Soil-cement columns, an alternative soil improvement method

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ABSTRACT

Within the European Research project INNOTRACK (2006-2009), SNCF, Keller Foundations and IFSTTAR tested the feasibility of an alternative soil reinforcement technique the FLAPWINGS, based on vertical soil-cement mixed columns with variable diameter. Field load tests have been carried out on two columns built in a silty soil. The columns have been instrumented, using the French extensometer technique, in order to estimate the distribution of load along the column. The results show the strong mechanical response of the column. Moreover, from the excavated columns, samples were collected to perform laboratory tests. They show some heterogeneity of the new mixture and consequently on the distribution of unconfined compression strength and stiffness modulus. Nevertheless it was acceptable to justify the technique. Another interesting observations that the mechanical behaviour of the soil-cement column might be assimilated to jet grouting inclusions in terms of UCS resistance for similar soils and similar cement contents. A new tool has been developed by Keller that shows interesting results.

Keywords: mixing column, pile load testing, soil improvement, core retractable tool

1. INTRODUCTION

In order to reduce the Life Cycle Cost of railway infrastructure, many research works are performed concerning of track support structure. Development and implementation of several subgrade improvement methods allowing limited traffic interruption and privileged recourse to local material are the keynote of the work of the research European project INNOTRACK (INNOvative TRACK system) (2006-2009). The technique proposed by the SNCF/KELLER/IFSTTAR was a ground reinforcement with vertical soil-cement columns. Research based upon field and laboratory tests were carried out aiming at:
- studying the feasibility of soil-cement columns in some soils as an alternative soil reinforcement technique.
- assessing the load distribution along the column, in order to obtain a shaft friction and a tip resistance.
- carrying out mechanical laboratory testing to measure unconfined resistance $R_c$ and elastic modulus $E_c$ from the samples extracted from excavated columns.

An experimental site has been selected and the tests were performed in an area close to the TGV station Haute Picardie in 2006. A research report was provided [1].

The technique used in the research work represents the wet soil-mixing method as the soil is mixed with a cement grout characterized by a Water/Cement (W/C) ratio. Many publications linked to research works exist on this technique as it is widely used in Sweden and Japan (SGF Report 4:95 E [2] and CDIT [6]).

In the paper, we consider static field load tests performed on two 600 mm soil-cement columns; characterized by two different W/C ratios respectively 1 and 0.83. Their bearing capacity as well as the local response in terms of shaft friction and tip resistance has been analysed.

A comparison is made between the response of a soil cement columns and jet grouting columns through UCS resistance of soil-cement mixtures samples got from both techniques. Besides, design rules [3] are available to calculate the bearing capacity of jet grouting columns from local design rules (shaft friction and tip resistance).

An interesting issue is to compare the available design rules with the results of the soil-cement columns pile tests even if the mixing mechanisms can be considered as different.

The cement content determined at the end of the building of columns by the two techniques. In addition, in both cases, soil inclusions are located within the mixed material.
Moreover, the Keller soil mixing tool (FLAPWINGS) has technically evolved. A new version has been proposed. In this paper, a description of the experimental test site and of the built columns is made as well as the presentation of results of UCS tests from test sites soil-cement samples.

2. EVOLUTION AND SPECIFICITIES OF THE MIXING TOOL

In the railway environment (soil improvement between the tracks), the technique can be used as follows:
- a steel tube was jacked vertically through the railway structure layers (ballast, sub-ballast, treated soils) down to the natural soil; i.e. about 1-1.50 m deep; in order to make the tool reach the layers that were to be improved;
- the folded device was inserted through the steel tube. At the base of the tube, it began to rotate and as it moves away from the tube, it opened up in order to perform the mixing phase of existing soil and cement grout and achieved 600mm reinforcement columns.

Other applications are also possible (Figure 1):
- Soil improvement of a paving and foundation raft and building up of secant columns,
- Subgrade reinforcement of railway and highway embankments.

The first tool developed by Keller Foundations [1] had an opening system that was simple with stems that were operated with an external jack located at the top pole of the drilling machine. The external diameter of the closed tool was 300 mm core retractable tool that was too big for classic tubing or for preboring with usual diameters.

Keller Foundations has designed a new patented device [9] (FLAPWINGS) (Figure 2) to achieve soil-cement columns following execution requirements in a railway environment. It consisted in a 150 mm core retractable tool able to open up in order to perform the soil mixing phase on a 600 mm column. The new designed tool also allows us to open and close the retrieval blades but it is controlled by a two way hydraulic jack located in the mixing tool.

