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# Full-scale field-testing of lime-cement columns in a very sensitive clay

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**Abstract.** As part of the construction of a new E6 highway between Jaktøyen and Storler in Trondheim, Norway, an area for performing full-scale field-testing of lime cement columns was defined. The soil conditions in the area cover non-sensitive clay to about 6-8 m over a silty quick clay down to at least 30 m. The aim of the full-scale field-tests was to assess how lime-cement columns would perform in a very sensitive clay (i.e. quick clay). The present paper describes the results from field and laboratory tests to characterize the field-testing site, as well as descriptions and field observations regarding the installation and results from testing of lime cement columns. The results are also compared to results of tests on laboratory mixed specimens of stabilized clay. Based on the data from the field trials, it was established a characteristic strength of 425 kPa (for 90 kg/m<sup>3</sup> of binder) for the stabilized silty quick clay after two months which is a significantly higher value than the one used in the standard practice in Norway.

## 1. Introduction

The E6 between Jaktøyen and Storler, 15 km south of Trondheim, has been extended to a four-lane highway during 2014-2018. The development of the motorway itself consisted, among other things, of larger terrain interventions in the form of large fillings and cuts. In addition, a number of bridges and passageways were planned and constructed in connection with crossings of the new highway [1]. As a preparatory part to the design, a number of experiments were carried out on a separate experimental field next to highway area.

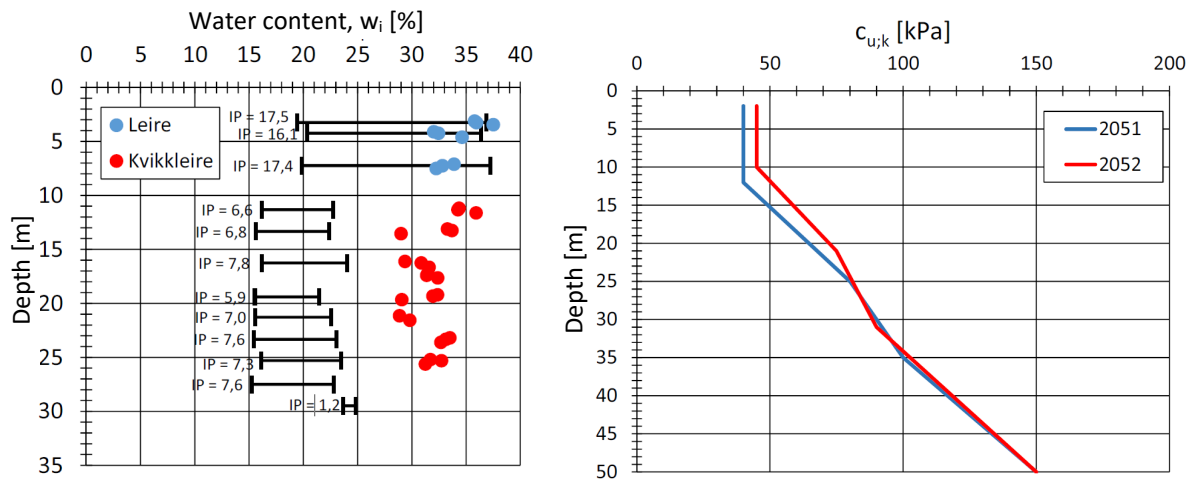
The present paper presents the results from supplementary ground investigations carried out on the geotechnical experimental field, as well as description of installation and results from testing of lime-cement piles in the experimental field. The aim is to share with the geotechnical community some of the Norwegian experiences when stabilizing very sensitive (quick) clays.

