Technical note

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Copy to:	SUSI partners
Date:	2020-12-17
Revision no./Rev.date:	0
Document no.:	20200055-03-TN
Project:	Sustainable Soil Improvement (SUSI)
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Work package 3: Recommendations for the practical application of the results

Contents

Review and reference page

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FS 32989/EMS 612006

1 Introduction

Research at NGI has shown that it is possible to reduce the amount of binder necessary to give sufficient improvement of soil strength and deformation properties of sensitive clays, compared to what have been normal practice. However, recent results indicate that there is a lower limit to the quantity of binder that is required to stabilize sensitive clays. Further laboratory testing has been carried out to possible define this lower limit (NGI, 2019 and 2020). There are also different types of binders available, with different properties, and it is also necessary to quantify the environmental impact of the use of these binders, at this limit values for binder amount. Together, detailed information of the lower quantity of binder that is required to stabilize sensitive clays and the environmental impact of the different binders will provide a foundation for deciding which design alternative is more sustainable. Additionally, the practical evaluation of binder reduction needs to be assessed in a real application case (see work package 3 on the figure below).

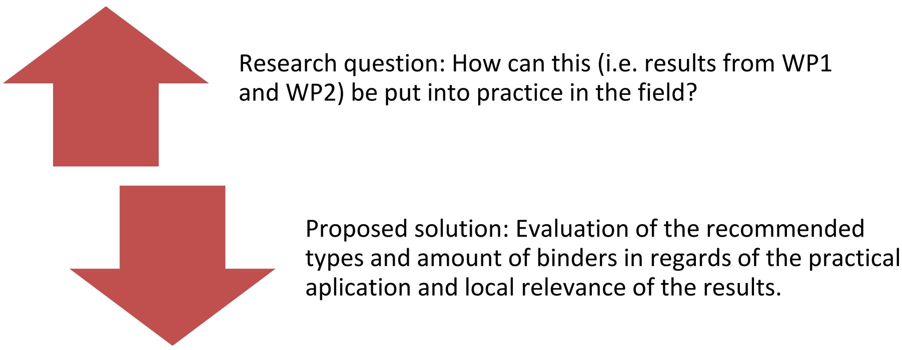
The project SUstainable Soil Improvement (SUSI) aim is to determine how the different binders perform in terms of improving strength and deformation properties of sensitive clays, and the environmental and economic impact of the different binders. SUSI is a research collaboration project between Melhus municipality (project owner), NGI (project leader), Franzefoss Minerals and JLE Grunnforsterkning; financed by RFF Trøndelag through the grant 310057.

The project is divided in three work packages:

Work package 1: Laboratory testing to determine optimal quantity of binder necessary to improve strength and deformation properties of sensitive clays.	Work package 2: Cost-benefit and environmental-benefit evaluation for the different binder types used in work package 1.	Work package 3: Recommendations for the practical application of the results obtained and relevance for the community by evaluating the outcomes in a real case in Lundamo, Melhus.

This present technical note summarizes the work done in the work package 3 (WP3).

2 Description of WP3



The work included in WP3 consists of considering the practical aspects of installation of lime cement columns with low binder amounts. In addition, a case study is analysed where a quick clay area in Lundamo, Melhus, needs to be stabilized. The case study includes a benefit/cost-analysis. Three alternatives for stabilization have been compared:

- Topographical changes
- Soil improvement – traditional
- Soil improvement – optimised based on results from WP1

3 Results from WP1 and WP2

Laboratory works were performed in WP1 to investigate the index properties and shear strength of a typical Trøndelag clay when stabilised with various binder types and contents. Clay samples were taken from the Norwegian GeoTest Site (NGTS) for quick clay at Tiller-Flotten, Trondheim (L' Heureux et al., 2019).

The binder used were partly standard cement CEM II, i.e. a mix of appr. 80 % Portland cement and appr. 15-20 % fly ash, and a binder consisting of a mixture of quicklime and LKD (lime kiln dust), which are locally available in Trøndelag. These binders are products labelled Stabila B100, B80, B60 and B40 (B40 is not sold commercially), and contain 100 %, 80-85 %, 60-80 % and 0 % quicklime, respectively. The remaining part is LKD. Most of the laboratory tests were performed with 50 % cement and 50 % with one of the Stabila products.

