Evaluation of Ground Improvement by Groups of Vibro Stone Columns using Field Measurements and Numerical Analysis

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ABSTRACT: Vibro Stone Columns are widely used to improve the load-settlement characteristics of soft soils either as an infinite pattern under wide spread loading or as a column group beneath shallow foundations. The design is usually based on analytical and semi-empirical procedures. The results of field measurements of the stress and stiffness modification due to the vibro stone column installation are presented. Additionally the results of extensively instrumented load tests on groups of columns are presented. These results were used to calibrate a true 3-D numerical model, which is further on used to examine various parameters such as area ratio and improvement factor, influence of column length and end bearing situation, load distribution amongst the columns, influence of plate stiffness and vault formation in distributing layers.

1 INTROCUCTION

Since the 1950ies depth vibrators originally developed for the compaction of granular soils are used to install stone columns in weak soils by displacing and if possible compacting the in situ soil. The load settlement behaviour of stone column reinforced ground depends on the interaction of load introduction, the column material and the surrounding soil. Due to the complex interplay it is not amazing that design of stone columns is mainly based on experience and simplified analytical approaches.

Most analytical design procedures deal with the improvement of soft soils by an inifinite pattern of stone columns or a single column. Both behave differently from a finite group of columns acting together to support single footings. It is particularly this field of application where stone columns can play an important role in order to avoid differential settlement. Therefore numerical studies carefully calibrated with in situ measurements are used to investigate the load carrying mechanism of groups of stone columns in soft soil.

Generally it is assumed that the surrounding soil maintains its original strength and stiffness parameters whilst the improvement is dominated by the highly compacted stone column material. In this approach the potential improvement of the in situ soil acts as a hidden safety in the system. Conversely numerical simulation permits to consider installation effects by adjusting the stress state of the surrounding soil, which may have also increased in stiffness.

2 IN SITU MESUREMENTS DURING COLUMN INSATLLATION AND LOAD TESTING

2.1 *In situ stresses resulting from column installation*

The results of earth and pore pressure measurements during the installation of stone columns in two test fields each consisting of 25 columns in a square pattern were presented by Kirsch (2004). During the installation of each single column within the test fields pore water pressures as well as total horizontal earth pressures were measured. The gauges were installed at a depth of approximately 4,7 m in weak to stiff sandy silt of medium plasticity (MI). After completion of each stone column with a length of approx 6 m to 9 m and diameter of approx. 0.8 m the stress state both in terms of pore water pressure and effective stresses reaches a higher level than before column installation.

Horizontal stress increases at a given point measured during the installation of the whole group of 25 columns in each of the two test fields are shown in figure 1. Displayed are the effective horizontal stresses after column installation in relation to the initial stresses and normalised by the vertical overburden pressure leading to a specific k-value, the factor of restraint. In figure 1 the measured increases of the restraint factor are assigned to the installation direction, i.e. to the individual column location expressed by its distance from the pressure gauge.

It becomes evident that the stress state rises to a value of up to 1.6 times the initial stresses due to the ground displacement when the location of column installation gets closer to the measurement location. Once a critical distance of about four to five times the column diameter d_S is reached the displacing effect is superimposed by a stress relief attributable to remoulding and dynamic excitation caused by the vibrations leading to a considerable loss of strength.

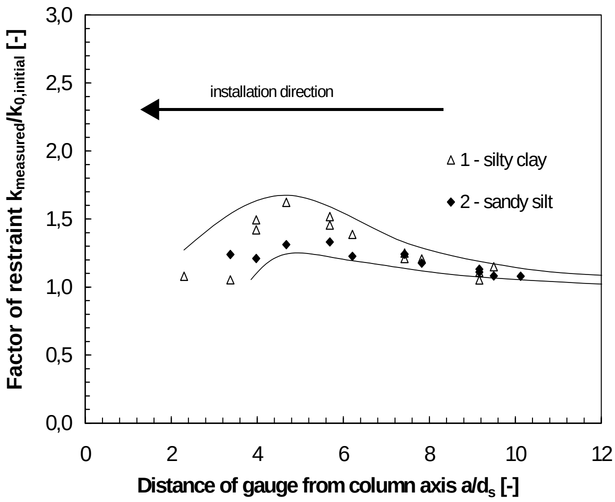

Figure 1. Factor of restraint measured during the installation of stone columns (d_S = 0.8 m).

