Application of cement deep mixing method for underpinning

Application de colonnes de sol-ciment pour travaux de reprise en sous œuvre

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ABSTRACT: This paper presents a case history of the application of wet deep soil mixing columns for underpinning of the existing floor slab of an industrial building, which settled due to different encountered post-constructive pathologies related to ground conditions. The soil-cement columns were constructed with the application of the new developed Springsol® tool that permits the underpinning of existing foundations, infrastructure transport platforms and embankments, as well as working in limited spaces and under low headroom conditions. The quality control regarding laboratory testing of core and wet grab samples is reported. Design procedure and the finite element analysis that verify settlement calculations are described. The FEM is focused on the axisymmetric numerical modeling in Plaxis.

RÉSUMÉ : Cet article présente une étude de cas de réalisation de colonnes de soil mixing par voie humide pour la reprise en sous œuvre du dallage d'un bâtiment industriel, ayant tassé après sa construction à cause de pathologies du sol. Les colonnes de sol-ciment ont été réalisées avec la méthode Springsol®, qui permet la reprise en sous oeuvre de fondations existantes, d'infrastructures de transports et de remblais, à partir d'emprises étroites et sous faible gabarit. Les contrôles le qualité réalisés en laboratoire sur des éprouvettes carottées et sur des prélèvements frais y sont présentés. Le mode de dimensionnement ainsi que les analyses par éléments finis pour estimer les tassements sont également décrits. Les calculs EF ont été réalisés avec le code Plaxis en axi-symétriei.

KEYWORDS: deep mixing, soil-cement columns, Springsol®, underpinning, FEM.

1 INTRODUCTION

In order to reduce settlements, increase bearing capacity of natural ground and improve the overall stability, different ground improvement techniques can be put into practice, but not all of them can be applied for underpinning projects. The limitations for the applications are mainly related to capacity of the machinery to pass existing foundation structures as reinforced slabs or footings, and insufficient working spaces and/or low headroom conditions.

The soil-cement deep mixed columns for ground improvement of soft soils have an extensive application for different geotechnical projects due to their higher strength and lower compressibility than the untreated natural soft soil. The application of traditional deep mixing methods, both wet and dry, was very restricted for the underpinning of existing foundations, improvement of existing embankments and infrastructure platforms, due to the form and dimensions of the mixing tool.

With objective to present new wet deep soil mixing system called Springsol® a case history with its application in underpinning project is reported in this paper. To prevent further settlements and guarantee bearing capacity of the foundation of the industrial building that presented various post-constructive pathologies, the Springsol® deep mixing columns were proposed as an alternative method to basic project underpinning solution comprising jet-grouting, traditional tube-a-manchette grouting and micropiles for different areas of the building. Due to its technical, economic and environmental advantages, soil-cement columns were accepted and executed as a global solution. In the following chapters the main characteristics of the Springsol® system will be described as well as the analysis of the solution adopted and performed for this project. Some recent applications of the Springsol® technique are given in Melentijevic et al., 2012.

2 SPRINGSOL® SOIL CEMENT COLUMNS

Springsol® device was originally developed for improvement of soils under existing railways due to its spreadable form (Innotrack 2009, Le Couby 2010). The folded tool is introduced through the casing to the required depth at the beginning of the column head. Once it reaches the end of the casing and penetrates the underlying soft soil, the blades spread out forming the soil-cement column down to the required depth.

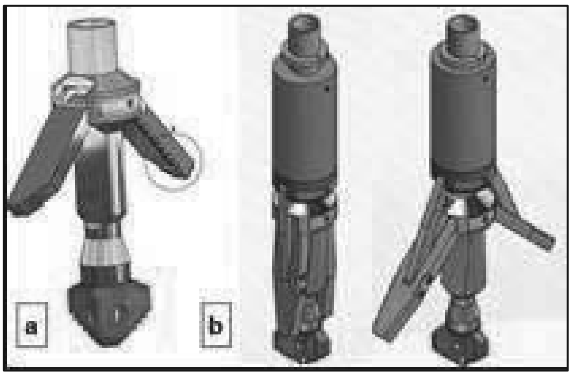

Figure 1. The Springsol® spreadable tool: (a) original and (b) modified.