Figure 1: Soil improvement applications

Figure 2: New soil-mixing folding tool FLAPWINGS
The main advantages of the new tool FLAPWINGS are:
- Small boring machine is required to achieve this kind of field works. Then, it is useful for field areas difficult to access like for example within a building and with limited heights for field works,
- 150 mm drilling with possible tubing (closed tool)
- Possibility of protecting the drilling with steel tubes in order to avoid pollution with grout of the top layers like ballast for example,
- Column diameter of the mixed column : 600 mm,
- Possibility to reach compact top layers in order to reinforce soft soil layers underneath.

3. TESTS ON THE 300 MM CORE RETRACTABLE MIXING TOOL

3.1. Soil investigation

The experimental site [1] was investigated with in situ tests (pressiometer test) and laboratory tests. We only consider the pressiometer test in the paper.
A 12 m long borehole was done to achieve pressiometer tests. No water table was found. The borehole pointed out:
- from 0 and 1.20 m: dark silt layer characterised by a limit pressure $p_l$ around 0.54 MPa (1 value)
- from 1.20 m to 5 m: clayey sandy silt with chalk particles ; with a limit pressure $p_l$ encompassed between 0.27 MPa $\leq p_l \leq 1.31$ MPa
- from 5 m to 6.5m : a silty chalk layer with a limit pressure $p_l \geq 2.94$ MPa (1 value),
- from 6.5 m to 12m : a chalk layer with a limit pressure $p_l \geq 2.44$ MPa ,
- water contents were about 20%.

3.2. Characteristics of columns

The soil-cement column technique was considered as an alternative to rigid inclusions and stone columns. Indeed, the latter was generally assumed to be too soft in terms of stiffness and bearing capacity whereas the rigid inclusions appeared to be rather too stiff. The intermediate case represented by soil-cement columns would provide a better homogeneity of the distribution of load on the sub-grade layer as well as a homogeneous settlement profile.
As for stabilization or reinforcement purposes, there was a great need for homogeneous admixture in (soil-cement) columns [2], we analysed this aspect in the paper.
The set up of columns was done with wet soil mixing method i.e. the soil was mixed with cement grout. A specific device has been used in order to achieve an homogeneous soil-cement mixing. The cement used was a CEM III/C 32.5 N PM-ES.
The built up procedure of columns can be described as follows:
- the Ø 600mm diameter rotating mixing tool is jacked and sheared the soil by mixing it with cement. One top-down phase:
  - from top to base: rotation and injection and from base to top: rotation and injection.
  - soil-cement columns were instrumented using the French extensometer technique. Indeed, a close ended steel tube was installed in each column on the day the construction of the column occurred. Consequently, the cement set with the enclosed steel tube and both elements were tied up.
  - after a few days, a specific pile head was built with steel reinforcement to ensure a good connection between the head of the column so that the LCPC load cell could be positioned and the load could be applied vertically.
  - the soil-cement column with the enclosed steel tube was loaded as a whole.

The soil-cement column was built in about one hour. The columns P1 and P2 have been built respectively on the 30th and 31st October 2006 by Keller. The anchors required for the reaction frame were built on 31st October 2006. Samples 160mm in diameter and 320mm long were collected at the head of the test column to perform unconfined compression tests. The length of the columns located the column bases at an intermediate level between the silt and the good chalk layer. The physical properties of the columns are described in table 1.

Table 1. Characteristics of the columns

<table>
<thead>
<tr>
<th>Column n°</th>
<th>Diameter (mm)</th>
<th>Length (m)</th>
<th>W/C</th>
<th>Density* kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>600</td>
<td>5.30</td>
<td>1</td>
<td>338</td>
</tr>
<tr>
<td>P2</td>
<td>600</td>
<td>5.30</td>
<td>0.83</td>
<td>397</td>
</tr>
</tbody>
</table>

* estimate mass of cement in one m$^3$ of soil-cement column
3.3. Excavation of the columns and Laboratory tests (INNOTRACK project)

Two columns are considered in this paper: column P1, column P2 and a test column similar to P1 in terms of density and W/C ratio (but not loaded). The test column and column P2 were excavated (Figure 3). The shape was regular and looked like a cylinder. The measured diameter of the test column was about 640 mm (more than the 600 mm diameter expected).

