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Enhanced quality control of dry deep soil mixing using machine data

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ABSTRACT: Urban development in challenging ground conditions, such as sensitive marine clay, often requires advanced geotechnical solutions. Ground reinforcement with dry deep soil mixing (DDSM) with lime cement (LC) is a widely used technique in Norwegian practice for increasing safety factor and minimizing deformations during excavation.

The quality achieved of the stabilized material is very important. With an increased focus on sustainability in geotechnical works, it is important to have good control methods to ensure that the quality of the stabilized material is sufficient, with as little material use as possible.

The research project CURIOUS (Campus Ullevål: Research and Instumentation Of Underground Structures) was initiated by NGI to further study and improve the design of deep excavations in sensitive marine clay supported by sheet pile walls and DDSM with LC. In the project, a total of 100 000 m of DDSM with LC was installed. Traditionally, tests like pull-out tests (FOPS) and cone penetration tests (CPT) are carried out on a certain percentage of the LC-columns installed to evaluate the strength of the stabilized volume. In CURIOUS, an as built control based on the machine parameters was introduced, visualizing deviations of machine data parameters such as binder content mixing ratio and blade rotation speed in a 3D BIM model.

This paper presents the results of the as-built control for DDSM with LC-columns and demonstrates how quality assessments can be enhanced by correlating traditional test methods with installation data. The findings highlight how integration of machine data can improve material efficiency while maintaining sufficient stability of the geotechnical works.

KEYWORDS: Dry deep mixing, machine data, as-built control, ground improvement

1 INTRODUCTION

1.1 *Background*

Dry deep soil mixing (DDSM) with lime cement columns (LCC) is a widely used method for ground improvement in the Scandinavian countries (Karlsrud et. al. 2005, 2012). The design strength and performance of the stabilized columns are often conservatively chosen compared to what is measured in the ground (Helle et. al. 2024). One reason for this is because there are lots of uncertainties regarding the installation of the columns. With the focus on more sustainable solutions in the construction industry, there are several studies on how DDSM can be made more sustainable. Studies looking at different binders (Hov et. al. 2023, 2024) and methods for testing and verifying the strength of the stabilized soil in the field (Helle et al., 2024; Ritter et. al. 2024) have been done. This study goes further into the installation method and machine parameters to study how this can affect the result and quality of the ground improvement.

The Norwegian Geotechnical Institute (NGI) has initiated a three year strategic project to study the possibilities of optimizing ground improvement with DDSM. The project; Campus Ullevål Research and Instrumentation of Underground Structures (CURIOUS), is initiated in connection with NGI developing a new office building in Oslo, Norway. The overall project goal is to move the research front towards a more sustainable design and construction of deep supported excavations in urban environments by implementing enabling technologies.

The excavation was designed with a sheet pile wall supported by internal struts in addition to installation of DDSM with LCC to increase stability and to reduce deformations. In CURIOUS the performance of the LCC have been evaluated and compared to in-situ measurements (Løyland et. al., 2025). To evaluate the structural properties of the LCC it is also important to look at the construction and production aspects of the DDSM-method. A method for an as-built assessment of DDSM-works has been presented by Kahlström et. al. (2022). The assessment has been updated in parallel with the production so that measures can be implemented when the rig is already in the area. Kahlström's method is based on average values of an installed LCC, where this study has improved the method. This study presents an as-built assessment based on machine parameters, focusing on deviations in specified machine parameters with depth, and evaluating how this affects the quality of the LCC.

2 DRY DEEP MIXING

2.1 *Method*

Ground improvement with DDSM is a widely used method in Scandinavian countries. The method uses a machine to mix a powdered binder into the clay so that columns of reinforced clay are established. The machine uses a rotating mixing tool to a required depth. At the bottom position, the direction is reversed, and the powdered binder is discharged using compressed air. The mixing tool rises at a specified rotation speed and elevation speed. The powdered binder reacts with the existing water in the soil and creates columns with improved strength and stiffness compared to the original soil.

In Norway ground improvement with DDSM is used to stabilize slopes, shoring of excavation pits and for reducing settlements (Norwegian Geotechnical Society, 2012). The stabilization pattern depends on the purpose of the DDSM, and can be installed in patterns of single LCC, LCC establishing ribs/panels and in a block pattern. Typical diameters for a single LCC in Norway are 0,6 m to 0,8 m, and the maximum installations depth, limited by the machines, is 25 m.

When installing LCC, there are several factors that contribute to the result. In addition to soil parameters and binder type, a large part of the process is the actual mixing and execution of the LCC.

2.2 *Machine Parameters*

The installation has a significant impact on the result. It is common to specify the machine parameters to the contractor.

