

Deep soil mixing from the pontoon with integrated GNSS measurement and online visualization of the drilling position

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ABSTRACT: Satellite-assisted surveying is a matter of course, as it is widely used in different fields of the specialist industry for geotechnical solutions. However, the application of these methods on a rotary drilling rig that produces soil-mixed columns from a floating pontoon that moves with the tides of the Baltic Sea requires new approaches. For the planned investment of a new biorefinery in Timrå, about 400 km north of Stockholm, Sverige BAUER GL AB was contracted to stabilize soft clay layers adjacent to the Baltic Sea. For deep soil mixing (DSM) the single column mixing (SCM) technique was applied, covered by the relevant European Norm EN 14679 for the execution of Deep Mixing. The resulting stabilization of the clays and also quick clay was designed for an increased shear strength to allow for construction of a rubble mound founded on the very soft seabed sediments and underlying compressible soils. The rubble mound serves as a sea barrier for the subsequent land reclamation for a new Biorefinery development. The drill points of the soil-mix columns with their top of column levelled - on average - four meters below the surface of the Baltic Sea, were approached with the help of GNSS using a navigation system integrated in the operator's screen. The elevations were calculated against the tidal range. To measure the mixing tool deviations, the drill rod was also equipped with sensors and the actual position was calculated. With this setup, the equipment operator was able to detect geometric deviations for the soil-mix columns and initiate immediate countermeasures to keep within required tolerances. The information generated was used without media disruption to create the as-built documentation visualized automatically on Bauer's GIS platform. In addition to the georeferenced soil-mix columns, the 3D platform also contains the design and actual execution parameters including production documentations.

KEYWORDS: Offshore, Soil Mixing Method, GNSS Survey, 3D, Online Visualization, Digital Twin

1 PROJECT OVERVIEW

Svenska Cellulosa AB (SCA) is a Swedish forest industry company with headquarters in Sundsvall, Sweden. A new biorefinery is being planned near an existing pulp factory, north of Sundsvall in the central part of Sweden. The scope of this project was to reclaim land using DSM and related earth and marine works. The area for the new biorefinery will consist of the existing land area (app. 150 000 m²) and reclaimed land in Skönviken (app. 50 000 m²), hence app. 200.000 m² total area.

The technical design team and the client have agreed on the application of the single column mixing (SCM) technique to stabilize unstable and cohesive soils beneath the future foundation of the rubble mound. This method is expected to improve the stability and enable construction of the rubble mound on the very soft subsoil. SCM is a well-known technique to stabilize almost all soil types including very soft clays to soft clays, organic soils, and loose sands and is widely applied with decades of experience e.g. in Japan, Scandinavian countries, and in some parts of United States (Porhaba, 1998).

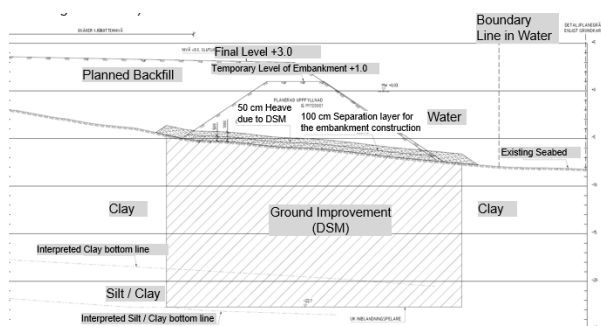


Figure 1: A drawing for anticipated soil layers

The Ground Improvement of the underlying soft clay and silt is required to achieve a sufficient stability for the blast rock backfill operation to construct the rubble mound embankment. Prevailing soil conditions consist of clay with moisture contents ($w=60-70\%$), silt-clay layer ($w=45\%-80\%$) and beneath these layers moraine above the bedrock.

Within the project's scope, 5266 nos Ø800mm lime cement columns and 1 514 nos Ø 3,0 m SCM columns (wet mixing method) were installed.

