TEST FIELD OF WET DEEP MIXING IN KRISTIANSTAD FOR RECONSTRUCTION OF EMBANKMENT DAM

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SUMMARY

The reconstruction of Hammarslundsvallen dam requires ground improvement capable of penetrating dense berm fill and stabilizing of soft cohesive soils down to 20-meter. A full-scale Wet Deep Mixing field test was conducted to verify installation tolerances, equipment performance, and optimization of soil improvement mix design. A bench-scale testing was performed with an extended water–binder ratios, grout volumes, and workability limits to define mixability and strength criteria prior to the test field program. A total of 21 columns, each 2.0 m in diameter, were installed within the specified verticality tolerances. CPT, FKPS, wet-grab sampling, and core drilling were carried out in the test field to evaluate the effects of construction parameters and mix design on column homogeneity and strength characteristics. The field test results demonstrate that a full-scale WDM trial is the most effective approach to optimize mix design, verify execution tolerances, and reduce design uncertainty, while establishing a structured testing framework for quality control.

1 INTRODUCTION

Kristianstads kommun (Kristianstad Municipality) is currently undertaking the reconstruction of Hammarslundsvallen; an embankment dam, that protects significant parts of the city of Kristianstad from being flooded. At the time of writing, detailed design is ongoing; including both the foundation works and a new earth-fill dam. GeoMind has been commissioned to lead the design of the foundation works, and following a successful tender process, Keller was engaged to carry out a full-scale field test.

This article focuses on the lessons learned, and the value generated, by performing a full-scale field test, as a complement to laboratory/bench-scale testing. The objective has been to improve the understanding of actual in situ performance for various mix designs. More detailed descriptions regarding geotechnical site characterization, the historical development of the dam, and the proposed new structure are available in project documentation published by Kristianstads kommun (2024; 2025). A short summary is provided in this paper.

1.1 Background

Hammarslundsvallen was originally constructed between 1860 and 1870, for the purpose of land reclamation. A significant area of arable land was created, within what had previously been a bay of Lake Hammarsjön. The original embankment was built using locally sourced materials, consisting of sandy glacifluvial sediments from Udden at the western abutment and sandy silty till from Ekenabben in the east.

An overview of the site and its surroundings is shown in Figure 1, while Figure 2 presents Hammarslundsvallen as it appears today.

Figure 1 Overview of the southeastern part of Kristianstad, indicating the location of Hammarslundsvallen and the former extent of the lake.

As Kristianstad developed, Hammarslundsvallen gradually transitioned from protecting farmland to safeguarding infrastructure of regional importance, including the wastewater treatment plant, the hospital, the highway E22, and residential areas situated below sea level.

To improve dam safety, a new earth- and rockfill dam was constructed downstream of the original embankment in 2003 – 2004, following a severe high-water event and concerns about structural stability.

