Assessment of stress history in glacial soils on the basis of cone penetration tests

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Abstract: In geotechnical engineering for environmental purposes the mechanical characteristics of soil including the stress history, deformation, permeability and strength parameters are the most important characteristics which govern the behaviour of the soil deposits. Therefore, the evaluation of these parameters is the one of the most important tasks in field and laboratory investigations. In the case of cohesive deposits in situ tests e.g. cone penetration tests (CPTU), dilatometer tests (DMT), and permeability tests (BAT) are typically used to develop profiles of mechanical soil parameters.

The paper presents the results of the field and laboratory tests of soils which prevail in the Warsaw region. The investigations are carried out in order to determine the stress history described by an overconsolidation ratio OCR and the coefficient of the earth pressure at rest Ko.

Special attention is given to the heavily overconsolidated clays which require relevant and internationally recognised standards for field tests and refined laboratory techniques. Due to the fact that the semi-theoretical and empirical correlations between the penetration test results and the geotechnical parameters play a crucial role in the soil characterisation, the main objective of this paper is to provide suggestions for a general methodology which should be applied when dealing with the assessment of the stress history in heavily overconsolidated glacial deposits.

The results of the site and laboratory investigations show that the existing formulae to determine OCR and Ko on the bases of cone penetration test data are in a very good agreement with laboratory measurements of these parameters. Taking into consideration the results of the laboratory and in situ tests it can be concluded that the existing formulae should be adapted to the local conditions and the history of soil deposits.

Résumé: La genèse géologigue des sols dans la région de Varsovie exige d'utilisation des méthodes prenantes en considération l'histoire du tension, définié par le coefficient de préconsolidation OCR. L' article present les resultants des essaix "in situ" – sondages statiques, ainsi que au laboratoire, des sols cohésives. Les resultats resues on a prifité pour l' analyse statistiques des nonfiabilités des measures, ainsi que pour la verification des relations émpiriques existents dans la literature, concernentes de determination du coefficient OCR. Les propositions orginales sont présentés aussi.

Keywords: in situ tests, cone penetration tests, overconsolidated materials, stiff clay

INTRODUCTION

In practical geotechnical engineering the overconsolidation ratio is one of the most important parameters which governs the behaviour of soil deposits particularly in heavily overconsolidated clays. The OCR influences the undrained shear strength τ_{fu}, the coefficient K_0 and the pore pressure response A_f. In addition the effective preconsolidation pressure σ_p' affects the allowable bearing and the actual settlement of foundations. Therefore, the evaluation of overconsolidation ratio is one of the most important tasks in field and laboratory investigations. In clay deposits the in situ tests, e.g. cone penetration tests (CPT, CPTU), are typically used to develop profiles of the undrained shear strength. The necessity of determination of the stress history in geotechnical practise leads to the development of the interpretation methods for in situ tests on OCR and σ_p' evaluation. Considerable efforts have been made in developing the dilatometer, the self – boring pressuremeter, and the piezocone for this purpose. Although several theoretical and analytical interpretations of these tests have been proposed (Młynarek and Lunne 1987, Kulhawy and Mayne 1990, Robertson 1990) the estimation of OCR from these devices relies mainly on empirical and local experience. Therefore, the application of existing approaches to the evaluation of soil properties from cone penetration results requires consideration of the local condition and history of soil deposits.

The paper presents some results of field and laboratory tests of soils which prevail in the Warsaw region. Special attention is drawn to a heavily overconsolidated clay which requires relevant internationally recognised standards for field tests and refined laboratory techniques.

Semi-theoretical and empirical correlations between penetration test readings and geotechnical parameters play an important role in soil characterization. Thus the objective of this paper is to suggest a general methodology which should be applied when dealing with an assessment of a stress history in heavily overconsolidated glacial deposits.

ESTIMATION OF THE STRESS HISTORY IN OVERCONSOLIDATED SOILS

The overconsolidation ratio (OCR) describing a natural soil stress history is defined as the ratio of the preconsolidation pressure, σ'_p, and the in-situ vertical effective stress, σ'_{vo}. The OCR influences the undrained shear strength, the lateral stress coefficient, the pore pressure response, etc. In addition, the effective preconsolidation pressure affects the allowable bearing pressure and the actual settlement of foundations. Therefore the evaluation of overconsolidation ratio is one of the most important tasks in field and laboratory investigations. Conventional methods used to determine OCR from laboratory oedometer tests on undisturbed samples obtained from the field are influenced by the type and procedure of testing and also by the sample disturbance. One alternative is to estimate the OCR from in-situ tests. Several relationships between overconsolidation ratio of clay and CPT/CPTU readings have been proposed.

