Observations from Reverse Column Penetration Tests (RCP) on Lime-cement Columns in Klett, Trondheim, Norway

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Abstract. In the construction of a new E6 Expressway between Jaktøyen and Storler in Trondheim, Norway, lime-cement columns were used extensively as stabilization measures for slope cut works in the clay strata. Non-sensitive clay, about 5-10 m thick, overlying sensitive clay and quick clay down to a depth of 25 m were found at the site. Reverse column penetration tests (RCP) were adopted as one of the quality control measures of the lime-cement columns. This paper presents the results of the RCPs from one of the areas in the project and examines the possible increase in shear strength of the lime-cement columns with depth. The variability of the RCP test results are also discussed.

1. Introduction
The deep mixing method (an in-situ soil treatment in which native soil or fill are blended with cementitious and/or other materials, such as lime, typically referred to as binders) for in-situ ground improvement has now been adopted in several countries around the world, including Japan, United States of America and the European Nordic countries. In Norway, soil stabilization with deep mixing has been applied to soft-to-medium stiff clays with sensitivity ranging from about 5 to over 100. The method aims to increase the strength and stiffness of these soils by forming columns, panels or blocks of stabilized clay.

Experience demonstrates that the strength and stiffness of a stabilized clay can show large variations [1] and therefore, there is a need for assessing the quality of the stabilization works with the deep mixing method. Testing of stabilized clays can be performed by various in-situ tests, laboratory tests on laboratory-mixed specimens on representative samples, or laboratory tests on samples taken from stabilized columns. Core sampling of the completed deep mixing columns and measuring the unconfined compressive strength (UCS) of the core samples are common quality control methods to ensure the quality of the deep mixing works. However, UCS test on core samples cannot simulate the in-situ confining stress conditions experienced by the deep mixing columns. In addition, core sampling is costly and time consuming in order to obtain high quality samples. For deep mixing projects adopting UCS testing as quality control, it has been very common to assume a design shear strength of the cement-improved soil to be a constant value versus depth.

In the Scandinavian countries, in-situ field tests, namely column penetration tests and reverse column penetration tests (RCP) [2], are widely used as a quality control testing method for lime-cement columns installed by the dry mixing method. These tests can measure the shear resistance of the lime-cement columns at their in-situ stress conditions along the entire depth of the columns.
This paper presents an analysis of the results of RCPs carried out in one of the areas in the E6 Expressway between Jaktøyen and Storler development project in Trondheim, Norway and examines the possible factors that cause the increase in shear strength of the lime-cement columns with depth.

2. Description of the project
The E6 Expressway project in Trondheim, Norway includes 8.1 km of a new four-lane motorway. According to Juvik et al [3], the construction between two areas, Sørnypan and Storlersbakken, both located at Klett, the motorway involves formation of slope cuts, having maximum height of 12 m and gradient of 1:2, in sensitive clay and quick clay. In this location, the soil profile consists of a 1 to 3 m thick dry crust layer, below which there is a 5 to 10 m thick layer of non-sensitive clay, overlying quick clay or sensitive clay (hereafter referred as quick clay) down to 25 m depth. Lime-cement columns were used extensively to stabilize the clay along the proposed slope cuts. As quality control measures for effectiveness of the lime-cement column works, a total of 138 RCPs were carried out at the locations of the completed lime-cement columns, in addition to core sampling and UCS tests. Figure 1 presents a photograph of the slope cuts at Sørnypan [3].

3. Binder details and design shear strength of lime-cement columns
During the design phase of the project, Long et al [4] summarized the properties of the soil improved with different binder contents using a test site set up at Klett. The geotechnical design was then based on the “expected” shear strength after 60 days of curing for the non-sensitive clay and quick clay following the Norwegian Guidelines for Lime-Cement Stabilization Works [5]. Table 1 presents these expected shear strengths.

| Quantity of binder (kg/m³) | Expected shear strength of lime-cement improved non-sensitive clay (kPa) | Expected shear strength of lime-cement improved quick clay (kPa) |
|---------------------------|-------------------------------------------------|-------------------------------------------------|
| 50                        | 150                                             | 275                                             |
| 70                        | 200                                             | 350                                             |
| 90                        | 250                                             | 425                                             |
| 110                       | 300                                             | 500                                             |
Bruce et al [6] discussed the differences of opinion regarding the most appropriate strength envelope for deep mixed soils and recommended that a reasonable but conservative strength envelope be used for stability analyses, which is a total stress characterization of deep mixed soil strength with total stress friction angle equal to zero.