At present, Springsol® columns permit an application in ground improvement for underpinning of existing foundations (both slabs and footings), paving, embankments and subbase below infrastructures (both highways and railways). Originally it was developed to form columns of 400 mm diameter. Due to continuous necessity for construction of soil-cement columns of larger diameters the Springsol® soil mixing tool has technically evolved into the new modified version, permitting achievement of different column diameters ranging from 400 to 700 mm. The modified tool also includes the automatic system for opening and closing blades thus having the possibility to form variable diameter along the column depth. Figure 1 shows the nowadays available original and modified improved Springsol® tool. The folded tool is of a diameter of 150 and 165 mm for the original and modified version respectively.

Some of the advantages of the method are:

- No pollution of the subgrade layer with the cement slurry, due to insertion of the casing that enables the recovery of spoil.
- The spoil collection with the system installed at the base of the mast of the drilling rig, connected to the peristaltic pump drawing the spoil directly to the container.
- The high production rate.
- Working under difficult execution conditions and limitations, i.e. under low headroom conditions and within reduced spaces.
- Execution with small batching plants and small drilling rigs in reduced limited spaces, etc.

The quality of soil-cement columns regarding their homogeneity and strength is influenced by two parameters:

- Im (rev/m) - blade rotation number determining the mixing efficiency defined as a total number of mixing blades passing along one meter of tool penetration, and
- Ii (kg/m^3) - cement quantity introduced per m^3 of the treated soil.

Table 1. Springsol® columns performance and geo-mechnaical parameters.

Parameter	
Diameter (mm)	400-700
Water / Cement ratio	0.6-1.2
Penetration velocity (cm/min)	15-50
Im (rev/m)	min 350
Ii (kg/m^3)	150-350
UCS (MPa)	0.5-6.0
E_{50}	(50-500) UCS
Shear strength	20-40% UCS
Bending strength	8-15% UCS

The general execution parameters and geo-mechanical characteristics (unconfined compressive strength - UCS, stiffness modulus – E_{50}, shear and bending strength) of the soil-cement columns executed by the Springsol® device are given in Table 1. These data are established on experiences gained on different projects and field tests carried out recently in Spain (Melentijevic et al 2012, Melentijevic et al 2013). These findings on geo-material properties are in agreement with worldwide published information on deep mixed columns (Bruce 2001, CDIT 2002, etc.).

3 PROJECT DETAILS AND ADOPTED GROUND IMPROVEMENT SOLUTION

In this chapter an example of application of the Springsol® technique for underpinning is presented. The industrial building in the central Spain presented different post-constructive pathologies regarding differential settlements of floor slabs and pavements as a consequence of poorly compacted anthropic fill material. The main structure (walls and columns) were founded on a natural ground, and due to its adequate geotechnical characteristics did not present any pathology. The shallow foundation on a natural ground was performed after a massive excavation of superficial layers of natural soil, applying the same material for construction of a fill without its appropriate compaction.

The affected area included more than 8000 m^2 with the installation of more than 2500 soil-cement columns. The length of soil-cement columns ranged from 5.50 m to 8.00 m in function of the thickness of the man-made fill, with the total length of columns of more than 15000 meters. Due to the form of the Springsol® tool, the columns were embedded approximately 20 cm in the natural ground. The columns of a 400 mm diameter, performed with the originally developed tool, were distributed in a square grid pattern ranging from 1.50 m to 2.00 m in function of the surcharge to be transmitted from the slab. The performed solution is schematically presented in Figure 2.