Schmertman (1974) showed that OCR can be obtained based on the estimation of undrained shear strength, s_u from CPT/CPTU data. Wroth (1988) gives relationships between OCR and the three parameters of the CPTU test: cone resistance q_t, sleeve friction f_t and water pressure on the cone u_t.

Sully, Campanella & Robertson (1988) proposed that the normalized pore pressure difference, PPD, could be related to OCR as:

$$OCR = 0.66 + 1.43\,(PPD) \tag{1}$$

where $PPD = (u_1 - u_2) / u_0$
u_1 = Pore water pressure on the cone
u_2 = Pore water pressure behind the cone
u_0 = Hydrostatic pore water pressure.

Jamiolkowski et al. (1985) suggested a relationship which can be used to estimate OCR:

$$(u_1 - u_0)/\ \sigma'_{vo} = f\,(OCR) \tag{2}$$

Sandven, Sennest & Janbu (1988) proposed to obtain the preconsolidation stress, σ'_p from the equation:

$$\sigma'_p + a = (q_t - u_0 + a)/N_{qc} \tag{3}$$

where
N_{qc} = Bearing capacity factor for clays
a = a coefficient.

Mayne and Holtz (1988) proposed to estimate the OCR from the equation:

$$\sigma'_p = 0.33\,(q_t - \sigma_{vo}) \tag{4}$$

$$OCR = (\sigma'_p/\sigma'_{vo}),$$

where
q_t = Cone resistance
σ_{vo} = Total vertical stress

Mayne (1991) presented a review of methods and suggested an approach based on cavity expansion and critical state theory. The correlation was of the form:

$$OCR = [1/(1.95M + 1) * ((q_t - u_2)/\sigma'_{v0})]^{1.33} \tag{5}$$

$$M = 6\sin\phi'/(3 - \sin\phi') \tag{6}$$

where
M = Slope of the critical state line
Φ'= Effective stress friction angle

Lunne, Robertson & Powell (1997) recommended estimating OCR in cohesive soils from the following formula:

$$OCR = k(q_t - \sigma_{vo}) / \sigma'_{vo} \tag{7}$$

Where the average value of k = 0.3 with a range of 0.2 to 0.5.

Mayne (1991) showed that the parameter k appears to vary with lower and upper bounds such that: $0.15<k<0.9$, with no correlation observed between k and plasticity index, I_p. Powell (1988) found the value of k = 0.2 for clay till and k = 0.3 for the UK soft clays. Larsson and Mulabdic (1991) found for Swedish clays the value of k = 0.29 with tendency to decrease with increasing liquid limit, w_L. Lunne et al. (1997) found the value of k = 0.34 for Norwegian clays. Borowczyk and Szymanski (1995) found that the k varies from 0.3 to 0.45 for Polish clays. Mayne (1991) found the value of k = 0.33 for the U.S. clays.

Due to the fact that the existing correlations between the results of cone penetration tests and overconsolidation ratio OCR play an important role, a verification of the interpretation procedure for each kind of soils and geological conditions is needed (Szymanski 2000).

FIELD AND LABORATORY INVESTIGATIONS

Description of the test site

In order to evaluate OCR parameters in cohesive soils and their variability with depth, comprehensive investigations were undertaken by the Department of Geotechnics of Warsaw Agricultural University. The in situ testing were carried out using cone penetration equipment (type HYSON-200 kN) CPT and CPTU. The in situ investigations were supplemented by oedometer tests performed on undisturbed samples taken by means of SHELBY and NESGI samplers securing sufficient quality of specimens (Borowczyk and Szyma ski 1995).

The test sites are located in the central part of the Warsaw Valley, on the post-glacial plateau. The subsoil consisted of upper Cretaceous deposits overlain by Tertiary soils (Oligocene, Miocene, Pliocene) with a stratification generally similar to the composition of the Warsaw Basin. The configuration of the top of the Oligocene, Miocene and especially Pliocene deposits is mainly caused by processes of erosion and that of glacitectonic origin.

In general (with the exception of surface anthropogenic fill) the tested subsoil consists of: the upper moraine deposits and Pliocene clays (Fig. 1).

