Proceedings of the 15th European Conference on Soil Mechanics and Geotechnical Engineering
A. Anagnostopoulos et al. (Eds.)
IOS Press, 2011

doi:10.3233/978-1-60750-801-4-1055

Grid space optimization of jet grouting columns

Optimisation de la distance entre les colonnes de sols cimentés par injection

E. Saurer[1], Th. Marcher
ILF Consulting Engineers, Rum/Innsbruck, Austria

M. Lesnik
INSITU Geotechnik ZT GmbH, Graz, Austria

ABSTRACT

Jet grouting is broadly used to improve soil with respect to strength, stiffness or permeability. Here, a tool for optimization of the grid spacing based on the Monte Carlo method is presented. The tool requires high quality probabilistic input parameters of both, column geometry and material parameters and returns a distribution of parameters to describe the global behaviour of the improved soil. Finally an example and some sensitivity studies are presented.

RÉSUMÉ

Cimentation par injection est largement utilisée pour améliorer les sols en ce qui concerne leur résistance, leur rigidité ou leur perméabilité. Dans cet article, un outil pour l'optimisation de la distance entre les colonnes basé sur la méthode de Monte Carlo est présenté. Pour obtenir un résultat précis, les distributions de probabilité de haute qualité des paramètres suivants: géométrie des colonnes et paramètres du sol, sont indispensable. Il en résulte une distribution des paramètres du comportement global du sol cimenté. Finalement un exemple et des études de sensibilité sont présentés.

Keywords: jet grouting, soil improvement, optimization

1 INTRODUCTION

Due to increasing demands for infrastructure in urbanised areas, a rising number of constructions are built on or in soft ground with poor properties in terms of stiffness and strength. In order to facilitate construction and to prevent structures from excessive deformations, jet grouting columns have become a widely used method for soil improvement.

Jet grouting columns are installed by first drilling a borehole into the ground. Then, starting from the bottom of the borehole, the soil is fractured and mixed with a cement-suspension under high pressure in radial direction resulting in cylindrical columns of cemented soil (Fig. 1). Three different methods for soil fracturing are common (i) with suspension only, i.e. single-fluid system; (ii) with suspension and air (i.e. double-fluid) and (iii) with suspension, air and water (triple-fluid system). By placing columns next to each another, a horizontal layer of improved soil is produced.

Jet grouting may be used (i) to transfer vertical loads along the column, e.g. instead of bored piles; (ii) as a stiff slab at the base of an excavation (i.e. horizontally loaded); (iii) as a bottom plug to prevent excessive water ingress [3] into

[1] Corresponding Author.

an excavation below ground water table or (iv) as temporary support in tunnelling (see Fig. 3).

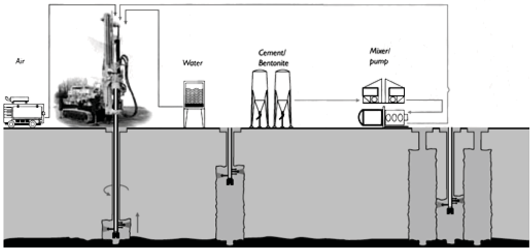


Figure 1. Principle of jet-grouting [11]

The major advantage of jet grouting for soil improvement is that the method can be applied over a wide range of soils. However, construction of jet grout columns is a rather cost intensive measure. Thus, optimization of grid spacing can result in significant cost reduction. But the grid spacing of the columns influences the overall behaviour of the improved soil in both vertical and horizontal direction.

In this paper a tool for the determination of the properties of improved soil is presented. The tool is based on the Monte-Carlo method allowing for the probabilistic distribution of geometry, strength and stiffness parameters of a single column. A sensitivity analysis based on this method is presented.