Typical machine parameters to be specified are the binder content mixing ratio, rotation speed and elevation speed.

Binder content mixing ratio – Specified as kg binder content per meter installed LCC or per cubic clay (kg/m^3). Typical values for binder content mixing ratio in Norway is 50 to 110 kg/m^3 depending on soil parameters and type of binder content.

Rotation speed – Specified as revolutions per minute (rpm) of the rotating mixing tool. Normal requirements regarding practical quality experience are that the rotation speed should be between 150 and 200 rpm.

Elevation speed – Specified as elevation of the rotating mixing tool per revolution (mm/rev). The choice of elevation speed depends on the design of the mixing tool, and normal variations are between 10 to 35 mm/rev.

2.3 *Testing*

Testing of the LCC involves the use of destructive in-situ tests as reversed column penetration test (FOPS), column penetration test (FKPS) or cone penetration test (CPTu). The tests give an indication of strength of the stabilized soil and the homogeneity. Depending on the scope of the DDSM, the control requirement according to Norwegian practice is testing between 0.3 and 2 % of the LCC (Norwegian Geotechnical Society, 2012).

3 CASE STUDY: CAMPUS ULLEVÅL

In this study, data from a construction project in Oslo, Norway is evaluated. The construction project includes an excavation pit for a 10-storey office building. The depth of the excavation is up to approx. 6.7 m. DDSM with LCC in a rib pattern is installed to support the sheet pile wall and to reduce deformations induced by excavation.

3.1 *Ground conditions*

The site is located at Ullevål in Oslo, Norway. The terrain level varies from level +97.1 to +98.3 in north and east to +95.0 in southwest.

The soil conditions are characterized by fill masses and dry crust in the upper 1-3 meters. Below is a layer of non-sensitive marine clay, down to approximately level +91, with a water content of 30 % and undrained active shear strength of 40-45 kPa. Down to bedrock there is a layer of highly sensitive (S_t > 100) marine clay with increasing strength with depth. Soundings indicate sand layers in the clay with a thickness from a few cm up to 2 m.

3.2 *Design*

DDSM with LCC was used in the construction pit to reduce deformations and increase the overall stability of the excavation. The design consisted of ribs with LCC, installed perpendicular to the sheet pile wall. The ribs consisted of double rows of Ø600 mm columns, installed with an overlap of 80 %. The installation pattern of a rib is shown in Figure 1.

The necessary coverage of the stabilized soil was determined using numerical software. The strength of the individual LCC was set in accordance with Norwegian design standards (Statens Vegvesen, 2012). A 3D BIM model of the ground improvement was also established to evaluate the LCC pattern, adjustments to the sheet pile wall and to avoid obstructing future constructions in the ground.

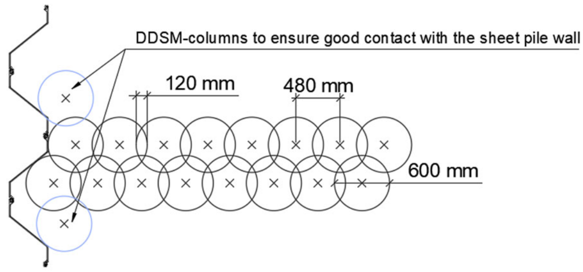

Figure 1. Installation pattern of DDSM with LCC for the Campus Ullevål project

3.3 *Production*

A test field was established to ensure sufficient strength in the stabilized material. Two different mixing ratios for the binder were tested at the testfield; Multicem 50/50 and Multicem 25/75, the numbers corresponds to the amount of cement versus cement kiln dust. Multicem 50/50 showed slightly more consistent results and was chosen for this project.

The required amount of binder content was also verified in the test field. The requirement of an undrained shear strength of 200 kPa for the stabilized material was achieved by a mixing ratio of 50 kg/m^3. In the non-structural parts a mixing ratio of 30 kg/m^3 was used. An illustration is given in Figure 2Figure 3 where the dark grey area shows the structural parts of the ground improvement, while the lighter grey area shows the part of the ground improvement stabilized for construction reasons.

Rotation speed was specified to 175 rpm, and elevation speed to 30 mm/rev.

The DDSM-machine produced text-files for each installed LCC including binder content mixing ratio, rotation speed and elevation speed for segments of 0.1 to 0.4 m.

