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Lime cement columns in alluvial soft soil

Colonnes de ciment et chaux dans le sol alluvial

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ABSTRACT
This paper deals specifically with the improvement, on land, of soft silty clay and highly organic silty clay through the addition of cementing agents, by means of dry mixing. Lime and different type of cement have been employed and the improvement measures on cylindrical laboratory-mixed specimens has been followed up for a certain period of time. It has been found that blast furnace cements work rather well for both soil type. In the field, instrumented trial embankments built both on improved and on non-improved ground have put on view the benefit of different binder dosages with L-C columns installed. Moreover, the actual improvement on site of the soil columns and the effects of the column installation on the soil nearby have been assessed by field testing.

RÉSUMÉ
Ce papier concerne l'analyse de nouvelles expériences d'amélioration de sol limoneux et argileux, fortement tourbeux. Il s'agit d'un traitement des couches de sol en profondeur au ciment et à la chaux, utilisant différents types de ciment et de mélanges ciment/chaux. On a pu vérifier et analyser le comportement, aprés malaxage, d'échantillons au labotatoire d'un côté et des colonnes sur terrain et sous remblais de l'autre côté. En plus on a mis en évidence l'opportunité de l'útilisation de certains mélanges ciment/chaux et de la quantité minimale des agents L-C ciment/chaux nécessaire à ameliorer remarquablement la résistance et la rigidité de couches de sol sur place.

1 INTRODUCTION

The Deep Mixing (DM) method with binders for stabilization of soft soil was introduced about 3 decades ago in the Scandinavian countries and Japan, almost simultaneously. Back then, lime (mainly in Europe) or Portland cement (mainly in Asia) were implemented, while the binder was added in the dry or wet in slurry, respectively.

Today, due to the growing demand for soil improvement and for more challenging applications, a broad range of methods can be recognized. The large number of existing DM techniques have been classified by Bruce (2001) on the basis of the state of the binder: wet (W) or dry (D); mixing technique: pure mechanical rotary energy (R) or enhanced with high-pressure jets (J); mixing tool action: mixing blade only at the tip of the drilling tool (E) or along the shaft (S) over a significant length.

In the present project, the method implemented in the field could be classified as a DRE, for indeed a dry composite binder is transported by compressed air through a nozzle located just above the mixing blades. The mixing process is therefore mainly mechanical.

A research project is currently in progress at Ghent University with the aim of studying the performance of DM methods in Flemish alluvial soils,. Laboratory and field testing on stabilized soil to evaluate the improvement and column installation effects have been carried out.

2 CHARACTERISTICS OF THE UNTREATED SOIL

The soil profile at the test site (located in Ghent) for the implementation of L-C column improvement has been defined after an extensive field and laboratory testing campaign.

The testing program consisted of a number of piezocone penetration tests, vane tests, dilatometer tests and borings for sampling of disturbed and undisturbed specimens.

The CPT soundings have clearly shown the presence of soft alluvial soil in the upper 8 m of the profile overlying a clayey sand formation (Tertiary). Moreover, the soft layer is not homogeneous; it shows two main sub-layers, corresponding to silty clay with sandy seams (from 0 to about 4 m below ground surface) and a highly organic silty clay (from 4 m to about 8 m below ground surface) with a sand content increasing with depth. Figure 1 shows a typical CPT profile and the OCR estimated by DMT. In the following paragraphs, the highly organic silty clay is denominated "peat" for simplicity.

2.1 *Physical properties*

Disturbed samples taken at several depths from the silty clay and highly organic silty clay (peat) have been tested on physical properties. Some parameters of each soil type are summarized in table 1.

2.2 *Mechanical properties*

The undrained shear strength of the silty clay and the peat at the testing site has been determined by means of CPTU soundings, field vane tests, dilatometer tests and triaxial testing. Figure 2 summarizes all measurements. The undrained strength profile in the figure shows that c_u ranges, in general, from 20 to 40 kPa. The lowest values do obviously correspond to the peat.

