Stabilization of soil with displacement columns of dry sand-cement/lime mix: construction methods, physical behavior and numerical modeling

Stabilisation de sol avec des colonnes de déplacement de mélange sec de sable-ciment/chaux: méthodes, comportement physique et modélisation numérique

Y.El-Mossallamy – *Ain Shams University, Cairo, Egypt, c/o ARCADIS Darmstadt, Germany*
P.Scheller – *Bauer Spezialtiefbau GmbH, Schrobenhausen, Germany*
T.Neidhart – *FH Regensbuig, University of Applied Science, Regensburg, Germany*
W.Reitmeier – *FH Konstanz, University of Applied Science, Konstanz, Germany*

ABSTRACT: In recent years small diameter displacement-columns to improve the bearing capacity of soft soil and to reduce settlements have been developed. The method is called Combined Soil Stabilization with Vertical Columns or CSV. A dry mixture of sand, cement with or without unslaked lime is forced into the soil by a continuous flight auger. Through capillary action ground- or pore-water penetrates the granulate column and allows it to harden. The paper describes the CSV Soil Stabilization System in detail: equipment, stabilization material, process, quality assurance and quality control procedures. A newly developed numerical model and design concept for the complex interaction between CSV columns and soil is presented. The results of the numerical analysis are compared to results of large scale field tests with extensive monitoring.

RESUME : ces dernières années, des colonnes de déplacement de petit diamètre pour améliorer la capacité portante du sol meuble et pour réduire le tassement ont été développées. La méthode est appelée stabilisation de sol combinée avec des colonnes verticales (Combined Soil Stabilization with Vertical Columns ou CSV). Un mélange sec de sable, de ciment avec ou sans chaux vive est injecté dans le sol par une tarière à pas continu. Par action capillaire, l'eau souterraine pénètre dans la colonne granulée et lui permet de prendre prise. Le rapport décrit la stabilisation de sol combinée avec des colonnes verticales en détail : équipement, matériel de stabilisation, procédé, assurance qualité et procédures de contrôle de la qualité. Un modèle numérique et un concept design développés récemment pour l'interaction complexe entre la colonne CSV et le sol est présenté. Les résultats des analyses numériques sont comparés aux résultats des tests à grande échelle avec un contrôle maximal.

1 INTRODUCTION

The CSV Soil Stabilization System is a new and economical method to improve soft soils. Based on the experience of using lime columns in the 1960's for the improvement of soils for highway loads, the CSV soil stabilization system has been developed in Germany in the last decade. The development began with the installation of short lime columns (Reitmeier, 1996). However, the potential applications of the CSV system increased significantly through the change to slender cement-sand-columns. The further development of the equipment made it possible to work with soil specific installation parameters (Reitmeier & Alber 2000, Scheller & Reitmeier in press). Today, slender CSV-columns longer than 10 m with a defined minimum diameter can be produced without difficulty.