From the head of a excavated test column, (different from P2), lumps at the top 2-3 m of the soil-cement columns were collected to achieve laboratory tests and to get mechanical parameters.

For design, the assessment of the shear strength of soil-cement from the results of field load tests presupposes that the stabiliser is mixed uniformly over the whole cross section and that the column can be considered as homogeneous. Such was not the case. Indeed, the sampling of the side part of the column (Figure 3) showed different materials within the soil-cement column sample. Soil areas, cement-areas as well as soil-cement areas could be clearly identified in the $\varnothing$80 mm sample. It illustrated the significance of the heterogeneity of soil-cement column in this sample. The samples 7 and 8 were collected at the column head by KELLER during the building of the columns and tested. During the installation of the column, the grout backflow seemed mostly composed of cement. The values of $R_c$ (unconfined compression test) and $E$ (elastic modulus) (Table 2) were expected to be larger than the values obtained from the samples collected at a bigger depth when the column was completed. For the collected samples (after the setting of cement), the ranges of $R_c$ were 4.98 – 8.95 MPa (we did not consider sample 1) in comparison with 3.2-4.6 MPa.

A sample of the side part of the column shows some heterogeneities with soil parts, cement parts and mixed parts (figure 4).

On Table 3, as a comparison, an abacus is given of the UCS results for jet grouting samples for different soils and different cement contents.
Table 2 Test results on soil-cement columns samples (silt)

<table>
<thead>
<tr>
<th>Sample number</th>
<th>∅ (mm)</th>
<th>Length (mm)</th>
<th>R_c (MPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>37.8</td>
<td>77.2</td>
<td>0.62</td>
<td>-</td>
</tr>
<tr>
<td>Sample 2</td>
<td>38.97</td>
<td>73.84</td>
<td>8.95</td>
<td>4.9711</td>
</tr>
<tr>
<td>Sample 3</td>
<td>38</td>
<td>73.3</td>
<td>6.41</td>
<td>-</td>
</tr>
<tr>
<td>Sample 4</td>
<td>37.80</td>
<td>68.20</td>
<td>7.26</td>
<td>2.431</td>
</tr>
<tr>
<td>Sample 5</td>
<td>37.95</td>
<td>80.92</td>
<td>4.98</td>
<td>4.086</td>
</tr>
</tbody>
</table>

Samples collected at the head of the column (P2) - 7

<table>
<thead>
<tr>
<th>∅ (mm)</th>
<th>Length (mm)</th>
<th>R_c (MPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>320</td>
<td>3.2</td>
<td>-</td>
</tr>
</tbody>
</table>

Samples collected at the head of the column (P2) - 8

<table>
<thead>
<tr>
<th>∅ (mm)</th>
<th>Length (mm)</th>
<th>R_c (MPa)</th>
<th>E (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>320</td>
<td>4.6</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3 Abacus UCS as a function of Cement content C and of the type of soil for jet grouting [10]

<table>
<thead>
<tr>
<th>Soil</th>
<th>Cement content kg/m³</th>
<th>Unconfined Compression Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>250</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>3 à 4</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>5 à 7</td>
</tr>
</tbody>
</table>

The results of the laboratory tests carried out on samples that come from the silt – cement mixing (cement content encompassed between 338 and 397 kg/m³) and the jet grouting samples are compared. In the latter, from table 3, for 350 kg/m³, the UCS values are between 5 and 7 MPa; values that are quite close to values obtained on table 2 from soil mixing columns. Then, it might be interesting as a first step to consider them as materials that have the same strength. It also justifies the fact that we could compare the column response under pile load test.

3.4. Instrumentation of the columns for pile load tests

The columns were instrumented using the French removable extensometer [4, 5]. A Ø 52/60 mm diameter and 5.30 m long closed ended steel tube was used. It was installed in the middle of the column just after the soil-cement column had been set up. A column head was built for each soil-cement column on the same day as the column; 60 cm squared concrete block and 25 cm thick. During the loading test, the load was applied on the column head. The top of the steel tube reached the top of the column head. When the soil-cement column load test was performed, several segments of packers and steel ribbons [4, 5] (with strain gauges stuck on it) (Figure 5) were installed in the steel tube to perform the strain measures.

3.5. Measurement devices and tests

Reaction frame and loading system used during the field test consisted in:
- a steel beam laying on wood beams and linked to four bars DYWIDAG Ø 22mm and consequently to four reaction piles Ø 200mm (Figure 6). They work in tension when the column was tested in compression.
- four displacement gauges with a 1/100th accuracy at the pile head
- five extensometer segments with deformation Δl/l (Figure 5)
- data acquisition system and a computer.