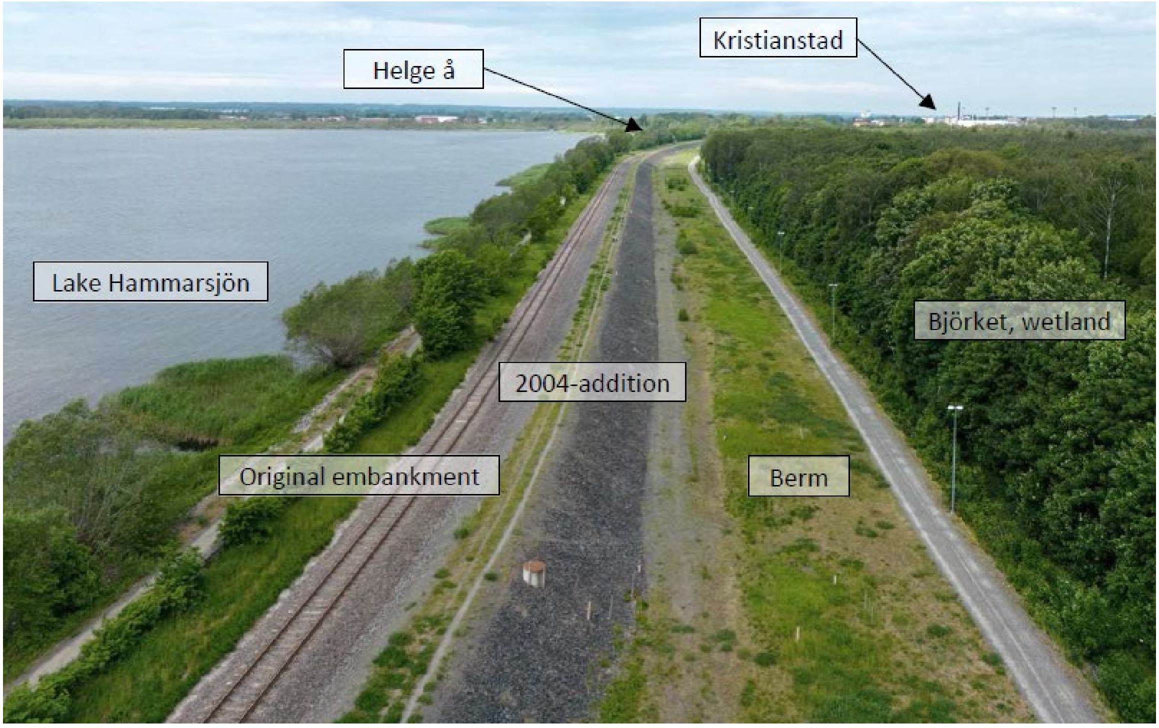

Figure 2 Overview of the embankment dam, its main components, and surroundings. The foundation works for the planned new structure will primarily be executed on the existing berm.

The 2004-addition was designed without any ground improvements. Stability was achieved by means of an extensive downstream berm, while the anticipated large settlements were to be managed through an active design approach during construction.

Unfortunately, the concept did not perform as intended (Kristianstads kommun 2024; 2025), ultimately leading to the decision to reconstruct the dam. This time with a robust foundation.

1.2 Foundation design choices

Regarding environmental, geotechnical and practical considerations, the existing berm was identified as the most suitable location for the new dam. This solution minimises the impact on the surrounding environment, while the berm itself provides a competent working platform. Having preloaded the underlying soft soils for approximately 20 years, it has also contributed to a significant strength increase.

Several foundation alternatives have been evaluated over the years, including various piling concepts, soil improvement by deep mixing, and extending the existing berm while continuing with an active design approach. In summary, deep mixing was selected due to its apparent cost advantages compared to piling, and a completely different level of robustness, relative to continuing the active design strategy, which has proven problematic over the past two decades.

However, what initially appeared to be a somewhat straightforward application of the conventional Swedish dry deep mixing (DDM) method, commonly referred to as lime-cement columns (*KC-pelare*), revealed several technical limitations.

The existing berm is made up of a heterogeneous mixture of sandy silty soil from previous excavations in the old embankment, and a 0 – 200 mm fraction of crushed rock. Hence, the berm is not readily penetrated by the typical Swedish DDM slender mixing tool and rod, necessitating substantial staged earthworks, replacing the working platform.

Furthermore, deep mixing is required to depths of up to 20 m in a shear wall configuration to ensure the stability of the proposed dam. Whether slender columns installed in double rows fulfil this requirement is up for debate…

From a cost-efficiency perspective, achieving a higher design strength, than what is typical for soft columns ($s_u \leq 150$ kPa), would be very advantageous. However, for this to be technically sound and credible, the homogeneity of the improved soil becomes significantly more critical.

These challenges ultimately led the municipality, with strong support from its third-party reviewers, to explore alternative solutions. The internationally established relative to DDM, wet deep mixing (WDM), emerged as a promising option. This was not necessarily due to the wet mixing aspect (slurry vs. dry powder); but rather because WDM typically employs more robust installation equipment.

1.3 Design requirements for WDM at Hammarslundsvallen

For WDM to be considered a viable alternative, a set of key requirements were defined:

- Execution of the method must be performed from the existing berm, penetrating up to 3 meters of relatively coarse and compacted fill.
- The spatial deviation at approximately 20 m depth must be measurable and limited, to avoid excessive overlap and gaps between adjacent columns.
- The columns must demonstrate adequate mixing and homogeneity; to be verified through both qualitative, and quantitative methods.

These requirements collectively imply that a full-scale field test is necessary to verify the suitability of the method for the project.

Finally, it is worth noting how closely some of these requirements align with the suggestions put forward by Kriege and Forsberg (2025), regarding when WDM may be considered as an alternative to DDM.

