Laboratory tests and numerical modeling for embankment foundation on soft chalky silt using deep-mixing

Essais au laboratoire et modélisation numérique de la fondation d’un remblai sur un limon crayeux mou des sols améliorés par malaxage en profondeur

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ABSTRACT: The deep-mixing is nowadays world-wide accepted method as a ground treatment technology to improve the permeability, strength and deformation properties of soils. Binders, such as lime or cement are mixed in-situ with the soil by rotating mixing tools. The method is undergoing rapid development, particularly with regard to its range of applicability, cost effectiveness and environmental advantages. The paper describes the results of laboratory tests on chalky silt samples mixed with cement of different content. The influence of the different mixing parameters on the unconfined compression strength and deformation modulus is shown and evaluated. Typical results of the laboratory tests were used in numerical modeling with PLAXIS 3D as input parameters to study the behavior of a 4 m high embankment constructed on this soil improved by deep mixed columns with different spacing and diameters. The parameters of the soil improvement technique were analyzed to study their influence on the settlement and the stability of the embankment. The trends of the calculation outputs are shown and evaluated.

RÉSUMÉ : Pour l’amélioration de la pérméabilité, de la résistance et des caractéristiques de déformation des sols mous la malaxage est considéré comme une technique courante, préconisée partout. La procédure consiste á malaxer, par rotation, les liants: la chaux ou/et le ciment et le sol in-situ à l’aide de l’outil de malaxage par rotation. Grace á la diversité technique et aux possibilités d’application de l’appareillage, ainsi que ses avantages économiques, tout en respectant les intéréts de l’environnement, cette technologie approuve un développement continu même dans nos jours. L’étude a pour but de faire connaitre las résultats des essais au laboratoire réalisés sur des éprauvettes prélevées du sol traité avec les liants: la chaux et le ciment, dont la teneur par éprouvettes était variable. L’analyse des résultats de ces essais a mis à l’évidence l’influence des divers paramétres de malaxage sur la résistance à la compression simple et sur le modul de déformation du sol traité. Ces résultats nous ont rendu possible d’appliquer le programme d’éléments finis PLAXIS 3D, en vue d’étudiar une digue de 4m de hauteur, reposant sur des colonnes de sol traité, ayant une disposition variable et des diamétres différents. Le but de cette étude était de fournir un moyen de calcul qui permat le suivi des tassements et la stabilité de la digue, en fonction de la variation des paramétres de malaxage.

KEYWORDS: deep mixing, laboratory test, numerical modeling

1 INTRODUCTION

Road and railway embankments have often been constructed on soft, saturated, organic subsoil. In the future this type of construction is suspected to increase, due to environmental and land management considerations. The low strength and the high compressibility together with the low permeability and the high creep potential result in stability problems, extremely large settlements with prolonged consolidation times, and long term secondary compression. One of the solutions to avoid these problems is deep-mixing stabilization of the subsoil.

The development of deep-mixing was started in Sweden and Japan in the late 1960’s with the application of a single mixing tool to produce column-type elements (Figure 1.). Since then, new technologies using different mixing tools or binder types have been introduced. Lately, another technology; mass stabilization, based on Finnish research is gaining acceptance, where the whole soil mass is treated normally to a depths of 2 to 4 m (Figure 2.).

The goal of deep-mixing is to improve the soil characteristics, e.g. increase the shear strength and/or reduce the compressibility, by mixing the soil with some type of chemical additives that react with the soil. The improvement occurs due to ion exchange at the clay surface, bonding of soil particles and/or filling of voids by chemical reaction products.

Mass stabilization is preferred if the subsoil is very poor e.g. peat, organic clay or soft clay deposits, and the thickness of the mass to treat is less than 5 m, the height of the embankment is low, and the main purpose of the treatment is to increase stability (Allu Stabilisation System). If the main purpose is to reduce settlements and the weak soil is thicker than 5 m; approximately 60 cm diameter single columns are used. With this technology the treated depths can be increased up to 40 m (Moseley and Kirsch, 2004, Logar, 2012).

Recently, the use of deep-mixing technology has been planned on several Hungarian railway projects. The „Sárrét” railway line rehabilitation is one of these projects; the railroad crosses an area where the subsoil is soft chalky silt. Both deep-mixing technologies could be applied on this site. This paper describes the preparation of their use at this project. Firstly, the mechanical properties of the improved soil were investigated in the laboratory, then, the effectiveness of the technology as embankment foundation was evaluated with the PLAXIS 3D finite element program using the laboratory test results.

