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Estimation of undrained shear strength of fine grained soils from cone penetration resistance

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Abstract

Background: Many previous authors have proposed empirical methods for the evaluation of undrained shear strength S_u of soft to stiff saturated cohesive soils from CPT cone resistance q_c data. Published works are rare on this topic for the cases of unsaturated and overconsolidated clays and therefore further studies are needed to study the S_u versus q_c relationship for such soils. This paper investigates the q_c – S_u correlation for Sudanese fine grained soils taking into account the soil type, moisture condition and stress history effects.

Methods: Database pertaining to many soil samples representing low to high plastic clays and silts collected from thirty different Sudanese states was used in this study for analysis. The S_u values were determined from laboratory by the UU triaxial test method on undisturbed soil samples taken from adjacent borings and the CPT was performed by a mechanical adhesion jacket cone type.

Results: The S_u values varied from 30.3 to 460 kPa in the clay soils and from 16 to 252 kPa in the silt soils with average values of 129 and 91 kPa respectively. The consistency of most clay soils could be described as firm to very stiff with few soft and hard samples. The values of empirical cone factor N_k were determined for the soil types considered and found to vary over a wide range of 35.1 to 55.6 with average values of 37.5 for clay soils and 44.1 for silt soils.

Discussion: A rigorous analysis of soil database was performed to model the S_u – q_c relationship taking into account the effects of plasticity index and overconsolidation ratio soil parameters. The cone factor N_k values determined were analyzed and compared to those experienced in previous studies from different countries. The study results revealed that for a given soil the N_k is not a simple constant but depends on several factors such as moisture condition and degree of stiffness prevailing in the field during testing. The N_k values obtained are in close agreement with and confirm the 35 figure reported in previous studies for highly plastic clay and silt soils. The average N_k values obtained are much higher than those reported in several countries for normally consolidated soft to firm saturated cohesive soils but are lower than values found in few studies for hard and overconsolidated soils. Interpretation of the CPT and S_u database is different for saturated and unsaturated soils which makes comparison of the N_k values difficult.

Conclusions: A reliable correlation cannot be directly developed between S_u and q_c for soils with different types and characteristics as both variables are influenced by

several factors. The effects of soil type, moisture condition and stress history should be considered in studying the q_c - S_u relationship. Reliable empirical relationships have been developed to estimate S_u from CPT q_c data for Sudanese clay and silt soils of different OCR values.

Keywords: Undrained strength, CPT, Cone resistance, Clays, Silts, Stress history, OCR

Background

The cone penetration test “CPT” is widely used as a site investigation tool for the classification and characterization of soils because there is a theoretical basis for interpretation of its data. The advantages which make the CPT superior to other techniques are; the method is relatively quick, simple and economical; the test equipment can be easily mobilized to site; the test data provide a continuous data record for the whole investigated soil depth; the method facilitates testing soils in their natural condition thus avoiding the soil sampling and handling effects and it provides repeatable and reliable data, i.e. not operator dependent.

The development and application of the CPT method has yielded considerable amount of valuable information on the characteristics and behavior of soils in many countries. Numerous empirical and semi-empirical methods have been proposed to classify soils and estimate important parameters such as shear strength evaluation, settlement predictions and the design of foundations for engineering structures from CPT data.

One of the main CPT method applications is to evaluate the undrained shear strength (S_u) of fine grained soils, the subject of this paper. Various authors have proposed empirical methods for estimating the undrained strength of cohesive soils from the CPT cone resistance (q_c) using an empirical cone factor (N_k) defined as the q_c/S_u ratio. The vast majority of previous research works on the S_u -CPT relationship were carried out on soft to stiff saturated cohesive soils using electrical cones with or without pore water pressure measurements. In general, low N_k values were found by many authors for soft and normally consolidated soils whereas relatively high N_k values were reported in few studies for some tropical and overconsolidated cohesive soils. Published research works on the q_c - S_u relationship are rare for the cases of unsaturated and overconsolidated cohesive soils which are predominant in arid and semi-arid regions. Further studies are needed to compare the N_k values and examine the validity of correlation methods proposed for saturated and normally consolidated soils.

The CPT was introduced to Sudan in 1977 and since then has successfully been applied in many research projects to classify and characterize local soils and in the design of various foundation types. Considerable experience and knowledge have been gained in understanding the CPT method and its value in the evaluation of local soils behavior.

Empirical relationships were proposed in two previous studies for estimating S_u directly from measured q_c values for some local clay and silt soils but no consideration was given to soil type and stress history effects. The present study was meant to contribute in this particular research area for Sudanese fine grained soils of different stress history and moisture conditions. The primary study objective is to determine the N_k values

for cohesive soils tested and investigate the possibility of developing a sound S_u - q_c correlation which takes into account the soil type and overconsolidation ratio effects. A short review of the relevant published research studies on the applications of the CPT for undrained shear strength evaluation is presented hereunder.