In short, the following conclusion was drawn from the laboratory results in WP1:

- Increasing shear strengths (c_u) with increasing binder content and with binders with higher CaO-active content
- To obtain $c_u \approx 300$ kPa, a binder content of 60 kg/m^3 is necessary for 50 % cement / 50 % Stabila B40, and 30 kg/m^3 for 50 % cement / 50 % Stabila B60, B80 and B100. The difference is thought to be caused by a difference in CaO-active content

In WP2, estimations of total construction costs, incl. mobilisation/demobilisation, and CO_2 emissions associated to these aspects were made. In short, it was concluded that:

- 100 kg of 50 % CEM / 50 % Stabila B100 gave highest cost and CO_2 emissions per m^3 stabilized soil, appr. 235 NOK and 82,5 kg CO_2 per m^3 stabilized soil
- 30 kg of 50 % CEM / 50 % Stabila B60 gave lowest cost and CO_2 emissions per m^3 stabilized soil, appr. 142 NOK and 21,5 kg CO_2 per m^3 stabilized soil
- Appr. 40-70 % of total construction costs and 0,7-2,2 % of CO_2 emissions originates from installation works (excluding mobilisation/demobilisation of equipment). It should be noted that the construction cost will vary depending on site conditions, contractor, availability etc.

4 Practical aspects of low binder contents

4.1 Introduction

Historically, the normal binder content (Q_b) in Norway for lime cement columns varies between appr. 80 and 120 kg/m^3. The installation equipment and technique available in the construction market are thus adapted for these amounts. Results in WP1 however, shows that a considerably lower binder content, down to appr. 30 kg/m^3, is sufficient in Trøndelag to obtain shear strengths of appr. 300 kPa. In some applications, an even lower binder content could be used if the shear strength requirement is lower. In practice, these low binder contents can be challenging. There are mainly two practical aspects to consider regarding low binder contents:

- Sufficient flow rate through the system to avoid clogging, whilst
- Maintaining enough mixing energy to obtain homogeneous columns

4.2 Flow rate of binder

In short, the installation equipment consists of a drilling rig and a binder tank. The binder is delivered by air pressure in the tank, normally 4-10 bar, through the hoses into the drilling rod and out of the mixing tool. The flow of the binder is maintained by a rotary valve controlling the delivery of the binder out of the tank. The rotary valves that normally are used in today's equipment are manufactured to maintain a binder flow rate of appr. 1-3 kg/s, i.e. this flow rate can be assumed is required for a controlled binder delivery.

Consequently, to achieve low binder contents in the soil, the flow rate should be kept as low as possible. It is however not likely that a lower flow rate than 1 kg/s is possible due to a limited fluidness or flowability of the binder. The fluidness is a measure of how easily the powder flows through hoses and valves and differs for different types of binders. It is higher in quicklime than cement or LKD. For quicklime it is normally required to have a fluidness > 70 %. This requirement is fulfilled for Stabila B60. Experience with CKD, i.e. cement kiln dust, has shown that appr. 1 kg/s is achievable, and it is realistic to assume that the LKD is similar.

It is therefore assumed a minimum flow rate of binder of 1 kg/s. The minimum binder content per unit volume of soil is then controlled by the "speed" of the installation, and this must be sufficiently low to obtain homogeneous columns.

4.3 Mixing energy

To create a homogeneous column, the mixing energy must be sufficient. The mixing energy is often qualitatively described by the blade rotation number (BRN) and is defined as the number of mixing blades that rotates per m of column:

$$BRN = \Sigma M \frac{N_u}{V_u},$$

where ΣM = number of blades on the mixing tool
N_u = rotation speed (rev/min)
V_u = retrieval speed (m/min)

According to NGF (2012), the recommended rotation speed of 150-175 rev/min. The corresponding Swedish values are similar, but with a slightly higher rotation speed, up to 200 rev/min. This has also been used in projects in the Trøndelag region with good results. The retrieval speed is normally 2,5-5 m/min. The parameter retrieval rate (mm/rev) is also used to calculate the mixing energy. This normally varies between 15 and 25 mm/rev.

