Ground Improvement and Its Numerical Analysis

Amélioration des Sols et l'Analyse numérique

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ABSTRACT: Recent developments in specialist ground engineering revealed the need for a unified design approach for ground improvement techniques. A variety of procedures for the installation of vertical improvement columns are in use world-wide. Depending on the column stiffness the foundation acts more like a pile or like a soil improvement. It is obvious, that the inherent mechanical phenomena are manifold and the methods for analysis and design vary from simple empirical approaches to more sophisticated analytical procedures. The numerical simulation of the deformation behaviour plays an important role for the better understanding of the mechanical performance of the soil. One has to distinguish settlement reduction due to the enhanced stiffness of the composite soil structure and settlement acceleration due to the function of the columns as vertical drains. Different approaches of numerical analyses are presented and the use of numerical simulation as a tool for the safe and economic design of the improvement of soft soils is discussed.

RÉSUMÉ: Les récents développements dans le domaine des fondations spéciales ont montré la nécessité d'homogénéiser les logiciels de calcul des techniques d'amélioration de sol. A travers le monde, il existe actuellement une multitude de façons de dimensionner ce genre de procédé. Les simulations numériques des déformations jouent un rôle important pour la compréhension des performances mécaniques du sol. Il faut d'une part distinguer la réduction des tassements due à l'augmentation de la rigidité de la structure composite du terrain et, d'autre part, l'accélération des tassements due au rôle de drain vertical que jouent les colonnes. Différentes approches d'analyses numériques sont présentées et l'utilisation d'une simulation informatique est envisagée lors des études d'amélioration de sol, comme un outil fiable et économique.

1 INTRODUCTION

1.1 *Improvement techniques*

The erection of structures on subsiding and derelict ground is becoming a major task in today's civil engineering work. Increasing loads as well as the need to work in areas with soft and incapable soils necessitate the improvement of the actual ground condition. The choice of the appropriate technique has to be made depending on the type of soil, the loads applied and the time available for the improvement process. A rough classification can be undertaken by distinguishing ground improvement solely by compacting the existing ground and the improvement by reinforcing the soil with additional material. In the latter case there are techniques with and without certain displacing effects, hence the improvement becomes a combination of compaction and reinforcement. Table 1 gives an overview on the existing methods of ground improvement.

Table 1. Rough classification of ground improvement techniques

Type	Technique
Compaction by static methods	- Pre-loading - Pre-loading with consolidation aid - Compaction grouting - Influencing ground water table
Compaction by dynamic methods	- Vibro-compaction - Compaction using vibratory hammers - Dynamic compaction (drop weight) - Compaction by blasting - Air pulse compaction
Reinforcement with displacing effect	- Vibro stone columns - Sand compaction piles - Lime/cement columns installed by displacing methods
Reinforcement without displacing effect	- Mixed-in-place methods - Jet grouting - Permeation grouting - Ground freezing

All of these techniques have their advantages and disadvantages and their limits of application. For a more detailed description in that regard please refer to Bergado et al. (1994) or Kirsch & Sondermann (2001). Today the design of a ground improvement measure is accomplished by analytical or semi-analytical methods. Design charts or certain design approaches based on a set of equations exist for most of the techniques listed in table 1. For an overview on the design methods reference is made to Moseley (1993) or Bergado et al. (1994). Often these design approaches require a good deal of experience with the specific improvement method and tend to be conservative. In all cases where the limits of the design methods are reached or complex ground conditions introduce uncertainties into the calculations, numerical computations can offer the design engineer additional information. Parametric studies help deciding on the appropriate improvement technique for the specific problem. Nevertheless conventional design methods can not yet be substituted by numerical computing. All numerical analyses need comparative studies either by field observations or conventional design methods to prove their usefulness. Starting from these secured numerical results variation of parameters and a sensitivity analysis can be performed with the help of finite element computations.

1.2 *State-of-the-art in numerical analysis*

Most of the techniques produce a vertical zone of improved ground in the subsoil by increasing the stiffness through compaction, by the introduction of additional material respectively or by the implementation of a vertical drain. State-of-the-art numerical simulations use the finite element method to a great extend. This stands especially when complex geometrical conditions are to be modeled. Although the distinct element method or the finite difference method play a certain role when it comes to the analysis of shear failure in granular materials and the pore water pressure field respectively, all further studies as described in this paper refer to the finite element method.