## 2. Ground conditions and description of the experimental area

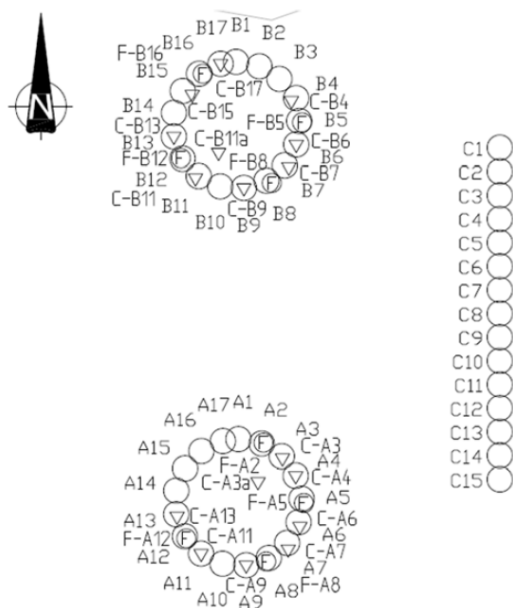
The test area was approximate 150 m south of the new E6 at Sørnypan. The area consisted of thick marine deposits and quick clay. Basic ground investigations prior installations were carried out. They included one total sounding to map the relative strength of the soil, any layer boundaries and depth to bedrock (which was actually not found in the area). Two piezocone tests (CPTU) were also carried out in two points to map more accurately the layering in the area and determine geotechnical soil parameters as the undrained shear strength in the clay. Two electric pore pressure sensors were installed at 5 m and 15 m depth in one borehole. One borehole was used to take 13 samples with a piston cylindrical sampler of Ø72 mm. The samples were examined in the laboratory. Routine tests and one CRS test were also carried out.



The soundings indicate a thin layer of dry crust down to 1-2 m depth. Total soundings indicate a layer boundary between clay and quick clay at 9 m depth. The quick clay layer extends down to at least 20 m depth. The CPTU tests suggest that there is also a layer of clay with larger deposits of sand and silt beneath the quick clay layer. The probes are stopped in soil sediments at 50 m depth. Sample series from borehole 2051 shows medium hard clay with scattered silt layers from 2-7.5 m depth, with water content 34% and plasticity 17%. Index testing results confirm the presence of quick clay between 11-30 m depth, with water content 32% and plasticity 7%. Figure 1 shows a depth profile of water content and plasticity for borehole 2051 and the undrained shear strength ( $c_{u;k}$ ) profile interpreted from CPTU probes from the boreholes 2051 and 2052 before installing the lime-cement columns. The shear strength corresponds to a medium hard clay with increasing strength in depth.



**Figure 1.** Variation with depth of water content, Atterberg limits and plasticity for borehole 2051, and undrained shear strength before installation of lime-cement columns for boreholes 2051 and 2052.



**Figure 2.** Plan over the lime-columns installation in the field-testing area: ring A, ring B and row C. The CPTUs (C-) and RCPs (F-) are also marked.



**Figure 3.** Mixing tool used for installation of lime-cement piles

### 3. Installation of lime-cement piles

Lime-cement piles were installed in two rings (A and B, figure 2) with a 2 m radius on August 13<sup>th</sup>, 2014. In each ring, 17 lime-cement piles were installed, totaling 34 piles. In addition, 15 piles were installed in one row (C) on August 14<sup>th</sup>, 2014. An example of the mixing tool used for pile installation is presented in figure 3. There lime-cement columns were installed with the following characteristics:

- Pile length = 15 m
- Pile diameter = 0.8 m
- Distance center-center = 0.8 m
- Piles overlap = 0.1 cm

The binder used as a stabilizing agent was a 50/50 mixture of Standard Cement FA and lime of the type Stabila B40. Stabila B40 is a product of the filtered dust from waste combustion and other remote heating plants, mixed with calcium oxide (CaO).

The amount of binder varies internally in the rings. The mixing energy was also varied between the two rings. This was done to study the effect of the mixing energy on the strength of the stabilized soil, in addition to find the sufficient mixing energy, rotational speed and penetration speed to be used during installation of the final lime-cement columns in the project. For the A-ring, a rotational speed of 150 rpm/min and penetration speed of 25 mm/rpm were used. For the B-ring, a rotational speed of 175 rpm and a penetration speed of 15 mm/rpm were used. For the C-row a rotation speed of 200 rpm and a penetration speed of 25 mm/rpm were used. Table 1 presents a summary of the amount of binder, rotation speed and penetration speed used in each lime-cement column.