The number of blades is normally 6 or 8. With these values, BRN will vary between 240 and 400 for a 6-blade tool, and 320 and 530 for an 8-blade tool. There is no guidance on BRN in NGF (2012), but a BRN ≥ 300 is normally assumed in Sweden to give satisfactory homogeneity for mixing a binder consisting of lime and cement in inorganic clays. It is possible that this could be lowered somewhat in quick clays which normally are easily remoulded, but this is yet to be tested systematically.

The binder content in one column is thus dependent on several variables; flow rate through the rotary valve, rotation and retrieval speed, column diameter and mixing tool. The binder content per unit volume of soil is decreased by:

- Increasing the column diameter (spreading the binder per metre of column over a larger column area)
- Increasing the retrieval rate (allowing the mixing tool to pass through the soil mass at a faster rate)
- Increasing the number of blades (allowing a higher rotation speed whilst maintaining a certain BRN value)

4.4 Minimum binder contents

Assuming BRN = 300, a column diameter of 800 mm, 1 kg/s of binder flow rate and a retrieval rate ≈ 20-25 mm/rev, the following theoretical binder contents are obtained:

- 6-blade tool and N_u = 170 rev/min → Q_b ≈ 35 kg/m^3
- 6-blade tool and N_u = 200 rev/min → Q_b ≈ 30 kg/m^3

- 8-blade tool and N_u = 170 rev/min → Q_b ≈ 28 kg/m^3
- 8-blade tool and N_u = 200 rev/min → Q_b ≈ 24 kg/m^3

In theory, it is possible to lower the minimum amount of binder content further, e.g. by increasing the column diameter to 1000 mm and/or increasing the retrieval rate up to 35 mm/rev or even higher. 10-blade tools are also available, and it is also probable that rotary valves or other types of feeders that enables lower a flow rate could be used.

It is worth noting that the lowest possible binder contents are dependent on the contractor and their equipment. There are currently four contractors in Scandinavia with equipment for soil improvement with binders, and they all have somewhat different machines and equipment. Some of their equipment have limitations, e.g. for retrieval rate or rotation. It is possible to modify or rebuild equipment, but such changes in equipment or adjustment in execution needs to be thoroughly tested in the field.

In practice, based on the current available equipment, it could be concluded that the minimum binder content of Q_b ≈ 25-30 kg/m^3 is achievable for 800 mm columns. For 600 mm columns, Q_b ≈ 40-55 kg/m^3 can be achieved.

5 Case study: Lundamo

5.1 Introduction

As a part of WP3, a case study has been performed on a quick clay zone in Lundamo, located in Melhus municipality, Trøndelag. The area consists of relatively steep slopes which are over 50 m in height, Figure 1. At the top of the slope, the ground conditions consist of a top layer with sand down to appr. 8 m depth followed by a clay layer to large depths. From appr. 20 m depth the clay has been classified as quick.

Low factors of safety have been calculated, and in 2008 the area was classified as a quick clay zone with "høy faregrad" according to NGI (2001). It should be noted that this classification was done on a larger area than the area analysed in this case study.

In connection with a housing development plan, stabilization measures were in 2008 designed consisting of topographical changes. It was suggested that the top of the slope is excavated to appr. 5 m, and that the toe of the slope is heightened with fill material up to appr. 5 m. These changes increase the calculated factor of safety and hence reduce the probability of failure.

An erosion protection measure along Nordstubekken have already been executed by NVE. This measure has re-classified the quick clay zone to "middels faregrad". The topographical changes are described in Multiconsult (2013).

