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Use of Cone Penetration Test for Classification of Some Sudanese Soils; the State of the Art

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ABSTRACT

The cone penetration test (CPT) method has successfully been applied in Sudan for research, foundation design and the solution of geotechnical problems for various engineering structures since 1977. Based on analyses of database accumulated during four decades correlation relationships have been developed to classify local soils from CPT data. This paper presents the state of the art and the main findings of previous studies carried out on the application of CPT for soil classification. A simple and reliable CPT method based on the statistical "discriminant analysis" technique was proposed in 1980 to classify a given soil of known CPT parameters into one of four main USCS soil groups. Another correlation was proposed in a different study between CPT data and relative consistency of highly plastic clay soils. The original soil classification method was further modified in 2003 to include more database and incorporate additional features relating to the consistency of clay soils and relative density of sandy soils. The accuracy of the CPT based soil classification method was examined amongst worldwide known methods by comparison of the soil types predicted from CPT and the actual soil profiles. The comparison study showed that the method performed quite well in classifying alluvial soils which are similar to those used in their development.

المستخلص

تم استخدام اختبار المخروط الاختراقي (CPT) في السودان منذ العام 1977 لغرض اجراء البحث العلمي وتصميم الاساسات ومعالجة بعض المشاكل الجيوتقنية لمنشات هندسية م تلفة. تقدم هذه الورقة بيانا بالاحوال التقنية الراهنة وأهم نتائج الدراسات البحثية التي أجريت بغرض أستخدام نتائج اختبار (CPT) لتصنيف التربةالسودانية. في العام 1980 تم اقتراح طريقة مبسطة وموثوق بها في شكل علاقات ارتباط رياضية يمكن استخدامها لتصنيف انواع التربة السودانيةعلي أساس نتائج هذاالاختبار. استخدم في هذه الطريقة اسلوب مميزالدالة لتحليل البيانات وتصنيف أنوع من التربة لأحد أربع مجموعات رئيسيةحسب النظام الموحد لتصنيف التربة (UCSC). كذلك تم في دراسة أخري اقتراح علاقة رياضية بين نتائج اختبار (CPT) والاتساق النسبى للتربة الطينيةعالية اللدونة. الطريقة الاصلية لتصنيف التربةعلى أساس نتائج إختبار CPT تم تعديلها في العام 2003 بعد تحديث قاعدة البيانات وإعطاء سمات إضافية لتقديردرجات تناسق التربة الطينية والكثافة النسبية للتربة الرملية. أعدتدراسة مستقلةلاختباردرجة دقة الطريقة التي أقترحت في العام 1980 ضمن طرق أخرى معروفةعالميا لتصنيف التربة بناءعلى نتائج إختبار (CPT) وذلك بمقارنة التصنيف المبنى على هذه الطرق معا لوصف الحقيقي لطبقات التربة في المواقع التي شملتهاالدر سة. نتائجالمقارنة أظهرت ان الطريقة أعطت نتائج جيدة في تصنيف انواع التربة الرسوبية النهرية.

Keywords: Cone penetration test CPT, Soil classification, Sudanese soils, Discriminant analysis.

1. INTRODUCTION

The cone penetration test "CPT" is used in many countries as a site investigation tool in the field of geotechnical engineering for the classification and characterization of soils. Other site investigation techniques include the conventional drilling and laboratory testing methods, dynamic cone penetration (DCP) test, standard penetration test (SPT), field vane shear test, pressuremeter test and plate loading test.

In the CPT `test, a standard cone is pushed into the ground at a constant rate and continuous measurements are made of the soil resistance to penetration defined in terms of cone resistance, qc, and of a surface sleeve defined as local side sleeve friction, fs. The CPT has proved its reliability in solving some foundation problems in the regions where a sufficient experience has been gained in the test data interpretation.

A great effort was devoted in previous research works in different countries to the use of CPT data for soil classification and description of soil strata penetrated during testing. It has been reported by many authors that the cone resistance qc, skin friction fs and friction ratio, Rf may be used for soil classification. The most popular soil classification methods based on CPT data are probably those proposed by Begemann [1], Schmertmann [2], Robertson [3] and Fellenius and Eslami [4].These methods may be useful when applied in soils similar to those for which they have been developed but differences may well be indicated in other regions because of their empirical nature. It is therefore recommended to examine the validity of any system before being used in countries where the experience on the interpretation of CPT data is not adequate.