The soil-cement columns have been loaded following the LPC (Laboratoire des Ponts et Chaussées) method and the standard method [7]. The load applied increased through constant load increments (each load was applied during one hour) until failure load. After the load test, two columns were excavated; in particular the load tested column P2.
3.6. Load tests and analyses

Two W/C ratio were tested, 1 and 0.83 respectively. In figure 7, we show the plot of the pile-head load $Q_0$ – pile head displacement $S_0$ (mm) curve for the two column tests. For column P1, seven load steps had been achieved whereas for column P2, 10 load steps were performed. In both cases, the maximum reached settlement were respectively 5.8 mm (maximum load 300 kN) and 7.2 mm (maximum load 450 kN) as the columns showed a bearing capacity greater than expected.

In the paper, we add an interpolation made from the Chin method [8] to evaluate the bearing capacity as well as the distribution of the resistance along the column i.e. shaft friction and tip resistance.
3.6.1. Column P1

The load test was performed after 36 setting days. The maximum load applied was 300 kN for a settlement of 5.8 mm (about 1% of the pile diameter). The creep load reached $Q_c = 250$ kN. The load distribution along the pile and its mobilisation were determined from the unit strains $\varepsilon$. Young moduli were estimated from the results of $R_c$ laboratory tests (table 2) in order to draw the mobilisation curves of the shaft friction $q_s$ for different soil layers and different depths. On figure 8, we noticed that the biggest part of the load is mobilized on the segment A which would transfer it to the underneath levels. The limit load $Q_u = 300$ kN was composed with 86% by shaft friction ($Q_s = 258$ kN) and 14% by the tip ($Q_p = 42$ kN). Chin method [8] was used to estimate the bearing capacity of the soil cement column. From Chin method, the bearing capacity was estimated at 417 kN with a shaft friction of 266 kN (64%) and a tip resistance of 151 kN (36% of the total load). Therefore, as expected, the shaft friction had been fully mobilized for a settlement of 5.8 mm whereas the tip mobilization required more settlement to be fully mobilized.

The tip resistance stress reached about 0.5 MPa (151 kN/($\pi x 0.3^2$)) which is rather small in comparison with the pressumeter results (0.97 MPa at 4.8m and > 2.94 MPa at 5.8m) if we analysed the results in the same way as for a pile. However, in terms of soil reinforcement, the mechanical properties of the soil were actually improved.

3.6.2. Column P2

The load test was performed after 38 setting days. The maximum load reached for column P2 was 450 kN with a settlement of 7.2 mm (about 1% of the pile diameter). The creep load $Q_c$ reached $Q_c = 400$ kN. The load distribution along the pile and its mobilisation were determined from the strains $\varepsilon$. On the figure 9, we noticed that again, the biggest part of the load was transferred to the level A. The limit load $Q_u = 450$ kN was composed with 62% by shaft friction ($Q_s = 279$ kN) and 38% by the tip ($Q_p = 171$ kN). From Chin method, the bearing capacity was estimated at 811 kN with a shaft friction of 570 kN (70%) and a tip resistance of 241 kN (30% of the total load). In this case, the shaft friction had not been mobilized for a settlement of 7.2 mm contrary to column P1. Again, the tip mobilization required more settlement to be fully mobilized.

On figure 9, at the load step 9 (400 kN), the steel tube and the column slid on each other as the shaft friction reached its maximum. Therefore, from this load, we were not able any more to measure the distribution of load along the column. The evaluated shaft friction and tip resistance were made from the load of 400 kN. Therefore, we were only able to analyse data from the extensometer until the load step at 350 kN.

As far as the shaft friction was concerned, the mobilisation curves of the unit load; for the different depths along the sleeve: A – B – C – D – E, are represented on figure 9. The plots show that the load carried at the levels B and A are much bigger than the other levels as at those depths, we were reaching a strong soil resistance area. As a comparison to the column P1, the $q_s$ values, for P2 at the load step 300 kN, were equal to: level E : $q_s = 5$ kPa, level D : $q_s = 20$ kPa, level C : $q_s = 18$ kPa, level B : $q_s = 45$ kPa, level A, $q_s = 47$ kPa

For the two columns, the distribution of load looked similar with about 70 % taken from the shaft and 30 % from the tip. However, the difference in terms of bearing capacity could not only be explained by the W/C ratio and the cement contents of 338 and 397 kg/m$^3$. The actual distribution of cement along the column would need to be considered.