2 SINGLE COLUMN MIXING (SCM) IN GENERAL

Bauer has developed several soil mixing technologies in the past decades. Each of them has its own advantages and is therefore used for different applications. The developed SCM technique is a soil-mixing process whereby soils are mixed in situ with a binder. The process involves rotation of a single mixing tool (paddle with auger starter) penetrating into the soil while simultaneously injecting the binder. The binder may be delivered in its dry form (dry mixing method) or mixed with water to form a self-hardening slurry (wet mixing method). Both low and high pressure may be applied for the delivery of the binder depending on the system used.

In general, following main steps are considered for SCM column design:

- Binder type and dosage depending on required strength criteria and durability aspects
- Selection of the slurry volume ratio and w/c ratio (wet mix) in relation with the water demand of the prevailing soil
- Selection of penetration and withdrawal rates, and injection rate depending on soil type / desired treatment performance
- Determination of adequate equipment, mixing tool and installation pattern

In this project, binder type (CEM II/A-LL 42,5R) with a content per soil volume of 150 kg/m³ (200 kg/m³ in the quick clay) were pre-determined by the designer. Determination of binder dosage was a challenge due to vastly varying geotechnical properties of upper and lower areas to be treated that require different binder contents and injection ratios. Therefore, site team has worked on an optimization (by increasing the binder content for the quick clay layer by an additional second stroke step) that has allowed adequate treatment of both «upper» quick clay and embedment to the underlying silt layers and enabled a problem-free wet-grab sampling procedure. Selected slurry rates were 1410 l/m for the

silt-clay layer and 1880 l/m for the upper clay (mostly upper 4 m only). W/C ratio of 1.0 was used for the entire treatment area. As per replacement ratio and overlap, 90% and 300mm (between border and their adjacent columns on horizontal lines) were selected respectively for the 3m dia tool, which results in a safer approach.

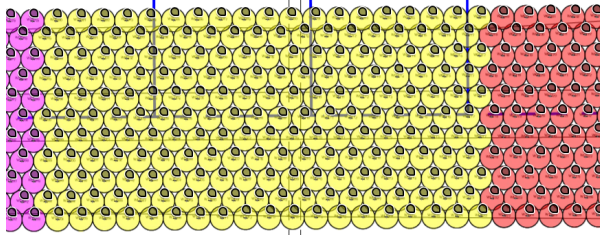


Figure 2: Installation pattern for 3m diameter column

The initial design was a replacement ratio and overlap of 90% and 200mm respectively for the 2m dia tool.

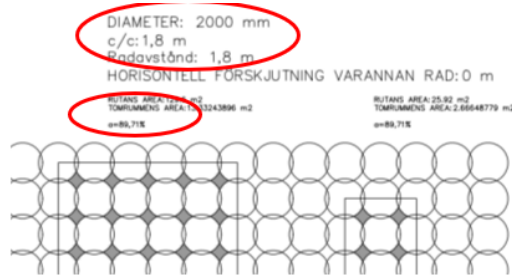


Figure 3: Installation pattern for 2m diameter as per initial design

The driving factor for the project success was the consideration of a 3m dia mixing tool in combination with deployed superior Bauer equipment. Being able to drill with a 3m dia mixing tool enabled reduction of the total drilling quantity from approximately 73.000m to ~22.000 (70% reduction in drilling quantity) with 90% of initial scope executed compared to the initial planning of 2m dia mixing tool diameter, while maintaining the replacement ratio and increasing the overlap substantially. Achieved reduction of drilling quantity is due to larger tool diameter as well as reduced total overlapped lengths.

3 EQUIPMENT

The most crucial aspect for achieving high drilling performance is the selection of the adequate equipment. Bauer has achieved a high production performance owing to a 3m diameter mixing tool, a drilling rig (BG45) that empowers the drilling process with the large diameter tool and mixing unit CMS 45 that can supply ~45m³ binder slurry per hour.

