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Results from ground improvement with lime-cement columns in quick and sensitive clay on the E6 Trondheim-Melhus

Résultats de l'amélioration des sols avec des colonnes chaux-ciment dans de l'argile rapide et sensible sur la route E6 Trondheim-Melhus

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ABSTRACT: The E6 Trondheim-Melhus project includes 8.1 km of new four-lane motorway. In two places the road runs in a cutting through quick and sensitive silty clay that has been stabilised with lime and cement. The clay is soft to medium firm. Based on results from a test site in the design phase, the expectation was that 90 kg/m^3 of lime and cement mixed into quick clay would give a strength of 425 kPa after 2 months of curing. For non-sensitive silty clay, a strength of 250 kPa was expected after 2 months. The lime-cement stabilization is complex and serves multiple purposes. Two overpass bridges are founded directly on a block, single and double panels ensure stability in the cuttings, the road-bed is stabilized by grids and individual columns, and the stability of the water supply and sewage ditches is ensured through longitudinal double panels. Column testing includes the use of reversed column penetration tests (RCP), CPT (cone penetration test) and sampling. A shear strength of more than 1000 kPa has been measured with RCP in the columns after only 6 days of curing. Otherwise, the RCP and CPTU tests show the same column strength as expected in advance. Uniaxial and triaxial testing of the samples obtained show that we achieve a greater shear strength than what was expected and what the engineering design was based on. There seems to be a significant difference between the strength in stabilised quick clay compared to non-sensitive clay.

RÉSUMÉ: Le projet de la route E6 Trondheim-Melhus comprend une nouvelle autoroute à quatre voies sur 8,1 km. En deux endroits, la route coupe à travers une tranchée d'argile silteuse rapide et sensible qui a été stabilisée avec de la chaux et du ciment. L'argile est molle à moyennement ferme. Sur la base des résultats d'un site d'essai pendant la phase de conception, on s'attendait à ce que 90 kg/m3 de chaux et de ciment mélangés dans de l'argile rapide donnent une force de 425 kPa après 2 mois de durcissement. Pour l'argile silteuse non sensible, une force de 250 kPa était attendue après 2 mois. La stabilisation du mélange chaux-ciment est complexe et sert à plusieurs fins. Deux viaducs sont fondés directement sur un bloc, des panneaux simples et doubles assurent la stabilité dans les tranchées, le lit de la route est stabilisé par des grilles et des colonnes individuelles, et la stabilité de l'approvisionnement en eau et des fossés d'égout est assurée par des panneaux doubles longitudinaux. Le test de colonne comprend l'utilisation de tests de pénétration de colonne inversée (RCP), des tests de pénétration de cône (CPT) et des échantillonnages. Une résistance au cisaillement de plus de 1 000 kPa a été mesurée avec des RCP dans les colonnes après seulement 6 jours de durcissement. Quant aux tests RCP et CPTU, ils révèlent une force de colonne conforme à celle prévue. Le test uniaxial et triaxial des échantillons prélevés montre qu'on obtient une plus grande résistance au cisaillement que celle qui était prévue et sur laquelle la conception d'ingénierie était basée. Il semble y avoir une différence significative entre la force dans l'argile rapide stabilisée par rapport à l'argile non sensible.

Keywords: Ground improvement; Lime and cement; Quick clay; Bridge foundations; Slope stability

1 INTRODUCTION

The E6 Trondheim-Melhus project includes 8.1 km of new four-lane motorway between Trondheim municipality and Melhus municipality in central Norway. Part of the project is also 4.6 km of local roads, 6.2 km of pedestrian and cycle paths, 7.2 km of noise reduction mounds and walls, together with river diversion and erosion control of the streams Søra and Klasbekken in the areas of Leinstrand and Storler.

In two areas, Sørnypan and Storlersbakken, the motorway cuts into quick and sensitive clay. To ensure the stability in the cuttings the clay is reinforced with lime and cement before the excavation. In addition two overpass bridges, Leinstrandbrua and Klettrøbrua, are founded directly on blocks of reinforced clay. They are currently the two largest bridges in Norway founded with this method. Leinstrandbrua is situated in the middle of the cutting at Sørnypan.

The cutting in quick and sensitive clay at Sørnypan is 370 m long in total, where 270 m is in stabilized clay. The cutting in Storlersbakken is 100 m long. The total amount of columns in the project was 47 876, which add up to 941 216 meters of drilling and mixing. Around 18 000 tonns of lime and cement was used.