Evaluation of soil undrained shear strength from CPT data

The soil undrained shear strength can be evaluated from CPT on the basis of theoretical solutions using the bearing capacity equation [1, 2], cavity expansion theory [3], analytical and numerical methods [4], or strain path theory [5]. Empirical relationships have been proposed by various authors for estimating the undrained shear strength of cohesive soils (S_u) from the CPT cone resistance (q_c). Most of these relationships were based on the bearing capacity theory wherein S_u was directly related to the net cone resistance ($q_c - \sigma'_v$) according to the equation:

$$S_u = \frac{(q_c - \sigma'_v)}{N_c} \quad (1)$$

N_c is a theoretical cone factor and σ'_v is the effective overburden pressure at a given soil depth. The above expression became the theoretical basis of later empirical or semi-empirical correlations but in order to distinguish them from the theoretical solutions the empirical cone factor is denoted by N_k as follows:

$$S_u = \frac{(q_c - \sigma'_v)}{N_k} \quad (2)$$

Researchers from different countries used the above equation to determine the N_k values that match the nature and conditions of soils in their regions. Examples of the proposed N_k values are given in Table 1.

It has been recognized from previous studies that N_k is not a simple constant but varies significantly from site to site depending on several factors. The most important factors include the type, shape and roughness of the cone, the physical and mechanical soil properties and the testing methods used to determine soil shear strength [6]. Therefore, care should be taken in applying the relationships for soil types and conditions different from those for which they were proposed.

Table 1 Typical values of cone factor N_k for various soil types

Soil types and source	N_k range	References
Alluvial clays, Malaysia	12–19	Abdel Rahman [24]
Various NC soft clays, Germany	8–29	Gebreselassie [20]
Quaternary clay and clay stone, Germany	89.3	Gebreselassie [20]
Klang Clay, Indonesia	5–12	Chen [25]
Stiff fissured clays (general)	11–30	Terzaghi et al. [26]
High plastic clay and silts, Sudan	32–39	Ismail and Zein [21]
Alluvial clay and silt soils, Sudan	34–62	Hassan [17]
Soft to firm saturated clays, Nigeria	34.2–57.2	Otoko and Isoteim [22]
Busan clay, Korea	7–20	Hong et al. [27]
Soft Holocene clays, Hungary	12–32	Rémai [10]
Various soil types (worldwide)	5–70	Sanglerat [19]

In the studies carried out to investigate the factors affecting N_k values, more attention had been given to the soil type and stress history parameters expressed in terms of the plasticity index PI [7], and over-consolidation ratio, OCR [8]. A strong linear relationship was recently reported by Novobasi [9] between N_k and PI whereas no correlation was found between the two variables for the soils tested in other regions [10].

As for the OCR , it has been indicated that a reliable correlation can be established between S_u and $(q_c - \sigma'_v)$ if the insitu stress state and stress history are considered in data analysis. Various relationships have been proposed to directly evaluate the OCR of a given soil type either from CPT profiles or from the undrained soil strength (S_u). For example, [Mayne and Kemper [11] proposed the following relationship between OCR and the normalized net cone resistance $(q_c - \sigma'_v)/\sigma'_v$:

$$OCR = \frac{k_t(q_c - \sigma'_v)}{\sigma'_v} \tag{3}$$

k_t is an empirical parameter ranging between 0.12 and 0.5 for most of the database tested by mechanical cones and its value seems to be site and soil type dependent. A similar relationship was reported for some British clay soils [12] but with a different k_t value. [13] proposed the graphical relationship shown in Fig. 1 between $(q_c - \sigma'_v)/\sigma'_v$ and the OCR . An empirical relationship was recently proposed by Zein [14] to estimate the OCR from CPT data for Sudanese fine grained soils. The soils were divided into five groups according to the friction ratio (R_f) and the OCR was related to $(q_c - \sigma'_v)/\sigma'_v$, as given in Table 2.

The undrained soil strength S_u was related to the strength ratio $\left(\frac{S_u}{\sigma_{vnc}}\right)$ of normally consolidated soils and the OCR [15] by the equation:

$$\frac{S_u}{\sigma'_v} = \left(\frac{S_u}{\sigma_{vnc}}\right) OCR^A \tag{4}$$

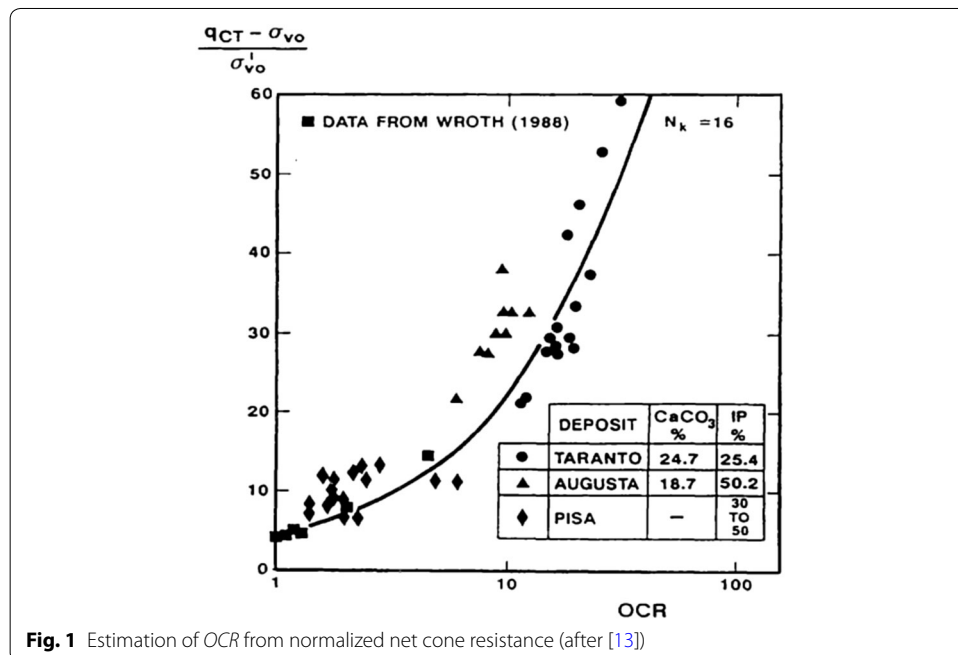


Fig. 1 Estimation of OCR from normalized net cone resistance (after [13])

Table 2 Prediction of the OCR of fine grained soils from CPT cone resistance

Friction ratio R_f (%)	Best fit line equation	R^2	Standard deviation
Over 7.0	$OCR = 0.034 (q_c - \sigma'_v) / \sigma'_v + 1.230$	0.793	0.982
5.0–7.0	$OCR = 0.047 (q_c - \sigma'_v) / \sigma'_v + 0.728$	0.714	1.227
3.5–5.0	$OCR = 0.049 (q_c - \sigma'_v) / \sigma'_v + 0.56$	0.645	1.322
2.0–3.5	$OCR = 0.013 (q_c - \sigma'_v) / \sigma'_v + 2.102$	0.737	1.539
Less than 2.0	$OCR = 0.018 (q_c - \sigma'_v) / \sigma'_v + 1.405$	0.845	1.237

A is a strength rebound exponent with a value of 0.7. The $(q_c - \sigma'_v)$ and S_u values in Eqs. (3) and (4) were normalized to effective overburden pressure to provide dimensionless parameters. The relationship shown in Fig. 2 was proposed by Schmertmann [6] between normalized undrained cohesion ratios of normally and overconsolidated clay soils and the OCR .

The Swedish experience suggests that OCR corrections should be applied for the soil strength of clay soils obtained from CPT data. The following relationship was developed between undrained cohesion (c_u), net cone resistance ($q_t - \sigma'_v$), empirical cone factor N_{kt} and the OCR for Swedish overconsolidated clays where q_t is the total cone resistance [16]:

$$c_u = \frac{(q_t - \sigma'_v)}{N_{kt}} + \left(\frac{OCR}{1.3} \right)^{-0.2} \tag{5}$$

The soil type and stress history effects on the $q_c - S_u$ relationship were investigated for Sudanese fine grained soils with different OCR values [17]. The soils were divided according to their OCR into normally to slightly consolidated ($OCR < 2$), moderately over consolidated ($2 < OCR < 6$) and heavily overconsolidated ($OCR \geq 6$). The study results showed that the OCR has a significant effect on the $q_c - S_u$ relationship but no reliable correlation was revealed for the soils tested.