In general the numerical analysis in geotechnical engineering has to fulfil certain basic requirements. The evaluation of the initial stress field and the possibility to simulate construction stages properly must be features of any program code used for the analysis. Sufficiently large element meshes confirmed by parametric studies or the use of infinite elements normally guarantee an accurate simulation of the ground as an infinite half-space. The elements used must be able to deal with geometrical and material non-linearities. Finally in special circumstances it becomes necessary to model the ground as a multi-phase medium. Guidelines for the use of numerical methods in geotechnical engineering can be found in the recommendations of the working group 1.6 of the German Geotechnical Society (Meißner (1991)).

2 APPROACHES IN MODELING

2.1 *Geometrical modeling*

Depending on the nature of the problem different degrees of complexity in the geometrical model have to be chosen.

Singe column analysis makes use of the rotational symmetry, with a sufficiently narrow mesh and sufficiently wide boundaries. When it comes to the analysis of infinite column grids the unit cell approach is commonly used. Depending on column diameter, column spacing and grid pattern a cylindrical unit cell with rotational symmetry is chosen. The same applies for the analysis of vertical drains, which are usually installed in similar patterns.

With regard to the analysis of ground improvement measures under longitudinal structures like embankments etc. plane strain conditions can be assumed. In this context it is necessary to adopt a virtual column diameter, in order to correctly model the overall stiffness of the improved ground. Alternatively the so called homogenization method can be adopted in which the columns are not physically modeled but the improved ground is treated as a composite material. For details of the technique refer to e.g. Schweiger (1989).

Finally the analysis of column groups requires the modeling of the spatial continuum taking advantage of possible planes of symmetry. As an alternative the homogenization method can also be used (Lee & Pande (1998)), although the interaction between columns, surrounding soil and footing cannot be simulated accurately.

2.2 *Installation procedures*

The load carrying mechanisms depend to a great extend on the interaction between column material and surrounding soil. In order to consider the lateral support of the column by the soil correctly the primary stress field and the influence of installation procedures have to be modeled. This can be done for instance by activation and deactivation of certain material properties and substitutional load groups during a step by step analysis. Especially the simulation of compaction effects is a major challenge in numerical simulation and usually dynamic effects are substituted by quasi-static loading. In that regard the verification of the numerical results by in-situ measurements plays an important role.

2.3 *Material modeling*

In order model the non-linear stress - strain behaviour of soils a great variety of constitutive laws is available. Unfortunately most of the advanced models require a relatively large number of parameters. Usually elastic – ideal plastic relations like the Mohr-Coulomb- or the Drucker-Prager-law describe the soil behaviour quite reasonably. For clayey soils the Cam-Clay model with its modifications can be used. For more details on the physical modeling of soils see for example Muir Wood (1990). Depending on the nature of the problem the level of complexity should be chosen. It might become necessary to define a different stiffness for loading and unloading or to care for strain hardening or softening corresponding to the initial density of the soil. In general it can be stated, that there is no universal constitutive equation.

3 EXAMPLES

3.1 *Single column - structural behaviour*

Due to its greater stiffness a single column will attract most of the stresses from the load carrying footing. Depending on its material, the column will act similar to a rigid pile carrying loads primarily by skin friction and end bearing or similar to a flexible stone- or sand column with a tendency of bulging along with plastification in the upper part. In order to develop the necessary lateral support the surrounding soil is compressed. Precompression can occur during installation of the vertical column, or during the loading itself. Depending on the area ratio of footing and column the soil is prevented from evading upwards. Based on results achieved in extensive model tests performed at the University of Glasgow as presented by Stewart & Hu (1993) and Davidson (1995) parametric studies concerning the influence of variations in area ratio, column slenderness and stiffness ratio have been performed by the authors. The system was simulated using a rotational symmetric FE-mesh with brick elements of secondary order shape functions. The non-linear behaviour was modeled using the Drucker-Prager yield criterion. The parameters used for the analysis where chosen in accordance with Lee & Pande (1998) and by the simulation of the tests results respectively. They are summarized in table 2. Fig.1 shows the deformed mesh and the vertical stresses in the soil at a late loading stage. The plastic deformation of the soil during bulging of a stone column is shown in fig. 2. Both figures depict the load carrying mechanisms: bulging of the column in the upper part, a certain amount of penetration of the column, which can be observed by the increased vertical stresses below the column toe , and partial ground failure in the surrounding soil. Depending on the loading stage and the ratios of the material parameters these mechanisms act with each other, which is typical for this kind of ground improvement.