2.2 *Stiffness development resulting from column installation*

The test fields were also instrumented with pressuremeter cells. Figure 2 shows the measured Ménard-moduli in relation to the distance from the latest installed column with an installation sequence approaching the pressuremeter cell.

We find that the stiffness rises to a maximum of 2.5 times the initial stiffness in a distance of about 4 to 5 times the column diameter d_S. Installation of stone columns closer than $4 \cdot d_S$ leads to a loss of stiffness even below initial stiffness indicating a potential liquefaction of the soil due to the dynamic excitation.

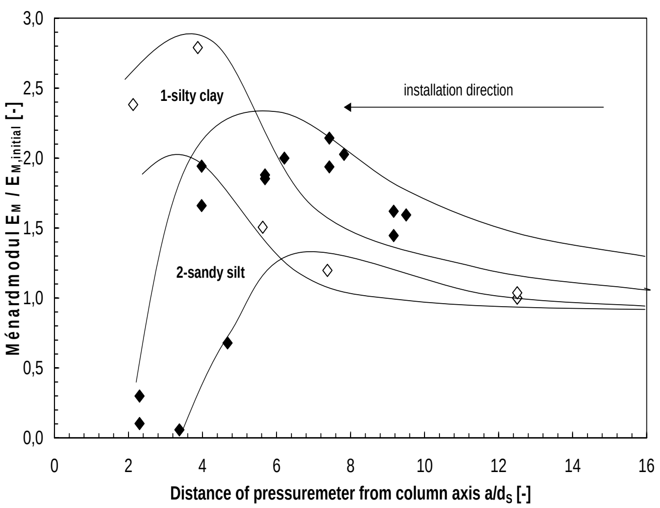

Figure 2. Development of ground stiffness during the installation of stone columns (d_S = 0.8 m).

2.3 *Summary of installation effects*

At present findings can be summarised as follows:

- Stress and stiffness increases in the surrounding soil due to vibro stone column installation can be verified by in situ measurements.
- The soil adjacent to the column is displaced and remoulded during column installation.
- The soil displacement leads to an increase in the stress state and the soil stiffness in a distance between $4 \cdot d_S$ and $8 \cdot d_S$ around the columns and the column group respectively.
- Dynamic excitation close to the column neutralises the initial stress and stiffness increases.
- The increases can be expected to be permanent in soils which do not tend to creep, i.e. soils having a significant content of non-cohesive material. However further investigation is needed.

2.4 *Group load tests*

In Summer 2002 extensively instrumented load tests were performed in order to investigate the behaviour of a group of five stone columns loaded by a square footing of 3 m x 3 m. The columns were installed as floating columns with a diameter of 0.8 m at a length of 9 m within a soft alluvial sediment. The relation of total column area to footing area results to A_C/A = 0.28. Figure 3 shows results of representative site investigation. Undrained shear strength of the soil was determined to be approximately 12 kPa to 18 kPa depending on the test procedure. Other important parameters are listed in table 1.

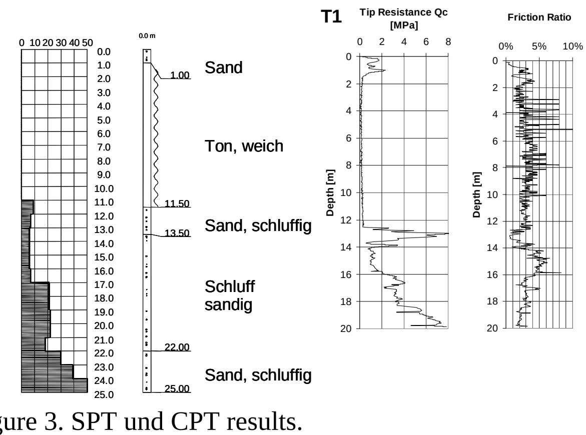

Figure 3. SPT und CPT results.

Table 1. Soil parameters.

Natural water content w_n [-]	0,636
Plasticity index PI	0,398
Index of consistency IC	0,236
Activity A	0,561
Inner friction angle φ' [°]	18
Cohesion c' [kPa]	14
Angle of dilatancy ψ [°]	4
Compression index C_C	0,454
P_0 [kPa]	55
Poisson's ratio ν [-]	0,4

The column pattern and the extend of the instrumentation consisting of pore water pressure cells (PWD), earth pressure cells (EPP, EBi) and Ménard pressuremeter cells (PM) are shown in figure 4.