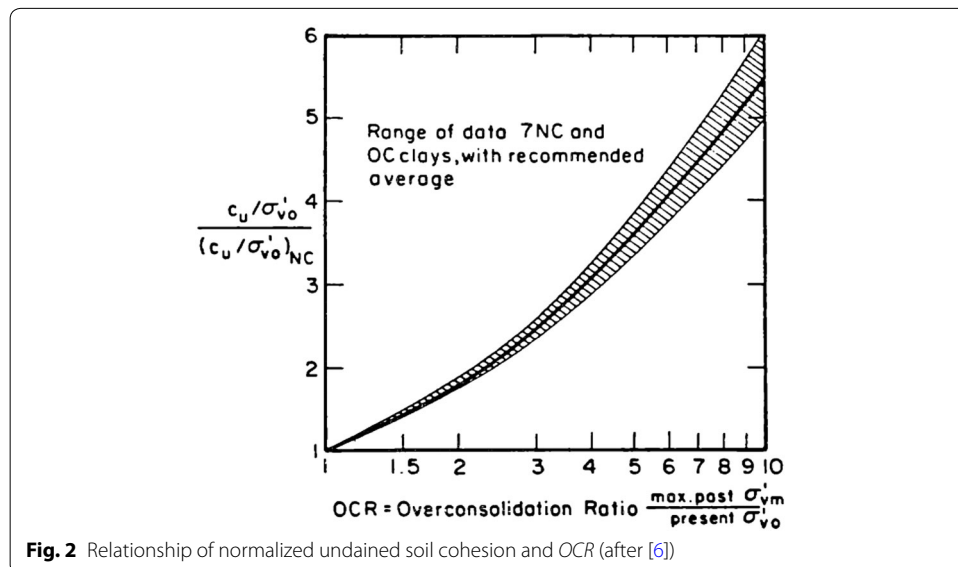


Fig. 2 Relationship of normalized undrained soil cohesion and OCR (after [6])

Soil database, techniques and methodology

The database used in this study was obtained from the results of CPT and undrained shear strength tests performed on fine grained soils from three Sudanese states. The database pertains to low to high plastic clay and silt soil samples collected from 30 different sites, 25 in Khartoum State (central Sudan), 3 in Kordufan State (western Sudan) and 2 in Gedaref State (eastern Sudan). The soils from Khartoum state comprised alluvial stiff to very stiff clay-silt-sand mixtures. Geologically, the vast majority of the samples lie within the superficial deposits of River Nile valley in Khartoum area.

In total, 138 soil samples with liquid limit and plasticity index values plotted in Fig. 3 were used for undrained shear strength determination. About 80% of the soil samples were taken from depths above ground water table in the boreholes which indicates that they were in an unsaturated condition.

The CPT soundings were performed by a mechanical adhesion jacket cone adjacent to the borings from which the soil samples were obtained for S_u determination. The selection of distance between the borings and CPT holes involved two opposing desires; to minimize the effects of soil failure zones and to lessen the problem of non-homogeneity of tested soil. The cone resistance q_c and sleeve friction f_s were measured at depth intervals of 200 mm and the friction ratio R_f was computed.

The undrained cohesion c_u and angle of internal friction ϕ_u shear strength parameters were determined from UU triaxial test results. For fully saturated soils where $\phi_u = 0$, S_u is independent of the confining pressure and is equal to c_u . For unsaturated or overconsolidated soils in which $\phi_u > 0$, the undrained strength was computed using the method proposed by Cleveland [18] explained hereunder.

At a point on a particular plane, the undrained shear strength was expressed by the Coulomb's theory as a linear function of the normal stress at failure σ_f as:

$$S_u = c_u + \sigma_f \tan \phi_u \quad (6)$$

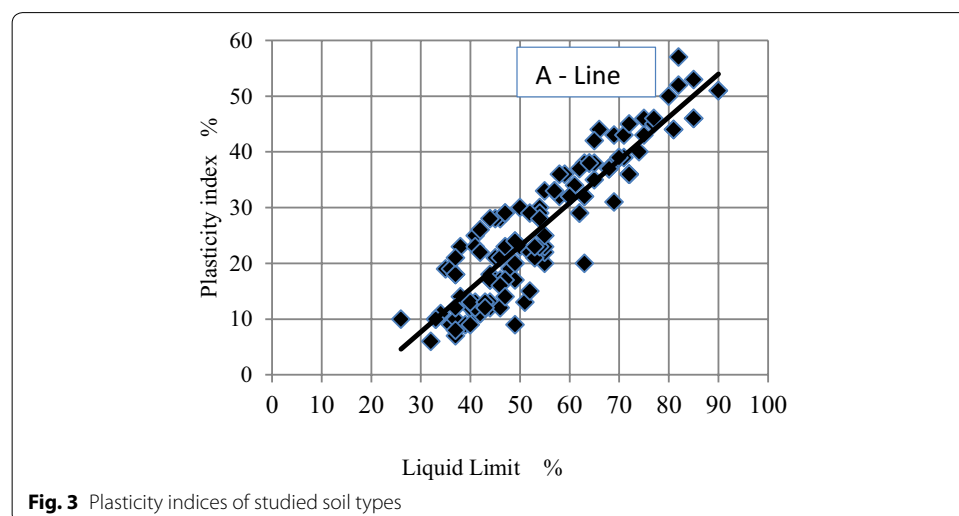


Fig. 3 Plasticity indices of studied soil types

The normal stress σ_f at failure can be related to the major and minor principal stresses σ_1 and σ_3 as:

$$\sigma_f = \frac{1}{2}[(\sigma_1 + \sigma_3) - (\sigma_1 - \sigma_3)\sin\phi_u] \tag{7}$$

Dividing Eq. 7 by σ_3 and rearranging:

$$\sigma_f = \frac{\sigma_3}{2}[\sigma_1(1 - \sin\phi_u) + (1 + \sin\phi_u)] \tag{8}$$

Substituting σ_f value of Eq. 8 in Eq. 6, the following relationship can be derived:

$$S_u = c_u + \frac{\sigma_3 \tan\phi_u}{2} [R(1 - \sin\phi_u) + (1 + \sin\phi_u)] \tag{9}$$

The c_u and ϕ_u values obtained from laboratory testing were substituted in Eq. (9). The minor principal stress σ_3 at which failure of the soil specimens occurs was assumed equal to the effective overburden pressure σ'_v calculated down to the appropriate sample depth. The total stress ratio (σ_1/σ_3), denoted by R was obtained by plotting the (σ_1/σ_3) ratio used for the tested specimens against σ_3 and then taking R values from the plot when σ_3 is equal to σ'_v .