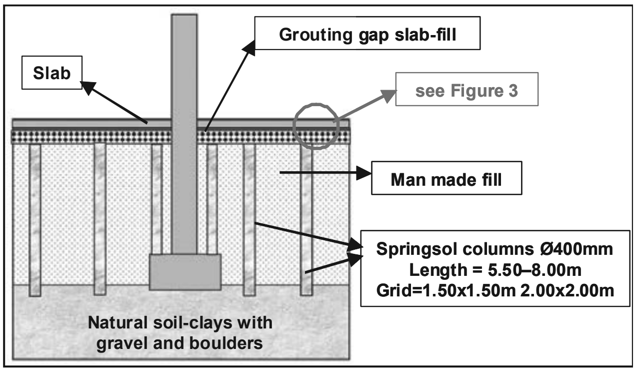

Figure 2. Cross section of the ground treatment solution.

The post pathology site investigation consisted of 46 dynamic penetration tests and 5 drilled boreholes with standard penetration tests, executed from the working platform, i.e. the existing floor slab level. The natural ground, detected at the depth of 5.50 to 8.00 m from the surface, consisted of clays of high consistency with gravels and boulders, with the $N_{20}>40$ (DPSH). The overlaying treated loose man made fill was formed of clays with gravels ($N_{20}<10$) proceeding from the natural ground after a massive excavation for the foundation of the main structure elements.

The soil treatment solution included following steps:

- Coring of the existing slab (diameter = 62 mm) for grouting of the gap between slabs and fill.
- Contact grouting between the slab and the fill in order to fill gaps due to settlement of badly compacted man made fill.
- Coring of the existing slab and contact grouted gap (diameter = 182 mm) for the passage of the spreadable tool.
- Execution of Springsol® columns (diameter = 400 mm).
- Filing the gaps of coring the existing slab.

Visual description of the executed steps previously mentioned is shown in Figure 3.

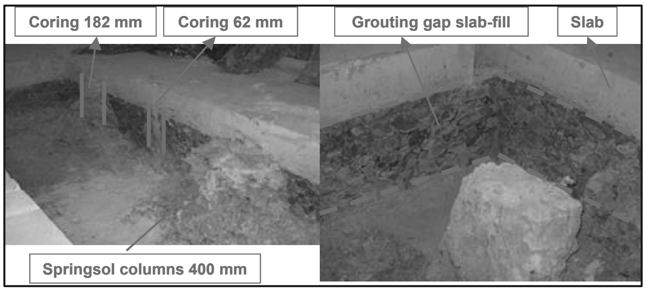

Figure 3. Visual control of the excavated treatment area.

4 GEOMATERIAL SOIL-CEMENT COLUMN CHARACTERIZATION

The cement used for the construction of soil-cement columns was of the Portland type CEM I 52.5 SR. The slurry mix was of a Cement / Water type with the relation 1/1. The average penetration rate for the construction of columns was 30 cm/min with the rotation velocity of 50 to 55 rpm and the average cement consumption of 350 kg/m^3.

The unconfined compressive strength tests (UCS) were performed both on drilled core samples and wet grab samples (cylinder dimensions height / diameter > 2), both of them usually being the main mean of the quality control of wet deep mixing methods. Three core samples were taken from different soil-cement trial test columns, 21 days after the completion of the soil-cement columns. The samples were cored at a distance of 110 mm to 120 mm from the centre of columns. The overall average total core recovery was more than 97% for all soil-cement columns. Wet grab samples were taken in the half an hour after execution of columns and were tested at same age as core samples. The UCS tests were also used to determine the stiffness modulus E_{50} (secant value of Young´s modulus of elasticity determined at 50% of UCS).

The UCS values of wet grab samples after 7 days varied from 1.4 to 3.9 MPa, while UCS values for drilled core samples on 28 days ranged from 2.2 to 4.4 MPa and axial failure strain values varied from 1 to 1.2 %. Stiffness modulus values determined from UCS tests varied from 270 to 330 MPa, with the average relationship between E_{50} and UCS resulting in approximately 100.

Some of the drilled core samples extracted from soil-cement trial test columns is presented in Figure 4. It can be observed uniformly treated Springsol® columns.

Figure 4. Drilled core samples of soil-cement columns.

5 NUMERICAL MODEL

5.1 *General data*

When using finite element analysis to model deep mixed columns installed in a periodic pattern, the problem is usually modelled in a 2D axisymmetric model, referred as a unit cell model. The homogenization equivalent model is usually not used due to lack of access to column stresses.