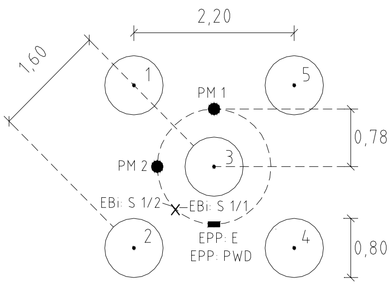

Figure 4. Plan view of column group.

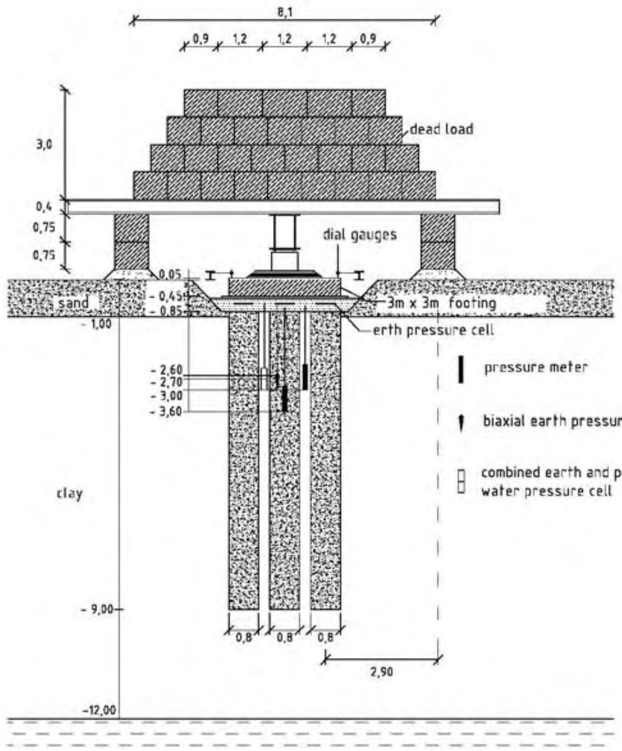

Figure 5. Cross section of test set-up.

The dead load consisted of 105 concrete blocks, which sum up to a load of 210 tons to be activated. The whole loading set-up comprises a total weight of approx. 260 tons including footing and steel girders (figure 5).

The load test was conducted as a maintained load test with loading stages held over a period of 10 days in total. The load-displacement curve is shown in figure 6. The soil within the column group was instrumented with two pressuremeter cells, three earth pressure cells and one pore water pressure cell, all of them installed prior to column production. In order to accurately measure the load distribution underneath the footing each column was instrumented with a large earth pressure cell. Another five pressure cells were used to measure the vertical stress in-between the columns. The measured stress concentration at different loading stages is depicted in figure 7.

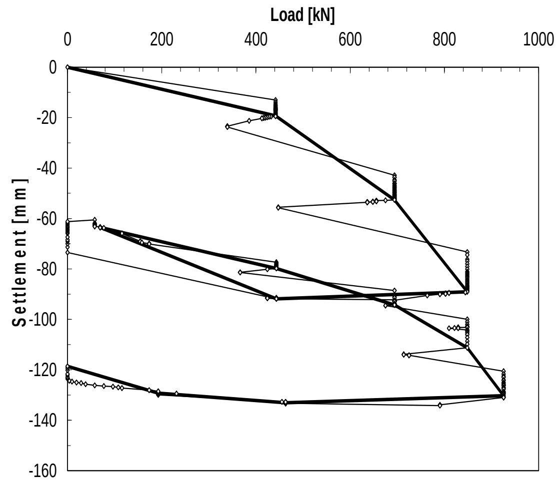

Figure 6. Load settlement response.