**Table 1.** Amount of binder, rotation speed and penetration speed used in each lime-cement column.

	Lime-cement column			Amount of binder
	A1-A3	B1-B3	C13-C15	30 kg/m <sup>3</sup>
	A4-A6	B4-B6	C10-C12	50 kg/m <sup>3</sup>
	A7-A10	B7-B10	C7-C9	70 kg/m <sup>3</sup>
	A11-A14	B11-B14	C4-C6	90 kg/m <sup>3</sup>
	A15-A17	B15-B17	C1-C3	110 kg/m <sup>3</sup>
<b>Rotation speed</b>	150 rpm/min	175 rpm/min	200 rpm/min	
<b>Penetration speed</b>	25 mm/rpm	15 mm/rpm	25 mm/rpm	

The contractor that installed the lime-cement columns in the test field reported that it was difficult to mix the lime-cement for low amounts of binder. The dimension of the drill bar used gave uniform mixing for large mixing quantities but became too large for the smaller quantities. This could be avoided by properly selecting the dimension of the drill rod for the actual mixing amount.

### 4. Testing of lime-cement columns and lime-cement stabilized clay

#### 4.1. Field tests

##### 4.1.1. Reverse Column Penetration Tests (RCP)

RCP probes were installed in eight of the lime-cement piles. The RCP probe consists of a 400 mm wide wing connected to a steel wire, see figure 4. After the desired curing time, the steel wire connected to the probe is pulled up through the lime-cement column and the pulling force is measured continuously. The purpose of the RCP is to map the strength of the lime-cement columns throughout the column. The measured values are used as a basis for determining the amount of binder to be added in the clay to obtain the necessary undrained shear strength after stabilization. RCP probes were

installed in columns A2, A5, A8, A12, B5, B8, B12 and B16. They were installed immediately after installing the lime-cement columns by pushing the probes down through the lime-cement columns to a depth of 16 m, i.e. 1 m below the lower level of the lime-cement column. After three days of hardening, the RCP probe was loosened to prevent it from getting stuck. This was done by a wheel loader pulling up the steel wire by approximate 30 cm. Then, RCPs were conducted after 6 and 7 days of hardening.



**Figure 4.** Photograph of the RCP probes to be installed in the lime-cement columns

The shear strength is obtained from the corrected pulling force (or resistance to extraction) with the following equation:

$$c_{u,ks} = F_{corr} (A \cdot N)^{-1} \quad (1)$$

where

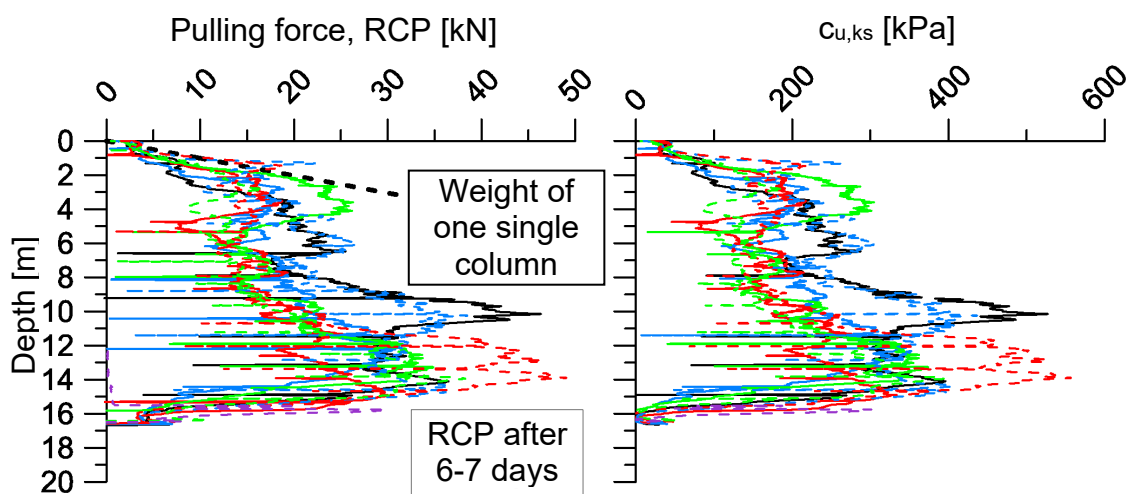
$c_{u,ks}$  = shear strength of lime-cement column