Table 1. Physical properties of the untreated soil

Index	Silty clay	Highly organic silty clay
Liquid limit	65.5	241.8
Plastic limit	22.8	135.0
Plasticity index	42.7	106.8
Natural water content	45.0	240.0
Organic content	1.7	18-30
Natural $CaCO_3$ content	5.1	11.2
Sand fraction, %	28.3	29.0
Wet density, g/cm3	1.7	1.2

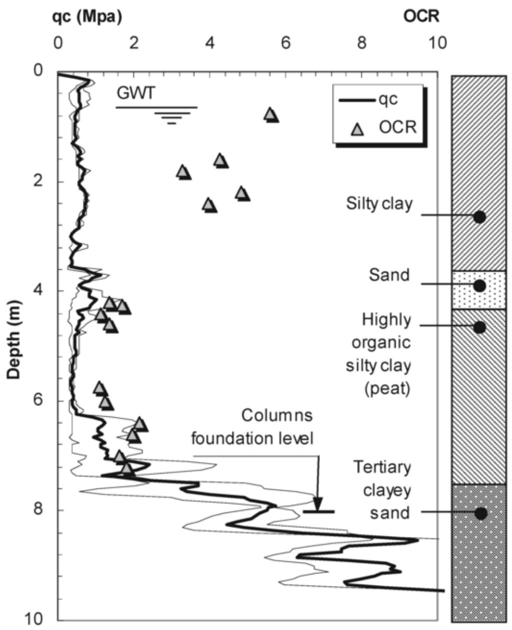


Figure 1. Natural soil profile at the test site.

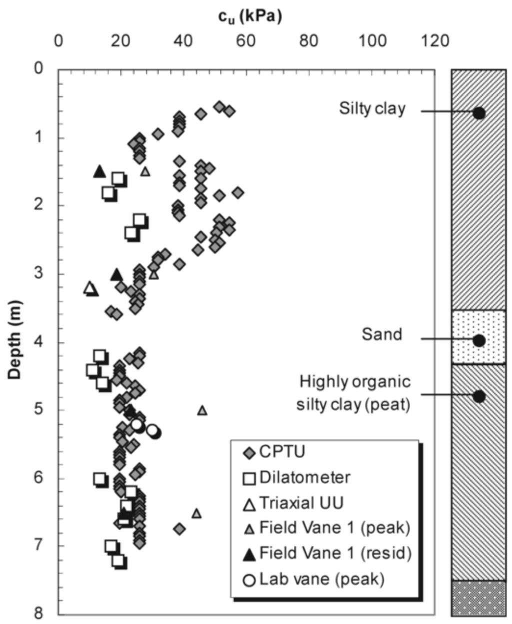


Figure 2. Undrained shear strength profile of the natural soil at the site.

3 BINDERS

In this project, quicklime and cement have been chosen as binders; however, different types of cement have been tried out (i.e. Portland cement, CEM I, composite cement, CEM II, and Blast furnace cement, CEM III). The name listing employed here complies with the standard EN 197-1; for example, CEM I 42.5 refers to a Portland cement with a nominal compressive strength of 42.5 MPa.

Lime and cement have been employed in different proportions (i.e. L/C 50/50, 20/80, 0/100, percentages in weight). Dry mixing was implemented in the laboratory as well.
The quantity of binder has been set to a range varying from 100 to 200 kg/m^3 (kg of binder per m^3 of natural soil). CEM I, CEM II and CEM III have been employed for the stabilization of silty clay. On the other hand, CEM II and CEM III have been used in case of the peat.

4 LIME CEMENT STABILIZATION IN THE LABORATORY

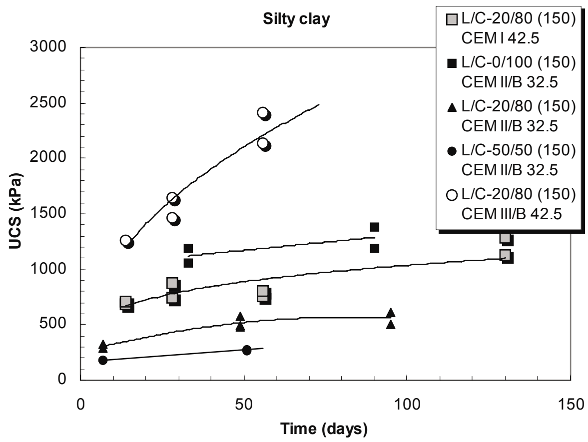
4.1 *Preparation of specimens*

The natural soil samples collected from a number of borings have been first selected (for each zone) and then thoroughly homogenized prior to stabilization in the laboratory. A dough mixer has been employed in the laboratory for mixing of natural soil with the binders (added dry). A mixing time of about 5 minutes was implemented. Immediately afterwards, small specimen (H = 9 cm, ϕ= 4.5 cm) have been molded either by static compaction (for silty clay) or by pouring (for peat) into plastic split cylindrical molds.