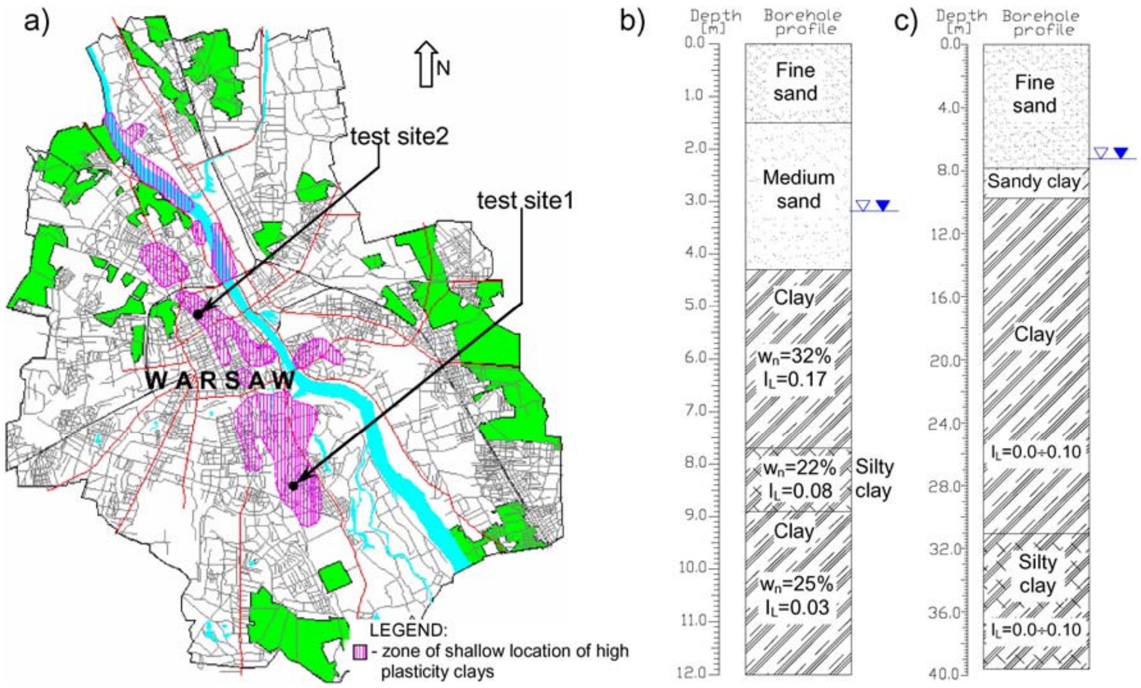


Figure 1. Test site: a) location, b) geological conditions at Stegny, c) geological conditions at Underground

The observation of the configuration of the layers (highly undulated) indicates significant soil inhomogeneity. Nevertheless the analysis of the field and laboratory test results indicated that the tested soils can be classified as stiff sandy clays in the upper Quarternary layers and stiff Pliocene clays in lower Tertiary layers.

Investigations results

The cone penetration test measures cone tip resistance, q_c and sleeve friction, f_s. New devices (piezocones) also measure pore water pressure, u. Standard piezocone penetration tests were performed using the penetration rate of 0.02 m/s.

The cone penetration tests with pore pressure measurements (CPTU) were carried out in the close vicinity of the boreholes and points of sampling at each test area. The typical results of these tests are shown in Fig. 2 (Bajda 2002).

Traditionally, from CPT data, soils are classified on the basis of the cone resistance, q_T, and friction ratio, $f_s/(q_T-\sigma_{VO})100\%$. Several charts have been developed for classification of soils (Robertson 1990).

The cone resistance, q_c and pore water pressure, u are used to estimate geotechnical parameters describing soil deposits.

In the laboratory the stress history in the clay was determined by oedometer tests on undisturbed samples. It is still the best method to obtain the preconsolidation stress, σ_p', provided that the recovered samples are of high quality. In laboratory tests on samples taken from the tested area a criterion for the acceptable volumetric strain for reconsolidation to the in situ effective stress was used to determine the quality of the tested soil specimens. The soil samples taken from subsoil by SHELBY and NENZI samplers were of excellent quality. This fact leads to a conclusion that the compression curves obtained in oedometer tests are acceptable for a reliable determination of OCR.