$F_{corr}$  = total pulling force, corrected for the steel wire friction inside the lime-cement column

$A$  = area of the RCP wing

$N$  = RCP factor, set to 10 according to [2]

$F_{corr}$  is estimated by pulling up of the steel wire itself without connecting to the test probe at the site. The area of the RCP's wing used was about 83 cm<sup>2</sup>. RCP results show an average strength in the non-quick clay layer of 200 kPa (range varying between 100-280 kPa). The quick clay layer shows a strength around 280 kPa (range varying between 200-500 kPa) which is around 40 % higher than the strength obtained in the non-quick clay layer.



**Figure 5.** Corrected pulling force from RCP and weight of one-single pile. Near the surface, the entire pile is lifted, hence the apparent low strength at the top. Undrained shear strength ( $c_{u,ks}$ ) of lime-cement columns from RCP.

#### 4.1.2. CPTU tests

Fifteen CPTUs were performed in the neighboring columns where RCP were conducted. The purpose of the CPTUs was to map the strength of the lime-cement columns throughout to optimize the amount of binder. Two additional tests were carried out next to the installed columns to identify any strength reduction in the neighboring clay as a result of the installation of the lime-cement columns. CPTUs were performed in columns A3, A6, A7, A12, B4, B7, B11 and B15 after 7-12 days of installation. In addition, CPTU tests were performed at points A3a and B11a, 1 meter in radial inward direction from A3 and B11, respectively. CPTUs were also performed in columns A1, A4, A9, A11, B6, B9, B13 and B17 after 54-55 days of installation. The shear strength from CPTU is estimated with the following equation:

$$c_{u,KS} = \frac{q_t - \sigma_{v0}}{N_{KT}} \quad (2)$$

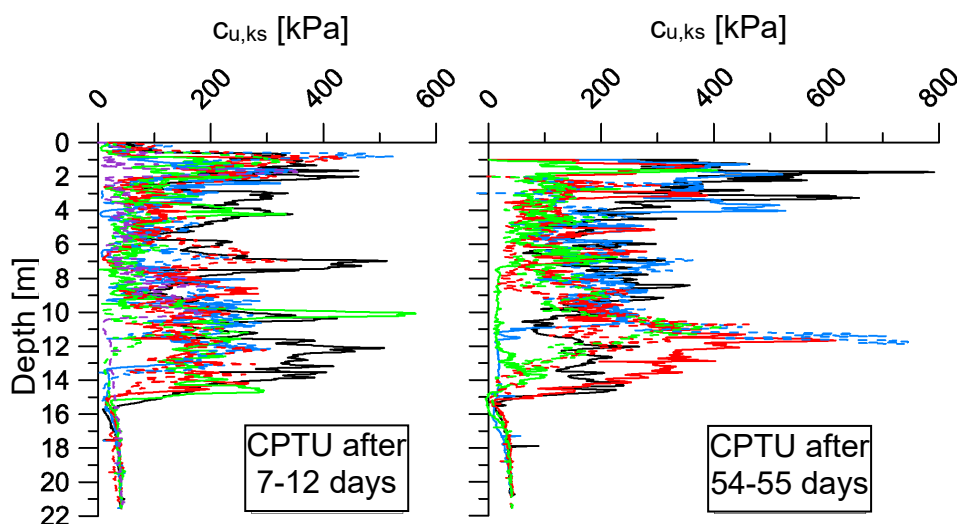
where

$q_t$  = corrected cone resistance

$\sigma_{v0}$  = in-situ total vertical stress

$N_{KT}$  = cone resistance factor set to 15 according to [5] to agree with RCP and laboratory data.

The results are shown in figure 6. Although the CPTU results show a large scatter, there is a clear indication that the strength after 54-55 days on average is about approximate 30-50% greater than after 7-12 days. It seems that the strength is lowest between 4 and 10 m depth.