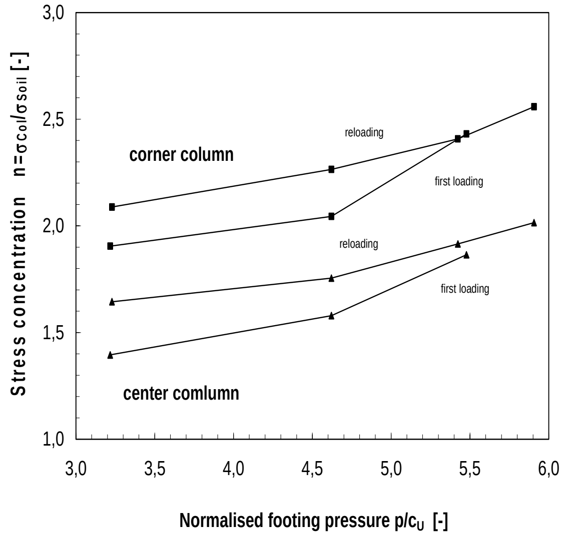

Figure 7. Stress concentration.

At the end of the first loading stage a total displacement of 9 cm was measured under a load of 920 kN corresponding to a pressure of 105 kPa. The measured stress concentration on the columns reaches values of n = 2.5 for corner columns and n = 2.0 for the centre column, both depending on the loading stage. It should be noted, that the pressure cells were embedded in a sand layer of 30 cm below the footing and were situated 15 cm above the column head.

3 NUMERICAL ANALYSIS

3.1 *Simulation of installation effects in numerical analysis*

The numerical analysis of stone column group improvement is capable of modelling installation effects such as the vibrator penetration by the cavity expansion approach and global effects of stiffness increases by an enhancement zone surrounding the column group (Kirsch, 2006). Figure 10 illustrates these two main installation effects of vibro stone columns.

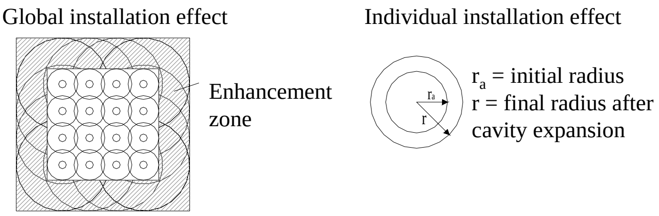

Figure 8. Global and individual installation effect of vibro stone column ground improvement.

The improvement due to vibro stone columns is defined by the improvement factor β being a settlement reduction factor. The additional improvement due to stiffness increase $f = E/E_{init}$ is defined by β*, whilst the additional improvement due to the cavity expansion α is denominated as β**.

$$\begin{aligned} \beta \quad &= \frac{s_{\text{without improvement}}}{s_{\text{with improvement}}(\alpha = 0, f = 1)} \\ \beta^* \quad &= \frac{s_{\text{with improvement}}(\alpha = 0, f = 1)}{s_{\text{with improvement}}(\alpha = 0, f > 1)} \\ \beta^{**} &= \frac{s_{\text{with improvement}}(\alpha = 0, f = 1)}{s_{\text{with improvement}}(\alpha > 0, f = 1)} \end{aligned} \qquad (1)$$

The improvement factors β* and β** from eq. (1) were calculated for the above mentioned installation tests of 25 stone columns (chapter 2.2) and are shown in figure 9 and 10.

Depending on the stiffness increase factor as a global installation effect the additional improvement β* reaches values of up to 1.25, meaning that the consideration of the global installation effects leads to a rise of 25% of the calculated improvement factor, where no installation effect is considered. The stiffness increase factor accounting for global installation effects was measured as f = 2.0 in a zone limited by $b_1=2 \cdot d_S=1.6$ m and $b_2=5 \cdot d_S=4.0$ m around the column group.

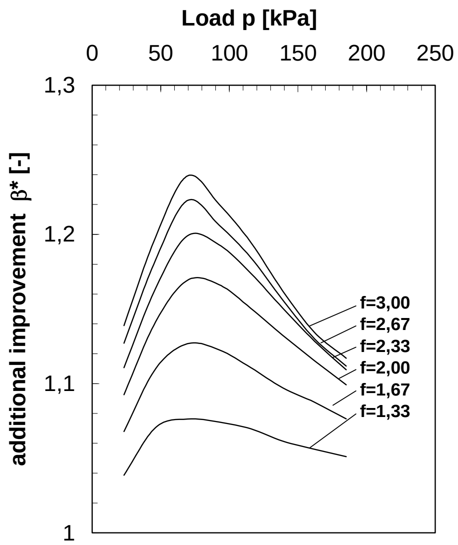

Figure 9. Improvement factor β* as defined in eq. (1) for different stiffness increase factors f in the enhancement zone.