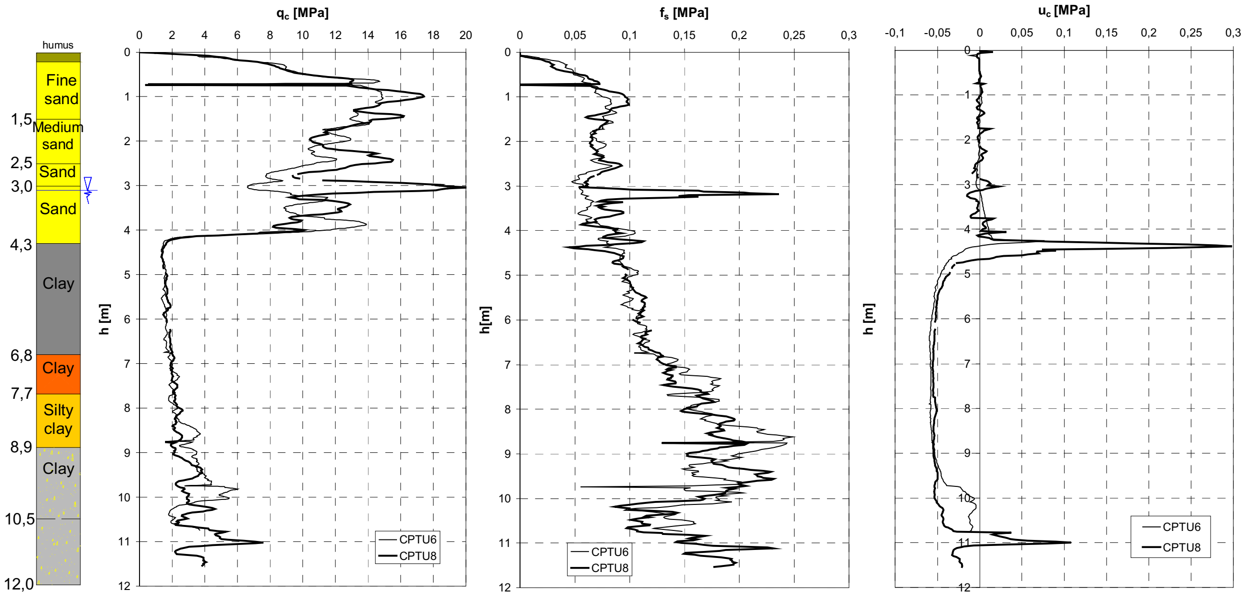


Figure 2. Cone penetration test results (CPTU)

STATISTICAL TREATMENT OF THE DATA

Scope of statistical analysis

The natural variability of the soil, the limitation of available data, soil disturbance while testing or sampling and measurement errors all contribute to the uncertainty of the soil property evaluation. Several statistical methods have been applied to Cone Penetration Test (CPT) data in order to characterise better the soil stratum and estimate the design parameters. The accuracy of methods used may be evaluated by various measures. Measures based on the mean square error and the maximal errors have been used. The method which provides the lowest error for the same set of data is considered as the best estimation procedure.

Two types of uncertainties affect the soil property within a geologic layer:

(a) uncertainty which represents the natural randomness of a property and

(b) uncertainty which represents the uncertainty due to the lack of knowledge about a given property (coming from method, equipment).

In order to assure the correctness of results calculated using a given model the test data should avoid excessive errors. From further assessments one should know the uncertainty of all data used in testing the model. Because the uncertainty of the results of measurements must be calculated on a basis of repeated measurements performed in the same condition, the uncertainty of the results of the laboratory tests were not measured here and therefore it was assumed that they were carried out in a good working order.

Uncertainly evaluation of CPTU data

For the analysis of the uncertainty of the results of the cone penetration tests and also in order to evaluate the uncertainty of CPT data within homogeneous soil layers two selected test sites were taken.

Since it is difficult to perform tests strictly fulfilling all the requirements of uncertainty analysis the value of extended uncertainty, e_p, is assessed by two estimates:

- e'_p which includes batch variations (based on the measure of batch variation), calculated by formula:

$$e'_p = 1.96\sigma_{mean} \tag{8}$$

where:

$$\sigma_{mean} = \frac{1}{m}\sum_i \sqrt{\operatorname{var}\left(x_1^{(i)}.......x_m^{(i)}\right)} \text{ (mean standard deviation)} \tag{9}$$

- e''_p which includes batch variations (based on measure of total variation of data), calculated by formula:

$e''_p = 1.96s$ (10)

where:

$$s = \sqrt{\frac{1}{m-1}\sum (x_i - \bar{x})^2} \text{ (total standard deviation)} \tag{11}$$

Interval estimation of uncertainty is done as follows:

$e'_p \le e_p \le e''_p$ (12)

Uncertainty acceptability condition is assumed as:

$e_p \le e^0_p$ (13)

where $e^o_p = 0{,}1 \cdot \bar{X}$.