2 GEOTECHNICAL CONDITIONS

Apart from the aforementioned man-made ground (berm), the crossing of the historical bay comprises a wide variety of soils, including gyttja, clays and silts. However, this variety is primarily depth-dependent (z), which is consistent with the regional geological formations. Along the dam alignment (x, y), the main lateral variation is the undulating upper boundary of the till and glaciofluvial sandy deposits, which rise towards the abutments at Udden and Ekenabben, illustrated in Figure 3.

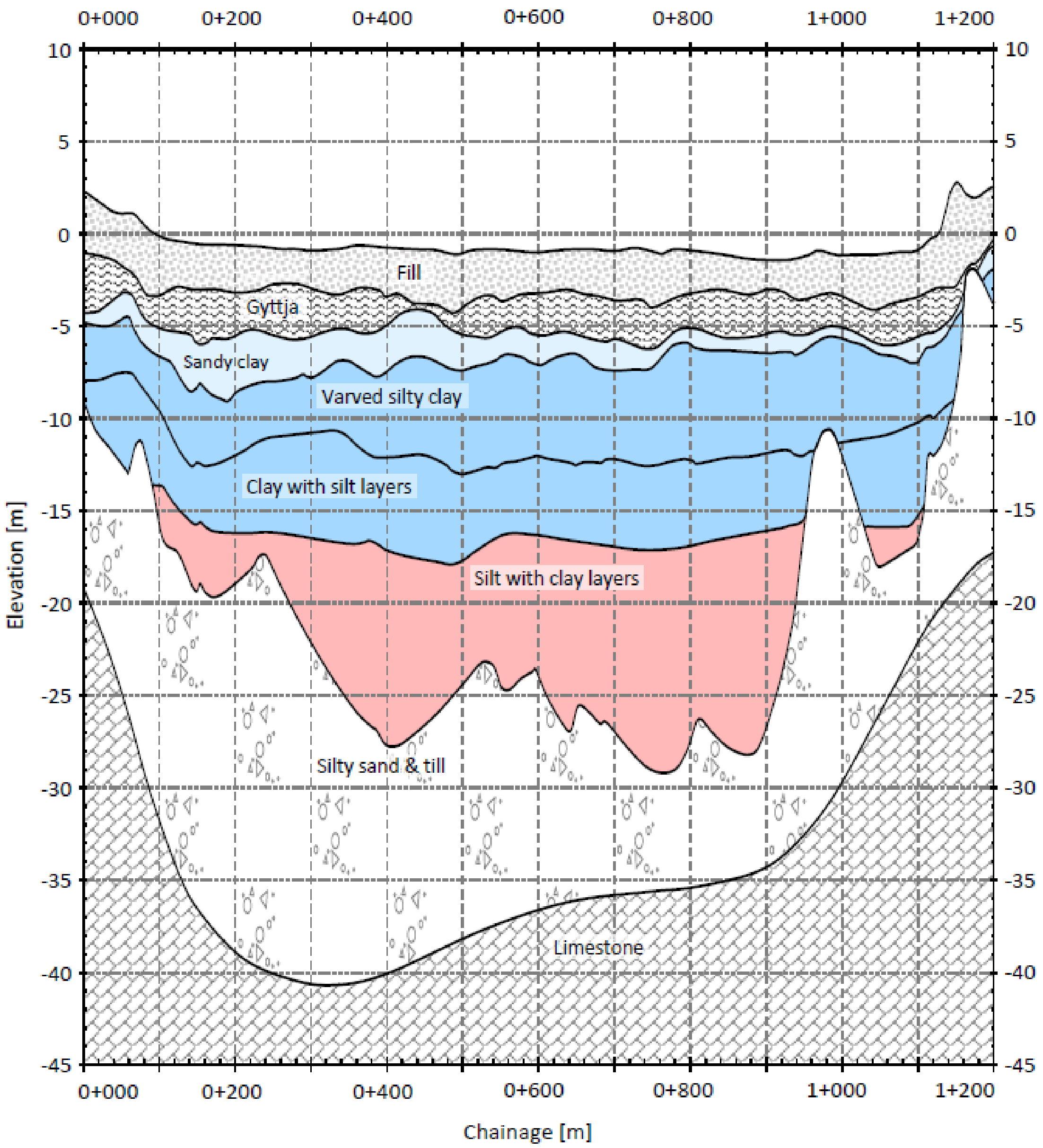

Figure 3 Geotechnical profile, corresponding to proposed dam.