To investigate the suitability of the CPT method for the classification of local soils and evaluation of their properties a research work was initiated in 1976 in Sudan by the Building and Road Research Institute (BRRI) University of Khartoum. The findings of the first study on the application of the CPT method were published in 1980 [5] and several studies were subsequently undertaken to cover aspects that have not been previously dealt with. The main research topics covered in the studies performed on local soils included soil classification and profiling; evaluation of the undrained shear strength of cohesive soils; correlation with the Standard penetration test (SPT); estimation of the compressibility characteristics of fine grained soils, and the prediction of the bearing capacity of bored piles. This paper is the first of a series of publications meant to present the state of the art and reflect the experience gained during four decades on the use of the CPT for estimating the characteristics of Sudanese soils and solving some problems related to the design and construction of foundations. The manuscript presents the main findings of previous studies on the use of CPT for classification of local soils. Although more sophisticated piezecone testing (CPTU) machines that facilitate measurements of cone resistance, sleeve friction and pore water pressure during testing have been procured by few local private geotechnical firms e.g. ESD [6] no classification method based on interpretation of their data has been reported so far. Therefore the review presented in this paper pertains only to the soil classification methods based on the CPT data measured by the friction mantle cone.

2. CPT METHOD AND DATABASE USED FOR SOIL CLASSIFICATION

The importance of establishing relationships between the soil types determined from conventional testing methods and the CPT for local soils is that some theoretical and empirical solutions of foundation engineering problems are based on the CPT. Most of the sites investigated in the various previous works are mainly located within Khartoum State but some areas in other parts of the country were considered in few studies.

The main findings of the research works accomplished so far on the application of CPT for the classification of local soils are presented in the following paragraphs.

The first soil classification method based on the CPT for local soils was developed in1980 [5] from analysis of CPT and standard laboratory test database pertaining to soil samples from Khartoum State area as well as sites in Jonglei and Upper Nile States in southern Sudan. A detailed description of the method is given elsewhere [7] but a brief account on the same is given hereunder. A large number of boreholes were drilled through soil of various types and representative soil samples were collected from different depths and tested in the laboratory to determine their types. All the samples were classified according to the Unified System for Classifying Soils (USCS) and divided into four main groups namely; clays, silty and sandy clays, clayey sands and silt-sand mixtures, and sands. For the purpose of making good and sound comparisons, the CPT soundings were made at test points very close to the locations of the conventional boreholes drilled to obtain soil samples required for testing. The cone penetrometer type used in all studies was mechanically operated deep sounding machines with rated capacities of 100kN. The type of cone regularly used in all studies was the adhesion jacket cone known as “Begeman’s tip” shown in Fig.1.

A typical graph showing the variations of CPT results with depth measured at one site in Khartoum State is shown in Fig. 2.