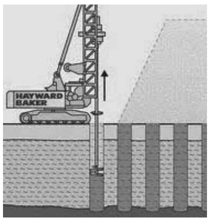

Figure 1.
Column-type deep-mixing

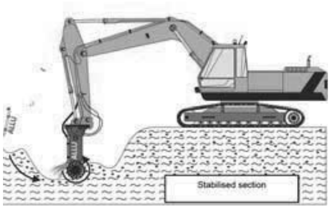

Figure 2.
Mass stabilization

2 LABORATORY TEST RESULTS

2.1 Parameters of deep-mixing technologies

The quality of the mixed depends on the applied binder type and quantity as well as the ratio of water to binder in the mixture. These quantites can be expressed by volume or weight. It is essential that the water content of the original soil is considered when calculating the water content of the slurry.

The binder quantity is described with the cement factor (α), and the in-place cement factor (α_{inpl}):

- $\alpha = m_{\text{cement}} / V_{\text{soil}}$ = binder weight / soil volume [kg/m^3],
- $\alpha_{\text{inpl}} = m_{\text{cement}} / V_{\text{mix}}$ = binder weight / mixture volume [kg/m^3].

The water content of the soil is described with

- $w_T / c = m_{\text{w,mix}} / m_{\text{cement}}$ = the total water-cement ratio [-].

The quality of the mixture is generally described with two parameters:

- q_u = the unconfined compressive strength [MPa],
- E = the Young's modulus [MPa]).

These mechanical properties are generally measured at 7, 14, 28, 42 and 90 days after mixing, because the stregthening of the improved soft fine grained soils is a long process, but the qualifying parameter is generally the 28 day unconfined compression strength [Filz et. al., 2003].

2.2 Properties of the chalky silt soil before treatment

Based on the laboratory tests, the main parameters of the original chalky silt are listed in Table 1.

The soil changes its color if its water content changes: the in-situ moist soil is pale yellow, while it turns light grey when drying. It has high lime content; the texture has small roots and organic threads, and high sensitivity. Based on laboratory tests, it is classified as highly plastic silt (MH).

Table 1. Soil properties of the chalky silt soil in „Sárrét"

w_L	w_P	I_P	w	e	E_s	$E_{s,ur}$	c_α	λ^*
%	%	%	%	-	MPa	MPa	-	-
72.1	54.4	17.7	71.1	2.08	2.1	15	0.0015	0.038

2.3 Data of chalky silt mixtures

In the testing program the use of both deep-mixing technologies was investigated. Thirteen different mixtures were prepared by varying α and w_T / c parameters (Table 2). Mixtures P1-P3 were made with low water contents and with slightly-varying cement contents. Mixtures 1-5 were prepared with lower water contents but highly varying cement contents. The mixtures 6-10 were made with a little bit greater water contents and with cement contents varied in the similar range. Since the water content of the original soil was high the addition of water was less significant in comparison to cement. The cement content dominated the behavior of the mixture.

2.4 Evaluation of stabilized soil parameters

In Figure 3, the increase of unconfined compressive strength with time is shown. As expected, the strength increases with time, but the hardening/strengthening rate is different from that of the concrete. The strength is less than 2.0 MPa for cement content of 50-300 kg/m^3. Generally, 0.5-2.0 MPa 28-day unconfined compressive strength is required for column-type deep-mixing, and somewhat lower strength for mass stabilization (Moseley and Kirsch, 2004). The data presented in figure three indicate that:

- 4 tested mixtures (P2, 1, 6 and 7) which have a cement content of 125 kg/m^3 or less did not reach 200 kPa unconfined compressive strength, but 3 of them would be acceptable for a mass stabilization, only P2 with a cement content of 50 kg/m^3 should be considered as too weak,
- the 28-day unconfined compressive strength of mixtures 2, 3 and 8 (cement content = 150-175 kg/m^3) was about 330 kPa, and for 90 days it increased to 500 kPa (50 %). These mixtures could be accepted for mass stabilization,
- the 28-day unconfined compressive strength of the rest of the samples with cement contents of 200-300 kg/m^3 were 500-2000 kPa with a 90-day to 1000-3000 kPa (50-100 %). These would be acceptable for column-type deep-mixing.