**Figure 6.** CPTU results after 8 and 55 days of curing.

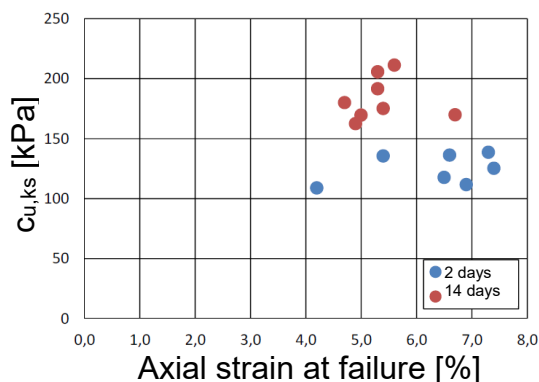
#### 4.1.3. Sampling and observations

Samples were excavated eight weeks (56 days) after installation of lime-cement columns. Visual observations indicated that ring A (with low mixing energy) had gotten significantly lower strength than ring B (high mixing energy). The samples were trimmed in the laboratory to a testing size of Ø54mm x 110mm.

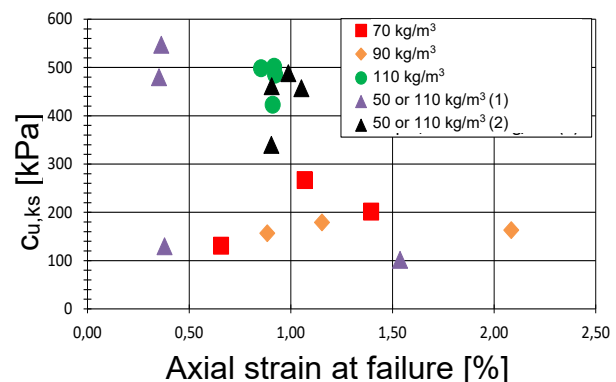
### 4.2. Laboratory tests

#### 4.2.1. Unconfined compression tests (UC) on laboratory-mixed samples

Seventeen UCs were carried on laboratory-mixed samples of quick clay from borehole 2051. The mixing procedure follows the one specified in ref. [2]. The tests were carried out after 2 and 14 days of curing. The results are presented in figure 7 and show a clear increase in the strength with longer curing time. On average, the strength increased by 46% from 2 to 14 days of curing. The trials after 14 days show higher stiffness and lower failure strain.



**Figure 7.** Undrained shear strength and axial failure strain from UC tests on laboratory-mixed samples. The amount of binder used was 90 kg/m<sup>3</sup>.



**Figure 8.** Undrained shear strength and axial failure strain from UC tests on field-mixed samples after 85 days of curing (57 days in-situ and 28 days in storage).

#### 4.2.2. Unconfined compression tests (UC) on field-mixed samples

Eighteen UCs were carried on field-mixed samples of quick clay from borehole 2051. The tests were carried out after 85 of curing. The samples come from the columns A-15, B-6, B-10, B-11 og B-15. Figure 8 shows the undrained shear strength and the strain at failure. Significantly higher undrained shear strength and lower failure strain than the laboratory-mixed samples are observed. Two of the excavated samples (from A-15 and B-6) were missing labeling when received in the laboratory. They are therefore not clearly identified with the lime-cement columns number and may have a binder amount of mixing rate 50 or 110 kg/m<sup>3</sup> (samples with (1) and (2) in figure 8). The samples taken from the same column are shown with the same symbol in figure 8. All samples are from shallow depths which means that are from the non-quick clay layer. RCP results shown in figure 5 indicate that the shear strength in the quick clay layer (deeper) was 50% higher than the shear strength at 2 m depth.

