a tool developed for Norwegian Water Resources and Energy Directorate [7]. The present value of the benefit of a landslide mitigation-measure based on a reduction of yearly nominal probability for a landslide, and the preserved values within the hazard zone are calculated. The preserved values include both loss of human lives and material values, as well as socioeconomically consequences as for example closed roads. Non-priced consequences are not included. The calculations of benefit/cost for Hegramo (Table 3) include engineering costs of 1.5 MNOK per measure, and site-specific evaluations of houses, roads etc. Since there are uncertainties regarding the calculations, they include sensitivity analyses where the probability for a landslide event is over- and underestimated with 100% and 50% respectively.

Calculations of emission of CO_2eq (Table 4) are based on VegLCA [8]. Topographical measures and KCl wells both have lower emissions compared to lime-cement piling. The largest share of the emissions of each measure is associated with diesel consumption of the excavators (topographical measures, ca. 80%), production of lime-cement (lime-cement stabilisation, ca. 88%) and production of salt (KCl-stabilisation, 80%).

Calculations of benefit/cost included costs for CO_2 (Table 5), show that all the evaluated measures at Hegramo have positive benefit/cost. Due to lower costs, topographical measures obtain much greater benefit/cost than lime-cement and KCl. KCl wells achieve a positive benefit/cost, but with much smaller margin compared to lime-cement piling and topographical measures. The low benefit/cost of KCl is associated with inefficient installation procedures which may improve if the installation procedures are further developed in the future. When costs for CO_2-emissions are included, the benefit/cost for lime-cement stabilisation is slightly reduced. For the other measures, the cost for CO_2-emission is of little significance.

Non-price consequences must be evaluated site-specifically and are not included in the benefit/cost factors. Therefore, benefit/cost factors may not fully describe the benefit of the various methods. KCl wells may be the only available mitigation measure in areas with landscape types or objects worthy of preservation. Thus, the factor non-price consequences/benefit-cost will have a larger positive value for KCl wells than topographical measures.

Table 3. Calculation of benefit/cost for Hegramo in thousand Norwegian kroner (kNOK).

Measure	Cost pr. linear meter (kNOK)	Cost pr. 100 m (kNOK)	Present value costs (kNOK)	Present value benefit (kNOK)	Benefit/ cost	Sensitivity analyses
Topographical	12.5	1 253.5	3 300.0	82 350.0	24.95	13.48-46.6
Lime-cement	37.5	3 750.0	6 300.0	82 350.0	13.07	7.07-24.44
KCl slurry	516.6	51 657.0	63 790.0	82 350.0	1.29	0.70-2.41
KCl poles	624.6	62 457.0	76 750.0	82 350.0	1.07	0.58-2.01

Table 4. Calculated emission of CO_2 to achieve an improvement of stability of 15%.

Measure	CO_2 emission pr. linear meter (kg CO_2 eq/lm)	Total CO_2 emission (tons CO_2 eq)
Topographical	295	30
Lime-cement	11638	1164
KCl slurry	5029	503
KCl poles	3608	361

Table 5. Benefit/cost-calculation for Hegramo including cost for CO_2.

Measure	Benefit/cost incl. CO_2 2015	Benefit/cost incl. CO_2 2020	Benefit/cost incl. CO_2 2030
Topographical	24.90	24.87	24.74
Lime-cement	12.49	12.23	11.15
KCl slurry	1.29	1.29	1.28
KCl poles	1.07	1.07	1.07

5. Conclusions

Installing KCl wells by pre-drilling boreholes with flush boring is a gentle procedure causing very small, temporarily lasting excess pore-pressures locally around the wells. Thus, such installation procedures may be used in quick-clay slopes with marginal safety as long as the site is followed up by extensive monitoring systems in case of any unforeseen pore-pressure build-up. Installing poles of compressed KCl was the least labour intensive of the installation procedures tested on NGTS Tiller-Flotten. Some practical issues remain to be resolved before KCl wells can be used as landslide-mitigation, such as the fact that these KCl poles are not yet available on the market, the pre-drilling is time consuming and therefore the installation costs today are too high to justify installing KCl wells as landslide-mitigation in large quick-clay areas.

Topographical measures have higher benefit/cost factor and lower CO_2 emissions than lime-cement piling and KCl wells. The CO_2 emissions are considerably lower for KCl wells than lime-cement piles. If the installation procedures of KCl wells become more cost efficient, the benefit/cost factor may increase. Furthermore, KCl wells may be installed in areas where conventional landslide-mitigation measures are not applicable. Thus, the non-price consequences may justify KCl-wells installation.

Acknowledgments
The authors express their sincere gratitude the Regional Research Council Mid-Norway for financial support to Salt-stabilisation of quick clays (SAK 2018-2019) (R&D project no. 284697). Tore Westheim in Norwegian Public Roads Administration is acknowledged for his good spirit and hard work during installation of salt wells. Installation of KCl poles was made possible thanks to Dr. Ludger Waldmann and his team in K+S Aktiengesellschaft (http://www.k-plus-s.com/en/) for producing and providing the compressed KCl cubes.

References

[1] Eggestad A and Sem H 1976 Stability of excavations improved by salt diffusion from deep wells. Proceedings of the 6th European conference on soil mechanics and foundation engineering, March 1976, International Society for Soil Mechanics and Geotechnical Engineering: 211-216
[2] Helle TE, Aagaard P and Nordal S 2017 In-situ improvement of highly sensitive clays by potassium chloride migration. *J Geotech Geoenviron* **143(10)**: 04017074
[3] Hamel B, Strand SA, Kjøsnes AJ, Kvennås M, Bache BKF 2019 Saltstabilisering av kvikkleire (SAK) - Arbeidspakke 2: Kost/nytte og miljø. Norwegian Public Roads Administration R&D report: 1-24
[4] Helle TE, Kirkevollen OK, Bache BKF, Le TMH 2019 Saltstabilisering av kvikkleire (SAK) - Arbeidspakke 1: Installasjonsmetoder. Norwegian Public Roads Administration R&D report: 1-44
[5] Bache BKF, Kvennås M and Gjelsvik V 2019 Kostnadsberegninger av stabilitetstiltak. NGI technical note 20180146-01-TN, rev1, date 02.07.19
[6] NVE 2014 Sikkerhet mot kvikkleireskred – vurdering av områdestabilitet ved arealplanlegging og utbygging i områder med kvikkleire og andre jordarter med sprøbruddegenskaper.
[7] NVE 2016 https://www.miljokommune.no/Global/Klima/Webinarer/2018-06-10_Brukerveiledning%20NKA2016_1_30.pdf
[8] Statens Vegvesen 2018 h*ttps://www.vegvesen.no/fag/fokusomrader/forskning+og+utvikling/Avsluttede+FoU-program/Lavere+Energiforbruk+i+Statens+vegvesen+%28LEIV%29/rapporter*