The maximum combined thickness of gyttja, clay and silt along the alignment is approximately 30 m, while the average thickness is closer to 20 – 25 m.

Table 1 summarizes selected geotechnical parameters representative for the cohesive soils influenced by the berm. Representative profiles of undrained (UD) strength are provided as Figure 4.

It should be noted that, for all the layers except the gyttja, the in-situ water content is practically equal to the liquid limit. In contrast, the gyttja exhibits a significantly lower in-situ water content relative to its liquid limit, due to the compression induced by the berm.

Table 1 Summary of soil layers, and key geotechnical parameters.

Soil layer	General thickness [m]	Liquid limit, w_L [%]	Plasticity index, I_P [%]	Bulk density, ρ_m [t/m^3]	Sensitivity (vane), $S_{t,v}$ [-]	UD shear strength, s_u [kPa]
Fill	2	-	-	-	-	- (1
Gyttja	2	350	170	1,15	3 – 5	20
Sandy clay	2	40	15	1,80	3 – 5	- (1
Varved silty clay	5	70	45	1,65	5 – 8	15 (2
Clay with silt layers	5	65	40	1,70	3 – 7	20 (2
Silt with clay layers	7	40	15	1,80	3 – 5	30 (2

1) For material behaviour, the soil layer is generally considered drained

2) Corresponds to an average value, there is generally a linear increase with depth