Table 2. Parameters of the mixtures

mix-ture	w_T/c	α	α_{inpl}	q_u kPa				
				7	14	28	42	90
	-	kg/m^3	kg/m^3	day				
P1	6.8	102	96	70	80	70	93	104
P2	13.5	51	49	12	17	11	18	17
P3	3.4	204	187	303	418	567	727	980
1	5.3	127	120	58	69	92	88	93
2	4.4	153	144	196	235	343	334	430
3	3.8	178	166	301	297	312	380	598
4	2.7	254	231	655	878	1351	1384	1900
5	2.2	305	274	1037	1487	2125	2853	2991
6	6.8	108	97	81	71	94	82	117
7	5.5	134	120	81	92	165	174	246
8	4.5	162	144	196	231	334	424	508
9	3.4	214	188	370	542	910	1024	1559
10	2.7	268	231	508	670	1162	1458	1952

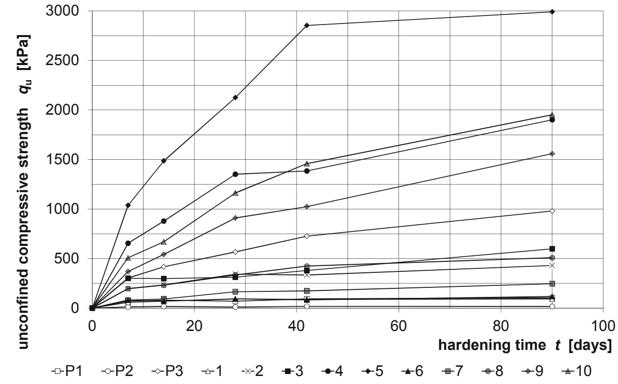

Figure 3. Measured hardening/strengthening of chalky silt mixtures

Figure 4 shows the relationship between the 28-day unconfined compressive strength (q_u) and in-place cement factor (α_{inpl}). The exponential trendline fits the points well with R^2=0.97. The chalky silt responded well to cement addition.

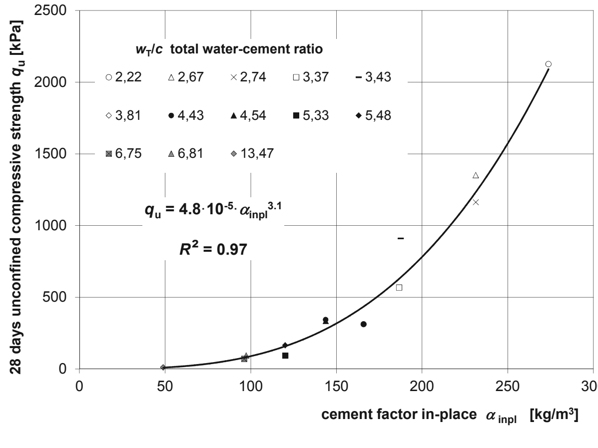

Figure 4. Measured relationship between $q_u - \alpha_{\text{inpl}}$

Figure 5 shows how the 28-day unconfined strength depends on total water-cement ratio. Samples with high water content show very low strength, and improvement of soil with $w_T / c > 8$ is not possible. When $w_T / c < 4$ the strength increased rapidly with decreasing water-cement ratio, but this also means the soil is very sensitive to changes in its properties. Since the total water-cement ratio hardly changes, it is clear that the role of cement factor is significant.

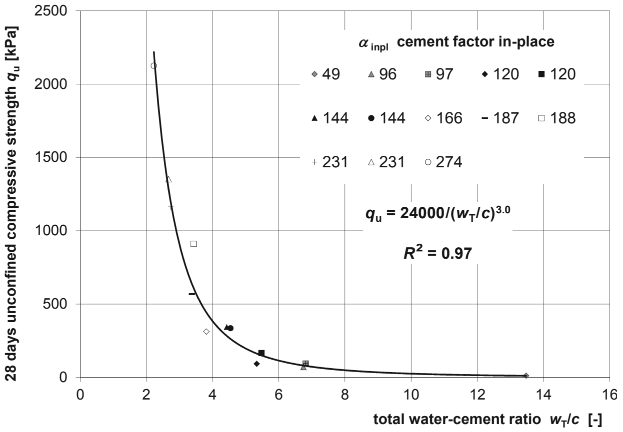

Figure 5. Measured relationship between $q_u - w_T/c$

Figure 6 shows the relationship between the unconfined strength and the Young's modulus. It can be seen that the trend-line fits very well. In this respect, the chalky silt of „Sárrét" behaves as expected: the modulus is proportional to unconfined strength. The equation from the figure can be simplified to

$$E_u = 70 \cdot q_u \tag{1}$$

where the units are both in kPa.