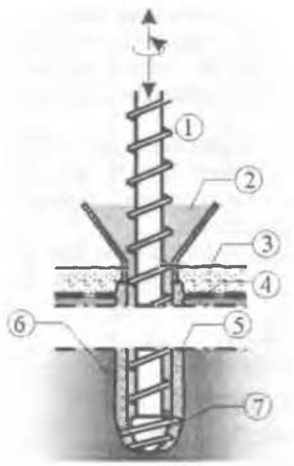


Figure 1. Installation Principle

2 CONCEPT OF CSV SOIL STABILIZATION SYSTEM

2.1 *Installation principle*

The installation principle for CSV columns is shown in figure 1. A dry mix of sand, cement with or without unslaked lime is forced into the soil by a continuous flight auger. The auger, which is equipped with a special pressurizing bit at its base, is pushed into the ground while rotating against the drilling direction. This process is referred to as force feeding. The auger runs through a material container transporting the material into the ground. During the downward as well as during the upward movement the auger continues to rotate in the same direction, transporting dry stabilization material from the container into the ground and compacts it through the pressurizing bit in the created displacement hole. The surrounding soil acts as a casing for the transport of the material. If the soil is not firm enough to fulfil this task, the installation parameters can be adjusted to allo the development of the required protective casing consisting of stabilization material necessary for a satisfactory material transport. The soil is completely displaced by the auger and replaced with the dry material during the installation of the CSV columns without any vibration. No soil mixing takes place. The auger stops at a preset downward pressure, which is in most cases refusal, or after reaching a predetermined depth. Through the capillary action and the excess pore-water caused by displacing the soil, the pore or groundwater penetrates into the column and allows it to harden (Maisch et al. 1998). The generated column diameter can be varied between 12 and 20 cm by adjusting the installation parameters according to the specific conditions and requirements.

2.2 *Types of CSV columns*

Two different column types can be differentiated according to the stabilization material used: Type A columns are made of materials with a chemical or physical effect on the surrounding soil without developing much strength of their own like lime or sand columns. More information can be found in Maisch (2000).

Type B columns are capable of carrying loads. They contain hydraulic binders and harden through hydration with pore or groundwater from the surrounding soil. During recent years type B columns have been installed in considerably greater numbers than type A columns using the CSV technique. Generally two main groups of type B columns exist:

End Bearing Columns: The columns penetrate into a soil layer with sufficient bearing capacity. Due to the large difference in stiffness of soil and columns nearly all structural loads are transferred through the CSV columns to the bearing layer. The design is based almost entirely on the internal capacity of the CSV column.

Floating Columns: The major factors that affect the behavior of floating columns are: a) the internal interaction between the individual columns of the column group, b) the column group / structure (e.g. footing, raft or embankment) interaction and c) the stiffness of the columns compared to the surrounding soil. These factors lead to a transmission of the applied structural loads to a greater depth in the soil. The improvement of the stress-strain relationship of the soil itself can be considered to estimate the load-settlement behavior of such floating groups of CSV columns.

The improvement can be due to one or several of the following effects: a) compaction during the column installation; b) reduction of water content around the columns; c) drain effects, d) load transfer by the CSV columns type B which act as structural elements after hardening, and e) arching and increase in lateral stresses between the columns.

2.3 *Installation criteria and technical data*

The most suitable soil conditions for the installation of CSV columns are very soft to stiff cohesive soils or loose soils which can be displaced laterally. The system can be adjusted to deal with soils containing varying organic contents. Not suitable are soils with firm or hard intermediate layers which cannot be penetrated with the displacement auger.

The equipment is of relatively low weight, see Figure 2. The hydraulic crawler rig weighs approximately 300 kN. A work platform with 200 to 300 mm coarse grained material combined with a geomembrane is sufficient in most cases.

The installation causes no vibrations and little noise. Dewatering below work platform level is not necessary and different groundwater tables do not get connected. There is no need to dispose of any spoil, a particular advantage on contaminated sites.

Figure 2. CSV equipment

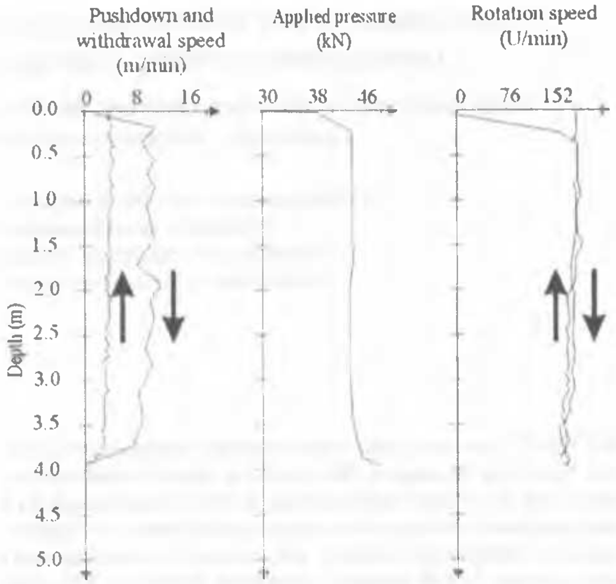


Figure 3. Quality assurance; recorded parameters during installation.