The S_u computed according to Eq. (9) varied between 30.3 and 460 kPa in the clay soils tested with an overall average value of 129 kPa, thus the consistency of most soils could be described as firm to very stiff with few soft and hard samples. The net cone resistance ($q_c - \sigma'_v$) varied from 0.60 to 31.0 MPa with an overall average of 5.4 MPa, which indicate rather stiff to hard soil conditions. For the silt soils, S_u ranged from 16 to 252 kPa with an average of 91 kPa whereas ($q_c - \sigma'_v$) ranged from 0.37 to 18.0 MPa with an average of 5.17 MPa.

Discussion of results

Cone factor of studied soil types

The empirical cone factor N_k defined herein as the $(q_c - \sigma'_v)/S_u$ ratio was computed for the different soils and the basic statistical data is given in Table 3.

The average N_k values varied from 35.1 to 55.6 for all soils which fall within the range of values reported by Sanglerat [19]. These average N_k values are much higher than the reported in Table 1 for normally consolidated soft to firm saturated fine grained soils but are much lower than the 89.3 value found by Gebreselassie [20] for quaternary clay and

Table 3 Statistical analysis data of the cone factor N_k for different soils

Soil type	Sample size	N_k range	Average N_k value	Standard deviation
High plastic clays (CH)	63	9.9–68.9	35.1	15.3
Low plastic clays (CL)	23	6.6–120	43.9	22.8
All clay soils	86	6.6–120	37.5	18.9
High plastic silts (MH)	30	13.2–68.4	36.4	13.7
Low plastic silts (ML)	22	9.2–76.8	55.6	18.2
All silt soils	52	9.2–76.8	44.1	17.7

clay stone in southern Germany. It appears that the low N_k values reported elsewhere pertain to fully saturated and normally consolidated fine grained soil samples. The N_k values obtained are in close agreement with and confirm the 35 figure reported by Ismail and Zein [21] for Sudanese highly plastic clay and silt soils. Also, the average N_k values for the low plastic soils compare favorably with those reported by Hassan [17] for similar soils.

Generally, for most soil types considered in this study the N_k values were higher than those reported in some other countries. Apart from the differences in the nature, testing techniques and geological history the higher N_k values may be attributed to the insitu conditions prevailing when the soils were tested. As stated earlier most soil samples considered in this study were in a naturally unsaturated condition. Suction stresses normally develop in unsaturated soils with magnitudes depending on their moisture condition. It is well known that the higher the soil suction the higher would be the shear strength and cone resistance values. Therefore, it seems difficult to compare the N_k values of unsaturated soils with those deduced for saturated soils.

Furthermore, the N_k value of cohesive soils appears to be dependent on the stiffness which can be roughly assessed in terms of the soil resistance to cone penetration measured during CPT testing. To investigate how the $(q_c - \sigma' \sigma'_v)$ value may affect the N_k values the soil database were arbitrarily grouped in two categories with $(q_c - \sigma' \sigma'_v)$ values lower and higher than 5 MPa. A comparison of simple statistical data of N_k values pertaining to the two soil groups is given in Table 4.

There is a difference of 25.3 in the values of average N_k pertaining to the soil groups of the lower and upper $(q_c - \sigma' \sigma'_v)$ ranges. For most soils having $(q_c - \sigma' \sigma'_v) \leq 5$ MPa the N_k values compare well with those proposed in some previous studies (Table 1) for soft to firm saturated clays. Also there is a good agreement between the N_k values obtained for soils with $(q_c - \sigma' \sigma'_v) > 5$ MPa and those revealed for similar soils in Sudan [17] and Nigeria [22]. Exceptionally high N_k values were indicated in few very stiff or hard clay and silt soil samples. It is believed that these samples had suffered great disturbance caused by their high resistance to sampling tube penetration that had lead to significant shear strength reductions and thus obtaining very high N_k values.