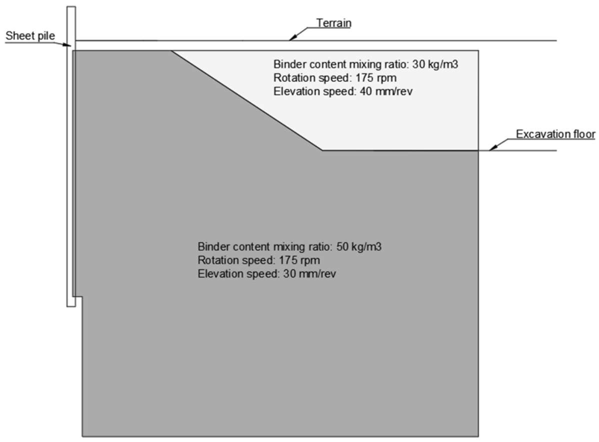

Figure 2. Cross section of a LCC-rib illustrating the design properties of the DDSM.

4 AS-BUILT MODEL AND QUALITY CONTROL

As only a few LCC are tested and verified by in-situ tests, it is recommended to perform an as-built review based on the documentation from the contractor. Based on deviations identified in the as-built review, measures can be taken, such as increased testing or installation of supplementary LCC.

Standard documentation of LCC includes as-built coordinates, stabilized length, average amount of binder content per volume unit per LCC, average rotation speed and elevation speed. Kahlström et al. (2022) describes a workflow for an as-built assessment using parametric design and visual programming for generating BIM-models assessing the need for optimizing the column design based on the retaining wall model, clusters of columns that was shorter than design depth, and areas where the binder consumption could be optimized based on results from field testing.

Looking at average values for, e.g., binder content quantity can give a false impression. There may be segments of the LCC with excessive binder content, while other segments of the LCC have insufficient binder content. If the deviation is due to the ground conditions, this may affect several LCC and a weak zone in a rib may occur. This could affect the LCC rib's ability to act as a stiffener for a construction pit.

In this study, an as-built review based on machine data at the depth is assessed. The text-files from each installed pile are processed in a python script, averaging the values per 1.0 m. The results are then processed in a new python-script making a 3D BIM model visualizing deviations from design parameters. The BIM model uses a traffic light system to illustrate the deviations, the limit for each color varies with the machine parameters and is summarized in table 1. For binder content mixing ratio it is more critical if the mixing ratio is lower than described, and as for the rotation and elevation speed both lower and higher values can result in unsatisfactory results.

Table 1. Color definitions for deviations in the 3D BIM model

Parameter	Design value	Green	Yellow	Red
Binder content mixing ratio	50 kg/m^3	+∞/ −5%	− 5-15%	− 15-100%
Elevation speed	30 mm/rev	±10%	±10-25%	±25-100%
Rotation speed	175 rpm	±25 rpm	± 50 rpm	>± 50 rpm

Figure 3 shows the 3D BIM model for the deviations in the rotation speed. The model shows an area in the north-western area of the site where there were deviations in rotation speed from approximately 5 m depth, and also deviations in length of the piles.

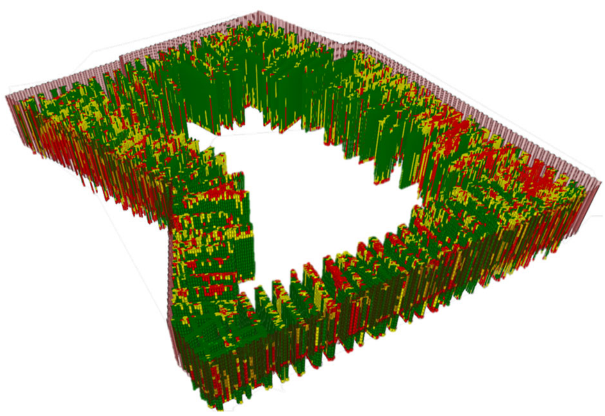

Figure 3. Illustration of 3D BIM-model colorized based on deviations of rotation speed

5 COMPARISON OF MACHINE DATA WITH RESULTS FROM IN-SITU TESTS

For a selection of LCC, the results from the in-situ tests are compared with the machine data with depth. Figure 4 shows an example of machine parameters and shear strength derived from in-situ tests (FKPS-tests) from three LCC. The dashed black line shows some deviation in binder content mixing ratio and rotation speed from approximately 10 m depth. This is reflected in the achieved undrained shear strength, which is reduced from a depth of approx. 10 m. However, for the continuous black line, a significant deviation in rotation speed leads to increased blowout of binder per depth increment, which also leads to an increase in the undrained shear strength achieved.

A comparison of the achieved undrained shear strength from eight in-situ tests in the north-western area of the site is compared with the deviations in rotation speed and binder content mixing ratio. Figure 5 shows the undrained shear strength is plotted with depth. The color of the line corresponds to the color definitions listed in Table 1. There does not appear to be any clear correlation for deviations in rotation speed and achieved undrained shear strength, but it seems that larger deviations rotation speed tend to result in higher undrained shear strength. This may be due to excessive use of binder per depth increment.