### 5. Interpretation and evaluation of material properties for the stabilized clay

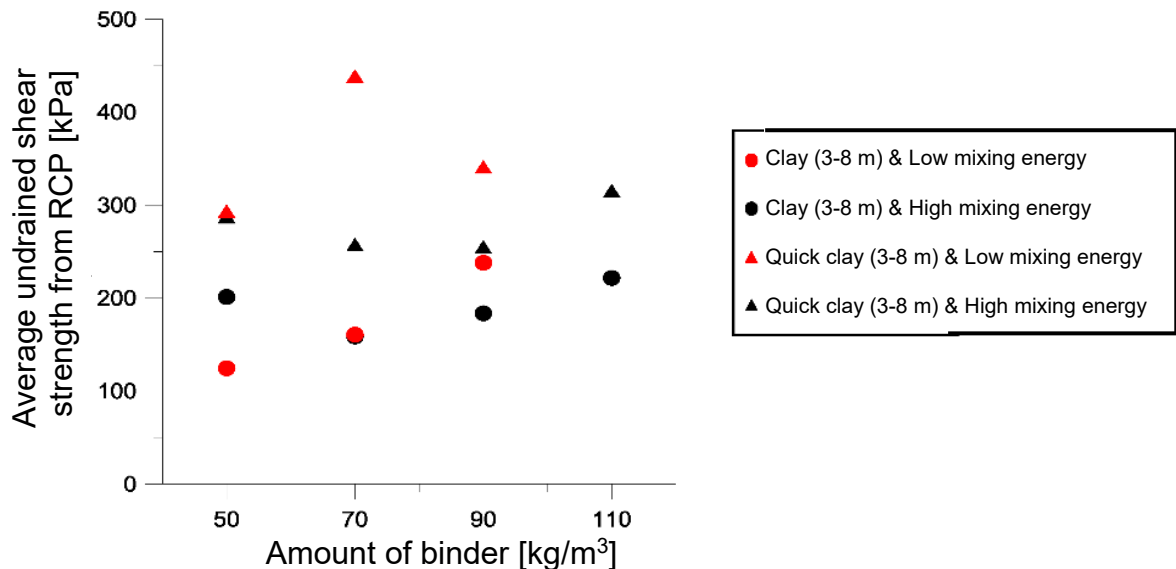
The CPTU and RCP show somewhat different strengths, and partly quite different variations with depth. CPTU show greater variation with depth which is partly due to the fact that CPTU measure strength in a small zone (5-10 cm) around the tip of the probe, while RCP measures a mean strength over the full width of the RCP wing (40 cm). CPTU probes will also tend to steer toward weaker sections of the column. For these reasons, RCP were given most weight for defining the designing strength.

UC tests on laboratory-mixed lime cement generally show lower shear strength than RCP and CPTU tests. This is in line with previous observations ([3], [4]) where field-mixed samples achieve substantially higher strength than samples mixed in the laboratory. The field tests can show over twice the strength. The difference is assumed to be due to the fact that there are significantly more favorable curing conditions in the field due to both to the stresses in the ground during field curing and the higher and more sustained temperature development during curing. UC tests on field-mixed samples show significantly higher strength than the laboratory-mixed samples.

#### 5.1. Effect of amount of binder on the shear strength increase

Figure 9 shows the average strength from RCP performed after 6-7 days over depth ranges of 3-8 m (clay) and 11-15 m (quick clay) for the various binder amounts used. Some scatter is observed in the achieved shear strength. Through the non-quick clay zone (depth 3-8 m), the experiments show as expected a clear indication of increased shear strength with an increased binder amount. Through the zone of quick clay (11-15 m) there is somewhat surprisingly no clear effect of the binder amount, but a

higher mixing energy increases the shear strength by approximate 20% by increasing the binder amount mixture from 90 kg/m<sup>3</sup> to 110 kg/m<sup>3</sup>. There is also no clear positive effect of the increased mixing energy, rather the opposite.



**Figure 9.** Average shear strength from RCP in clay (depth range 3-8 m) and in quick clay (depth range 11-15 m) for the various binder amounts.