Uncertainly assessment

The uncertainty of the measurement is calculated in two cases as follows:

- cone penetration resistance, q_c sleeve friction, f_s, and pore pressure, u, are measured in range sequences between each two depth intervals at each borehole profile separately. In each borehole in the range of depths, q_c, f_s and u parameters measured are q_{c1}, q_{c2}, f_{s1}, f_{s2}, u_1 and u_2. Calculated uncertainty results are presented in Fig. 3.

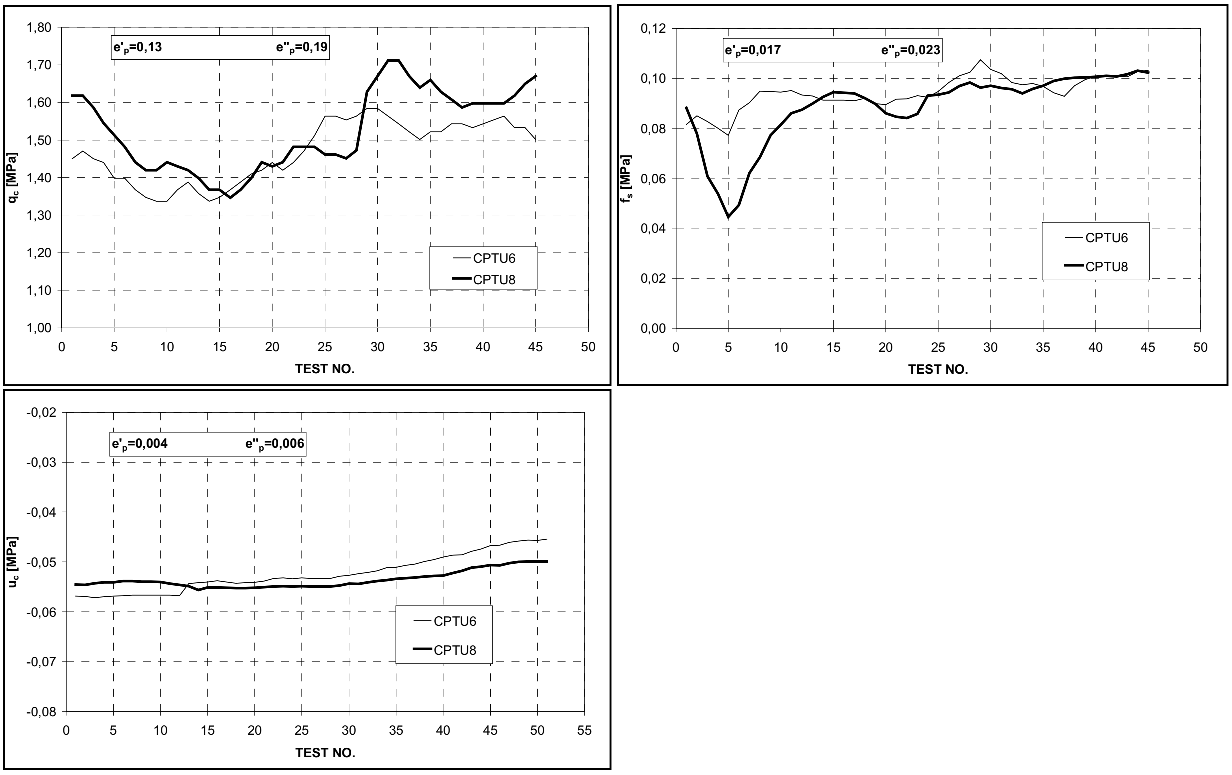


Figure 3. Cone penetration readings and uncertainty results

q_c, f_s and u parameters were measured at each borehole in selected sequences of the depth interval. The calculation of uncertainty are done for measurements parameters (q_c, f_s, u) from the two borehole profiles at the same site and the results are presented in Fig. 3. The results of the uncertainty analysis are as shown in the following table 1:

Table 1. Uncertainty measurements values

	e'_p	e''_p	e^0_p
q_c	0,13	0,19	0,15
f_s	0,017	0,023	0,009
u_c	0,004	0,006	0,005

For the calculated lower and upper estimates of uncertainty satisfy the acceptability condition for the case where data comes from different boreholes and are inconsistent.