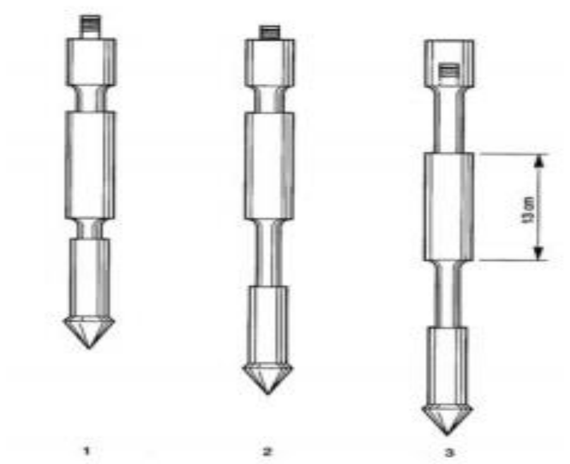

Fig.1. Adhesion jacket cone type regularly used in the studies reviewed

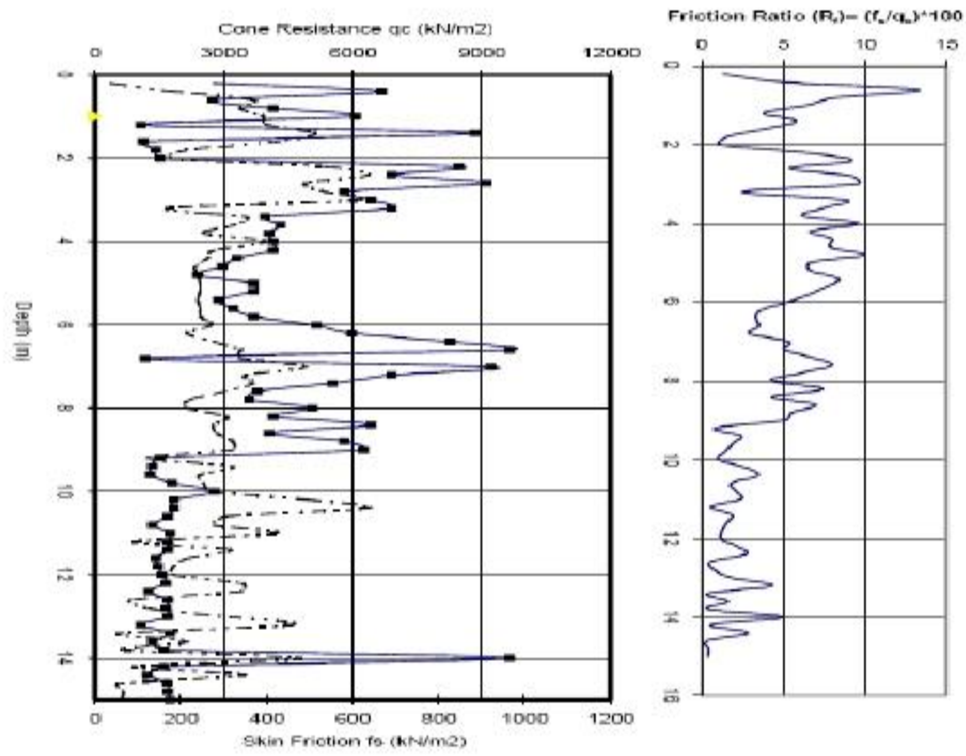

Fig. 2: Typical chart showing variations of CPT data (q_c, f_s and R_f) with depth

3. CPT SOIL CLASSIFICATION METHODS BASED ON DISCRIMIMANT ANALYSIS OF TEST DATA

Worldwide, different probabilistic statistical and geostatistical analysis approaches such as the “Bayesian updating methodology” have been adopted by some researchers in different countries for the interpretation of the CPTU data mainly i.e. with pore water pressure measurements for soil classification purposes [8, 9]. Other researchers have developed theoretical models and computer software packages based of statistical analysis approaches which account for model imperfection, statistical uncertainty and inherent variability [10]. The application of the soil classification methods based on statistical approaches other than the discriminant analysis method needs to be investigated for local soils.

In the first study on using the CPT method for classification of local soils [5] the cone resistance (q_c) and friction ratio (R_f) obtained for samples of all soil types tested were plotted on a combined graph. It was noted from plotting of the soil types on a combined q_c versus R_f graph that each soil group tends to occupy a certain region in the plot, though overlap between the groups can however be observed. To enable classification of a soil sample according to the CPT only, the specific zone occupied by each soil group should be defined. A statistical analysis technique known as the "discriminant method" was used to differentiate in mathematical terms between the zones corresponding to the four soil groups in the q_c-R_f plot. In this method, the term "soil population" which has the meaning of "soil group" is used to describe one set of data having similar characteristics. Each group has a certain function known as "decriminant function, X" of which parameters have to be derived from statistical analysis of the CPT data that is known for certain to come from that group. The descriminant functions derived from analysis for the four soil groups are given in Table 1.

Table 1: Discriminant functions for soil classification using CPT [5]

Soil Subgroup	Data size	Discriminant function*
Clay soils	82	$X_1 = 0.041*q_c + 4.04*R_f - 12.6$
Silty and sandy clays	81	$X_2 = 0.044*q_c + 3.18*R_f - 8.3$
Clayey sands and silt-sand mixtures	93	$X_3 = 0.070*q_c + 2.50*R_f – 7.0$
Sands	62	$X_4 = 0.10*q_c + 1.40*R_f - 7.9$

* In the table above the qc value is in kg/cm^2 units and R_f in percent.

According to the developed method, a soil sample of known qc and Rf values but of uncertain type is allocated to the nearest population where “nearness” here is a measure of probability. The nearest population is that from which a greater likelihood of the sample is coming and therefore the sample should be allocated to whichever population gives the greatest value of X in the equations given in Table 1.