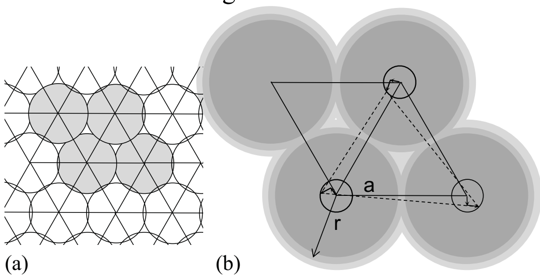
2 OPTIMIZATION METHOD

2.1 Scope and Method

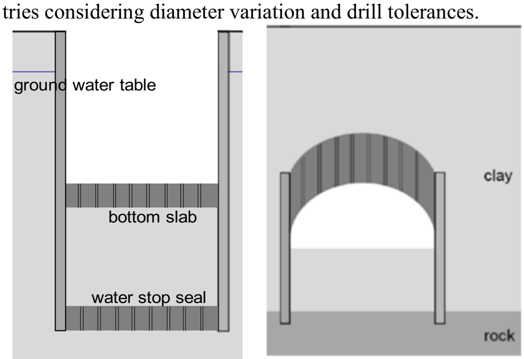
For geotechnical design, parameters of the improved soil, i.e. strength, stiffness and permeability, are required. Although the execution of jet grouting has been improved significantly in the last years [1], the derivation of the overall properties of the improved soil from the properties of the single column is not an easy task (e.g. [2]). Due to limited accuracy in column construction and the intrinsic heterogeneity of soil, the parameters of the single columns and hence the improved soil vary in space.

The tool presented here considers the variability explicitly as input parameters; i.e. the probability distributions of soil properties and of geometrical inaccuracies from column installation to compute the overall properties of the improved soil. On this occasion the grid spacing can be varied until the required overall properties are confirmed at maximum grid spacing.

The grid spacing may be described analytically by equilateral triangles (Fig. 2a). However, column geometries (location and inclination) can be as indicated in Fig. 2b.



(a) (b)
Figure 2 (a) planned grid; (b) possibilities of resulting geometries considering diameter variation and drill tolerances.



(a) (b)
Figure 3. Different applications of jet grouting measures: (a) deep excavation (b) temporary support in tunnelling using NATM.

The Monte Carlo method, which is used for the analysis, takes into account distributions of probabilistic parameters and returns probability distributions of overall properties; i.e. the size of wedges within the column triple (Fig. 2b) and overall stiffness and strength of the improved soil layer.

2.2 Model Parameters

Deterministic parameters are:

- Depth of jet grout column [m]
- Required overall design strength [MPa]
- Required overall stiffness [MPa]
- Required maximum permeability k [m/s]

While these required parameters of improved soil are in common defined from the boundary conditions of the construction, the geometrical column and the in-situ soil parameters require profound knowledge of soil and data of boring equipment. These parameters are considered with probabilistic distributions:

- Achievable column diameter
- Stiffness of jet grout column
- Strength of jet grout column
- Stiffness of soil
- Strength of soil
- Deflection from the vertical axis (depending from equipment in [%])
- Tolerated deviation of the drilling rig from starting point of the borehole [m]

Theoretical models to determine column diameters have been developed [2] and diagrams of ranges for reachable diameters as a function of soil types from experiments have been published [4-5]. Nevertheless, for a particular application, more precise distribution of the variation of the column diameter is needed. Therefore, a high quality field campaign prior to the design of the grid space is recommended to obtain reliable values. The most precise method is to excavate sample columns in a field test [8]. Another recently developed non-destructive method evaluates the column diameter from the hydration-time curve measured by a temperature sensors installed along the centre of the fresh column [9].

The probability distribution of column and soil stiffness and strength is defined as range, based on a number of standard laboratory and in-situ tests or by theoretical assessment [6-7].

2.3 *Analytical description of overall strength and stiffness*

For improved soil, when used as a slab at the bottom of an excavation (Fig. 3a, top), the main parameters of interest are the stiffness and strength perpendicular to the drilling direction; i.e. in horizontal direction, or the permeability when used as a water stop seal (Fig. 3a, bottom). Furthermore there may be occasions where the maximum allowable wedge size itself is of main interest (Fig. 3b).

The calculation of overall strength and stiffness in horizontal direction requires the consideration of the non-improved soil wedge within a column triple. Simplified the overall stiffness (E_G) can be calculated by smearing column and soil properties proportionally over the area of the improved soil, resulting in

$$E_G = \frac{2E_{jg}\pi r^2 + E_{soil}\left(a^2\sqrt{3} - 2\pi r^2\right)}{a^2\sqrt{3}} \tag{1}$$

where r denotes the radius of the jet grouting column and a is the grid spacing (Fig. 2b).

The overall strength in horizontal direction can be calculated using the effective remaining contact length between the columns a_{eff} (see Fig. 4). For the calculation of overall strength of the improved soil, the strength of remaining soil in the wedge is neglected since this value is comparably small.