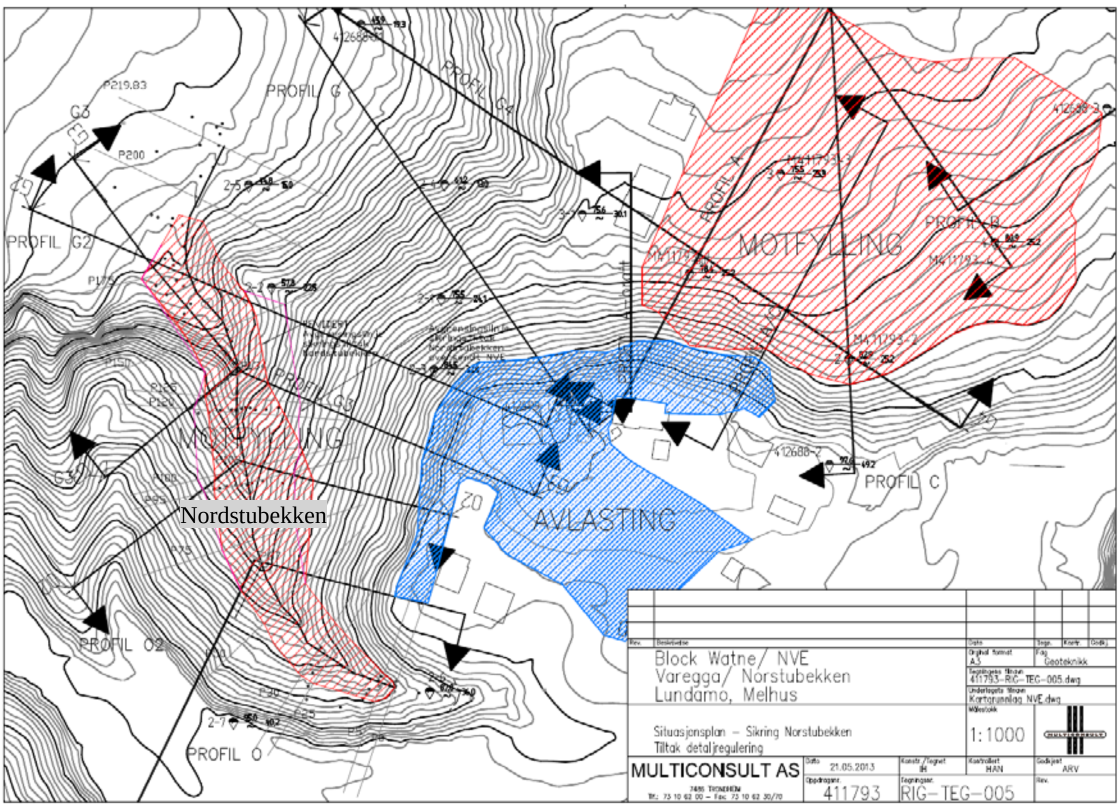


Figure 1 Plan view over the Lundamo slope and suggested measures with topographical changes. Drawing from Multiconsult (2013).

5.2 Soil improvement with lime cement columns

To compare the topographical measures with soil improvement with binders, a brief design of lime cement columns has been performed. The basic engineering properties of the Lundamo clay are similar to the Tiller-Flotten clay that has been used in the laboratory analyses in WP1. It is thus assumed that the laboratory results also can be applied in this case study, and it has conservatively been assumed that a shear strength in the columns of 250 kPa can be achieved using a binder content of 30 kg/m^3 with 50% cement and 50 % Stabila B60. Traditionally, a binder content of 100 kg/m^3 with 50 % cement and 50 % quicklime (Stabila B100) would have been assumed.

Stability calculations have been performed to obtain the extent of lime cement columns needed to stabilise the slopes. For the stability calculations, it is assumed that:

- An absolute safety factor of F_c = 1,4 is required (as opposite to an increase in per cent which are allowed for topographical measures)
- Column diameter of 800 mm
- A maximum depth of the lime cement columns of 20 m (i.e. appr. 12 m columns which are not installed in the top sand layer)
- A wall type pattern with sufficient overlap within the walls
- Coverage area ratio of 25-30 % and a shear strength c_u = 250 kPa in the improved soil. With an assumed in situ c_u = 80 kPa in upper part of the clay, this gives a stabilized "block" in stability calculations with c_u = 120 kPa.

Stability calculation have been done in one cross section, Figure 2. To obtain F_c = 1,4, lime cement columns must be installed at an approximate width of 30 m. It should be mentioned that the calculations are simplified but indicate the extent of a necessary soil improvement to a sufficient degree.

A plan view of the necessary soil improvement is shown in Figure 3. The length at the top is appr. 200 m, giving an area of appr. 6,000 m^2. The total soil volume that needs to be improved corresponds to appr. 22 000 m^3.