Even under very heterogeneous soil conditions homogeneous bearing conditions will be created. The usual distance between the columns ranges between 0.40 m and 1.50 m with column diameters between 120 and 200 mm, depending on soil conditions and installation parameters. At distances under 0.40 m damage to already installed columns can occur. Generally, the installation of closely spaced CSV columns can produce ground heave. 40 to 70 m of column or more can be installed per rig and per hour, resulting in a relatively short construction program.

Pushdown and withdrawal speed as well as the rotational speed must be adjustable in order to adapt to the local soil conditions. It must be guaranteed that the dry stabilization material is available in the container in sufficient quantities at any time. Any mixing of the stabilization material with the surrounding soil due to insufficient filling of the continuous flight auger must be prevented.

2.4 *Quality assurance and quality control*

The installation parameters are recorded as part of the standard quality assurance procedure in order to verify the depth and the integrity of the CSV columns. The applied pressure, the pushdown, withdrawal and rotational speed of the auger is automatically recorded for each column. Figure. 3 shows an example of such recordings. Material quantities are recorded and checked at least on a daily basis.

All materials are regularly tested by the supplier. Load tests on representative columns verify quality and load bearing behavior. Saw cut samples are tested to prove the internal strength. Column group tests might be required on large projects.

3 APPLICATION OF CSV COLUMNS

The CSV system is being used primarily for the reduction of settlements under structural loads. The number of CSV columns per m^2 can be easily adjusted to different loads within the same structure. The CSV system has been applied to increase the slope stability of relatively weak soil.

A particularly important application of CSV columns is in soils with organic content. Recent projects in organic silts and clays and in peat have been carried out successfully. More cement and increased force feeding can be required. A longer hardening process than in inorganic soils has been experienced.

The new technique is used successfully to stabilize the soft soils of more than 10 m thickness under various buildings, roads, industrial structures and highway and railroad embankments in Germany, Austria and the UK. The stability and serviceabilit requirements of all these structures were economically achieved.

4 DESIGN CONSIDERATIONS AND METHODS

The design of soil stabilization using CSV columns consists of two parts: The deformation behavior of the soil-column matrix (serviceability limit analysis) and the bearing capacity of the system (ultimate limit analysis). Analytical and numerical methods can be used to calculate the behavior of soil stabilization with type B columns (Neidhart & El-Mossallamy 2000). In case of end bearing columns, special care must be given to the properties of - and the penetration into - the bearing layer. The design diameter and compressive strength of the column should be stated and an indication of the relevant installation parameters (i.e. pushdown and withdrawal speed and rotational speed) should be given.

The column group action and the foundation-structure interaction need to be considered especially in the case of floating columns. Previous experience in the analysis of the behavior of piled raft foundations (El-Mossallamy & Franke 1997) was a pplied for type B columns. The following methods were examined:

- Equivalent raft: This approximation has proved its validity in many cases. However, it does not take into account the number of columns in the group and their interaction, which ma have a great effect. This method cannot estimate the load share of the columns and the load distribution among them.
- Method of constant reaction supports (Hansbo 1984): In this simplified approach the load that can be carried by the columns is estimated.. The columns are then designed to act as independent supports with constant known reactions.
- Methods based on the theory of elasticity: Randolph and Clancy (1993) have suggested an approximate analytical model based on the theory of elasticity to predict the vertical displacement of a single pile, a pile group and a piled raft foundation. This method can be used to estimate the performance of the CSV columns type B.
- Numerical modeling: In the last two decades there have been great developments in the power and availability of numerical methods based on finite differences, finite elements and boundary elements (integral equations). These methods have permitted the consideration of more complex influences (e.g. nonlinear behavior, inhomogenity, superstructure stiffness and general loading conditions).