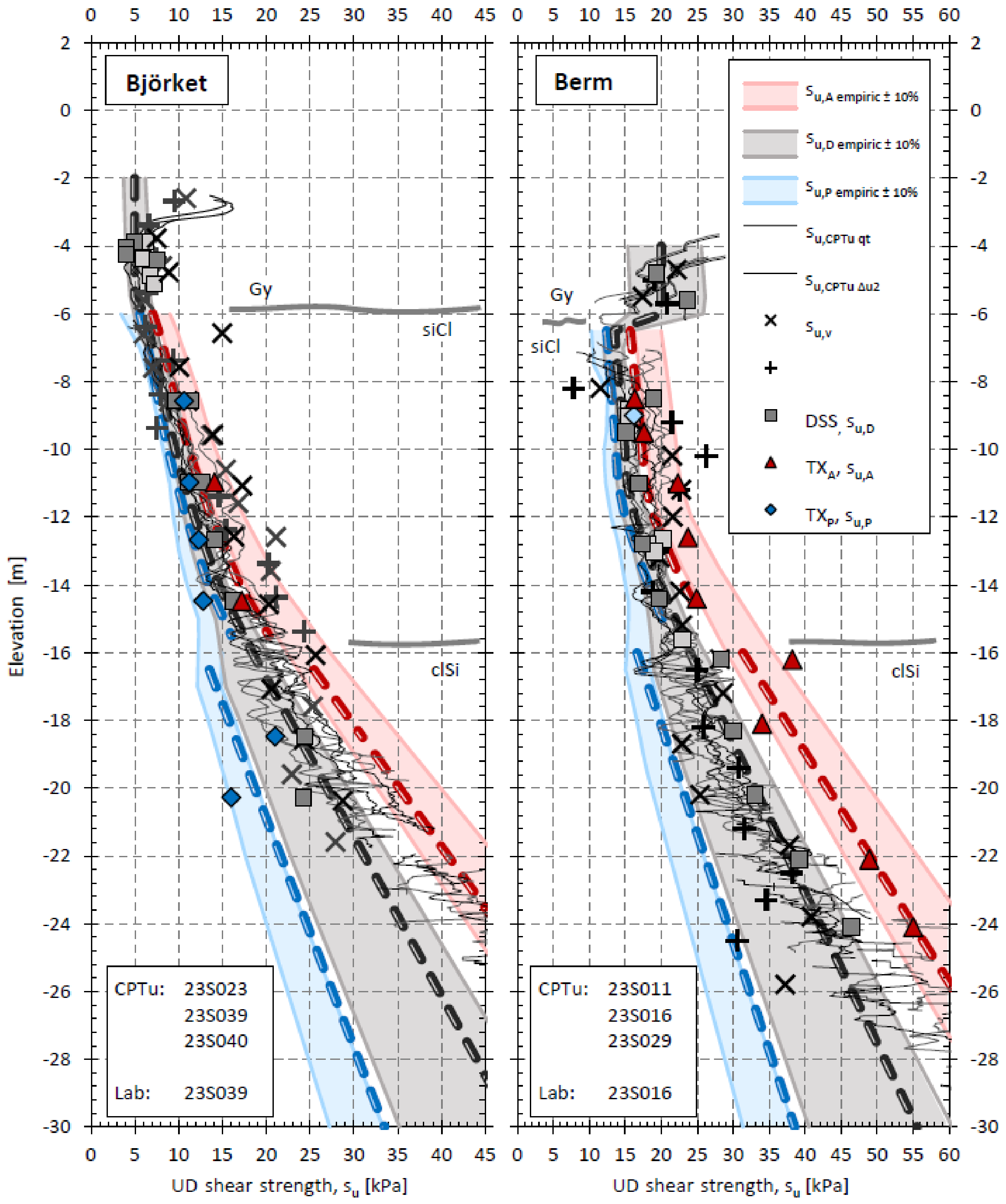

Figure 4 UD shear strength profiles for the downstream wetland area Björket and the berm.

3 TESTING PROGRAM

3.1 Bench scale test (Laboratory test)

As a key pre-field validation step under Federal Highway Administration guidance (FHWA, 2013) for WDM, the bench-scale test was performed prior to test field operation at site, focusing on silty clay and silt with clay layers due to fact that upper layers (gyttja, sandy clay) are foreseen to be mixed easily and less dependent on the execution and mix design parameters for getting homogenized column. Having bench scale test in the test field scope added the value as it's genuinely different from standard laboratory testing done for determination of binder dosages and water-binder ratio (w/b) in Sweden. The key facts forming this difference are summarized as follows:

- Broader range of w/b and grout volume with respect to soil volume address the workability challenges that may appear in-situ (flow table test, Figure 5)
- Defining the borders of strength of soil-grout mixture with abovementioned parameters (UCS tests, Figure 6)
- Providing relevant soil to a geotechnical contractor to incorporate practical field expertise into mix evaluation and simulate in the laboratory conditions to improve test field program beyond purely laboratory-based assessment
- Pocket penetrometer testing bringing early performance evaluation of soil-grout mixture (Figure 5)
- Determining the thresholds at which mix becomes more homogeneous or begins to adversely affect mixing efficiency which is a basis for test field program

Figure 5 Pocket penetrometer on soil-grout mixture specimen (a), Flow table and measurement on soil-grout mixture after preparation (b)

Figure 6 UCS test on specimens with strain-controlled loading device and failure of specimens

In total 12 different mix designs were applied in the bench scale program of which UCS results were summarized in Table 2. CEM II 52.5N with slag content (up to 21%) was used in the most of mixes as it may help improving long-term strength by enhancing the internal structure of DM in clayey soils (Kitazume, 2005).

Table 2 Summary of bench scale UCS test results for different soil samples

Soil layer	Cement dosage (kg/m3)	w_{total}[(1)]/binder	UCS at 14th days (kPa)	UCS at 28th days (kPa)	UCS at 56th days (kPa)
Varved silty clay and clay with silty layers	80-120	5.9 to 8.8	300/410	400/750	330*/750
Silt with clay layers	80-120	5.6 to 8.8	150/680	210/1100	330/1230

(1) w_{total} = Total water mass in soil and slurry

3.2 Test field

The test field at the embankment dam in Kristianstad serves to evaluate and optimize the selected technique, Wet Deep Mixing process before finalization of design for the project and full-scale construction. The purpose of the test field is to determine the mix design from the strength and execution aspect, assess the method's feasibility with existing fill materials, verify column installation tolerances, analyse early-stage hardening and strength development with respect to time. In total 21 columns with a diameter of 2.0 meter and depth of 20.0 meter were executed. The layout of the test field is given in the Figure 7. The mix design and recipes planned in the test field was expanded by mutual agreement based on the observations and results obtained in the bench scale stage as well as on the proposals included in the tender documents based on laboratory investigations.