The radius of the unit cell depends on the grid spacing:

$$R_{eq} = \frac{s}{\sqrt{\pi}} \qquad (1)$$

where: R_{eq} is the radius of the unit cell and s is the grid spacing.

In this project different square grid patterns (grid spacing varying from 1.50 to 2.00 m) depending on the surcharge of the slab (ranging from 10.00 to 20.00 kN/m^2) are taken into account.

In this study the commercial finite element code used for 2D modelling is Plaxis (version 8.6). Both the soft soil and the soil-cement column behaviour are modelled by the elastic-plastic Mohr-Coulomb failure criterion, while the slab is characterized by the elastic law. The load transfer layer formed by grouting the gap within the contact gravel layer below the existing slab of the approximate thickness of 20 cm is modelled by the Mohr-Coulomb law. Geotechnical parameters of each material (LTL-load transfer layer, CU-upper clay layer, CM-medium clay layer, NSC-natural soil clay layer, SC-soil cement column) used in the numerical analysis are given in Table 2.

The cross section of the FE model is presented in Figure 6 showing the geometry and soil layers used in analysis, as well as the finite element mesh.

Table 2. Material parameters.

Parameter	*LTL*	*CU*	*CM*	*NSC*	*SC*
Thickness (m)	0.2	4.0-6.5	1.5	>4.5	
Density (kN/m^2)	22	16	17	18	20
Cohesion (kPa)	500	5	10	20	500
Friction angle (º)	40	18	20	22	35
Young´s modulus (MPa)	300	2.5	5.0	50	300
Poisson ratio	0.2	0.3	0.3	0.3	0.2

5.2 *Results*

Figure 6 present the employed mesh in the FEM model, and the results regarding vertical displacements and axial stresses for the case of the grid spacing of 1.50 m corresponding to the surcharge of 20 kN/m^2.

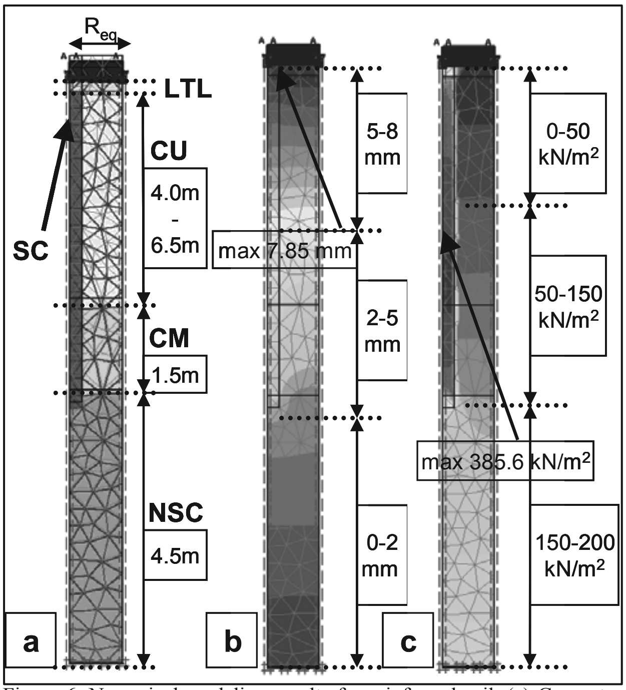

Figure 6. Numerical modeling results for reinforced soil. (a) Geometry of the unit cell – mesh and model dimensions. (b) Vertical displacements. (c) Axial stresses.

The homogenized settlements as well as negligible differential settlements due to high rigidity of the load transfer layer, formed by grouting the layer of gravel below the slab, and soil-cement columns can be observed in Figure 6-b.

The maximum allowable axial stresses in soil-cement columns defined by the UCS value and verified by the FEM analysis was not exceeded for different cases of grid spacing, surcharge and column lengths taken into consideration in the project.

The comparative study of the maximum vertical displacement, in cases without and with the soil improvement for different grid meshes is shown in Figure 7. The significant settlement reduction with the applied soil improvement can be observed in function of grid spacing and for different thicknesses of the soft soil layer.