5 PERFORMANCE OF CSV COLUMNS CONSIDERING THE INTERACTION BETWEEN SOIL AND STRUCTURE

A study was carried out to investigate the parameters affecting the performance of soil improvement using CSV columns type B. Two common spacings (Fig. 4.a) s = 0.5 m and s = 1.0 are considered in these analyses. An axisymmetric finite element model was applied to analyze the performance of a large extended forest of CSV columns (Fig. 4.b) using isoparametric triangular elements with 15 nodes (Program PLAXIS). The soil was idealized using the Mohr-Coulomb model. The column-soil interface was modeled using a friction element with a limit skin friction τ_{mf} = 60 kPa. The CSV columns were modeled as linear elastic material with variable E_{CSV} to study the effect of the relative stiffness E_{CSV}/E_s on the behavior of the stabilized soil. Floating as well as end bearing columns (Fig. 4.c) were studied.

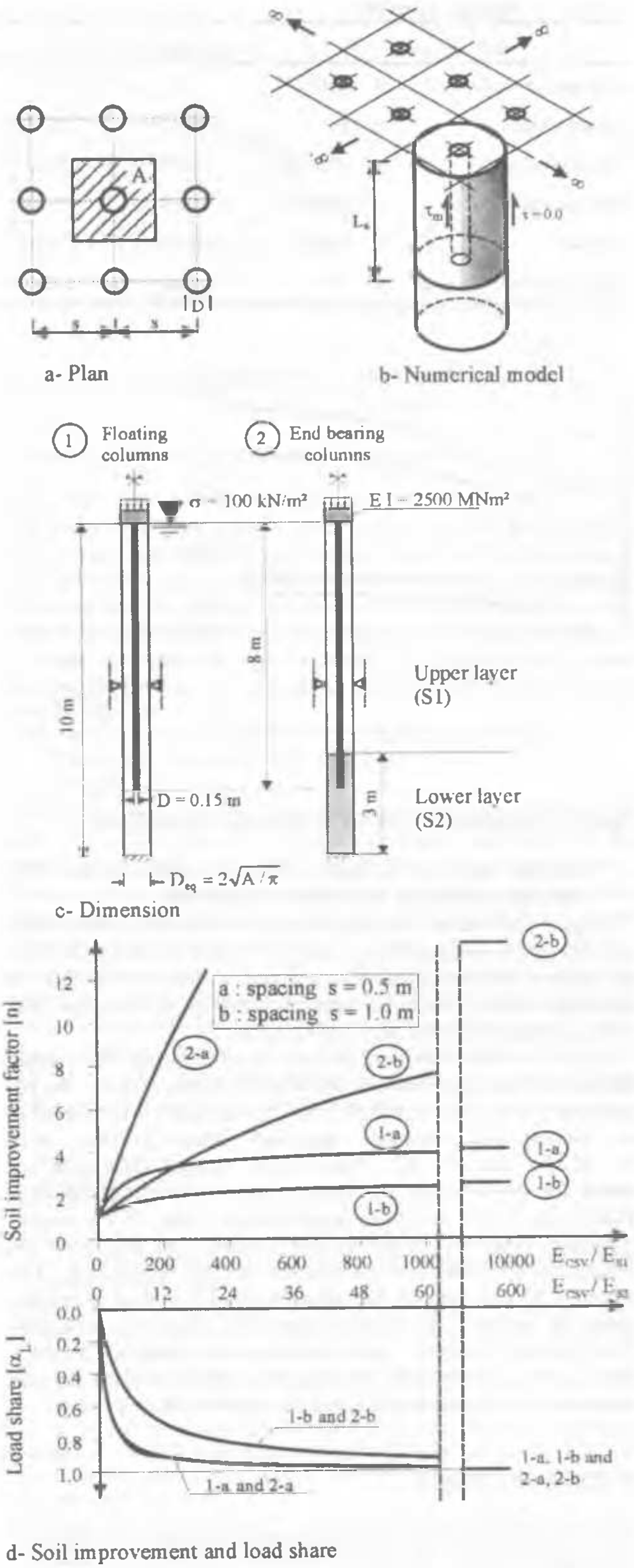


Figure 4. Performance of CSV Soil Stabilization System Type B

A raft with a stiffness of E I = 2500 MNm² was considered in the analysis to show the effect of the structural element distributing the load (e.g. concrete raft or stabilized embankment). The applied soil parameters are given in Table 1.