2 SOIL CONDITIONS

At Sørnypan the dry crust is approximately 1 m thick. Below there is soft to medium firm silty clay. The quick clay begins 6 to 10 m below the surface, and the thicknes of the layer is partly larger than 25 m.

The bottom of the cutting is 10 m deep, but due to the transversal sloping terrain the height difference from top to bottom is around 12 m.

At Storlersbakken the dry crust is approximately 3 m thick, with medium firm to firm clay below. The quick clay is situated between 6 and 10 m below the surface. Further down there is sensitive clay down to 14 m depth.

The cutting in this area is 4-5 m deep.

Soil conditions are summarised in the following table. The data is collected from Multiconsult (2005a), Multiconsult (2005b), NGI (2014a) and Rambøll (2011).

Tabell 1. Summary of soil conditions at Sørnypan

	Non-sensitive silty clay	**Sensitive silty clay**
w (%)	25-37	30-36
PL (%)	20-22	22
LL (%)	32-35	30
PI (%)	11-12	8
γ (kN/m^3)	19.3-19.9	18.4-19.3
s_u (kPa)	13-42	9-27
s_{ur} (kPa)	2.4-3.5	0.1-0.3
S_t (-)	7-17	89-150

Tabell 2. Summary of soil conditions at Storlersbakken

	Non-sensitive silty clay	**Sensitive silty clay**
w (%)	34-39	28-36
PL (%)	19	16-18
LL (%)	38	24-28
PI (%)	19	7-12
γ (kN/m^3)	18.8	18.3-19.2
s_u (kPa)	42-59	17-65
s_{ur} (kPa)	5-6	0.1-1.0
S_t (-)	7-9	30-190

Where w (%) is water content, PL (%) is plastic limit, LL (%) is liquid limit, PI (%) is plasticity index, γ (kN/m^3) is density of soil, s_u (kPa) is undrained shear strenght, s_{ur} (kPa) is remoulded shear strength and S_t (-) is sensitivity.

The undrained shear strength is collected from fall cone tests and unconfined compression tests.

3 THE CONCEPT OF GROUND IMPROVEMENT IN THE PROJECT

The fundamentals of ground improvement in the project where planned during the design phase. This was done by Norwegian Geotechnical Institute (NGI). However, we also designed and planned additional reinforcement measures to cover requirements that emerged during the construction period.

Ground improvement with lime and sement where used to fulfil many different purposes. They are summarised in the following list:

- Single and double panels to ensure stability in the cuttings
- The road-bed is stabilized with grids and individual columns
- Two overpass bridges are founded directly on blocks of reinforced clay
- The stability of water supply and sewage ditches is ensured through longitudinal double panels
- The excavated clay is reinforced to ensure stability and handling during the excavation

In hindsight, we also should have reinforced more of the clay below the Leinstrand overpass bridge in the the cutting at Sørnypan. There were some difficulties with the foundation of the bridge scaffolding in the quick clay. This could have been avoided with extra reinforcement under the scaffold.

3.1 *Stability of cuttings*

It would not have been possible to excavate the cuttings without the soil reinforcement. Especially at Sørnypan, that would have triggered a quick clay slide.

The stability of the cuttings are ensured with single and doubles panels, as seen in Figure 1. Distance between centres is 3.5 m. The heigth difference at Sørnypan is 12 m and the inclination of the excavated slopes are 1:2. The length of the lime and cement columns were originally 25 m. Before the stabilzation works began, the terrain was unloaded with 3 m. Hence the real column length became 22 m. The disadvantage of unloading and removing the dry crust before, is that the bearing capasity for the machinery is severely reduced. Measures has to be taken so that the machinery can move around in the area.

3.2 *Stability of road-bed*

Where the road-bed is situated in quick and sensitive clay, it is reinforced with two different patterns. The road-bed for the motorway under the overpass bridge is stabilized with a grid pattern with centre distance 3.5 m in both lonitudinal and transversal direction, as seen in Figure 1. The grid consists of two columns in each row. Outside the overpass bridge the road-bed is stabilized with transversal columns which is an extension from the panels in the cuttings. The length of the columns are 25 m. 15 to 24 m of the columns remains under the road-bed after the excavation.

For the exit ramp in the same area, the road-bed i stabilized with single columns with centre distance 1.1 m. The length of the columns are 10 m.