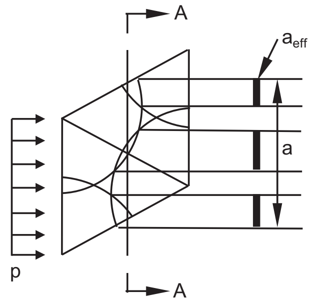


Figure 4. Effective length (a_{eff}) for the calculation of strength in horizontal direction.

The effective column contact length (Fig. 4) can be calculated as:

$$a_{eff} = 2\sqrt{3}\sqrt{r^2 - \left(\frac{a}{2}\right)^2} \tag{2}$$

Hence, the overall strength is:

$$f_{c,Global} = f_{jg}\frac{2\sqrt{3}}{a}\sqrt{r^2 - \left(\frac{a}{2}\right)^2} \tag{3}$$

where f_{jg} is the unconfined compression strength of the jet grouting column. Fig. 5 shows the effective contact length normalized by the grid spacing as a function of the grid spacing normalized with the column diameter 2r.

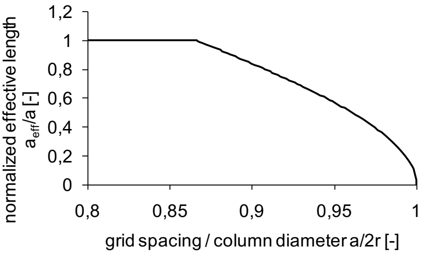
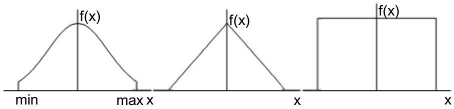


Figure 5. Analytical result of normalized effective contact length as a function of the grid spacing normalized with the column diameter.

2.4 Monte Carlo Simulation

In general, Monte-Carlo method [12] is particularly useful for modelling phenomena with significant uncertainty in input data. It relies on repeated random sampling to compute output results. The output of the simulation is a distribution of the probability of overall parameters.

Each probabilistic input parameter may be described by a distribution after Gauss, Simpson or a uniform distribution as shown in Fig. 6. Input parameters are average value, standard deviation, maximum and minimum values, depending on the distribution curve.



(a) (b) (c)

Figure 6. (a) Normal (Gauss), (b) triangular (Simpson) and (c) rectangular (uniform) distribution.

The analytical solutions provided in the previous section have been implemented into this simulation tool. In order to illustrate this, an example is provided in the next section.

3 EXAMPLE AND SENSITIVITY ANALYSIS

Consider a jet grouting slab installed at the depth of 30 m below the ground surface. Initially, a grid spacing of 1.3 m has been chosen. All further parameters for the analysis are summarized in Table 1. In this example, probabilistic parameters are described using a normal distribution curve (Fig. 6a). For each calculation a simulation with 100 000 runs has been performed.

Table 1: Probabilistic input parameters.

	mean value	stand. dev.	max.	min.
drilling inclination [%]	0.0	0.5	1.0	-1.0
start position [cm]	0.0	2.5	5.0	-5.0
column radius [m]	0.75	0.03	0.6	0.8
column strength [MPa]	4.0	1.0	2.0	6.0
column stiffness [MPa]	1500	200	1000	2000
soil strength [kPa]	50	2	45	55
soil stiffness [MPa]	10	1	8	12

The resulting distribution of strength of the improved soil layer is given in Fig. 7. Vertical lines denote mean value (dashed line) average value according to Schneider (thick line) and lower and upper values of standard deviation from mean values (thin black line). The characteristic value proposed by Schneider [10] is calculated by

$$x_k = \bar{x}\left(1 - \frac{\sigma}{2\bar{x}}\right) \tag{4}$$

where $\bar{x}$ denotes the mean value and σ the standard deviation.

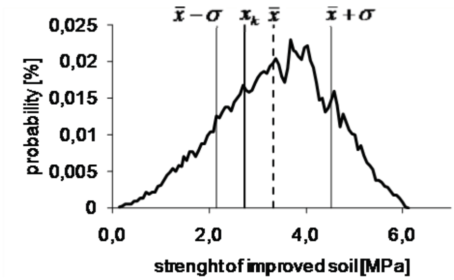


Figure 7. Probability distribution of strength of improved soil.

The probability distribution of the wedge size or the overlapping at the centre of a column triple is given in Fig. 8.

