Determination of significant material parameters for quality control of new techniques in geotechnical engineering using statistical methods

La détermination des paramètres significatifs des matériaux pour le contrôle de qualité de nouvelles techniques en ingéniérie des sols utilisant les méthodes statistiques

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SYNOPSIS: Applying new developed foundation techniques to real foundation problems one has to be sure that no damages will occur due to too high expectations. On the other hand an uneconomical overdimensioning caused by exaggerated safety philosophies should also be avoided. In such cases it is advisable to call in an independent expert, who will elaborate objective values of quality control, reliability and safety. For this purpose computer aided statistical methods should be used. How to succeed in this way this paper deals with a recently developed jet grouting method called Soilcrete as an example.

1 DEVELOPMENT OF A NEW FOUNDATION METHOD

The most important impulses for the development of the Soilcrete technique came from the research field of "Jet-Cutting". Applying the physical principles of these researches cutting and cleaning techniques were developed using high pressure jets of fuids. Therefore it also should be possible to cut and mix soils with jets consisting of e.g. a water-cementsuspension. The hydraulic feasibility of the suspension will then lead to a new hardening soil-cementmixture with a highly improved bearing capacity.

Starting from this more or less theoretical idea the technical realization follows in a second step using the experiences from other techniques, e.g. deep boring, high-pressure injections and grouting.

After a period of advanced in situ tests the new method of Soilcrete-columns then can be applied to a real construction problem. Before doing so, it is necessary to develop objective rules for controlling each single step of the works and of the complete product itself.

2 REALIZATION

2.1 Supporting or underpinning foundation blocks by soilcrete columns

Fig. 1 shows the arrangement of Soilcrete-columns which are to support a foundation block of about 3x3 m. The representative boring log shows, that the total length of each column will be up to 12 m with 2 m resting in bearing soil. The diameter of each column will be about 0,80 m.

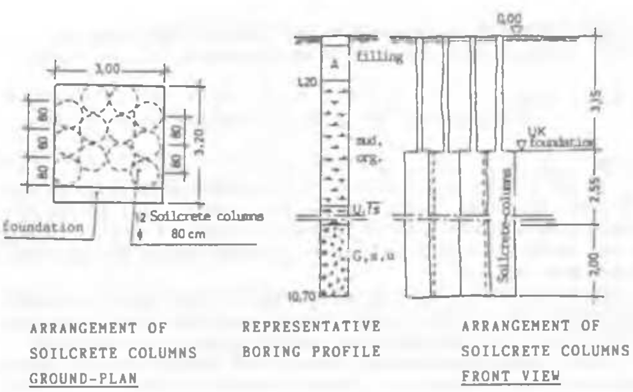

Fig. 1: Arrangement of the Soilcrete-columns supporting a foundation block

2.2 Requirements to the bearing capacity and to the material strength

According to the chosen arrangement of the columns an allowable load of about 0,6 MN is required. This means, that the ultimate bearing capacity per column must exceed 1,2 MN at least.

Together with a calculated diameter of the columns of about 0,80 m this value requires an ultimate material strength of the Soilcrete-mixtures as follows:

$$\text{erf } q = \beta_R = \text{rd. } 1{,}2 \text{ MN/m}^2$$

2.3 Load-test results

The bearing capacity of the single columns was proved by load-tests whose results are shown in Fig. 2:

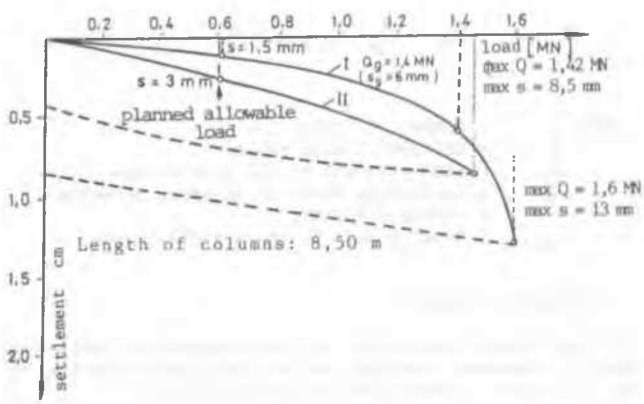

Fig. 2: Load-settlement-curves of two load-tests on Soilcrete-columns

These load-tests were evaluated according to German standards. They show ultimate bearing capacities of about 1,4 MN till 1,6 MN. According to the planned allowable loads of 0,6 MN, this leads to sufficient factors of safety of more than 2 accompanied by very small settlements (Fig. 2).

As a second result it can be assumed, that each other Soilcrete-column will perform respectively if they are carried out under the same conditions and show comparable properties such as suspension density, suspension volume, soil properties, column length, depth in bearing soil, column diameter etc.

3 MATERIAL STRENGTH

3.1 Testing of core samples and artificially produced soilcrete-cylinders

To test the material strength a few core samples were taken out of the hardened Soilcrete-columns directly. After that the samples were tested according to German standards for testing concrete (DIN 1048).

Additionally other parameters such as density, water content, void ratio etc. were determined.

As it is rather expensive to gain a sufficient number of core samples a lot of low-cost cylindrical samples were produced by filling the freshly mixed soil-suspension-material into suitable cylinders. After curing under similar conditions as in situ the 1-axial strength of these samples also were tested according the above mentioned standards. Thus a great number of test results also including values density, water content etc. were available.

3.2 Evaluation of the tests

The relatively wide scattering of the test results of core and "fresh" samples indicated a heterogene structure of the Soilcrete-material. This statement is a subjective impression even when the arithmetic mean value and the maximum and minimum values are considered.