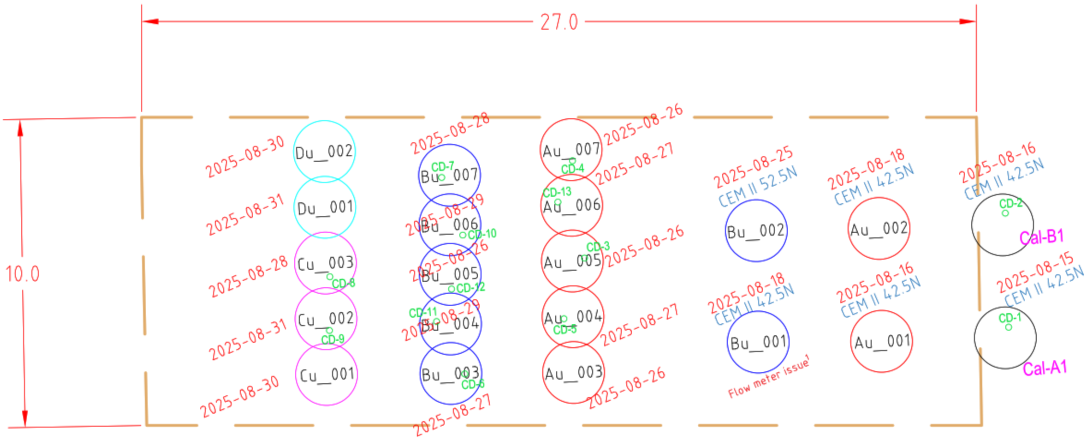

Figure 7 Layout of the test field columns

The execution of the columns were performed with a deep mixing rig weighing 100-ton with a setup comprising a pump, silos, mixer, agitator, and auxiliary equipment in Figure 8.

Figure 8 Drone picture showing test field with WDM

The test field was conducted not only focusing at different mix design, but also different execution techniques were implemented in the field test with aim of increasing homogeneity and productivity. In total, 8 different mix designs and recipes with varying cement dosage, water/binder ratio were applied.

Installation tolerances were controlled by a sensor attached to the mixing tool and measurements of deviations with respect to tolerance limit are summarized in Figure 9 and Figure 10.

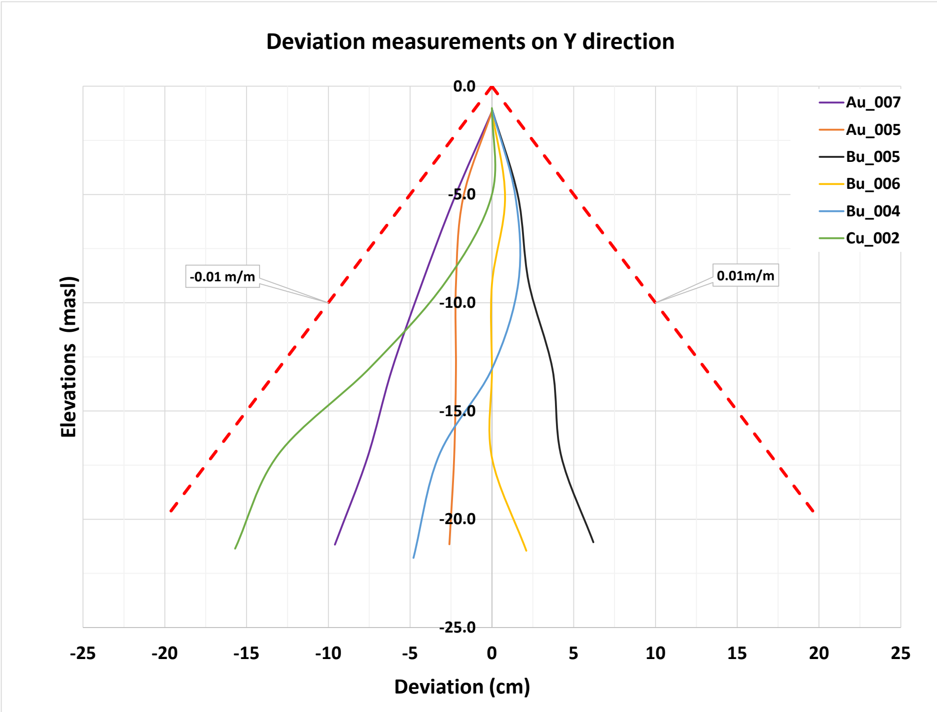

Figure 9 Deviation measurement on Y direction and limits specified for test field