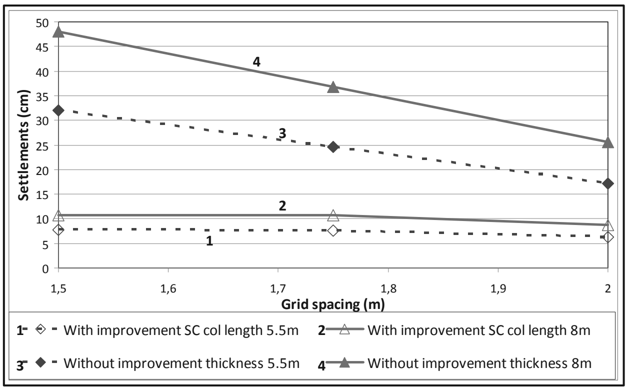

Figure 7. Maximum vertical displacements.

The numerical calculations were also analyzed in terms of load and settlement efficiency (ASIRI 2012) in order to determine the effectiveness of the soil improvement method. The load efficiency (E_L) is defined as a ratio of a transmitted load to the head of a soil-cement column and the total load acting on the unit cell. The settlement efficiency (E_{set}) represents the reduction of a settlement by a soil-cement column compared to the settlement of the unit grid without ground improvement. They are represented by the following equations:

$$E_L = Q_P / (W + Q) \quad (2)$$

$$E_{set} = 1 - S_M / S_0 \quad (3)$$

where: Q_P is the load acting on the head of soil-cement column, W is the dead load of the load transfer platform and Q is the force of the surcharge applied to the slab. S_M is the settlement of the soil reinforced by soil-cement columns measured at the surface of the load transfer platform and S_0 is the settlement of the natural soil without ground improvement.

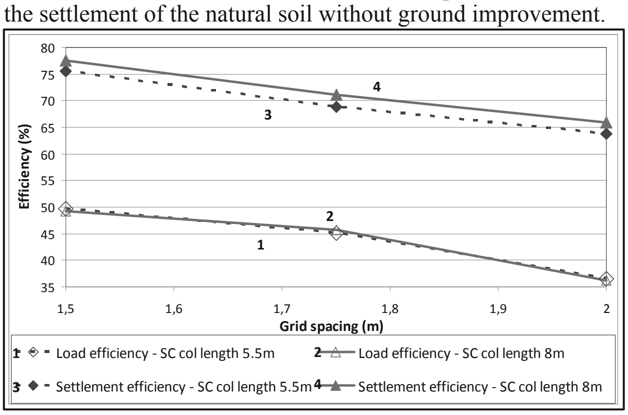

Figure 8. Load and settlement efficiency.

The results of the load and settlement efficiency are given in Figure 8 in terms of different grids adopted in the project for different surcharge loads and for different column length in function of the thickness of the soft layer. Both terms of efficiency have the same tendency. The load efficiency ranges from 36 to 50 %, while the settlement efficiency varies between 64 and 78 %. The difference of approximately 25 to 30 % between load and settlement efficacy relationships is observed.

It is important to emphasize that the estimated settlements obtained by the analysis by FEM were in accordance with the observed settlements after ground improvement by the performance of soil-cement columns and re-loading of the slab of the industrial building.

6 CONCLUSIONS

The general application of the wet deep mixing method by the Springsol® system for ground improvement of existing paving, embankments and subbase below railways and roads, and underpinning of existing structures is presented. The case history of underpinning of existing industrial building, which settled due to poorly compacted antrophic fill, with the use of the Springsol® system is reported.

The design procedure and the estimation of settlements by the finite element method (Plaxis commercial code) based on axisymmetric model is in concordance with the monitored settlements. The general homogenized nature of settlements, as well as insignificant differential settlements are achieved by the good interaction of the performed soil-cement column and load transfer layer formed by grouting of the layer of gravel below the slab. The evaluation of efficiency of the soil treatment by soil-cement columns, in terms of load and stress efficiency, is determined confirming its effectiveness.

7 ACKNOWLEDGEMENTS

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