Correlation of S_u and $(q_c - \sigma' \sigma'_v)$ for Sudanese soils

Direct Relationships

Several attempts were made to establish a direct relationship between S_u and $(q_c - \sigma' \sigma'_v)$ based on analysis of the database pertaining to all soil samples but without success. No meaningful relationship trends were observed when the two variables were plotted of against each other and the scatter of data points was very significant. This indicates that a simple correlation cannot be developed between $(q_c - \sigma' \sigma'_v)$ and S_u for all soil types and

Table 4 Variation of N_k with measured $(q_c - \sigma_{vo})$ values

Measured cone resistance q_c	N_k range	Average N_k value	Standard deviation
$(q_c - \sigma_{vo}) \leq 5$ MPa	6.6–72.6	30.5	14.97
$(q_c - \sigma_{vo}) > 5$ MPa	9.9–120	55.8	27.40

conditions as the relationship is influenced by several factors such as the testing methodology, soil type and stress history [6]. This finding confirms the conclusion of previous studies that the empirical cone factor N_k is not a simple constant but varies significantly from site to site.

Indirect relationships

As suggested in some studies [7, 8], indirect relationships may be developed between S_u and $(q_c - \sigma' \sigma'_v)$ by incorporation of the plasticity index PI and overconsolidation ratio (OCR) as parameters indicative of the soil type and stress history. The possibility of developing a reliable correlation of S_u and $(q_c - \sigma' \sigma'_v)$ based on both parameters was investigated for the Sudanese soils as discussed below.

Relationship between N_k and PI To investigate that a reliable relationship exists as claimed by some previous authors between the cone factor N_k and plasticity index PI , the two variables were plotted against each other for all soil types as shown in Fig. 4. As may be noted from this figure the data scatter is so significant such that N_k values varied widely from less than 10 to higher than 100 for soils with equal PI . This indicates that for the Sudanese soils tested no correlation can be developed to enable estimating the N_k from the PI .

$S_u - (q_c - \sigma' \sigma'_v)$ Relationships based on OCR To study the effect of OCR on the $S_u - (q_c - \sigma' \sigma'_v)$ relationship the soil database was firstly divided into clays and silts subgroups to account for the type variability in analysis. Kulhawy and Mayne [23] indicated that the normalization of the S_u values to $\sigma' \sigma'_v$ provides a form which is mode dependent and reliant on initial stress state, strain rate, direction of loading, degree of fissuring, and other factors. For undrained cone penetration analysis, the $(q_c - \sigma' \sigma'_v)$ is often related to undrained strength S_u through the factor N_k and thus the values of $(q_c - \sigma' \sigma'_v)$ and S_u normalized to effective overburden pressure σ'_v can be related in the same manner. The values of $(q_c - \sigma' \sigma'_v)$ were also normalized to σ'_v to have a dimensionless parameter similar to $S_u / \sigma' \sigma'_v$ ratio.

Various approaches of database analysis have been attempted to develop a suitable mathematical model based on the soil OCR which describes the correlation of

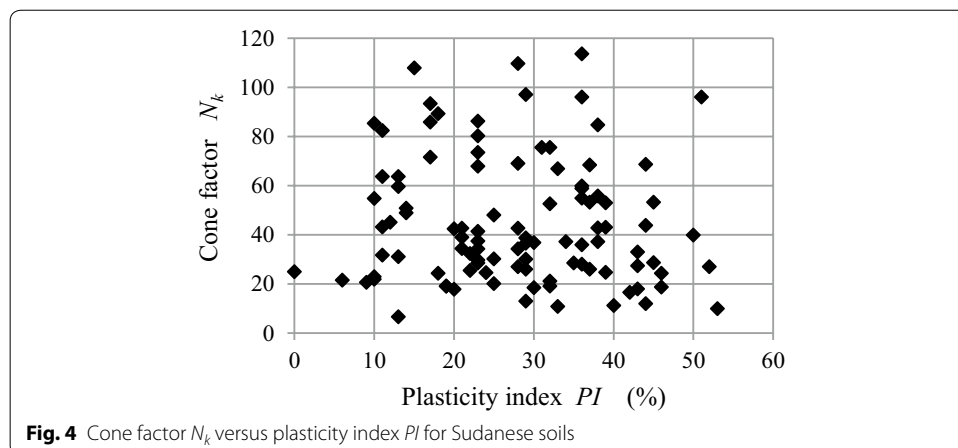


Fig. 4 Cone factor N_k versus plasticity index PI for Sudanese soils

normalized $(q_c - \sigma'_v)$ and S_u . It was revealed from analysis that the correlation of normalized $(q_c - \sigma'_v)$ and S_u values and the OCR can best be expressed by the general equation:

$$\frac{(q_c - \sigma'_v)}{\sigma'_v} = A \left(\frac{S_u OCR}{\sigma'_v} \right) + B \tag{10}$$

A and B are constants depending on soil type. The data pertaining to the mathematical terms in Eq. (10) were plotted as shown in Figs. 5, 6 and 7 to determine the constants A and B which represent the slope and the y -intercept of the best fit lines for clay soils, silt soils and all soils respectively.