3.3 Foundation of overpass bridges

The overpass bridges Leinstrandbrua and Klettrøbrua are founded directly on blocks of reinforced quick and sensitive clay. The constructions are prestressed slab bridges, and are respectively 121 m and 87 m long.

The first has 4 columns, in addition to the abutments, which all are founded on lime and cement blocks, in the quick clay, with 75 % coverage. The length of the columns below the foundations are 11.5 m. The blocks are shown in Figure 1.

The latter has 3 columns in addition to the abutments. The upper 10 m of the blocks has 100 % coverage, and the reinforcement is partially done in an old landfill. The method that was used here is called Modified Dry Mixing (MDM) method, and is described in Gunther et al. (2004). Because of the low water content in the fill material, water was injected into the soil with the binder that consisted of 100 % cement. The lower 15 m of the blocks were installed as regular dry mixing with 50 % lime and 50 % cement in the binder. The coverage of the lower parts were 30 % in one of the abutments and 50 % in the rest.

Figure 1. The area of Sørnypan after excavation. The panels that ensures the stability in the cuttings are visible on the sides. The grid pattern that reinforce the road-bed can be seen in the middle. At each side of the road-bed is the longitudinal panels that supports the water supply and sewage ditches. Also, 5 of the blocks that serves as foundation for the overpass bridge Leinstrandbrua are visible. (Photo: NPRA)

3.4 Water supply and sewage ditches

Much of the water supply and sewage ditches in the areas of Sørnypan and Storlersbakken are situated in quick clay. This is a challenge during the construction phase. The ditches are up to 2-3 m deep under the road-bed, and the manholes are even deeper. This was solved by installing double longitudinal columns on both sides of the ditches, which served as retaining walls. Furthermore we installed transversal columns at regular intervals to ensure the stability in the longitudinal direction. See Figure 2.

This was proven necessary with one incident early in the project. The panels in one area were accidentaly excavated and we had a slope failure in the original clay between the panels in the cutting. Neither workers or machines were damaged in the incident.

There was also installed columns as foundation for the manholes.

Figure 2. Longitudinal double panels serves as retain-ing walls for the water supply and sewage ditches. The trans-versal panel serves as a wall in the longitudinal direction. Because of the risk of reducing the stability in a larger area, the pipes where installed section by section. (Photo: Eivind S. Juvik)

3.5 Stability and handling during excavation

Excavation of quick and sensitive clay can be difficult as the material collapse into liquid form when remoulded. To improve the handling of the clay during excavation and transport, the material set for removal was also reinforced. Furthermore this improved the stability during the construction phase, and made it possible to work safely the entire time.

4 EXPECTED SHEAR STRENGTH OF REINFORCED CLAY

To investigate the properties of reinforced clay in the area, we initiated a test site at Sørnypan during the design phase. A description and the results from the test site is given in NGI (2014b).

The geotechnical design was based on the following expectations after 60 days of curing. In non-sensitive silty clay, 50 kg/m^3 of binder would give an undrained shear strength (s_u) of 150 kPa, and 90 kg/m^3 would give an s_u of 250 kPa. In quick clay, 50 kg/m^3 of binder would give an s_u of 275 kPa, and 90 kg/m^3 would give an s_u of 425 kPa.

The binder consisted of 50 % lime and 50 % cement. The expected values is based on a execution with a pile diameter of 0.8 m, a rotational speed of 175 revolutions per minute, a feed rate of 15 mm per revolution and a mixing tool with 6 blades. (NGI, 2014c)

5 EXPERIENCES FROM THE INSTALLATION

5.1 Rotational speed and feed rate

The original requirements for rotational speed of 175 revolutions per minute and feed rate of 15 mm per revolution, were based on a mixer with 6 blades. During the construction this was changed to 200 revolutions per minute and feed rate of 25 mm per revolution. To compensate for the loss of mixing energy this causes, the number of mixer whisks were increased to 10. This was done based on calculations of the mixing energy, or the Blade Rotation Number (BRN) as it is presented in Hayashi et al. (1999). The equation is as follows.

$$BRN = \sum M_d \times \frac{N_d}{V_d} + \sum M_u \times \frac{N_u}{V_u} \qquad (1)$$

Where $M_{d/u}$ (-) is the number of whisks, $N_{d/u}$ (revolutions/minute) is the rotational speed and $V_{d/u}$ (m/minute) is the installation speed. Subscript d is down and u is up.