In the case of deviations in binder content mixing ratio, there is a slight tendency for small deviations to also result in lower achieved undrained shear strength.

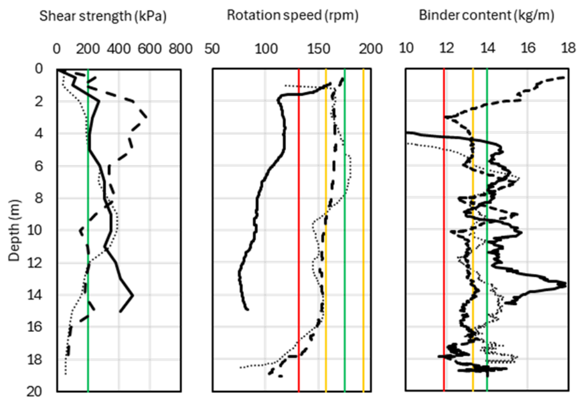

Figure 4. Rotation speed and binder content mixing ratio for three LCC and in-situ tests conducted in the same LCC

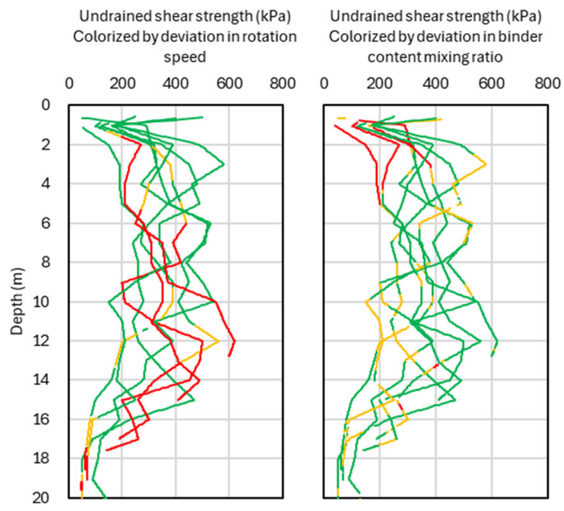

Figure 5. Undrained shear strength from in-situ tests colorized by deviations in rotation speed and binder content mixing ratio

6 DISCUSSION

The extended as-built assessment of DDSM based on machine data gives a detailed visualization of the execution of the LCC and can provide important information to both contractors and designers. However, there are some limitations and concerns with the method.

The as-built assessment divides each LCC into several segments. It is important to point out that even if a segment of the LCC does not meet the specified criteria, this does not mean that the entire column is of poor quality. Rather, the method should be used to see if there are larger, contiguous areas where the parameters do not meet the design requirements. The designer should also consider how the deviations affect the design. Tests of the completed columns may also show that the strength and stiffness of the LCC meet the design requirements regardless of minor deviations in machine parameters.

Geometrical imperfections may contribute to greater displacements and increased structural forces in a retaining wall system (Haugen et al. 2024). The consequences related to geometrical imperfections may influence the quality of the DDSM to a higher extent than minor deviations in the amount of binder content, rotation speed and elevation speed. Today, the DDSM-method for LCC does not include inclinometer measurements and deviations due to geometrical imperfections is challenging to quantify.

Comparison of the as-built review with the in-situ tests shows that there may be some correlation between the strength achieved and deviations in machine parameters. Nevertheless, due to conservative estimates of design strength in accordance with Norwegian practice, all in-situ tests show sufficient strength. As work is being done on ways to verify and utilize in-situ strength in the soil (Helle et. al. 2024; Ritter et. al. 2024), thorough quality controls and as-built reviews will be necessary in the future.

Future work will include examining whether machine parameters and deviations can be correlated to ground conditions and soil types. A future study can look at the possibilities to continuously optimize input data and machine parameters so that progress and material usage in a project can be optimized without compromising strength requirements. Such a study will be somewhat limited if data is only collected from one site, so it is necessary to collect corresponding data from additional sites for future studies.

7 CONCLUSION

At the Campus Ullevål project, DDSM with LCC have been installed to enable excavation and to reduce deformations on the sheet pile wall. As only a few of the LCC are tested using in-situ methods, a comprehensive as-built assessment has been carried out based on machine data for each individual LCC. The LCC are divided into segments of a specified length, and the deviations are presented in a 3D BIM model, making it possible to assess whether there were areas in the ground where measures should be implemented.

In the future, if machine data from several different sites is collected, a study of whether the machine data and deviations can be correlated to ground conditions should be carried out. If there is a correlation, the machine inputs can be optimized, which will contribute to a more sustainable production in the form of reduced material consumption, but also, by changing machine parameters on the rig, it will be possible to optimize progress.

8 ACKNOWLEDGEMENTS

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