Two factors were introduced to define the performance of CSV columns type B:

- the soil improvement factor n defined as the settlement without stabilization divided by the settlement with stabilization.

Table 1. Material properties

Soil parameter			Soil layer S1	Soil layer S2
Deformation modulus:	E	[MPa]	3	50
Poisson's ratio:	ν	[-]	0,33	0,33
Total unit weight:	γ	[kN/m³]	20,0	20,0
Effective unit weight:	γ´	[kN/m³]	10,0	10,0
Cohesion:	c´	[kPa]	10,0	0,0
Angle of internal friction:	φ´	[°]	20,0	35,0

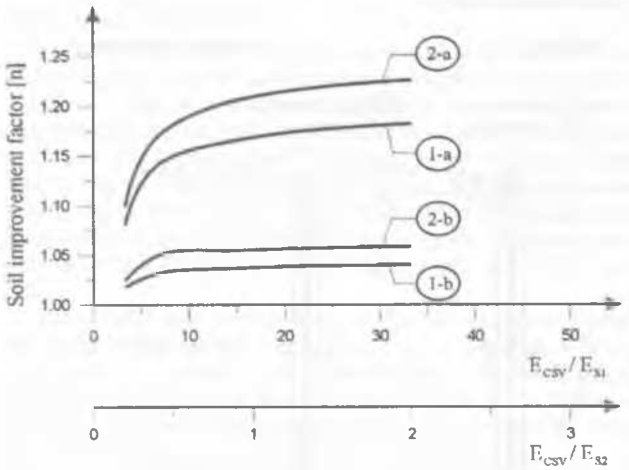


Figure 5. Performance of CSV Soil Stabilization System Type A

the load factor α_L defined as the load carried by the CSV columns divided by the total structural load.

Figure 4.d) shows the relationship between the relative stiffness (E_{CSV}/E_{S1} or E_{CSV}/E_{S2}), n and α_L. It can be recognized that the relative stiffness plays a larger role in end bearing than in floating columns. The load factor depends on the relative stiffness and reaches 1.0 for very stiff columns .

Figure 5 shows the performance of column type A without considering the improvement of the soil properties due to the installation of the CSV columns. The CSV columns were modeled as elasto-plastic material applying Mohr-Coulomb with c´= 10 kPa and φ´= 35°. There is only a small difference between the performance of floating and end bearing columns. This is due to the complete plastification of the CSV columns especially in the case of end bearing columns. The dilation of the column material improves its behavior but not significantly. The ratio of CSV columns to the soil area (A in Fig. 4.a) ranges between 14 for s=0.5 m and 56 for s=1.0 m. This large area ratio illustrates the relatively small improvement factor n CSV columns type A which are generally only efficient when the improvement of the surrounding soil can be taken into account.

6 CASE HISTORIES

Two case histories show practical applications of the CSV soil stabilization system. The first example deals with soil improvement beneath a railroad embankment (floating columns), the second with soil stabilization for the foundation of a structural building (end bearing columns).

6.1 *High speed railway, Cologne-Rhein/Main, Germany*

The new high speed railway Cologne-Rhein/Main in Germany is being constructed on a continuos track supported on a concrete slab. The allowable remaining settlements and the differential settlements are very limited. To approve the proposed soil stabilization with floating CSV columns an in-situ test with true-scale