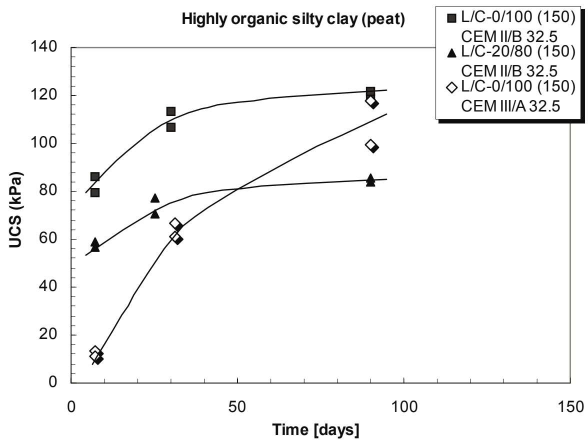
The stabilized specimen have been sealed with paraffin and stored under water in a conditioned room at 20°C.

4.2 *Unconfined compression tests*

Unconfined compression (UC) tests have been carried out at specific time intervals up to 90 days after the preparation of the



(a)



(b)

Figure 3. UCS of (a) silty clay and (b) highly organic silty clay, mixed in the laboratory with a binder dosage of 150 kg/m^3.

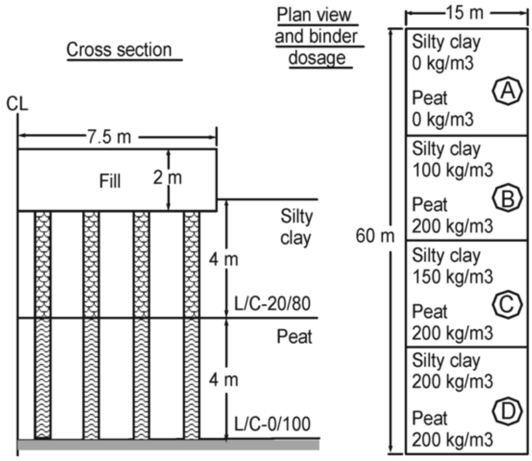


Figure 4. Layout of the trial zones of the embankments (A, B, C & D).

stabilized specimens (cfr. Verástegui et al., 2004). Some results have been summarized in Figure 3.

Figure 3.a shows that the combination L/C-20/80 with blast furnace cement leads to the highest UC strength (UCS) for stabilized silty clay. In fact, a ratio UCS_{stab} / $UCS_{natural} \cong 40$ has been reached in 60 days with a dosage of 150 kg/m3; moreover, the UCS seems to still increase.

On the other hand, the combination L/C-20/80 with Portland cement shows little extra improvement after the first month; nevertheless, the ratio UCS_{stab} / $UCS_{natural}$ reaches a value of the order of 12. The composite binders with CEM II/B do show that, the higher the ratio of quicklime/cement the smaller the UC strength; however, quicklime plays a very important role on the quality of the mix, as the scatter of UCS decreases with an increasing amount of lime.

Figure 3.b illustrates the development of the UC strength of stabilized peat with time. Clearly, the benefit of the lime here was less significant for the strength and mix quality. The UCS improvement on samples stabilized with CEM II/B seems to cease after 1 month, while specimens mixed with blast furnace cement, CEM III/A, show a slow but continuous increment. A ratio UCS_{stab} / $UCS_{natural}$ ranging from 2 to 3 has been evaluated after 90 days. Note that the specimens have not been subjected to any overburden in the curing stage.

5 LIME CEMENT STABILIZATION IN SITU

To the extent of controlling the quality of the DM method itself in the field, a number of trial stabilized columns, ϕ = 0.6 m, were installed on the test site with the dry mixing technique (more details were reported by Verástegui et al., 2004).

In the installation phase, the dry composite binder has been injected, by means of compressed air, at pressures not higher than 5 bar through a tubing down to the mixing tool. The DM column is formed below the mixing tool lifting the mixing auger while rotating continuously.