Based on figure 7, the shear strength on laboratory-mixed specimens, with a binder amount of 90 kg/m<sup>3</sup> after 6-7 days, is estimated to be approximate 150 kPa. For the same binder amount, RCP results show 250 to 350 kPa (see figure 9) for the quick clay layer. A similar comparison between CPTU and RCP results (not presented here) was done when an amount of binder of 110 kg/m<sup>3</sup> was used. The shear strength from the field tests is also consistently highest. For the lowest binder amount (30 kg/m<sup>3</sup>), the results show little or no increase in strength through the non-sensitive clay down to 10 m. In the quick clay layer, it seems that the binder amount of 30 kg/m<sup>3</sup> has an effect, but still considerably lower than at higher mixing rates. It should be emphasized that the database for the lowest amount of binder is limited and thus the uncertainty is high.

### 5.2. Effect of mixing energy on the shear strength increase

Figure 9 shows the average strength from RCP obtained from 3-8 m depth (clay) and 11-15 m depth (quick clay) for the low and high mixing energy. The A-ring was installed with lower rotational speed and greater penetration speed than the B-ring and is therefore mixed with lower mixing energy. One would expect a slight or greater increase in shear strength for higher mixing energy, but the average values from figure 9 do not support this hypothesis. On the contrary, the results can be perceived as the higher mixing energy is giving lower shear strength. However, there is always some uncertainty in the strength achieved for the given amount of binder, so the difference must be perceived as within the basic uncertainty.

### 5.3. Strength reduction in the neighboring clay

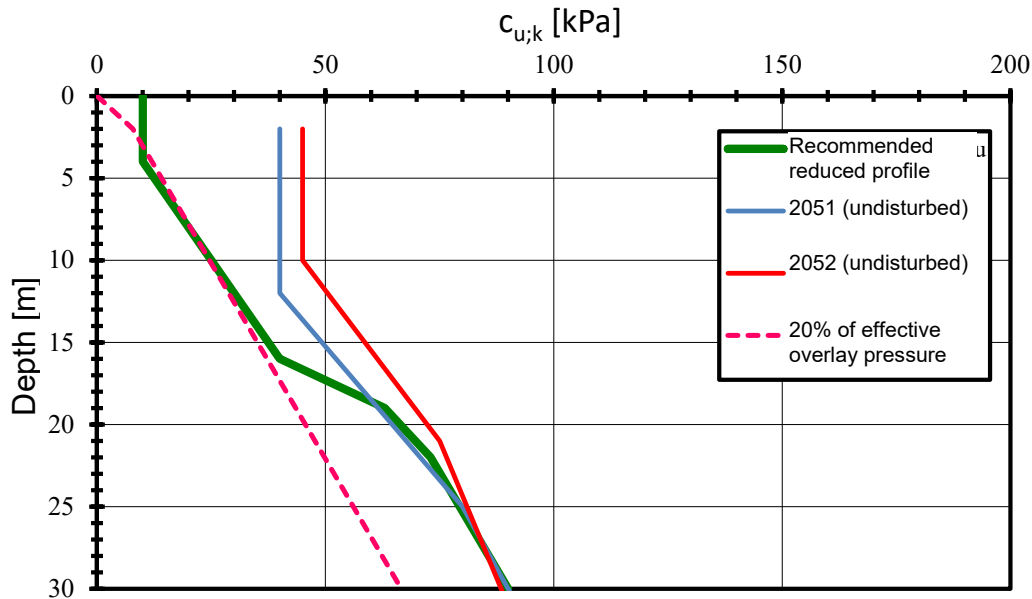
Installation of lime-cement columns may cause some disturbance and reduction of the shear strength of surrounding clay, partly through soil material set-off and the air pressure used during blowing of the powder through the nozzles of the mixing tool. To quantify this possible effect, two CPTUs were performed in the test field at a distance of 1 m in a radial direction towards the center of ring.

Empirical correlations to high-quality block tests have been used to interpret the reduction in strength. The validity of the correlations can be debated, but they should provide an adequate



approximation. The same OCR and pore pressure profile is used in the CPTU interpretation as for undisturbed clay to provide the most accurate comparison basis. The interpretation shear strength profile is shown in figure 10 together with undisturbed strength. A reduction in strength of about 20% of effective overlay pressure, but not less than 10kPa, is observed. This shows that a reduced strength should be used in a zone of 0.5-1 m below the lower boundary of the installed columns.