The design shear strength values of the two major clay strata in table 1 used in the project are generally in line with the recommendation in [6].

4. The Reverse Column Penetration Test (RCP)

The RCP is commonly used in Scandinavian countries as an in-situ quality control test for completed lime-cement columns. It is an in-situ test method that can measure the shear strength and homogeneity of the installed lime-cement columns. The RCP involves installation of a test probe with vanes connected to a steel wire at the desired depth right after completion of deep mixing. Installation is done by pushing the probe down to 0.5 to 1 m below the bottom of the lime-cement column. 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 for the assessment of the pulling force. The shear strength is evaluated from the pulling force. The continuous measurement also provides an indication of the homogeneity of the installed lime-cement column.

The shear strength is obtained from the corrected pulling force (or resistance to extraction) with the following equation [5]:

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

where

- $S_{u,ks}$ = 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 probe
- $N$ = RCP factor

For the design at Sørnypan and Storlersbakken [7], $N$ is set to 10 (according to [5] and based on the results from the test site set up at Klett) for the estimation of shear strength of lime-cement columns. $F_{corr}$ 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 cm². Figures 2 and 3 show a sketch and photograph of the typical RCP probes used, respectively.

![Figure 2. Illustration of RCP probe](image1)

![Figure 3. Photograph of RCP probes](image2)
5. Strength increase with depth of deep mixed soils

Kitazume and Terashi [8] recommended that the factors that affect the strength increase of lime-cement stabilized clay can be divided into four categories, namely i) characteristics of binders, ii) characteristics and conditions of soil, iii) mixing conditions and iv) curing conditions. Among these factors, the observation of strength increase of cemented soil due to an increased overburden stress during curing (Kitazume and Terashi [5] and Yamamoto et al [9]) is considered to be of particular relevance for the present study (Fig. 4).

The in-situ strength of a natural soft soil shows often a strong dependence on depth, which is related to the stress history (overconsolidation ratio) of the clay. Larsson et al [10] studied the possible correlation between the shear strength of dry deep mixing column and the in-situ strength of the original non-treated soil (called native soil) with reference to column penetration tests. They observed that for column penetration tests carried out at 12-16 days curing, there was no correlation between the shear strength of the dry deep mixing columns and the shear strength of the native soil. However, after 26-34 days of installation of the dry deep mixing columns, the correlation was strong. They concluded that the in-situ stress of native soil and the mixing process seem to have a stronger influence on the shear strength of the dry deep mixing columns than the shear strength of the native soil.

From the above observations, for a particular site having the same binder characteristics, soil conditions and mixing conditions, and where the shear strength of the cement-improved soil is found to increase with depth, the contributory factors can be any or both of the followings: 1) improvement of shear strength due to higher overburden stress during curing; and 2) improvement of shearing performance due to higher in-situ effective stress of native soil during shearing.

6. Method of analysis

For the present study, the properties of the clay strata, based on from field tests and laboratory tests ([7], [11] and [12]), were reviewed. The spatial variation of soil properties was assumed to be generally small and the properties of the non-sensitive clay and quick clay at the site were assumed to be homogeneous.

A total of 138 RCPs were carried out. There were variations in binder contents in the RCP-tested columns. Many tests were successful, but some RCP probes were not successfully pulled up due to the extremely high improved strength; some RCP probes were found to deviate from the centre alignment of the lime-cement columns midway in the test. After review of all RCPs, 28 RCPs carried out at 3-12
days after the completion of the lime-cement columns with binder contents between 53 kg/m³ and 82 kg/m³ were considered suitable for the purpose of the present study. To allow for sufficient data for comparison and study, these 28 RCPs are assumed to have a similar amount of binder.

7. Results

Among the 28 RCPs reviewed, the results were divided into two groups. The first group contains the RCPs at ages of 3-5 days and the second group contains the RCPs at ages of 7-12 days. Figures 5 and 6 show the results of the RCPs for each of the two groups, respectively.

Figure 6 shows a much higher strength for two RCP between depths of 7-15 m. Results of these 2 RCPs have been excluded in the further statistical analysis and the mean and range of the RCP results. Figures 7 and 8 presents the calculated means and lower and upper bound of the derived RCP shear strength.