From the laboratory research outcome, it was decided to use a combination quicklime/blast furnace cement (CEM III/B 42.5) at L/C-20/80 for silty clay and at L/C-0/100 for peat.

5.1 *Loading of trial embankments*

Four trial zones of embankments were built on top of the DM zones. The aim of these loading tests was to study the response of columns improved with different binder dosages. Figure 4 illustrates the general layout of each embankment and the dosage per specific soil layer. Note that the dosage for the peaty layer was fixed to 200 kg/m^3 in all zones. The spacing (axis to axis)

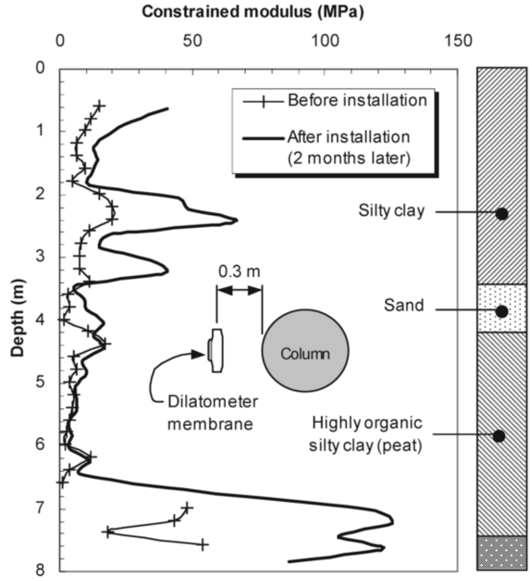


Figure 5. Evaluation of installation effects on adjacent soil within the trial embankment columns.

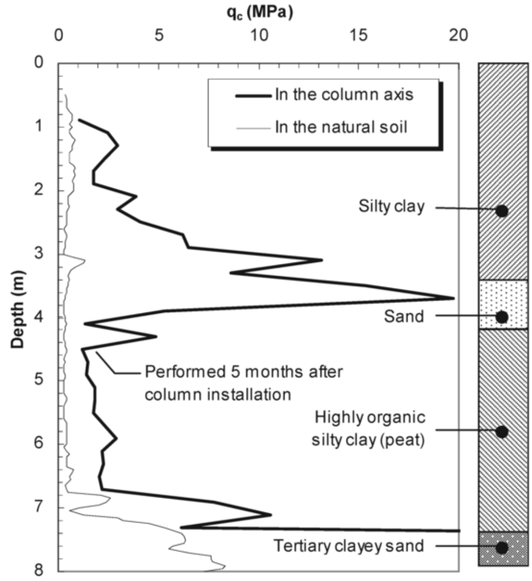


Figure 6. Evaluation of the improvement in situ by means of CPT on a column from embankment C.

between columns was set to 1.8 m in a triangular arrangement. In each zone, the embankment fill aimed at a net surcharge of 30 kPa.

5.2 *Evaluation of installation effects around a column*

Figure 5 illustrates the results of the assessment of column installation effects on the soil nearby a stabilized column within the column array for trial embankments. To that aim, dilatometer tests were performed in the close vicinity of a DM column before and 2 months after installation. It is clear that when comparing the state of the natural soil before and after installation in terms of the constrained modulus (correlated from DMT measurements) the installation effects seem to be not detrimental at all. On the contrary, the modulus of the soil shows an increase, where more sandy soil is present. No stress relaxation was observed around the column due to the combined action of the mixing tool and the compressed air.

5.3 *Evaluation of column improvement by means of CPT*

The in-situ evaluation of the improvement of stabilized columns by CPT tests has been carried out 5 months after installation. The CPT was performed through the axis of the column. Figure 6 illustrates the CPT profiles in the natural soil (untreated) and in the column axis. Clearly, a remarkable improvement, in terms of cone penetration pressure, can be observed in the upper silty clay layer where the ratio of $q_{c\ column}/q_{c\ natural}$ increases with depth to values of the order of 30 to 40. Similarly, an important improvement has been evaluated in the peaty layer with $q_{c\ column}/q_{c\ natural}$ ranging from 4 up to 7. The more sandy zones are clearly identified by the peaks of q_c.

5.4 *Monitoring of trial embankments*

Figure 7 shows the outcome of the settlement monitoring of the trial embankments, by means of settlement tell tale plates. A period of about 2 months was set between the end of column installation and the start of loading due to the trial embankments (30 kPa.).