These results indicate that the readings of the cone penetration tests can be applied for the soil property evaluation.

DISCUSSION OF THE TEST RESULTS

The interpretation of in situ tests in terms of stress history has attracted a lot of attention over the last years in the geotechnical literature mainly for cone penetration and dilatometer tests. Several relationships between the overconsolidation ratio of clays and piezocone penetration readings have been proposed (Jamiolkowski et al. 1985). The basic types of the investigated models used for all types of soils are:

- linear model of the form:

$$y = \alpha A + b \qquad (14)$$

- non-linear model of the form:

$$y = \alpha_o A^{1} \qquad (15)$$

where:

y = variable being modelled
A = a modelling variable
α, α_o, α_1, b are coefficients.

The selected models used in this investigation for determination of overconsolidation ratio (OCR) were as follows:

$$OCR = \alpha_o Q \qquad (16)$$

$$OCR = Q^{\alpha} \qquad (17)$$

$$OCR = \alpha_1 Q^{\alpha_2} \qquad (18)$$

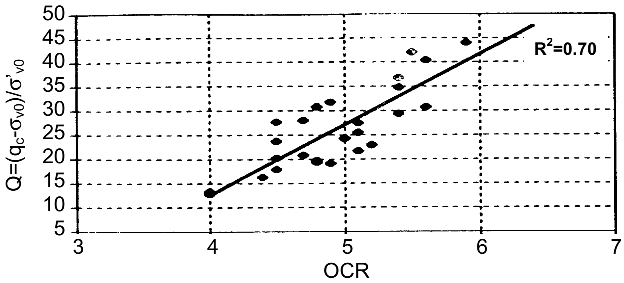
$$OCR = \alpha_3 + \alpha_4 Q \qquad (19)$$

$$OCR = \alpha_5 + (f_s/\sigma'_{vo}) \qquad (20)$$

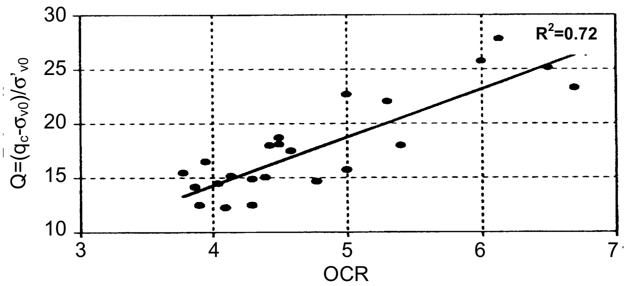
where:

Q = Normalized net cone resistance
f_s = Sleeve friction
σ_{vo} = Total overburden pressure at the appropriate level
σ'_{vo} = Effective overburden pressure
α, $\alpha_o \div \alpha_5$ are coefficients.

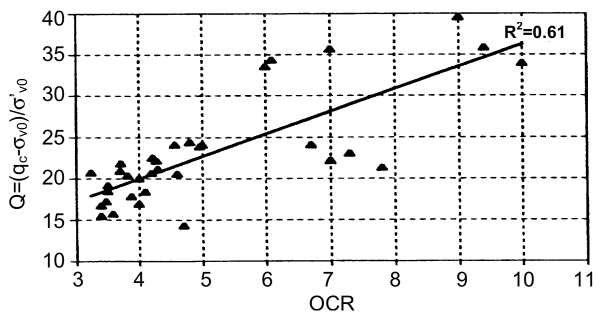
The relationship between normalized net cone resistance, Q and laboratory determined OCR for boulder clay and pliocene clays is shown in Figure 4.



a) Relation between normalized net cone resistance and laboratory determined OCR in boulder clay soils



b) Relation between normalized net cone resistance and laboratory determined OCR for pliocene clay soils



c) Relation between normalized net cone resistance and laboratory determined OCR for pliocene silty clay soils

Figure 4. Relation between normalized net cone resistance and laboratory determined OCR

The comparison between the OCR predicted and OCR determined is shown in table 2.