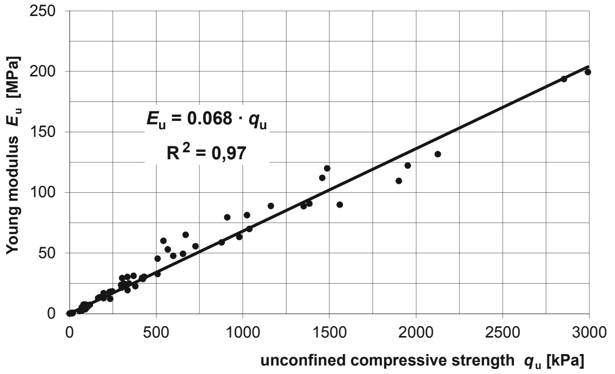

Figure 6. Measured relationship between $q_u - E$

3 MODELING OF DEEP-MIXING TECHNOLOGIES

3.1 *Site evaluation*

The second part of our research program was to apply a calculation method and give some guidelines for design. Both technologies (column-type and mass stabilization) were studied for expected design conditions at the Sárrét site. Variation in soil layering, soil strength and compression parameters, and embankment height will dictate the choice of technology. The PLAXIS 3D program was used to assess the effect of stabilization on stability and settlement.

The geometry of the embankment and the parameters of the untreated soil are shown in figure 7. Groundwater level was assumed to be even with the ground surface. Sandy-gravel, suitable for structural fill, was used for embankment material. A 3-m wide, 52.5 kPa distributed load was placed on top of the ballast during the stability analysis.

Column diameters were 60 cm, with a 5.0-m uniform length extending into the gravel layer. The columns were placed in 2.0×2.0-m and 3.0×3.0-m square grids (Figure 8). In order to model partial mass stabilization, 1.8-m diameter equivalent columns were placed in 2.4×2.4-m, 3.6×3.6-m and 5.4×5.4-m square grids (Figure 9.). Total mass stabilization has been analyzed by modeling the treated soil as a homogeneous composite of mixed and in-situ soils with averaged strength properties.

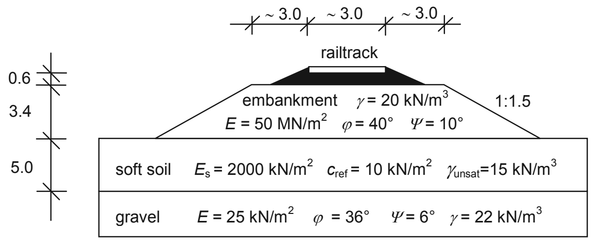

Figure 7. The model geometry and soil properties

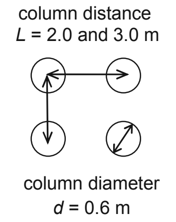

Figure 8.
Column-type deep-mixing

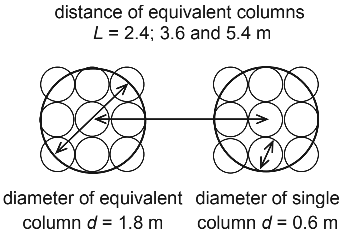

Figure 9.
Partial mass stabilization

The unconfined compressive strength of the 5 mixtures was used for modeling as base parameters (Table 2). Strength assigned to the column material in the analysis was assumed to be half of the unconfined compressive strength measured in the laboratory. In PLAXIS, this strength is represented by the cohesion (c_{ref}). Based on laboratory tests, Young's modulus for the columns was 70 times the unconfined compressive strength. The value of Poisson's ratio was $\nu = 0.2$.

Table 2. Mechanical parameters of the mixtures

Mohr-Coulomb		mixture				
		1.	2.	3.	4.	5.
E_{ref}	kN/m^2	7000	1500	20000	40000	70000
q_u	kN/m^2	100	200	300	600	1000
c_{ref}	kN/m^2	50	100	150	300	500

The analysis modeled the construction and load stages in five steps:
- placement of deep-mixing soil material,
- construction of initial 2-m high embankment in 30 days,
- construction of final embankment height in 30 days,
- final state (consolidation up to 5 kPa pore pressure).
- stability analysis considering traffic load.

3.2 *Analysis of settlement reduction*

The results were evaluated by plotting the calculated settlements versus the unconfined strength of improved soil elements (Figure 10.). The following conclusions can be drawn:
- with increasing strength all technologies reduce settlement, but the effectiveness depends significantly on column diameter and spacing,
- there is a relation between column spacing and q_u. If q_u is too small, the column spacing is no longer effective, no matter how close. At a higher q_u, the column spacing scheme is efficient,
- for partial and total mass stabilization settlements reduce rapidly as q_u increases, up to 0.4 MPa. Beyond this value, the improvement is much less significant,

- 60-cm diameter column-type improvements reduce the settlements linearly with increasing unconfined strength, but not very markedly,
- 60-cm diameter columns are more effective in 2.0×2.0-m grid spacing than in 3.0×3.0-m, although the settlements are halved at $q_u = 1$ MPa for the larger grid as well,
- there is little difference between the reduction curves of the 60-cm diameter columns in 2.0×2.0-m grid spacing and of the 1,8-m diameter equivalent columns made in 5.4×5.4-m grid spacing,
- the improvement with 1,8 m diameter equivalent columns in 3.6×3.6 m grid spacing is dramatic, the settlements are halved at about $q_u = 0{,}2$ MPa,
- total mass stabilization can be the most effective technology. Even for very small unconfined strengths (q_u = 0.1 MPa) the settlements are reduced to one-fourth.