As expected, the reference embankment (A) shows the largest settlements and a very rational tendency was observed for the trial embankments on improved soil (B, C and D). The binder dosage for embankment B seems to be not high enough to allow for some significant benefit.

Also lateral deformations have been monitored by means of inclinometers installed on one side of the trial embankments (at about 1 m away from the side boundary). Figure 8 reflects the measurements, 1 month after loading. As expected, the horizontal deformations in a vertical close to embankment D are the smallest as compared to the values for embankment C. Embankment B, on the other hand, shows to induce by far larger lateral deformations, confirming the indication that such binder dosage employed in the soil deposit is insufficient to allow for a considerable improvement.

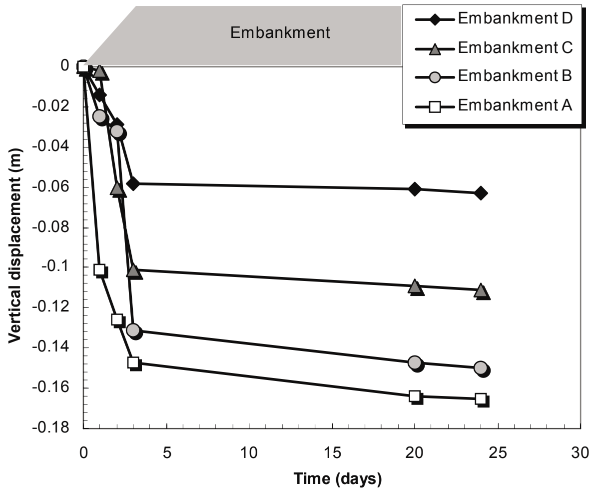


Figure 7. Settlement of the trial embankments.

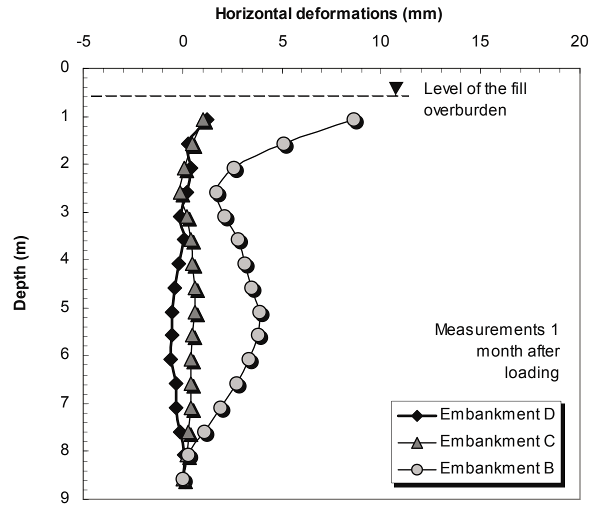


Figure 8. Horizontal deformations in a vertical close to the trial embankments.

6 SUMMARY AND CONCLUSIONS

Two soil type have been studied under DM: silty clay and highly organic silty clay (peat).

The laboratory research has shown good potential for the stabilization by blast furnace cements, of silty clay and peat. A ratio $UCS_{stab}/UCS_{natural} \cong 40$ has been reached for silty clay (in 60 days) with L/C-20/80 (150 kg/m^3). The tests on peat indicate a slow but continuous improvement with a ratio $UCS_{stab}/UCS_{natural}$ ranging from 2 to 3, after 90 days (specimens without surcharge loading during the curing).

In the field, the assessment of the DM column installation effects (using this type of dry mixing method) with the column array for trial embankments allows to conclude for no stress relaxation. The evaluation of the improvement by means of CPT (performed 5 months after installation) shows a remarkable improvement in the silty clay layer where $q_{c\ column}/q_{c\ natural}$ increases with depth to values of the order of 30 to 40. In the peaty layer, on the other hand, $q_{c\ column}/q_{c\ natural}$ ranges from 4 up to 7. The monitoring of trial embankments aimed at finding out the level of the benefit of the columns on the settlements and lateral deformations. A settlement reduction of about 65% was evaluated at the highest binder dosage (200 kg/m^3). The lowest binder dosage of 100 kg/m^3 was found to be insufficient to produce considerable improvement in the soil conditions studied here.

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