The case study has not analysed or considered:

- Installation effects in semi-stable slopes and need for temporary protection measures to avoid failure during execution (could for example include unloading at the top of the slope, monitoring of pore pressures etc.)
- Difficulties of penetration through the upper layer of sand, and through the clay with relatively high shear strengths (600 mm diameter could be needed)
- Possible access for machines, need of preparatory works and consequences for the existing houses and possible minor topographical changes

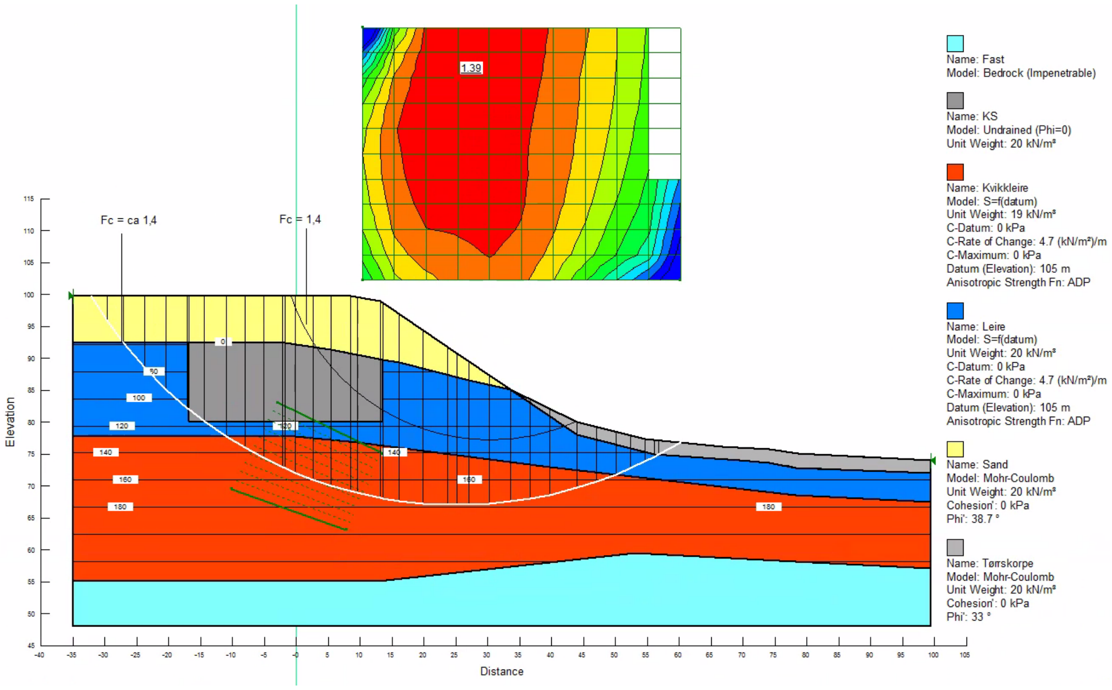


Figure 2 Result of a stability calculation with soil improvement (Profil A in Fig. 1).