At the same time as you uphold the mixing energy (Blade Rotation Number), the time consumption during installation is nearly halved with this solution. It decreased from 2.6 m per minute to 5.0 m per minute.

5.2 Reversed column penetration test (RCP)

We experienced values up to 1000 kPa of measured shear strength in the columns, and the high values developed after only days of curing. This caused difficulties with pulling the reversed column penetration test (RCP).

It was necessary to pull the steel wires almost every day to prevent them to fasten in the columns of lime and cement. When this was not done, the steel wire was teared of.

5.3 Amount of binder

In this project the amount of binder is lower than what is normally used in these type of projects in Norway. At the same time we utilize more of the shear strength in the design, than what has been done before.

The diameter of the installed columns in the project was 0.6 m. We had difficulties installing 8.5 kg/m (30 kg/^{3}) and 14.1 kg/m (50 kg/m^3) in the beginning. These low amounts of binder were to small for the installation equipment to handle. The solution to the 14.1 kg/m was to encrease the rotational speed and the feed rate, as described earlier. With these changes this became possible to install.

The installation of 8.5 kg/m was impossible with the general procedure. To obtain this we increased the installation speed 3 times compared to normal procedure. This resulted in poorer quality of the columns, but it was still sufficient for its purpose which was to ensure stability and handling during the excavation.

5.4 Installation in areas with low stability

Prior to the ground reinforcemnt, the slope stability of the areas of Sørnypan and Storlersbakken was poor. With this kind of work you increase the pore pressure in the ground, which decrease the stability even more. It was a great concern in advance that the slope stability could be critically low.

To prevent this we installed piezometers to monitor pore pressure in the ground and established critical values in which the construction work had to be stoped.

As an additional measure, the installation of columns where conducted in every fifth panel, so that the increas in pore pressure would not be to large in local areas.

6 RESULTS FROM TESTING

Testing of the lime and cement columns has been done with reversed column penetration test (RCP), cone penetration test (CPT) and sampling with analysis in the laboratory. This section presents results from the testing.

6.1 Reversed column penetration test (RCP)

It has been done a total of 138 reversed column penetration tests (RCP). Figure 3 shows results from the testing.

Generally, the shear strength in the columns increases with depth. The strength values in Figure 3 are picked as an average of the depth intervals with the same amount of binder.

All of the tests are done between 2 and 10 days after installation of the columns. Note that the expected values presented in chapter 4 are based on 60 days of curing. However, most of the tests shows higher shear strength than expected only after 2-10 days.

6.2 Cone penetration test (CPT)

It has been done a total of 16 cone penetration tests (CPT) in the project. 5 tests stoped in the upper part of the columns, with reduced amount of binder, due to high resistance.

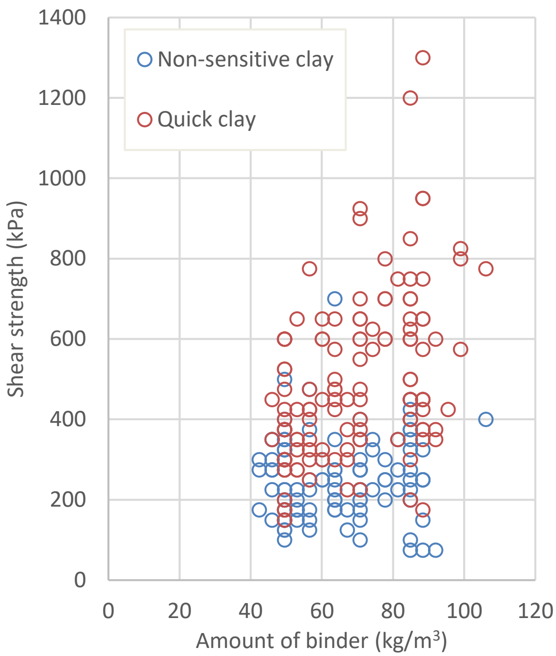

Figure 3. Shear strength from reversed column penetration tests (RCP). The tests are done between 2 and 10 days after installation.

Figure 4 shows the tests that reached the lower load-bearing parts of the columns. The CPT's with blue color are in columns with 43-64 kg/m^3 of binder. The ones with red color are in columns with 74-86 kg/m^3 of binder. The CPT's are calculated with a cone factor (N_{kt}) of 12.

6.3 Sampling and laboratory testing

Before we began excavating the cutting at Sørnypan, an test pit of 6 m depth was dug. The samples from the test pit was analysed in the laboratory to ensure that we had obtained the necessary shear strength.