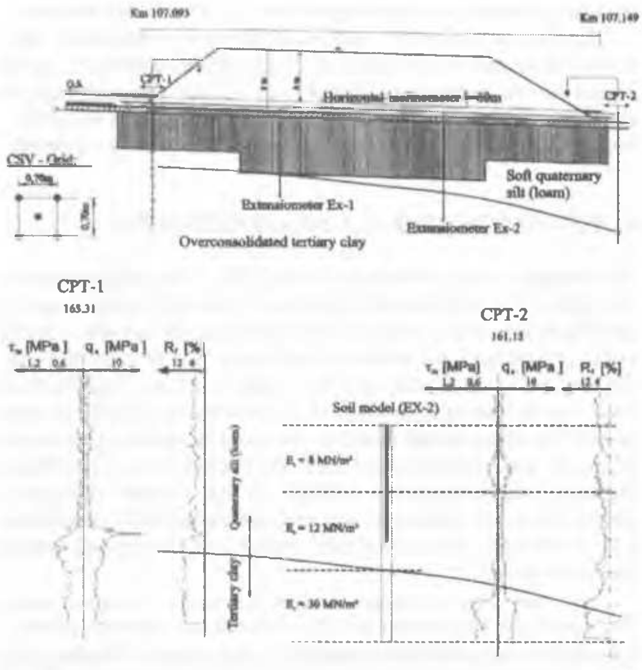


Figure 6. In-situ true scale test for the high speed railway, Cologne-Rhein/Main, Germany

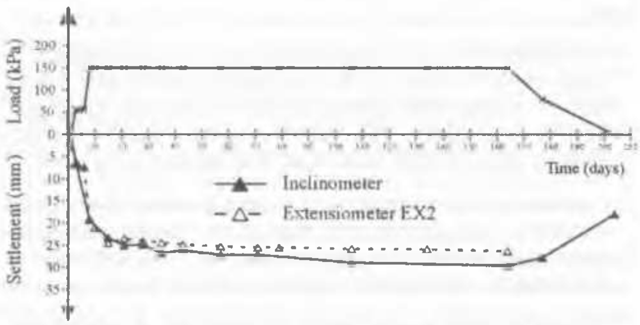
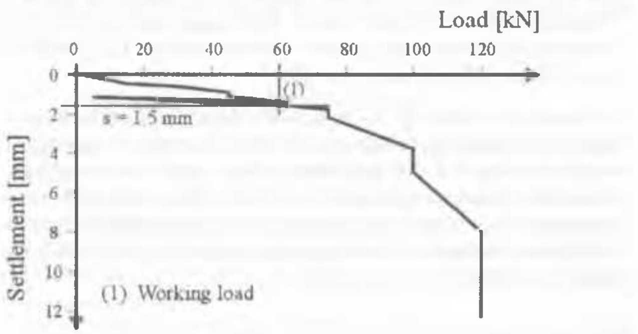


Figure 7. Observed development of load and settlement with time



$$\text{Group action factor} = \frac{\text{Settlement of the group}}{\text{Settlement of single column}} = 20$$

Figure 8. Load-settlement behavior of single column

1:1 was carried out. Figure 6 shows the geometry of the load test, the soil stratification, the instrumentation and the results of the conducted cone penetration tests (CPT).

Total settlements of approximately 30 mm were observed (Fig.7). The settlement did not increase significantly after two months due to the ability of the CSV columns to accelerate consolidation. This effect was beneficial for scheduling the continuous track construction. The test results were confirmed b computational analysis using the forest-of-columns model. eometry and soil parameters are summarized in Figure 6. Calculated total settlements of 30 mm and the factor of improvement n = 3.7 correspond well with the measurements.

The results of a load test on a single column are shown in Figure 8. Compared with the results of the true scale test. group action factor of about 20 can be calculated. The factor of group action is defined as the settlement of the group of columns related to the settlement of a single column under the same average load. These results show the relatively big difference between the performance of single floating columns and a large group of the same columns. This group action can be realisticall estimated only through a reliable adjusted numerical model.

6.2 *New House of Primates in Leipzig, Germany*

The foundation of the new House of Primates in the zoo of Leipzig, Germany was constructed using the CSV soil stabilization system. As part of the quality control a group of 16 columns was tested (Fig. 9). The 4.00 m long test columns penetrate the upper weak layer and are socketed into the lower firm bearing stratum of dense sand and gravel. A square concrete footing was placed on top of the columns. The loading system consisted of hydraulic jacks working against reaction beams and ground anchors. A three dimensional analysis was carried out to simulate the load settlement behavior of this foundation by using the GAPR program (Geotechnical Analysis of Piled Raft, El-Mossallamy & Franke 1997). The soft silt layer was modeled with a deformation modulus E = 5 MPa, the dense sand and gravel layer with E = 90 MPa and the CSV columns with E_{CSV} = 2000 MPa. The applied limit skin friction at the column/soil interface was: τ_{mf} = 150 kPa for the dense sand/gravel and τ_{mf} = (20 + 5 x depth) kPa for the silt layer.