It turns out that the consideration of the individual installation effect by applying a cavity expansion of between 0% and 8% of the column radius leads to additional improvement factors of up to 1.45. To match the stress increase surrounding the columns in the above mentioned test fields (chapter 2.2) a nominal cavity expansion factor of α=0.04 has to be considered.

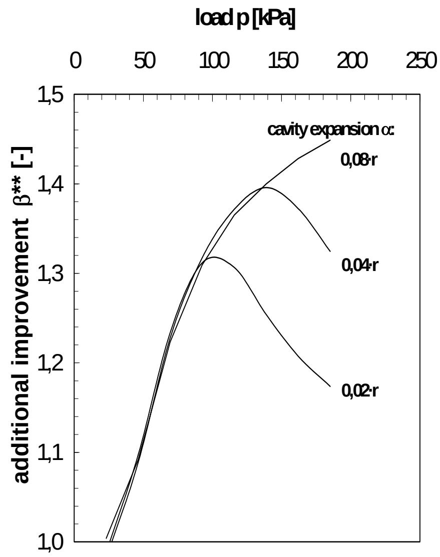

Figure 10. Improvement factor β** as defined in eq. (1) for different cavity expansion values α for each column.

In order to judge the results of the numerical analysis a comparison is made with the results of standard analytical design methods. Priebe (2003) allows the computation of settlements of a stone column group in a “floating” situation where the columns are not set on a hard layer. The routine of Goughnour and Bayuk (1979) was extended by Kirsch (2004) to calculate the settlements of a group of columns. Both methods are compared with the calculated load settlement response in figure 11.

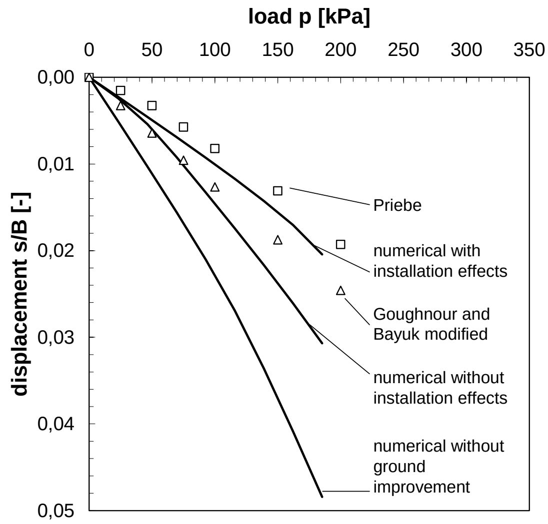

Figure 11. Analytical and numerical results of the load settlement behaviour of a group of 25 stone columns.

3.2 *Back analysis of load test*

In order to translate real behaviour into the numerical model a couple of simplifying assumptions are necessary. Material properties of column and soil are idealised as being non-linear using an elasto-plastic flow rule with isotropic hardening. The footing is computed with its real stiffness. Modelling takes advantage of the two planes of symmetry reducing the structure (figure 5) to a quarter of the total system and modelling 10362 finite elements with 62244 degrees of freedom.

Figure 12 shows the result of the simulation of the load test described in chapter 2.4. Deformations of the first loading and unloading stage as well as the stress distribution are reproduced quite correct by the simulation. The reloading and final unloading turn out to be too stiff in the model, which is due to the fact, that the total capacity obviously is over predicted by the simulation, which can be seen by the shape of the load displacement curve. Therefore the presented numerical result describes reality only for the settlement of column groups well below failure state.

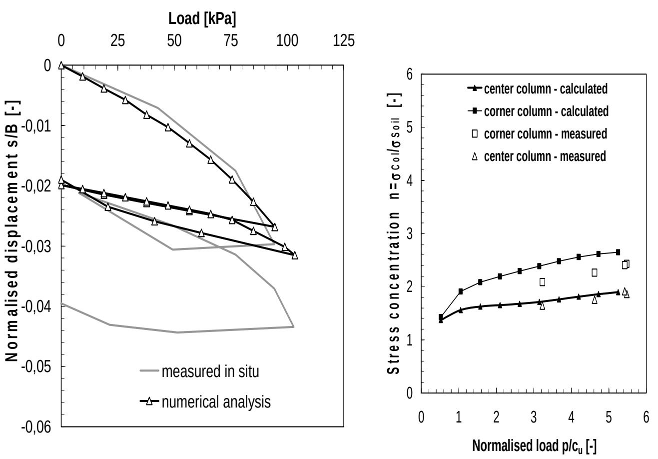

Figure 12. Load settlement-response and stress distribution.