Figure 5 shows results from uniaxial compression tests and triaxial shear tests (CAUa and CAD) on samples from the test pit at Sørnypan.

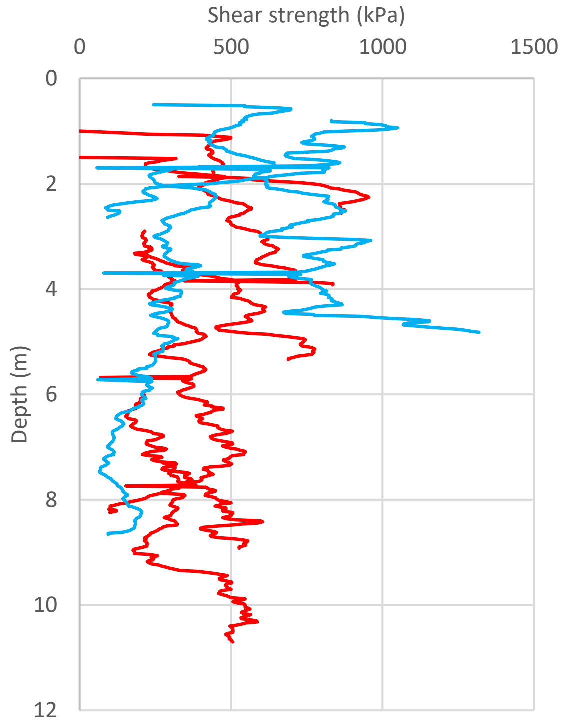

Figure 4. Cone penetration tests (CPT) in columns. Blue color are CPT's in columns with 43-64 kg/m^3 of binder, and red color are in columns with 74-86 kg/m^3. The CPT's are calculated with a cone factor (N_{kt}) of 12.

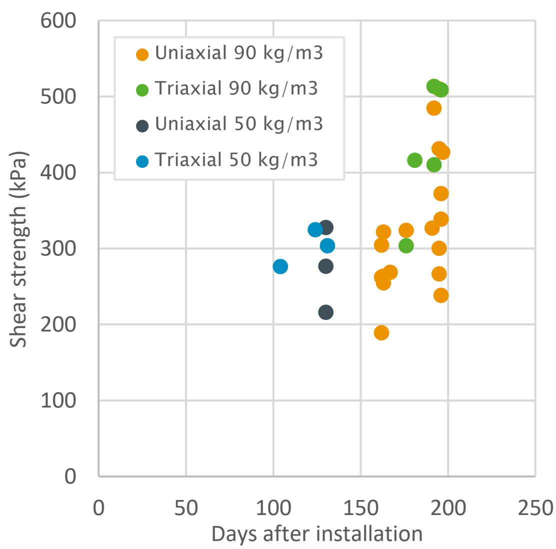

Figure 5. Laboratory tests of samples from the test pit at Sørnypan.

7 CONCLUSIONS

From the reversed column penetration tests (RCP) we see significant difference between the strength in stabilised quick clay compared to non-sensitive clay. After 2-10 days of curing we measured higher values than what was expected after 60 days, on more than ¾ of the columns tested.

For the cone penetration tests (CPT), the columns with 90 kg/m^3 of binder shows no greater strength than the ones with 50 kg/m^3. This indicates that other factors than the amount of binder is important for the obtained strenght. We see from the RCP's that the remoulded shear strength is an important factor. The same is the depth below the surface and the mixing energy.

Both the RCP and the CPT are tests that requires some sort of interpretation. The laboratory tests are howevere more certain. From the triaxial tests we have that all is close to or above the expected values after 60 days of curing. The 90 kg/m^3 sample that reached a strength of 304 kPa is of non-sensitive clay.

The testing of reinforced soil with lime and cement that is presented in this article, shows that we obtaine higher values of shear strength in the field than we do when mixing samples in laboratories. At least this is shown for these types of soil conditions.

If we can utilize more of the shear strength in the geotechnical design of soil reinforcement, there can be significant savings in both time, cost and greenhouse gas emissions in projects. When we utilize more of the strength in the design, this can reduce costs and greenhouse gas emissions due to reduced amounts of binder. Furthermore construction time can be reduced, as higher strengths in reinforced material can improve the design og reduce the need of reinforcement.

We propose that ground improvement projects in similar soil conditions as this, can use the results in this article as part of their decision basis when they select design parameters.

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