Besides, for both columns, the shaft friction was fully mobilized at the levels E, D, C and B with measured values greater in the case of the column P2. At level A, the skin friction was not completely mobilized in both cases as it went on increasing with the applied load.

As far as the shaft friction is concerned, the mobilisation curves of the load; for the different depths along the sleeve: A – B – C – D – E, are represented on figure 10. The plots show that the load carried at the levels B and A were much bigger than the other levels due to the vicinity of the good soil layer. At these levels, the $q_s$ values are equal to: levels D and E (D and E gathered together due to experimental reasons) : $q_s = 13$ kPa, level C : $q_s = 13$ kPa, level B : $q_s = 37$ kPa, level A, $q_s = 72$ kPa (Figure 11).

A general remark is that none of the two pile tests have been conducted until failure. The maximum loads reached were 450 kN.
On Figure 12, we have tried to plot the p-l-q_s points from tests P1 and P2 in a proposed abacus for jet grouting [3].

As far as shaft friction is concerned, the following values of q_s were chosen: for pile segments A and B:
- the p_l considered are respectively 1.34 and 1.14 MPa,
- the shaft friction taken as the average of the maximum values obtained during pile tests P1 and P2 i.e. respectively 70 kPa and 43 kPa.

The following values of q_s have been chosen: for pile segments C and D:
- the p_l considered are respectively 1.05 and 0.58 MPa,
- the shaft friction taken as the average of the maximum values obtained during pile tests P1 and P2 can be taken as one value i.e. respectively 15 and 20 kPa.

In all the cases, the points are lower than the silt line probably due to the fact that the piles could not be been loaded until failure as the two techniques enter the non-displacement pile category.
4. FEASIBILITY TESTS ON THE NEW DEVICE

On 2009, an experimental site has been chosen in Woerth (67), France on an EHPAD field work. The chosen cement content was about 280 kg/m³.

The built up procedure of columns is the same as the procedure described in paragraph 3: i.e. two top-down phases were performed in order to get the best soil-cement mixture and the most homogeneous material. Some results of UCS tests on samples from soil-cement columns are given on Table 4. If we compare from Table 3, the values obtained are comparable to silt–cement mixtures.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil</th>
<th>L/d ratio</th>
<th>Dates</th>
<th>Age</th>
<th>Rc</th>
<th>Young Modulus</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>Silty Clay</td>
<td>2.0</td>
<td>23-nov.-09</td>
<td>66.00</td>
<td>2.66</td>
<td>NC</td>
<td>1.58</td>
</tr>
<tr>
<td>2.50</td>
<td>Silty Clay</td>
<td>2.0</td>
<td>23-nov.-09</td>
<td>66.00</td>
<td>3.40</td>
<td>NC</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Some pictures of the samples are shown on Figure 13. Some inclusions are observed within the soil cement mixed material but it can be considered as acceptable for this technique used in a clayey soil.

Figure 12: Abacus for the calculation of shaft friction $q_s$ in jet grouting columns for silt and clay [3]

Table 4 Test results on soil-cement columns samples (silty clay)

Figure 13: Photos of soil-cement samples before and after UCS tests
5. CONCLUSIONS

The planned objectives regarding the feasibility of the soil-cement columns have been reached. From the first test sites, it can be assumed that the mechanical behaviour of the soil-cement column might be assimilated to jet grouting inclusions in terms of UCS resistance for similar soils and similar cement contents.

The pile load tests showed bearing capacities for the two columns 417 kN and 811 kN respectively extrapolated from the Chin Method. The difference between the two columns, beyond the influence of the W/C ratio and the density of cement, illustrated the better distribution of cement in the column P2 in comparison to the column P1.

Using the extensometer technique, it was possible to achieve the distribution of load along the column. Indeed, the distribution of load along the columns seemed constant regarding the Chin method calculations with 70% of load taken by the shaft and 30% taken by the tip. The distribution of cement and soil in the soil-cement column needs to be checked to avoid heterogeneity issues.

A new 150 mm core retractive tool has been developed and also showed good results in terms of homogeneity of the mixture and soil-cement material resistance.

Other pile load tests should be carried out to validate our hypothesis relative to the similarities in the DSM and jet grouting columns mechanical response (bearing capacity, shaft friction and tip resistance).

REFERENCES