It is important for every numerical simulation and meaningful comparison between measurement and analysis, that the whole stress history including installation of loading devices is incorporated into the analysis.

3.3 *Parametric study*

The analysis of the influence of other parameters such as stiffness of the supporting footing, geometry and material characteristics provide a valuable tool to better understand the load settlement behaviour of stone column groups and its sensitivity under varying conditions.

The computations were done using the finite element code ANSYS, in which the material model as described above was incorporated, and taking advantage of the ANSYS parametric design language. Figure 13 shows an example of the investigated situations.

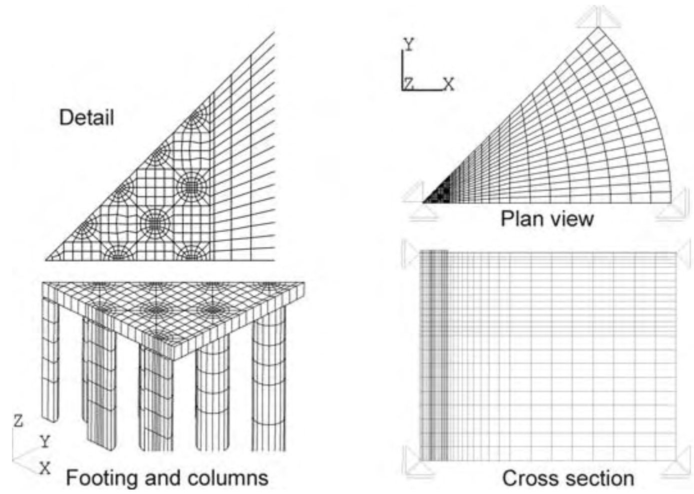

Figure 13. System for a group of 41 columns.

The principal design parameters for a ground improvement measure with stone columns are material properties of the column such as the angle of inner friction φ' and the angle of dilatancy ψ as well as geometric conditions such as the area ratio a and the length ratio λ (figure 14):

$$a = \frac{A_{Columns}}{A_{Footing}}, \quad \lambda = \frac{l}{T} \qquad (2)$$

$A_{Columns}$ total cross sectional area of columns [m²],
$A_{Footing}$ area of the footing [m²],
l lenght of columns [m],
T thickness of weak soil layer [m].

The column stiffness alone has no major influence on the settlement behaviour, since the column material undergoes plastic deformation at relatively low loading stages due to the stress concentration. Other parameters of influence are the system stiffness K_S as a measure of the relation between plate stiffness and ground stiffness as well as the coefficient of horizontal support e. Both are described in detail in Kirsch (2004). Here only some results of the investigation with the above mentioned major parameters shall be presented.

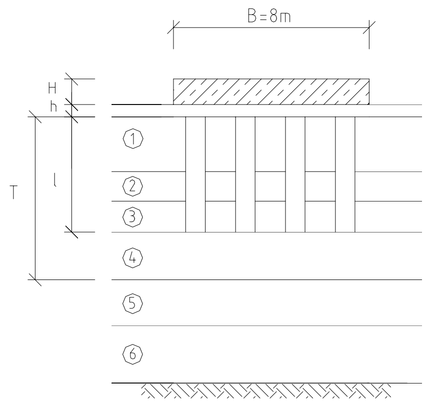

Figure 14. Sketch of geometric parameters.

Figure 15 depicts the settlement improvement factor β for various inner friction angles of the column material as a function of the area and length ratio respectively.