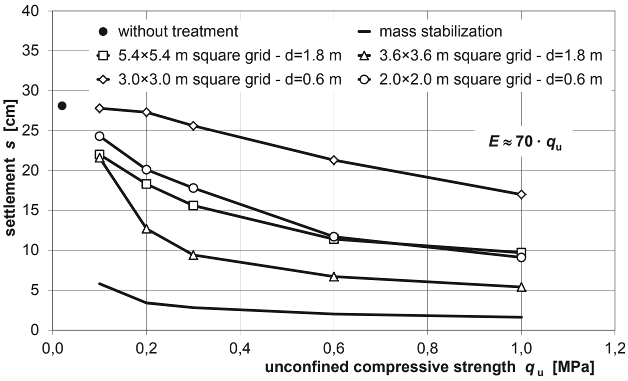

Figure 10. Calculated relationship between *s* - q_u

3.3 Stability analysis

The influence on sliding stability was evaluated by plotting safety factor as a function of unconfined strength (Figure 11.). For untreated soil, *SF* = 1.18 and it could be significantly increased with even a slight amount of treatment.

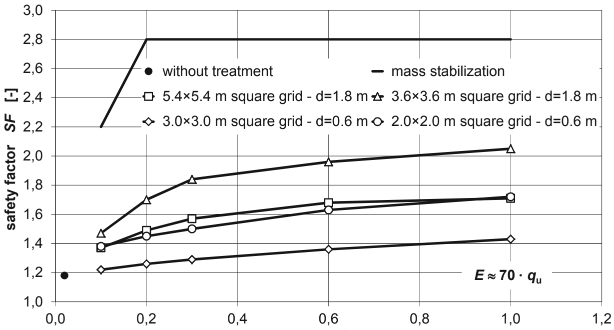

Figure 11. Calculated relationship between *SF* – q_u

The results can be summarized in the following:

- the lines for different diameters and grid spacing are very similar (except for mass stabilization),
- the four lines show that for $q_u > 0.5$ MPa, improvement is not necessary,
- the 0.6-m diameter columns with 3-m grid spacing is the least effective just reaching *SF* = 1.4 value with the maximum strength investigated,
- the most effective technology to insure stability is the partial mass stabilization. With 1.8-m diameter equivalent columns and 3.6-m grid spacing, the required *SF* = 1.35 value can be achieved with even small unconfined strength,
- the line for total mass stabilization shows a very different behavior. It generates a high safety factor even for small strength values, but quickly reaches a plateau. Beyond this point the mechanics of the stability failure changes with the failure surface travelling through the embankment slope only.

4 CONCLUSIONS

For road and rail embankment foundations, soil improvement is a frequently-used technique. Column-type deep-mixing and mass stabilization are effective soil improvement technologies to reduce settlements increase safety against slope failure. To prepare new railway rehabilitation projects the usability of both methods was investigated on a special soil type: chalky silt in Sárrét (Hungary).

While the underlying chemistry may be complex, the performance of the mixed material can be evaluated by standard laboratory and field tests. Laboratory tests have clearly demonstrated that the Sárrét chalky silt is suitable for improvement by cement. While it cures relatively slowly, an adequate strength is reached in about 40 days. Unconfined strengths up to 1,0 MPa can be reached by adding relatively small amounts of cement. Its uniform and predictable response to treatment allows the engineer to design the field improvement. For example, the relationship between unconfined strength and total water-cement ratio can be described with simple equations. The Young's modulus of the chalky silt can be calculated as 70 times the unconfined strength.

Finite element modeling was used to study the effectiveness of the mixing improvement. Column-type and mass stabilization scenarios were analyzed using strength and compressibility values from laboratory test results. Both technologies showed reductions in settlement and increase in stability. Based on the figures presented, the effectiveness of various solutions can be evaluated at the first design stages easily and rapidly. Using the trends from the figures, an optimal solution can then be arrived at during the detailed design phase by making only some calculations with PLAXIS for the actual design conditions.

In the future, a further refinement of the proposed method can be achieved by assessing and involving the cost-effectiveness of the alternatives in the design.

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