The observed load-settlement behavior of the column group is shown in Figure 10 in comparison with the numerical results. Observed and calculated performance are in good agreement.

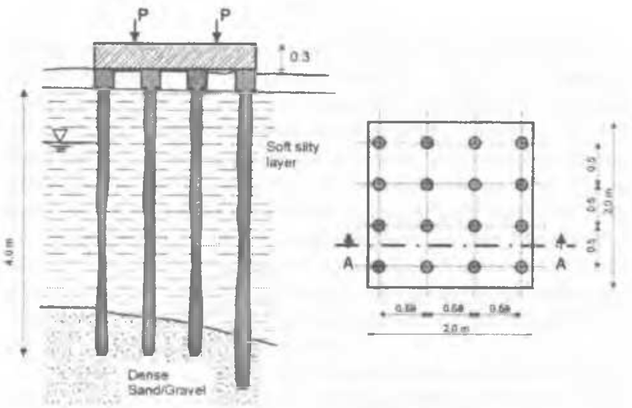


Figure 9. Group load test for the new House of Primates in Leipzig.

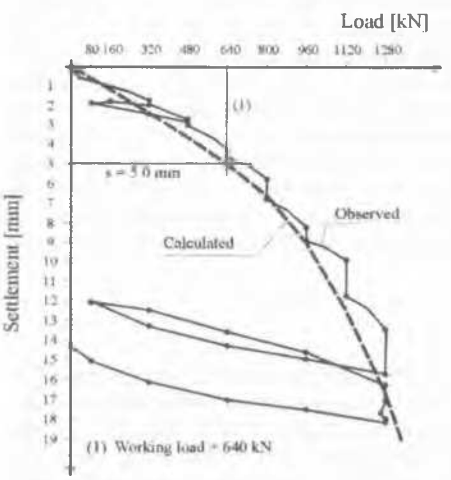


Figure 10. Load-settlement behavior of the column group

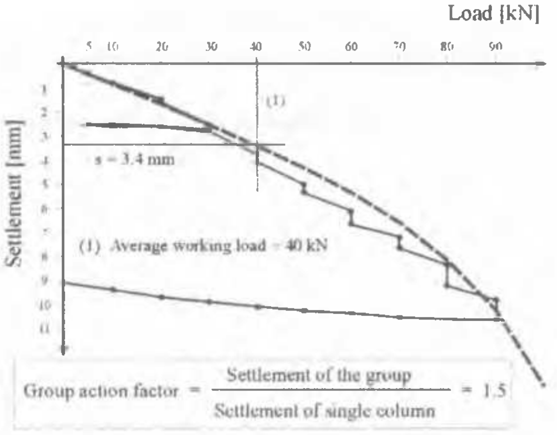


Figure 11. Load-settlement behavior of single column

The model of an equivalent raft close to the column tips was confirmed and gives very realistic results for the serviceabilit state. The resulting soil improvement factor for these end bearing columns is approximately n = 66. The same program using the same soil and column parameters is further applied to stud the behavior of a single column. Figure 11 shows a comparison between the measured and calculated values with a very good agreement. In this case the group action factor at the working load is only 1.5.

7 SUMMARY AND CONCLUSION

Since 1995 the CSV Soil Stabilization System has been used on more than 150 projects in Germany Austria and the UK. Its technical reliability and economical merits have been proven. The particular advantages, namely low equipment and mobilization costs, installation without vibrations, high flexibility in design and application and its potential use in organic soils make it increasingly popular. The CSV System is becoming an established soil improvement technique for particular applications and soil conditions. Different design procedures allow a wide spectrum of applications of the CSV Soil Stabilization System in order to improve the deformation and stability characteristics of soft soil with a high level of confidence.

8 LITERATURE

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