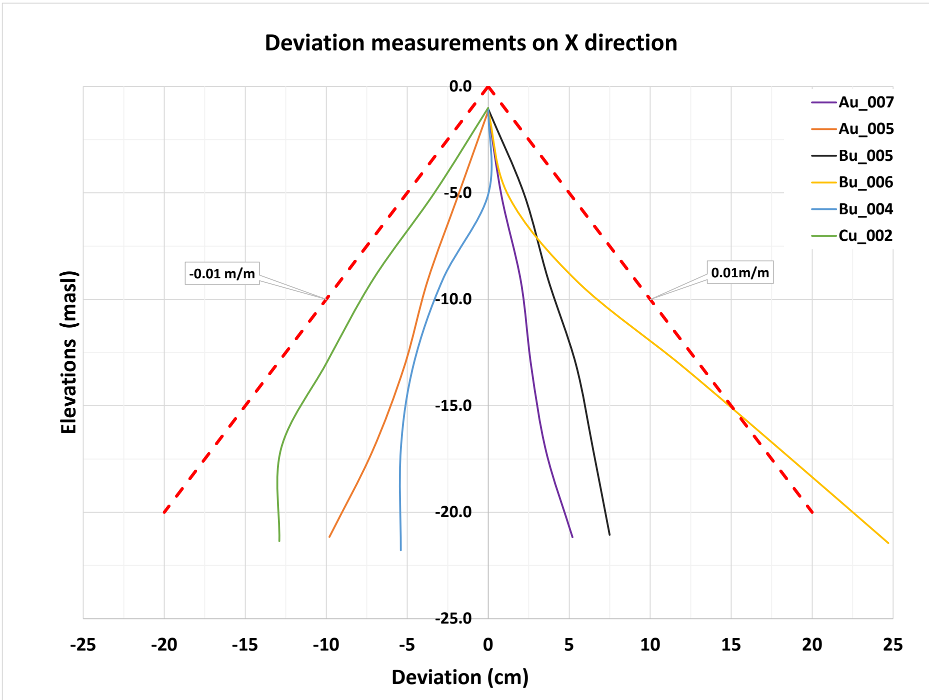

Figure 10 Deviation measurement on X direction and limits specified for test field

4 RESULTS FROM TEST FIELD COLUMNS

In the test field, there were several testing methods implemented to fulfill the purpose of the field test, which are summarized hereunder.

- Wet grab sampling (Figure 11) with respect to different soil layers and depths and preparation of specimens for UCS test and seismic tests
- Full length core drilling with Geobor-S method and selection of specimens for UCS test
- FKPS and CPT tests at the early age of columns
- CPT tests after core drilling work were done (between 100 to 150 days after execution).

Figure 11 Wet grab sampling with a tool attached to the rig and specimen preparation

An example of undrained shear strength (c_u) derived from UCS testing of wet grab and core drilling specimens is presented in Figure 12, representing results from two columns. The figure also includes the CPTu tip resistance profiles corresponding to these two columns for comparison. The c_u values obtained from the core drilling specimens are relatively uniform with depth, ranging between 600 and 800 kPa. Although the dataset from the wet grab specimens is limited to depths corresponding to those of the core samples, the measured c_u values are comparable and show no significant deviation from the core drilling results.

Interpretation of the CPTu data indicates higher undrained shear strength values, with c_u estimated to be approximately 1000 kPa.