These results demonstrate that the influence zone and the strength reduction in this zone as a consequence of lime-cement columns installation must be considered thoroughly in a project.



**Figure 10.** Reduced undrained shear strength in the neighbouring zone of the lime-cement columns.

Two piezometers located approximately 7 m from the center of the ring of lime-cement columns and installed at depths of 10 m and 20 m showed significant excess pore water pressures during installation of lime-cement columns. Long et al. [5] presented that in the 10 m piezometer, an excess pore pressure of 80 kPa was generated above the in-situ value of about 65 kPa. At 20 m the installation of the columns initially caused a reduction in the pore pressure from some 135 kPa to 115 kPa followed by the development of an excess pore pressure of about 10 kPa. Two months after the installation, the excess pore pressure in the 10 m piezometer had reduced to about 20 kPa but little reduction was observed in the 20 m piezometer.

## 6. Conclusions and recommendations

After stabilization and seven days of curing, a characteristic undrained shear strength of 50-250 kPa was achieved in the top layer of clay and 150 kPa-350 kPa in the quick clay, based on interpretation from RCP and CPTU. Laboratory experiments on field-mixed showed significantly higher shear strengths.

When assessing different experimental results and establishing recommended characteristic shear strengths, the effect of time and difference between strength obtained on laboratory-mixed samples, samples taken from columns, and strength interpreted from in-situ tests (RCP and CPTU) should be considered.

For this particular project, the characteristic shear strengths recommended are considered to be on the conservative side. Recommended values for undrained shear strength for two months curing time are summarized in table 2, they apply for a binder of Stabile B40/Cement in a 50/50 proportion. The recommended rotation speed and penetration speed for installation was 175 rpm/min and 15 mm/rpm.

**Table 2.** Recommended characteristic shear strength ( $c_{u,k}$  in kPa) for the stabilized clays in the project

Binder amount (kg/m <sup>3</sup> )	Clay	Quick clay
50 kg/m <sup>3</sup>	150 kPa	275 kPa
70 kg/m <sup>3</sup>	200 kPa	350 kPa
90 kg/m <sup>3</sup>	250 kPa	425 kPa
110 kg/m <sup>3</sup>	300 kPa	500 kPa

The work carried out at E6 between Jaktøyen and Storler motivated a data gathering that has been later published as a large database of laboratory results from laboratory-stabilised Norwegian clays [6]. The main purpose was to identify which are the soil parameters and binder mixes that mainly influence the strength and the stiffness of the stabilised clay and provide guidance on expected values that can be applied in design.

### References

- [1] Juvik E, Solås L, Koa I, Bache B and Hove S 2019 Results from ground improvement with lime-cement columns in quick and sensitive clay on the E6 Trondheim-Melhus Proceedings of the XVII ECSMGE-2019 Reykjavik 0199
- [2] NGF 2012 Veiledning for grunnforsterkning med kalksementpeler Norsk Geoteknisk Forening Oslo [in Norwegian]
- [3] Hanson S 2012 Kalksementatbilisering ved E6 Trondheim-Stjørdal, parsell Trondheim dagsone vest MSc thesis NTNU, Trondheim [in Norwegian]
- [4] Karlsrud K, Eggen A, Nerland O and Haugen H 2015 Some Norwegian experiences related to use of dry-mixing methods to improve stability of excavations and natural slopes in soft clays *Proceedings of the Deep Mixing 2015 Conference Deep Mixing 2015, San Francisco, CA, USA*, Deep Foundations Institute Hawthorne NJ 87–100
- [5] Long M, L'Heureux J-S, Bache B, Lund A, Hove S, Sødal K, Amundsen H, Nordal S and Montafia A 2019 Site characterisation and some examples from large scale testing at the Klett quick clay research site *AIMS Geosciences* **5** 344-89
- [6] Paniagua P, Bache B, Karlsrud K and Lund A 2019 Strength and stiffness of laboratory-mixed specimens of stabilised Norwegian clays *Proceedings of the Institution of Civil Engineers - Ground Improvement* [doi.org/10.1680/jgrim.19.00051](https://doi.org/10.1680/jgrim.19.00051)