BG45: The mixing tool (No.1) and the rods (No.2) are connected to a rotary drive (No.3). The guiding system (No.4) helps to keep the verticality of the drill string while drilling. The rotary drive provides the required torque to penetrate the tool into the ground and to properly mix the soil with the self-hardening binder slurry.

Mixing tool: A 3m dia mixing tool is placed at the bottom of the rods and consists of: a double-cut starter auger equipped with teeth and round shank chisels, a series of mixing blades/paddles along the bottom part of the shaft, the top blades are equipped with additional cutting ledges in order to ease the withdrawal of the tool, a variable nozzle-ledge for the injection is placed at the back side of the cutting ledges. After the start of the project, to increase the homogeneity of the quick clay, the mixing tool was modified by adding a static bar (Figure 4, right) at the middle of the tool. The improvement was also observed at compressive strength test results, which have increased significantly after the optimization.



Figure 4: Main equipment BG45 (left), optimized mixing tool with static bar (right)

Mixing Unit CMS 45: with a maximum mixing capacity of 45 m³/h; including an agitator tank of 4m³ capacity and two 4NE 80 mohnopumps with a max. delivery rate of 700l/m³ at 24 bars.

4 GNSS MEASUREMENT

4.1 Traditional staking and borehole trajectory determination

In special foundation works, the borehole path is determined, and the starting points are marked out using a tachymeter and an inclinometer, which is guided in a torsion-resistant manner in the drill pipe core. During the drilling process, the centers of the starting points are first marked out using a stationary tachymeter. Once drilling is complete, the deviation in two axes is determined using a reversal measurement to eliminate the probe error by means of an inclinometer, which runs inside the drilling rod. The measurement is usually taken in meter increments. The fixed head point is determined by tachymetric measurement using a prism. In order to adequately determine the rotation of the inclinometer within the rod, it is also necessary to determine the orientation of the inclinometer axes using a tachymeter. For such a measurement, it is crucial that the drill rod remains in a static position throughout the entire measurement process. Determining the drilling path using an inclinometer is a time-consuming task. This is because no further drilling operations are possible during the measurements.

This method is also used exclusively for determining the borehole trajectory in dry environments. On the one hand, no fixed reference point can be marked on the water surface, and on the other hand, direct access to the drill pipe is required in order to lower the inclinometer manually. The tidal range-induced movements of the drilling rig and the waves influence the position of the drill pipe during the course measurement, which can lead to incorrect results for the borehole course.

4.2 Project-specific solution from Sverige BAUER GL AB

Given that setting out and borehole alignment using a tachymeter and inclinometer were not feasible due to the problems described above, an alternative method had to be identified that would ensure sufficient accuracy for the project. The Bauer Assistant Positioning System (B-APS) was identified as the optimal solution. (BAUER Maschinen GmbH, 2017) The system comprises two GNSS antennas (Trimble Zephyr3), which were attached to the mast of the machine, a dual GNSS receiver (Trimble BX992), which calculates the

satellite data received, as well as a radio modem was employed for the reception of correction data from a base station (in the event of a failure of the correction data service provided via NTRIP). The corresponding B-Tronic software module and a number of inclination sensors were also included, situated in both the mast and the drilling rod.

The most significant challenge was determining the precise drilling depth, which was subject to constant fluctuations due to the location of the construction project in the Baltic Sea and the ongoing work on a barge. A bespoke form of depth measurement was developed as a solution, which utilizes the height value of the GNSS receiver. As a consequence of the local transformation and the heights of the fixed points employed in relation to sea level and the known height of the GNSS antennas to the upper edge of the barge (based on the technical drawings and measurements), the height of the upper edge of the barge can be used as the reference height. The drilling depth is determined by taking the top edge of the barge as the reference height and calculating the depth of the drilling tool in meters above sea level, taking into account the additional depth of the drilling tool.