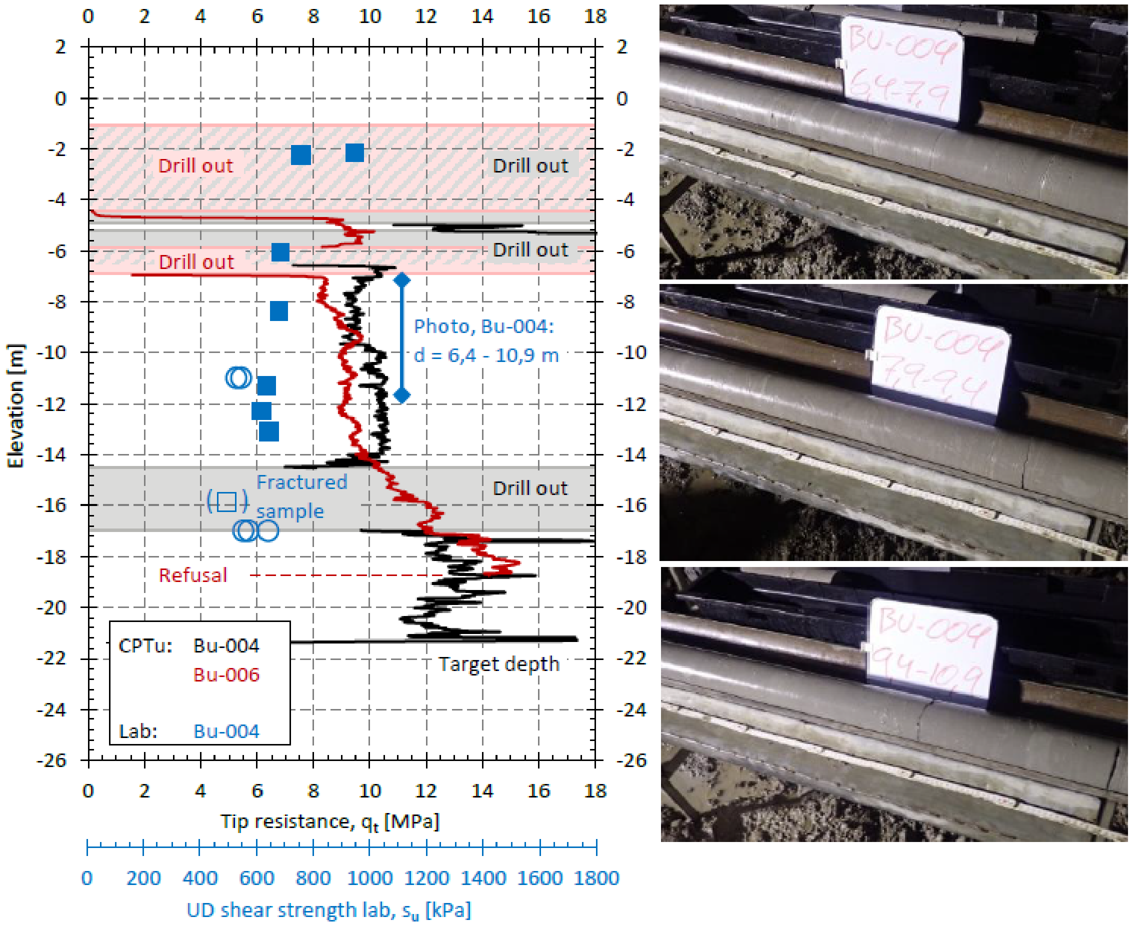

Figure 12 (Left) preliminary results from in situ and laboratory testing. (Right) photos of cores obtained from column Bu-004. Laboratory testing was performed between 100 and 150 days after installation and includes core samples (boxes) and wet grab specimens (circles).

5 CONCLUSION

Based on the comprehensive test field program, the following technical conclusions support the project design and construction strategy:

- Full-scale trials validated execution tolerances under challenging ground conditions; however, data acquisition was limited operationally and should be enhanced during production.
- The test field confirmed that WDM can penetrate 2–3 m of dense, compacted fill and achieve target depths of 20 m within specified verticality and positional tolerances.

- Limitations of conventional DDM namely restricted penetration through compacted fill, concerns regarding column integrity, and uncertain deep shear-wall performance, justified the selection of WDM for ground improvement.
- Bench-scale testing contributes the test field from the more common practice which requires input from abroad to modify and extend the conventional tests.
- Early involvement of an geotechnical contractor contributed positively to practical test field design and methodology refinement.
- In WDM, performance is governed not only by strength but also by homogeneity and mixability, controlled by rotation speed, penetration/withdrawal rate, water–binder ratio, and execution techniques (e.g., mixing cycles, water pre-cut). These are some of the significant differences to DDM technique.
- CPT and FKPS testing proved effective for early-stage strength assessment.
- Wet-grab specimen preparation was affected by low grout volumes and soil plasticity (Atterberg limits), introducing additional variability in test results. The methodology should be refined or updated depending on soil conditions.

Overall conclusion from this test field confirms that the full-scale field test program for WDM technique is an effective way to refine mix design, validate execution tolerances and reduce design uncertainties as well as structure a robust test program which will be part of quality control stage.

6 REFERENCES

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