Table 2. Parameters used for material modeling

Parameter	E [kPa]	ν [-]	φ' [°]	c' [kPa]	ψ [°]
Soil	1400-2000	0.3	5-15	5-25	0.1-5
Column	70000-200000	0.3	30-37.5	0.1-5	0.1-30

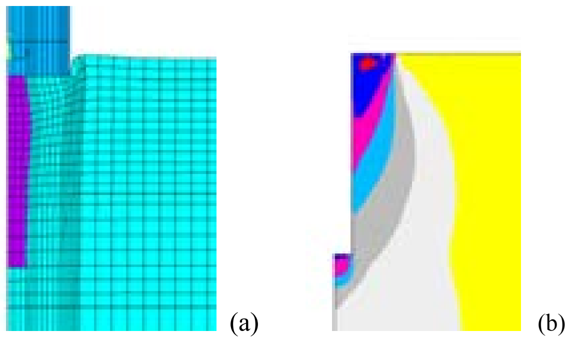

Fig. 1. Deformed mesh (a) and vertical stresses in the soil (b)

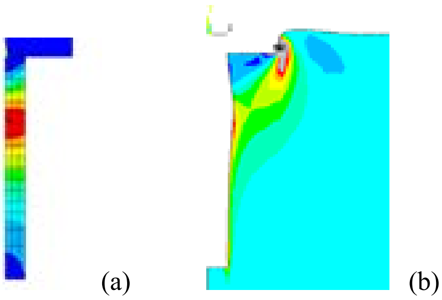

Fig. 2. Plastic deformation in the column (a) and the surrounding soil (b) during bulging

Fig. 3 shows the load settlement performance of the test footing with and without a center column as well as the results of the numerical simulations.

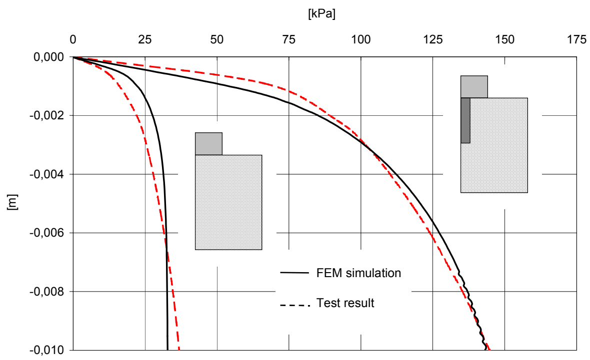

Fig. 3. Load-settlement response

3.2 *Vertical drains – coupled analysis*

Ground improvement effects the soil not only by the reduction of the total settlement under load but also by speeding up the process of settlement. To simulate these consolidation effects with finite element procedures it is necessary to follow the concept of effective stresses. Hence the structural deformation has to be coupled with the field of the pore water pressures. In the following equation system, having both displacements *u* and pore water pressures *p* as nodal degrees of freedom, the stiffness-matrix *K*, the matrix of permeability *H* and a coupling matrix *Q* are given by:.

$$\begin{bmatrix} [0] & [0] \\ [Q]^T & [0] \end{bmatrix} \begin{Bmatrix} \{\dot{u}_e\} \\ \{\dot{p}_e\} \end{Bmatrix} + \begin{bmatrix} [K] & -[Q] \\ [0] & [H] \end{bmatrix} \begin{Bmatrix} \{u_e\} \\ \{p_e\} \end{Bmatrix} = \begin{Bmatrix} \{f\} \\ \{q\} \end{Bmatrix}$$

By the numerical solution of this system of differential equations the direct coupling of structural and fluid mechanics is achieved. For the necessary integration over time the implicit backward Euler method can be used. For the accuracy of the results the value of the initial time step is fundamental. Detailed information can be found in Vermeer & Verruijt (1981) or Kirsch et al. (2000).

As an example for the application of coupled analysis ground improvement with a quasi infinite pattern of stone columns has been chosen. For this kind of analysis the unit cell approximation is sufficiently accurate. Fig. 4 shows the reduction of the time needed to end the consolidation process as a function of the ratio of unit cell radius *b* and column radius *a*, i.e. the density of the pattern.