In order to minimize potential mesh stresses in the superordinate coordinate system, a local transformation was initially carried out using a Leica iCG70T rover. A mesh with minimal stress is created using several known 3D fixed points, which have been provided with position coordinates and height data. The number of available fixed points has a direct impact on the accuracy of the local system transformation. It is possible that older fixed points may have undergone a change in position due to external influences, rendering them unsuitable for the transformation. However, the selection of the points in question resulted in a notable reduction in the position and height deviations of the fixed points. Ultimately, the maximum positional deviation of the fixed points was 10 mm, while the maximum height deviation was 9 mm. Consequently, the Mesh layer stresses within the system, which have an influence on the positioning accuracy, were minimized to the greatest extent possible.

A test field was established on land in order to evaluate the positioning accuracy. In order to facilitate the creation of the test field, the target coordinates of the center point of the pillars were marked out as an iron pin using a total station. Subsequently, the drilling rig was relocated with the center of the drilling tool over the previously marked point. A 360° monitoring prism was affixed to the tip of the drilling tool, and its positioning was recorded using a total station when it was positioned over the drill-point, with the recorded values subsequently saved. Concurrently, the data displayed by the B-APS system were recorded.



Figure 5: Leica Total Station TS16 (left) and Stake Points Screen TS16 (right)

Subsequently, the target coordinates were compared with the actual coordinates of the B-APS system, and the target coordinates were also compared with the actual coordinates of the total station.

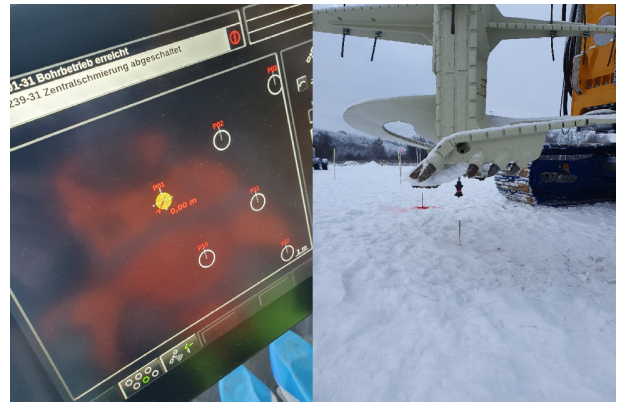


Figure 6: B-APS Screen (left) and Drill Tool with Prism on Target Point

The evaluation of the deviations yielded an average of 2.6 cm in positioning, with a maximum deviation of 5.1 cm (as determined by comparing the total station with the target coordinates). In light of these values and the specifications of the B-APS system, it can be concluded that the system functioned correctly with deviations within considered tolerances.

Point nr	Diff. TP to B-APS			Diff. TP to TS		
	Diff E [m]	Diff N [m]	Distance [m]	Diff E [m]	Diff N [m]	Distance [m]
P00	-0,013	0,010	0,016	0,004	-0,007	0,008
P01	-0,011	-0,009	0,014	-0,014	0,018	0,023
P02	0,016	-0,032	0,036	-0,023	-0,017	0,029
P03	-0,015	0,010	0,018	-0,004	0,051	0,051
P05	-0,015	0,018	0,023	0,004	0,035	0,035
P08	-0,018	-0,002	0,018	0,013	-0,001	0,013
	Average variance [m]			Average variance [m]		
			0,021			0,026

Figure 7: Exhibited deviations during onshore system checks

5 QUALITY CONTROL

Extensive quality control procedures were applied to ensure the SCM works being executed according to the design. BAUER's B-project data management system allows for electronic and simultaneous data acquisition and reporting. With B-project, relevant execution data such as cement quantity, injection volumes at any particular depth, penetration / withdrawal rates, blade rotation number (BRN) as well as verticality can be obtained / monitored / processed.

These production and quality data are automatically transformed into a 3D GIS System, visualizing all DSM-elements with measured deviations and offsets. This data processing reduces complexity of mass data and visualizes the production for site engineers and for the client. The automated evaluation allows immediate quality checks and helps to prevent consequential defects.