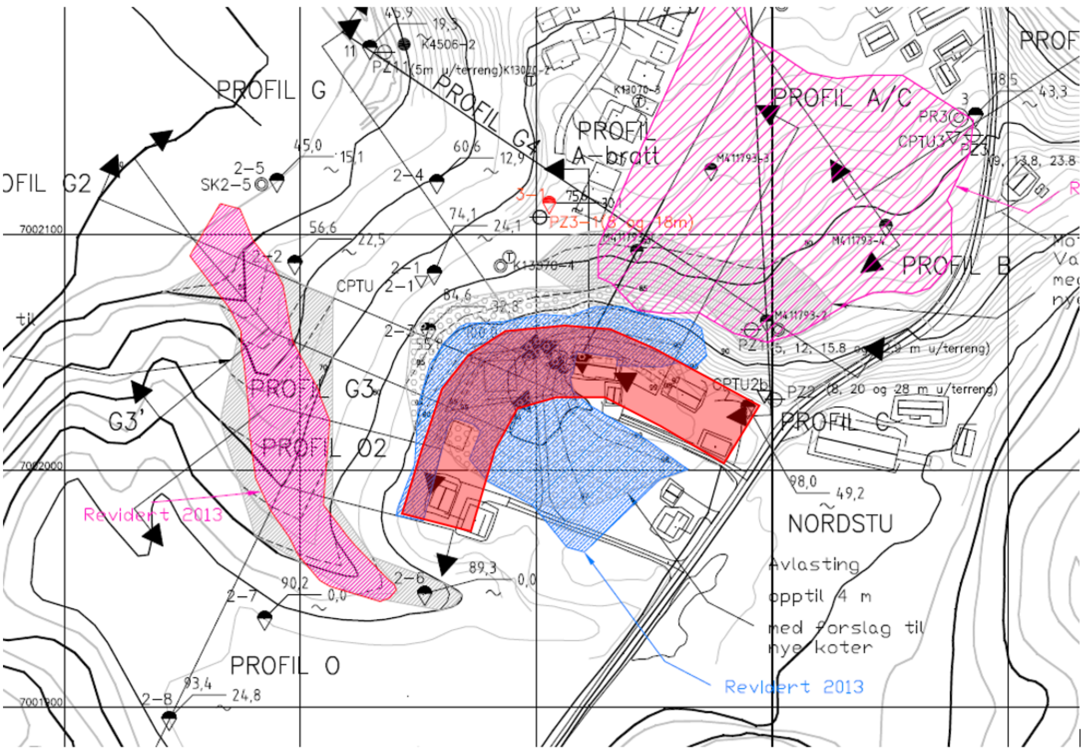


Figure 3 Plan view with a sketch over the area required (red) for soil improvement (existing houses not considered in this sketch).

5.3 Benefit/cost-analyses

A benefit/cost-analysis have been made by NVE according to the reference NVE (2016). This analysis compares the values that are secured by the decrease in failure probability to the cost of the measure. The following three alternative measures have been compared:

- Topographical changes described by Multiconsult (2013)
- Soil improvement with lime cement columns (LC) – traditional
  - Q_b = 100 kg/m^3 with cement and Stabila B100
- Soil improvement with lime cement columns (LC) – optimised
  - Q_b = 30 kg/m^3 with cement and Stabila B60

Estimates of the values that are secured are based on assumptions on the extent of houses and infrastructure that potentially would be destroyed in the case of a quick clay landslide. The landslide extent is estimated based on the guidelines given in NIFS (2016) and illustrated in Figure 4. The values that are secured include 8 homes, 6 garages, 200 m regional road, 150 m private road and 11 000 m^2 of agricultural field.

Figure 4 Release area in light pink (løsneområde) and run out area in blue (utløpsområde).

The benefit/cost-analyses is based on a "faregradscore" = 28 and a yearly likelihood of failure 1/150 before any measures, and "faregradscore" = 22 and a yearly likelihood of failure 1/300 after erosion protection of Nordstubekken. Soil improvement with lime cement columns have been assumed to give a reduction of 9, whilst two alternatives in reduction of 6 and 9 have been assumed for topographical measures. Results of the benefit/cost-analysed are presented in Table 1.

Table 1 Results from benefit/cost-analyses (calculations performed by NVE)

	Measure	Faregradscore before - after	Construction costs (NOK)	Amount CO_2 (tonnes)	Benefit/cost
Before erosion protection of Nordstubekken	1: topographical measures	28 - 16 (13)	4 565 000	149	1,47 (1,69)
	2: LC optimised	28 - 13	4 850 000	599	1,54
	3: LC traditional	28 - 13	7 282 000	2 214	1,06
After erosion protection of Nordstubekken	4: topographical measures	22 - 16 (13)	3 450 000	110	0,65 (0,99)
	5: LC optimised	22 - 13	3 735 000	560	0,86
	6: LC traditional	22 - 13	6 167 000	2 175	0,54
Erosion protection of Nordstubekken	-	28 - 22	1 115 000	39	4,13

6 Conclusions

The following conclusions are made for the Lundamo case study:

- Erosion protection of Nordstubekken gives a large benefit/cost, i.e. a low cost combined with a large reduction in "faregrad"
- The benefit/cost for topographical measures varies depending on the reduction in faregrad, but -6 is probably the most suitable assumption since the reduction in safety factor is only around 10-15 %
- Traditional soil improvement with lime cement columns gives a relatively low benefit/cost, mainly due to large construction costs and large CO_2 emissions
- Optimised soil improvement gives considerably higher benefit/cost compared to traditional and is close to or even higher that of topographical measures (excluding erosion protection)
- As the optimised soil improvement gives appr. 62 kg less CO_2 per m^3 soil, a total of 1 350 tonnes CO2 is spared in the Lundamo case study (WP2) compared to a traditional stabilisation with 100 kg/m^3 with lime and cement