In the concrete technology statistical and probabilistic methods are employed to get more general statements which additionally are resecured by means of probabilistic methods. Transfering these methods to the test results of the Soilcrete-samples it should be possible to get reliable factors of scale for the material strength of the new Soilcrete-material.

Assuming, that the results originate from one basic totality, the number of tests n, the arithmetic mean values $\bar{x}$ and the standard deviation s have to be determined. The indicating value of material strength then results from the following equation (1):

$$\beta_N = \beta_S \cdot t_{\alpha,n-1} \cdot s \qquad (1)$$

with:
- n = number of tests
- $\bar{x}$ = arithmetic mean value
- β_S = mean strength of the test series
- β_N = indicating value of material strength
- s = standard deviation
- $t_{\alpha,n-1}$ = t-value acc. to the t-distribution

3.3 Evaluation results

From the single results of the core samples an indicating value of material strength can be calculated according to equ. (1) with a probability of 95% as follows:

$$\beta_{N,1} = 4{,}65 - 1{,}73 \cdot 1{,}67 = 1{,}76 \ \mathrm{MN/m^2}$$

With the same probability the following indicating value of material strength of the "fresh" cylindrical Soilcrete-samples is calculated:

$$\beta_{N,2} = 4{,}44 - 1{,}75 \cdot 1{,}35 = 2{,}07 \ \mathrm{MN/m^2}$$

These results mean that with a probability of 95% only 5% of all values will be less than $\beta_{N,1}$ or $\beta_{N,2}$ respectively.

3.4 Additional tests

If quality control tests were possible using fresh made samples only, the test series could be quite comprehensive without rising costs. Therefore in a first step the difference of the relations of the variances of both random samples from a critical boundary value were examined using the Fisher-test:

$$F = \frac{s_1^2}{s_2^2} < F_{\alpha,n_1-1/n_2-1} \qquad (2)$$

with:
- s_1^2, s_2^2 = variances of the random samples 1 and 2
- n_1-1, n_2-1 = degree of freedom of the random samples 1 and 2
- F_α, n_1-1/n_2-1 = F-value from the F-distribution dependent on the degrees of freedom and on the chosen probability of error

According to equ. (2) the following values for the 1-axial strength of the core samples (random sample 1 with $n_1 = 21$ and $s_1 = 1{,}67$) and of the "fresh" samples (random sample 2 with $n_2 = 15$ and $s_2 = 1{,}35$) can be calculated:

$$F = 1{,}53 < 3{,}51 = F_{0{,}02;\ 20/14}$$

This result shows, that with a probability of 98% both random samples seem to belong to a joint basic totality with the same variance. If so, one must be sure that this is also valid for the two means respectively. Thus a joint density function is described by the variance and the mean. Therefore in a second step the scattering of the mean value of the basic totality was calculated according to equ. (3):

$$\mu = \bar{x} \pm t_{\alpha;n-1} \cdot \frac{s}{\sqrt{n}} \qquad (3)$$

with:
- μ = mean of the basic totality
- $\bar{x}$ = mean of the random sample
- s = standard deviation of the random sample
- n = number of tests
- $t_{\alpha,n-1}$ = t-value acc. to the t-distribution

According to this equation the mean of the core samples will range within the following interval:

$$3{,}59 \ \mathrm{MN/m^2} \le \mu \le 5{,}71 \ \mathrm{MN/m^2}$$

Because the mean value of 1-axial strength of the "fresh" samples (random sample 2 with $\bar{x}_2 = 4{,}44 \ \mathrm{MN/m^2}$) also lies within this interval, it can be assumed that both random samples belong to a basic totality with the same mean value μ.

Both of these statistical control tests show that with a probability of 95% both random samples stem from the same basic totality with an according density function.

That means practically that it is sufficient to prove the material strength of the Soilcrete-columns by testing the artificially made "fresh" samples only.

3.5 Further parameters for quality control

For the further reliable quality control additional parameters can be determined by simple and unexpensive tests, as there are e.g. dry and wet density, void ratio and water content. These values can be determined from lump samples, taken directly of dug out columns.

With a probability of 99% equ. (3) shows, that the mean dry density γ_d of the core samples will lie within the following interval:

$$12{,}61\ \mathrm{kN/m^3} \leq \bar{\gamma}_d = \mu \leq 13{,}0\ \mathrm{kN/m^3}$$

If the γ_d-values of lump samples also range within this interval, it can be assumed that these columns exhibit comparable material properties. Thus easily additional evident quality controls can be performed.

4 SUMMARY

Recently lots of new foundation techniques are developed. Normally no sufficient generally approved experiences are available for these methods. Therefore in most cases it is difficult to introduce such a new technique for real foundation problems without overdimensioning the foundation itself and without taking too high risk at the same time. This could be easier if there were objective values of quality control, reliability and safety.

This paper deals with the recently developed jet grouting method Soilcrete as an example. It shows how simple statistical methods can be employed to elaborate such objective values e.g. for the strength of the Soilcrete-material itself. Base of the evaluation are series of core samples, from boring holes, samples of "fresh" material which is filled in cylinders, cured and tested and mere lumps of material taken out of the Soilcrete columns. It is shown that it is sufficient to use the latter low-cost samples for quality and safety control.

There are more statistical methods which can be used for solving similar problems, e.g.:

- Analysis of variance
- Regression Analysis

These methods also can objectively be secured by statistical tests such as confidence intervals, errors of estimation and probabilities. Respective examples are given in the following list of publications.

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