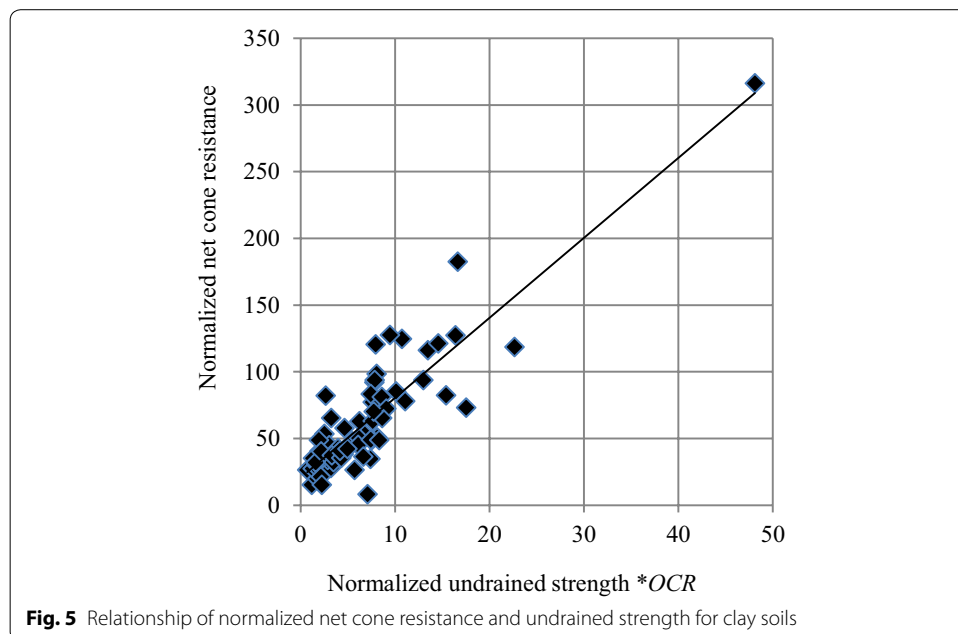
The clay soils exhibited a best fit line slope (constant A) equals to 6.0 Eq. (11) which is much lower than the 13.9, Eq. (12) revealed for the silty soils. This indicates that the $\left(\frac{S_u OCR}{\sigma'_v}\right)$ term is more sensitive to $\frac{(q_c - \sigma'_v)}{\sigma'_v}$ variations in the silts than in the clay soils. On the other hand, the clay soils indicated a best fit line y -intercept (B) of 8.1 which is much lower than 20.7 derived from analysis for the silt soils.

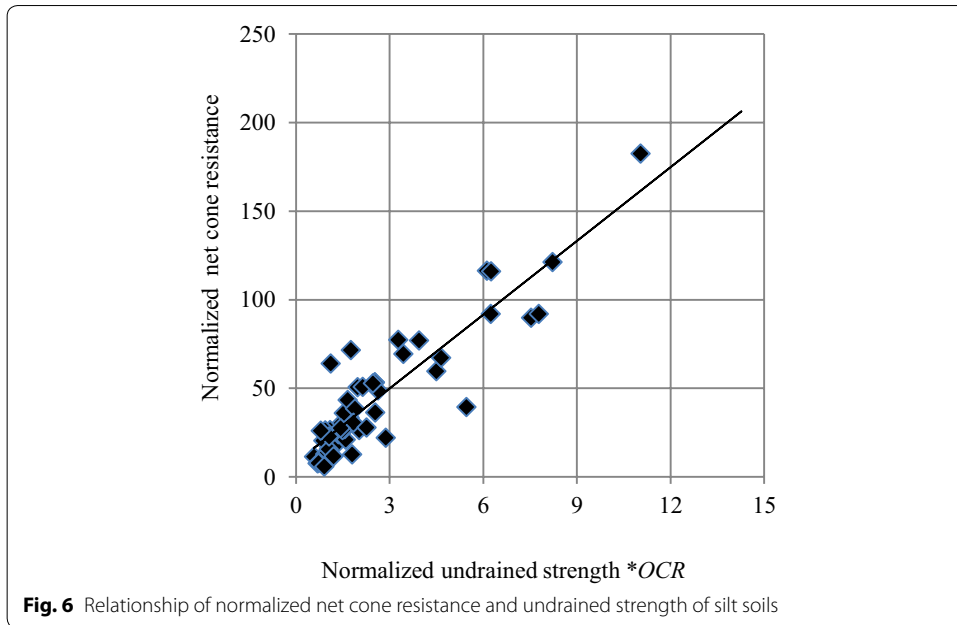
The trends shown in Figs. 5, 6 and 7 indicate that there is a sound line relationship between the terms $\frac{(q_c - \sigma'_v)}{\sigma'_v}$ and $\left(\frac{S_u OCR}{\sigma'_v}\right)$ for each soil group. The relationships derived from linear regression analysis are given by Eqs. (11) and (12) for the clay and silt soils respectively.