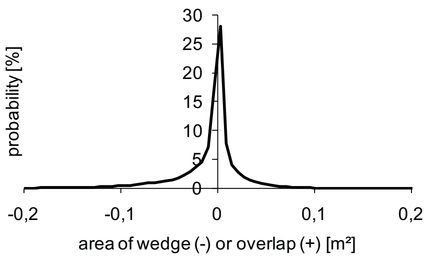


Figure 8. Distribution of wedge & overlap in column triples.

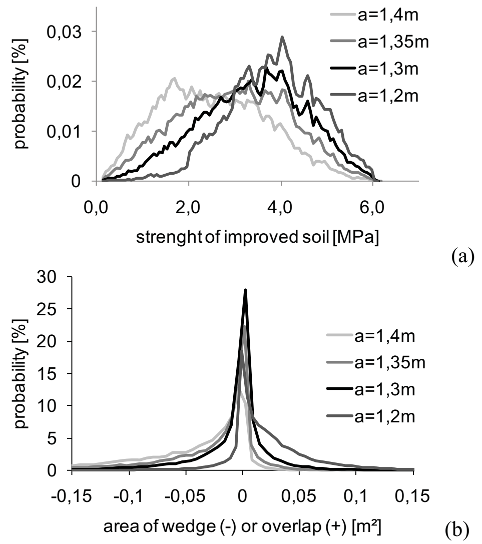


Figure 9. Results from variation of the grid spacing between 1,2 m and 1,4 m (a) strength; (b) wedge size.

At this stage, the grid spacing can be varied until the maximum grid spacing is reached at which all boundary conditions concerning strength, stiffness, wedge size and permeability are fulfilled. For illustration the grid spacing is varied between a=1.4 m and a=1.2 m. Resulting probability distributions are given in Fig. 9a. Fig. 9b shows the distribution of wedge size or overlap for different grid spacing.

Plots showing average values and standard deviations of strength and stiffness against the grid spacing between 1.0m and 1.5m are given in Figs. 10 and 11. While the strength drops significantly with increasing grid spacing, the decrease is minor significant for the stiffness.

Another interesting parameter is the distribution of unimproved wedges of certain size within the improved soil. This is of particular importance in case the improved soil is used as a water stop seal (Fig. 3a) or when used as a temporary support in tunnelling (Fig. 3b). For two wedge sizes, the dependency between the probability of a wedge exceeding the size of >0.0m² and >0.1m² is shown in Fig. 11. For a proper assessment of this value, in particular for small numbers of probabilities (e.g. if the probability of a wedge size larger than 0,1m² should not exceed 1/1000), both high quality input data and a large number of iterative runs using Monte Carlo is required to find representative ranges.

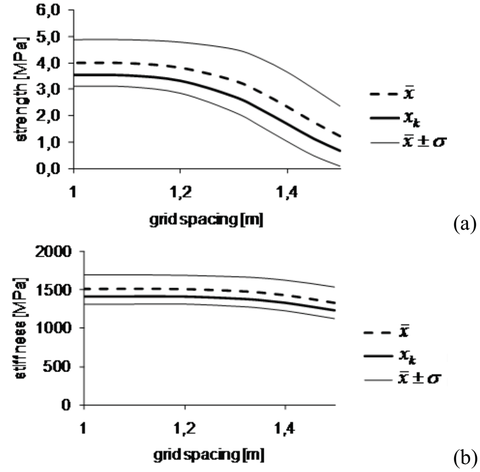


Figure 10. Key values of (a) strength and (b) stiffness plotted against the grid spacing.

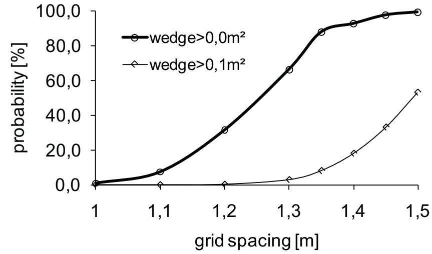


Figure 11. Probability of existence of a wedge (>0,0m²) and of wedges exceeding the size of 0,1m² plotted against the grid spacing.

An additional sensitivity study with respect to the deviation from verticality between 0.5% and 2.0% has been performed. Doubling the maximum deviation results in a decrease of strength of about 20% (Fig. 12). The dependency of wedge size probability against the maximum deviation is even more pronounced (Fig. 13).