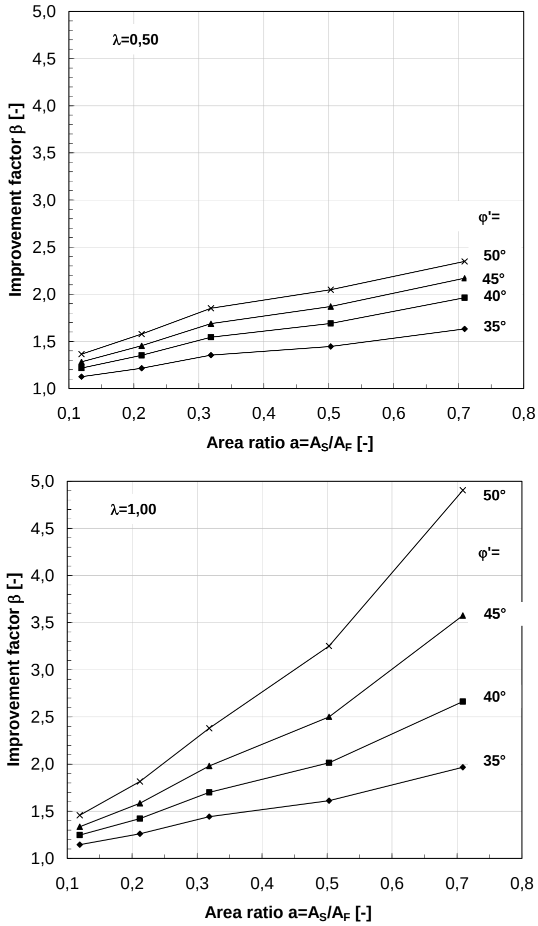

Figure 15. Improvement factor β for various area and lenght ratios, K_S=0.35, e=2.67.

3.4 *Example of application*

For the design of the ground improvement underneath the foundations of multiple bridge piers an improvement factor of β=2.0 under a working load of 200 kPa was deemed necessary. The preliminary design was done by applying an area ratio as low as a=0.13 with columns reaching the stiff layers (λ=1) and an angle of inner friction of the columns of φ'=45°.

Since the weak soil was composed of a boulder clay with relatively high content of non cohesive material a considerable additional installation effect was introduced into the preliminary design. Using figure 15 a basic improvement factor of β=1.35 can be evaluated. At a pressure of 200 kPa additional improvement factors due to individual and global installation effects can be evaluated from figures 9 and 10 to be β*=1.1 and β**=1.3 thus leading to a total improvement of β=1.35·1.1·1.3=1.93.

A sketch of the in situ load test is shown in figure 16. The improvement factor β=2.1 was determined by comparing the load test result with calculated settlements of the footing without any ground improvement measure.

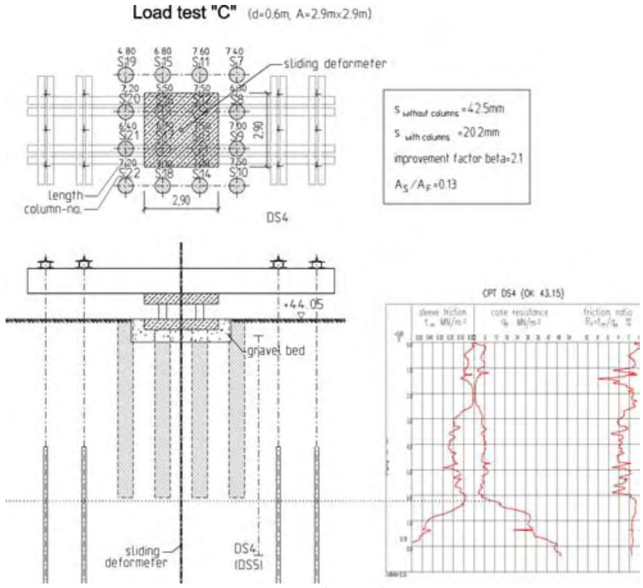

Figure 16. Result and test set up for a four column load test.

4 SUMMARY AND CONCLUSIONS

The extensive instrumentation of two test fields allowed the assessment of the influence of the stone column installation on the soil properties. The isolated and combined analysis of the additional improvement due to the installation effects showed that these effects can raise the basic improvement by a factor of approx. 1.5 depending on the loading stage. The numerical model used in the parametric studies was calibrated with an instrumented load test and proved to be valuable for deformation analysis below failure state. The charts so developed were used for the preliminary design for a major ground improvement measure and showed a reasonable agreement with the results of in-situ load tests.

The group behaviour of stone columns depends on numerous interactions which make the use of numerical analysis advantageous compared to semi-empirical solutions. To date load tests - which should be based on the results of preliminary numerical studies in order to avoid unfavourable results - still seem to be necessary for the safe assumption of the overall improvement factor.

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