It should be noted that the simplified soil improvement design includes a number of uncertainties, but the analyses still show that the method can be an advantageous alternative when the type of binder is optimised. This is not the case for a traditional type and amount of binder. It is probable that these conclusions for benefit/cost can be applied in other semi-stable quick clay areas as well.

All laboratory results are based on a specific clay from Tiller, but NGIs experience is that the conclusions can be applicable also to other clays in the Trøndelag region as well. The work is thus seen as valuable and has shown that soil improvement based on results in the SUSI-project can be advantageous compared to topographical methods, at least in Trøndelag.

It has been shown that low binder contents can in practice be challenging. The possibility of low binder contents depends on maintaining a sufficient flow of binder through the system avoiding clogging, whilst also maintaining enough mixing energy to obtain homogeneous soil improvement. Different contractors and equipment have various limitations, but overall it is concluded that a binder content of appr. 25-30 kg/m^3 normally is possible for 800 mm columns and 40-55 kg/m^3 for 600 mm columns.

7 Acknowledgments

To RFF Trøndelag (Regionale Forskningsfond Trøndelag) for their generous grant 310057 to perform the project Sustainable Soil Improvement (SUSI).

To the partners in SUSI: Martin Mengede (Franzefoss Minerals), Håkon Rueslåtten and Jan Lyng (JLE Grunnforsterkning AS) and Caroline Mevik (Melhus municipality) for valuable comments in the present technical note.

To the project Norwegian GeoTest Sites infrastructure (NGTS), grant No. 245650/F50 from the Research Council of Norway, for facilitating the clay materials and the data that describes it.

To Stein-Are Strand at NVE for helping with the benefit/cost-analyses.

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Kontroll- og referanseside/ Review and reference page

Dokumentinformasjon/*Document information*		
Dokumenttittel/*Document title* Work package 3: Recommendations for the practical application of the results		**Dokumentnr./*Document no.*** 20200055-03-TN
Dokumenttype/*Type of document* Teknisk notat / Technical note	**Oppdragsgiver/*Client*** Regionale Forskningsfond Trøndelag	**Dato/*Date*** 2020-12-17
Rettigheter til dokumentet iht kontrakt/ *Proprietary rights to the document according to contract* NGI		**Rev.nr.&dato/*Rev.no.&date*** 0
Distribusjon/*Distribution* FRI: Kan distribueres av Dokumentsenteret ved henvendelser / FREE: Can be distributed by the Document Centre on request		
Emneord/*Keywords* quick clay, lime, cement, benefit/cost analysis, stability		

Stedfesting/*Geographical information*	
Land, fylke/*Country* Norway, Trøndelag	**Havområde/*Offshore area***
Kommune/*Municipality* Melhus & Trondheim	**Feltnavn/*Field name***
Sted/*Location* Lundamo & Tiller-Flotten	**Sted/*Location***
Kartblad/*Map*	**Felt, blokknr./*Field, Block No.***
UTM-koordinater/*UTM-coordinates* **Zone: East: North:**	**Koordinater/*Coordinates*** **Projection, datum: East: North:**

Dokumentkontroll/*Document control*
Kvalitetssikring i henhold til/*Quality assurance according to NS-EN ISO9001*

Rev/ *Rev.*	**Revisjonsgrunnlag/*Reason for revision***	**Egenkontroll av/ *Self review by:***	**Sidemanns-kontroll av/ *Colleague review by:***	**Uavhengig kontroll av/ *Independent review by:***	**Tverrfaglig kontroll av/ *Interdisciplinary review by:***
0	Original document	2020-12-13 Sølve Hov	2020-12-15 Vidar Gjelsvik		

Dokument godkjent for utsendelse/ *Document approved for release*	**Dato/*Date*** 17 December 2020	**Prosjektleder/*Project Manager*** Priscilla Paniagua

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