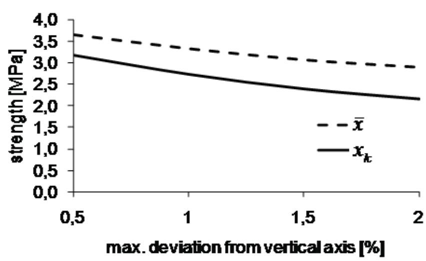


Figure 12. Strength as a function of maximum deviation from verticality of borehole.

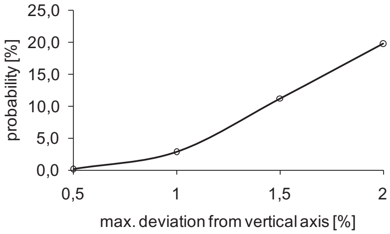


Figure 13. Probability of wedge sizes exceeding 0,1m² plotted against maximum deviation from verticality.

4 CONCLUSIONS

A tool for the analysis of properties of improved soil using jet grouting has been presented. The method takes into account probability distributions of input parameters and is based on Monte Carlo method to calculate the distribution of global properties of improved soils. Using this tool, the grid spacing of jet grouting columns can be optimized.

In order to get reliable input and hence output parameters, initially a detailed field test campaign is essential. Of course, field test are usually rather expensive. However, the cost of such a field campaign is legitimate when comparing it to saved investment due to the optimization of the grid spacing. Still this does not replace the quality check during execution but serves as a tool to estimate construction costs more precisely in advance during design.

An example showing several dependencies of resulting parameters from the input values has been presented. While the dependency of stiffness from the grid spacing is limited, the decrease of strength in horizontal direction is more significant. This is of particular importance when jet grouting is used as invert slab in deep excavations or as a temporary support in tunnelling.

The presented method allows determination of the probability of wedge size of remaining non-improved soils between a column triple, which is an important number for determination of safety against hydraulic failure, dimensioning dewatering or calculation of remaining water ingress in the case of deep excavations and safety of miners during tunnel excavation.

The sensitivity study shows that in particular the deviation from the planned drilling direction correlates highly with the probability distribution of wedge sizes. This study emphasizes the importance of good quality work and equipment with high precision of the drilling rig.

With increasing optimization of the jet grouting for soil improvement also the importance of a rigorous quality control increases. But in the very end, the monetary investment for the construction is significantly reduced using the presented tool for optimization of jet grouting columns.

ACKNOWLEDGEMENT

The authors are grateful to the fruitful discussions with Mr. Urs H. Grunicke.

REFERENCES

[1] M. Shibazaki, State of practice of jet grouting. *Proc. 3rd Int. Conf. on Grouting and Ground Treatment, New Orleans*, (2003), 56–71.

[2] G. Modoni, P. Croce & L. Mongiovi, Theoretical modeling of jet grouting. *Géotechnique* **56**(5), (2006), 335-347.

[3] M. Lesnik & S. Semprich, Düsenstrahlverfahren für tiefliegende Dichtsohlen – Ursachen und Vermeidung von Leckagen. *Beiträge zum 15. Christian Veder Kolloquium, TU Graz*, (2000), 115-129.

[4] G. Botto, Developments in the techniques of jet-grouting. *XII Ciclo di Conferenze di Geotecnica, Torino,* reprint by Trevi, 1985.

[5] A.L. Bell, Jet grouting in ground improvement, (ed. M. P. Moseley), Blackie, (1993), 149-174.

[6] S. Horpibulsuk, N. Miura & T.S. Nagaraj, Assessment of strength development in cement-admixed high water content clays with Abrams' law as a basis. *Géotechnique* **53**(4), (2003), 439-444.

[7] S. Coulter & C.D. Martin, Single fluid jet-grout strength and deformation properties, *Tunnelling and Underground Space Technology,* **21**(6), (2006), 690-695

[8] A., Malinin, I., Gladkov, & D. Malinin, Experimental research of Jet-Grouting Parameters in different soil conditions *Proc. GeoShanghai,* ASCE GSP No. 206, (2010), 49-54.

[9] K. Meinhard, R. Lackner & D. Adam, Thermisches Berechnungsmodell zur Durchmesserbestimmung von Düsenstrahlsäulen, *Baugrundtagung Dortmund* (2008).

[10] H.R. Schneider, Determination of characteristic soil properties. *12th ECSMGE* Vol. 1, (1999), 273-281.

[11] Keller Grundbau, *Company brochure*, 2010.

[12] N. Metropolis & S. Ulam, The Monte Carlo Method, *Journal of the American Statistical Association*, **247**, Vol. 44, (1949), 335-341