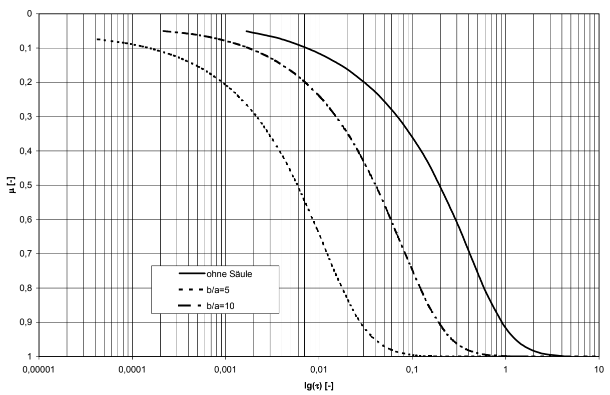

Fig. 4. Settlement acceleration

As a case history the performance of a ground improvement measure by vertical drains under a road embankment is presented. In Fig. 5 the results of measured and computed settlements during the consolidation process are shown. Since the ground improvement was achieved by the use of drains, no reduction in the total amount of settlement was reached. The construction of the embankment was assumed to proceed in two stages corresponding to a surcharge of 40 kPa and 136 kPa respectively. The measured settlement was in good agreement with the predictions done on the basis of FEM simulations.

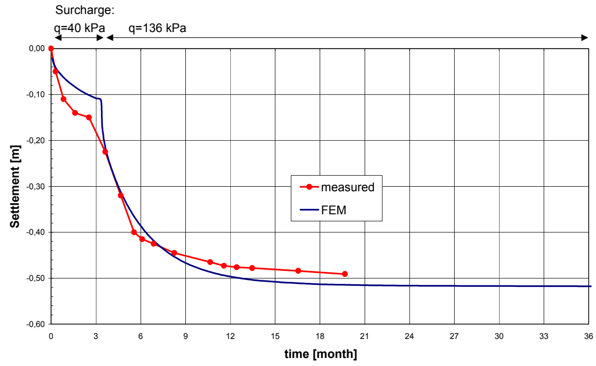

Fig. 5. Time-settlement curve

3.3 *Column groups – spatial analysis*

To gain more information on the group behaviour of improvement columns under single footings or plates the spatial modeling becomes necessary. At the Institute for Foundation Engineering and Soil Mechanics of the Technical University of Braunschweig, Germany extensive numerical simulations of column groups under vertical load are carried out at the present time. The research is focussed on the load distribution between column material and surrounding soil in different loading stages, the settlement performance and failure conditions. The validation of the chosen numerical model is done with the help of in-situ measurements or by comparing the results with those of laboratory model tests. Below some of the results of back analyses of the above mentioned Glasgow model tests are presented (fig. 6).

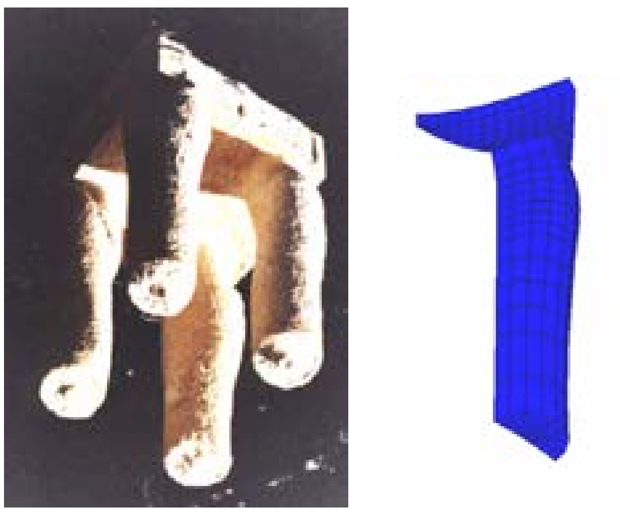

Fig. 6. Physical model and simulated result

For the simulation of tests performed with model footings on a group of four columns the mesh shown in fig. 7 was used. For the geometrical modeling only the eighth part of the system needed to be considered taking advantage of the planes of symmetry provided with the corresponding boundary conditions.

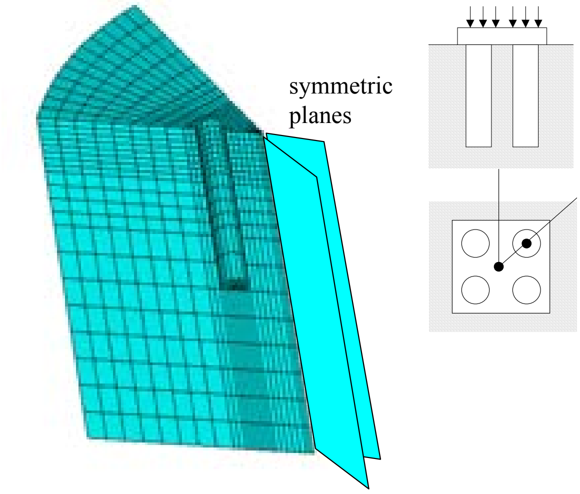

Fig. 7. FEM mesh

The stress distribution on the soil in the center of the footing and on the columns was compared with the results gained from stress measurements during the tests (Kirsch (1995)).