$$\frac{(q_c - \sigma'_v)}{\sigma'_v} = 6.0 \left(\frac{S_u OCR}{\sigma'_v} \right) + 20.7 \tag{11}$$

$$\frac{(q_c - \sigma'_v)}{\sigma'_v} = 13.9 \left(\frac{S_u OCR}{\sigma'_v} \right) + 8.1 \tag{12}$$

The goodness of the above relationships was assessed by the coefficient of determination (R^2) achieved from the regression analysis. R^2 values of 0.79 and 0.81 were obtained

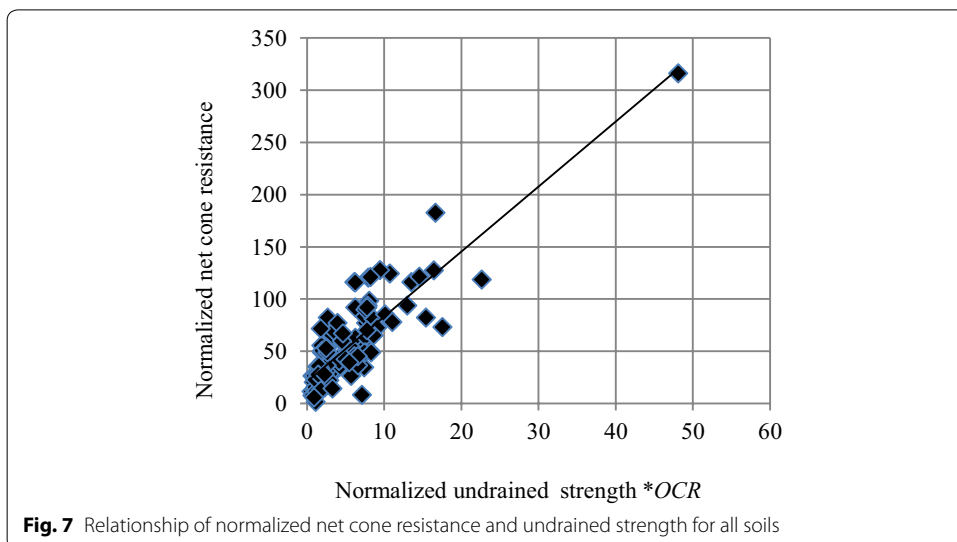




for the clay and silt soil types respectively. A relationship of lower correlation ($R^2 = 0.74$) was obtained as given by Eq. (13) for database pertaining to all samples which reflects the soil type effect.

$$\frac{(q_c - \sigma'_v)}{\sigma'_v} = 6.23 \left(\frac{S_u OCR}{\sigma'_v} \right) + 20.94 \tag{13}$$

The normalization of the S_u and $(q_c - \sigma'_v)$ to σ'_v has lead to a better matching of the soil parameters as indicated by the fairly high R^2 values achieved from database analysis. Very low R^2 values (<0.35) were obtained when the database were analyzed without normalization.



Therefore, the study results show that reliable relationships may be established between undrained shear strength and net cone resistance parameters when the soil type and stress history effects are considered in analysis. In the absence of soil data determined from conventional triaxial testing Eqs. (11) and (12) may be used estimate S_u from known values of q_c , OCR and σ'_v . The OCR values required for applying these equations may be either estimated from Table 2 for Sudanese soils or from the Robertson's chart shown in Fig. 1. Though high R^2 coefficient values were achieved from analysis the developed relationships are of empirical nature and should be applied with care, until they are supported by additional data in future research works.

Conclusions

The following conclusions may be drawn on the correlation of undrained shear strength S_u and CPT cone resistance q_c for Sudanese clay and silt soils:

- The empirical cone factor N_k relating the net cone resistance ($q_c - \sigma'_v$) to undrained strength S_u varied over a relatively wide range with average values of 37.5 and 44.1 for the clay and silt soils studied.
- A direct relationship cannot be established between ($q_c - \sigma'_v$) and S_u for soils of different types and characteristics as their values are influenced by several factors. The effects of certain parameters such as soil type and stress history should be considered in studying such a relationship.
- For a given soil N_k seems to depend on the moisture condition and degree of stiffness prevailing in the field during testing. Interpretation of CPT and shear strength data is different for saturated and unsaturated soils and this makes comparison of the N_k values difficult. Soils with higher cone resistance values tend to give higher N_k values than those with lower values.
- A rigorous analysis was carried out to develop a mathematical model describing the relationship between ($q_c - \sigma'_v$) and S_u which takes into account soil type and stress history factors.
- Reliable relationships have been developed to estimate the undrained shear strength from CPT cone resistance for fine grained soils with different OCR values. The developed relationships should be applied with care in practice until they are supported by further data.

Competing interests

The author declares that he has no competing interests.

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