The coefficients of variation (COV = ratio of one standard deviation to the mean) of the results of RCPs versus depth were determined. Figure 9 compares the COV for the two curing periods. The COV for the upper part of the lime-cement columns (i.e. at depth of 2-10 m) are generally lower than those below 10 m.

Except for the extremely low strength values in the top 2 m, Figures 7 and 8 indicate that there is no significant increase in shear strength between 2 and 10 m, in the non-sensitive clay. Below 10 m however, in the quick clay, there is an important increase in shear strength. At depth of 20 m, the shear strength values are about 1.7 times and 2 times of those at 15 m for lime-cement columns at ages of 3-5 days and 7-12 days respectively.

The range of the shear strength form RCPs is higher for tests at 7-12 days. For example, at a depth of 20 m, among the 26 RCPs reviewed, the minimum and maximum shear strength are about 180 kPa and 1200 kPa respectively.

![Figure 5](image1.png) Estimated shear strength from 9 RCPs on lime-cement columns with 3-5 days curing

![Figure 6](image2.png) Estimated shear strength from 19 RCPs on lime-cement columns with 7-12 days curing
8. Observations and discussion

8.1. Shear strength of lime-cement columns installed in non-sensitive clay and quick clay

Juvik et al [3] analyzed the shear strength of the lime-cement columns determined from RCPs for the entire project and observed that there seemed to be a significant difference between the strength in stabilized quick clay and that, generally, the shear strength of the treated columns increased with depth. In the present study, the increase in shear strength with depth from RCPs was further reviewed. Figures 7 and 8 suggest that there is no increase in shear strength between depths of 2 and 10 m, meaning thereby no strength increase with depth in the non-sensitive clay. A positive correlation between shear strength and depth can be observed from the RCPs below 10 m. The increase in strength becomes even more significant below 15 m. The increase in shear strength with depth is, in addition, even higher as the curing period increases. It is believed, although there may be strata thickness variability at the site,
that the portion showing a strong correlation between shear strength and depth is within the quick clay stratum.

8.2. Shear strength in the top 2 m of the lime-cement columns

The shear strength from RCPs was found to be lower than the "expected" strength (table 1) in the top 2 m of the lime-cement columns. This can be due to the small overburden stress at shallow depths during the mixing process as well as curing of the lime-cement columns. Low confining stress during the RCPs may also be a contributory factor of the low resultant shear strength. A higher variability of the RCP shear strength was also observed in the uppermost portion of the lime-cement piles.

There will be no adverse impact of a lower shear strength in the top meters for the E6 Expressway project because most of the top material are to be removed in the proposed slope cut works. Nevertheless, it should be noted that the RCPs were only performed in the early stage of curing, and that further gain in shear strength can be expected with time. However, it may be worthy to be aware of the potentially lower and more variable strength in the uppermost portion of the lime-cement columns. This should be accounted for if the stability of a slope or embankment is sensitive to the strength variation in the uppermost portion of the deposit.

8.3. Variability of shear strength from RCPs

Apart from the results at the top 2 m, the COV of the RCPs inferred shear strength was between 0.2 and 0.5. These results are consistent with the variability found by Larsson et al [10]. The COV-values between depths of 2 to 10 m are lower than those below 10 m. The variability of strength development for lime-cement columns installed within non-sensitive clay seemed to be lower than the variability for those installed within quick clay.

9. Conclusions

The results of RCPs for the lime-cement columns at ages of 3-5 days and 7-12 days from the E6 Expressway project at Sørnypan and Storlersbakken in Klett, Trondheim were reviewed. No significant increase in shear strength was observed for lime-cement columns at depth of 2-10 m, within the non-sensitive clay stratum. A significant increase in shear strength with depth was observed for lime-cement columns in the quick clay stratum, usually at depth below 10 m. The increase is more notable below a depth of 15 m.

Other than the two contributory factors discussed in Section 5, the characteristic of increase in shear strength with depth for cement-improved soil may also be material-related as noted in this study. It is thus recommended that further research be carried out to analyze the influence of each contributory factor on the increase in shear strength with depth for lime-cement columns installed at different types of soft clay. Useful and more definite findings could certainly be obtained by carrying out in-situ and laboratory tests on deep mixing columns and native samples, under controlled conditions of standardized binder content and in homogeneous soils.

Moreover, it is possible that apart from adopting a constant shear strength profile versus depth for the improved soils in deep mixing projects, there might be room for further optimization of the design shear strength profile of lime-cement columns installed at soft clay.

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