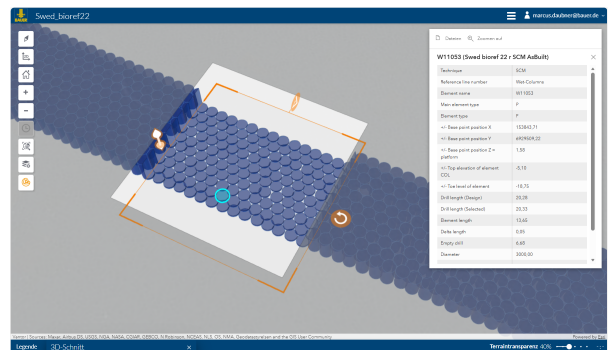


Figure 8: BAUER GIS Portal – automated 3D As-built Visualization

Initial quality requirements were as follows:

- Horizontal position tolerance ±0,1m
- Vertical position tolerance ±0,2m

- Vertical deviation $\leq 0,01\text{m/m}$ (1%)
- Blade rotation number (BRN) > 400 r/m
- Nominal column strength $C_{crit} > 115$ kPa
- Slurry recipe 150kg/m^3 ; w/c 1,0 ($\pm 3\%$ tolerance)

With help of BAUER's B-project system also the horizontal and vertical position tolerances and vertical deviation were successfully verified for conformity. Despite initial challenges at quick clay, by means of a double stroke in that particular layer, sufficient BRN and visual homogeneity (at wet-grab samples) was achieved for all layers.

Sampling activities such as coring and wet-grab sampling was the responsibility of the client's subcontractor. Bauer has supported the project site by providing its wet-grab sampling equipment that can be attached to the drilling machine. In total 197 wet-sample series from 89 columns, in addition 23 cores were sampled throughout the project.



Figure 9: Wet-grab sampling from fresh executed columns

Laboratory results show that all samples were hardened, and the results from QC testing exceeded the project requirements.

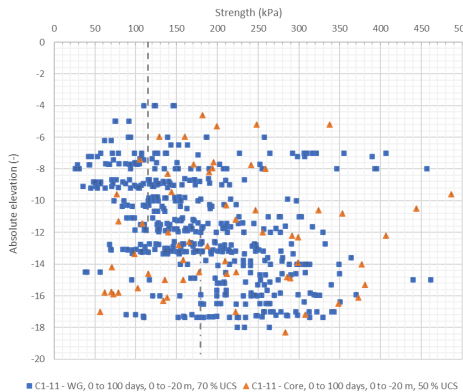


Figure 10: Shear strength C_u results from wet-grab and cored sampling (all testing ages)

Taking the further hydration of cement into account, even greater results are anticipated. In the study, Ahnberg (2006) carried on various clay soils in Sweden and determined that a UCS development of > 2 times can be expected, for standard cement as binder.

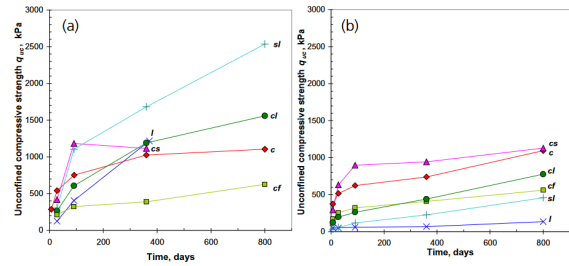


Figure 11: Examples of measured strength with time after mixing for (a) Löftabro clay and (b) Linköping clay with cement, lime and various composite binder (50:50). c = cement, l = lime, s = slag, f = fly ash. Binder quantity 100kg/m^3 . After Paper II.

6 CONCLUSIONS

A 3m-diameter mixing tool in combination with Bauer's drilling and mixing equipment has enabled reaching outstanding drilling and mixing performances. The adjustments of mixing tools and optimization of execution parameters during the construction with the help of Bauer's execution and off-site support teams have led to steady improvements of performance and quality, which were the key to complete the project with success. Integrated GNSS measurement on the drilling rig working on a barge required advanced know-how and qualified personnel on-site, which was provided by Bauer's Technical Support division.

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