With increasing displacement the ratio between stress on the column and stress on the soil becomes a constant value of 2.5 (fig. 8). This agrees well with the test results, which showed a ratio of approximately 2.25 at the end of the loading tests.

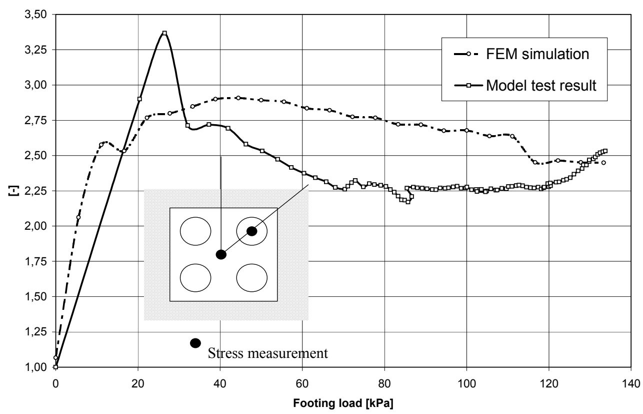

Fig. 8. Ratio of the vertical stresses on column and soil over footing pressure

4 SUMMARY AND CONCLUSION

A short overview on the possibilities of numerical analysis of ground improvement measures was given. Depending on the situation different strategies in geometrical and material modeling as well as in the modeling of installation processes can be chosen. Some examples of numerical analyses both of in-situ measurements and laboratory model tests were presented. Present effort is spent in the analysis and accurate simulation of the combined bearing behaviour of column groups under shallow foundations. In that regard sensitivity studies on the variation of geometrical, material and loading parameters are performed. Continuing validation with in-situ measurement and laboratory model tests provides the quality of the numerical simulations. Comparisons with conventional design methods are used to check their usefulness for the analysis of column groups and the interaction of soil, columns and footing.. The results of FEM solutions can help the designing engineer in his decision for different improvement techniques.

REFERENCES

Bergado, D.T. et al. 1994. Improvement Techniques of Soft Ground in Subsiding and Lowland Environment. Rotterdam. Balkema.

Davidson, W. 1995. Model Tests on Stone Column Reinforced Foundations. MSc-Thesis. Glasgow. Dept. Civ. Engg. University of Glasgow.

Kirsch, F. 1995. The Behaviour of Cohesive Soils Reinforced by Groups of Stone Columns. Report on Model Tests. Glasgow. Dept. Civ. Engg. University of Glasgow.

Kirsch, F. et al. 2000. Simulation von Konsolidationsvorgängen in der Bodenmechanik. 18. CAD-FEM Users' Meeting 2000. Int. FEM-Technologietage.

Kirsch, K. & Sondermann, W. 2001. Baugrundverbesserung. In: Grundbautaschenbuch, 6th ed. Berlin. Ernst & Sohn (in press).

Lee, J.S. & Pande, G.N. 1998. Analysis of Stone-Column Reinforced Foundations. Int. J. Numer. Anal. Meth. Geomech., 22, 1001-1020

Meißner, H. 1991. Empfehlungen des Arbeitskreises "Numerik in der Geotechnik" der Deutschen Gesellschaft für Erd- und Grundbau e. G. Geotechnik 14, 1-10.

Moseley, M.P. 1993. Ground Improvement. Glasgow. Blackie.

Muir Wood, D. 1990. Soil Behaviour and Critical State Soil Mechanics. Cambridge. Cambridge University Press.

Schweiger, H.F. 1989. Finite Element Analysis of Stone Column Reinforced Foundations. Graz. Institut für Bodenmechanik, Felsbau und Grundbau Mitteilungen Heft 8.

Stewart, W. & Hu, W. 1993. Analysis of Regularly Inhomogenious Soils – Report on Pilot Tests. Glasgow. Dept. Civ. Engg. University of Glasgow.

Vermeer, P.A. & Verruijt, A. 1981. An Accuracy Condition for Consolidation by Finite Elements. Int. J. Numer. Anal. Meth. Geomech., 5, 1-14.