Table 2. Comparison of model's coefficients, relative errors of the overconsolidation ratio (OCR) models for tested soils

Soil	Site	$OCR=\alpha_0 Q$				$OCR=Q\alpha$			
		α_0		MRD %	MSRD %	α		MRD %	MSRD %
Boulder clay	all	0.18		42	24	0.49		14	9
Boulder clay	1	0.19		39	22	0.50		14	8
Boulder clay	6	0.18		33	23	0.49		12	10
Boulder clay	9	0.18		8	7	0.47		7	5
Pliocene clay	all	0.27		23	13	0.54		18	9
Pliocene clay	5	0.30		24	12	0.56		7	5
Pliocene clay	4	0.27		18	9	0.52		16	7
Pliocene clay	2	0.26		19	10	0.56		14	10
Pliocene silty clay	all	0.21		44	18	0.49		44	21
Pliocene silty clay	2	0.23		38	22	0.56		30	21
Pliocene silty clay	7	0.20		24	11	0.46		25	10
Pliocene silty clay	3	0.20		10	6	0.43		4	2
		$OCR=\alpha_1 Q^{\alpha_2}$				$OCR=\alpha_3+\alpha_4 Q$			
		α_1	α_2	MRD %	MSRD %	α_3	α_4	MRD %	MSRD %
Boulder clay	all	2.16	0.25	12	5	3.62	0.05	11	5
Boulder clay	1	2.35	0.24	4	2	3.99	0.04	5	3
Boulder clay	6	2.58	0.19	9	4	3.85	0.04	9	4
Boulder clay	9	1.74	0.30	7	5	3.23	0.05	7	5
Pliocene clay	all	0.88	0.59	17	9	1.99	0.15	17	9
Pliocene clay	5	1.12	0.52	7	5	2.26	0.15	8	5
Pliocene clay	4	1.70	0.33	15	7	2.82	0.09	15	7
Pliocene clay	2	0.54	0.76	13	9	1.33	0.19	13	9
Pliocene silty clay	all	0.23	0.96	44	18	0.32	0.19	44	18
Pliocene silty clay	2	0.76	0.64	31	21	2.25	0.15	31	21
Pliocene silty clay	7	0.73	0.56	25	9	1.74	0.11	25	9
Pliocene silty clay	3	2.20	0.16	1	1	2.91	0.03	1	1

Equation (16) gives maximum errors ranging between 42% in boulder clay soils, 23% in pliocene clay, 43% in pliocene silty clays, and the mean error ranging between 21% in boulder clays, 11.3% in pliocene clays and 13.7% in pliocene silty clays. The mean systematic error (R) is 0.19 in boulder clay soils, 0.05 in pliocene clays and 0.36 in pliocene silty clays.

Equations (17), (18) and (19) give maximum errors ranging between 11 to 14% in boulder clay soils, about 18% in pliocene clay, 43% in pliocene silty clay, and a mean error ranging between 4 to 8.5% in boulder clay, about 7.4% in pliocene clay and between 13 to 16% in pliocene silty clay. The mean systematic error (R) varies from 0.03 to 0.06 in boulder clay soils, 0.08 in pliocene clay and between 0.3 to 0.5 in pliocene silty clay.

The comparison between predicted OCR from sleeve friction using equation (20) with the OCR references indicates a maximum error ranging between 22.7% in boulder clay soils, 24.5% in pliocene clays, 45.6% in pliocene silty clays, and the mean error ranging between 7.9% in boulder clays, 9.4% in pliocene clays and 16.1% in pliocene silty clays. The mean systematic error (R) is 0.016 in boulder clay soils, 0.16 in pliocene clays and 0.6 in pliocene silty clays.

The MSRD values are between 10% in boulder clays, 11% in pliocene clays, 21% in pliocene silty clay soils, and the correlation factor $_5$ varies between 3 to 3.5.

It is important to know that the OCR of cohesive soils can be estimated from a measurement of sleeve friction using a model in which the comparison between predicted and reference values of OCR gives a small error (MSRD ranging between 10 to 20%).

CONCLUSIONS

In geotechnical engineering the cone penetration test is one of the most important methods for the evaluation of soil parameters.

The analysis of the results uncertainty show that the cone resistance (q_c) and pore pressure measured behind the cone (u_2) can be applied for evaluation of soil properties.

The stress history in clay soils can be determined from the cone penetration readings supplemented by the analysis of oedometer compression curves. This comprehensive analysis makes it possible to determine stress history of tested soils with sufficient credibility.

The results of the investigations on the test site showed that the CPTU test is useful and attractive for the evaluation of OCR profiles in the Pliocene clays.

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