Osman and Ahmed [11] carried out a comparative study to evaluate the accuracy of seven soil classification methods based on CPT developed in different countries including the method proposed by Zein [5] for local soils. The methods were used for predicting soil types at three sites in Khartoum state chosen such that they resemble the broad range of formations predominant in the region. The soil types comprised highly plastic clay soils and alluvial soils in Khartoum and lateritic soils in Omdurman. Two deep boreholes were drilled in each site and two CPT soundings were made at adjacent distances from borehole positions. The soil samples were tested and classified according to the USCS. The classifications predicted by the different methods were obtained for the soils in the three investigated sites. A comparison was made between the actual soil profiles revealed from boring and testing and the profiles predicted from CPT data by the methods considered. The degree of success was established by comparing the number of matching predicted layers to the total number of actual layers determined from borings. The comparative study results expressed as a percentage of the predicted to actual soil profiles in each site obtained are summarized in Table 2 for the soil types covered.

The data analysis indicated that the seven soil classification methods considered in the study deviated from the actual soil profile by varying degrees. The deviations were attributed to the fact that the CPT parameters are influenced by several factors such as stress history, moisture content, density and local inclusions e.g. pebbles concretions and lenses. These factors may affect the final measured CPT parameters and alter their values even for the soil type present at the same site. The results of comparison revealed that none of the soil classification methods tested was able to correctly predict the actual profiles encountered at the three investigated sites. It was found that the methods proposed by Begemann, Schmertmann and Zein were partially successful in predicting the actual soil profiles. It worth noting that Zein method performed well in alluvial soils which are similar to those it was developed for but showed little success when applied for heavy clays and lateritic soils.

Table 2: Summary of the comparative study results [11]

Site locations, soil type and classification method	Khartoum Sites		Omdurman Site
	Heavy clays	Alluvial deposits	Lateritic soils
Begemann [1]	100	66	66 - 100
Vos [12]	50 - 100	33 - 50	50 - 66
Douglas [13]	33 - 40	50 - 83	20 - 50
Schmertmann [2]	60 - 66	-	23 - 33
Zein [5]	20 - 33	66 - 86	20
Fellenious and Eslami [4]	0	33 - 75	0 - 20
Robertson [3]	33 - 100	33 - 100	0

In 2003, a study was carried out by Al Attar [14] to update and extend the application of the Zein's method for other local soil types. Widely different soil types collected from several Sudanese states namely; Khartoum and Gezira States in Central Sudan, Jonglei and Upper Nile States in Southern Sudan, Greater Kordofan State in Western Sudan and Gedaref in Eastern Sudan were covered in this study. For the purpose of analysis the database were broadly classified to fine grained soils and coarse grained soils. Fine-grained soils include two main groups of silty and clayey soils. These two main groups were further divided to low and high plastic subgroups whereas the sandy soils were divided to clean sands silty sands and clayey sands. Eleven soil types classified according to the USCS were considered in the study. The discriminant analysis method was also used to derive the appropriate mathematical expressions for each soil group or subgroup using the qc and Rf parameters and the computations were carried out by the SPSS version 9.5 software package. A summary of the discriminant functions derived from analysis for the various soil subgroups are presented in Table 3.

Table 3: Discriminant functions for soil classification using CPT [14]

Main Group	Soil Sub-group No.	Discriminant function	Data size	Accuracy %
SANDY SOILS	(1) All	$X_{all}= 4.934x10^{-4}q_c+1.553R_f-6.465$	398	68.6 to 74.3
	(4) SP/SW	$X_S = 4.749x10^{-4}q_c+2.260R_f-6.318$	134	66.7 to 88.9
	(5) SM and SC	$X_{(SM,SC)}=4.758x10^{-4}q_c+3.234R_f-9.002$	264	46.2 to 57.7
	(6) SM	$X_{SM}=5.187x10^{-4}q_c+2.933R_f-8.882$		36.4 to 72.8
	(7) SC	$X_{SC}= 4.318x10^{-4}q_c+3.137R_f-8.559$		33.3 to 46.6
SILTY SOILS	(2) All	$X_{all} = 3.784x10^{-4}q_c+1.830R_f-6.264$	207	39.5 to67.4
	(8) ML	$X_{ML}=2.868x10^{-4}q_c+2.143R_f-6.053$	156	55.6 to 94.5
	(9) MH	$X_{MH}=2.281x10^{-4}q_c+2.427R_f-6.820$	51	42.9 to 57.2
CLAY SOILS	(3) All	$X_{all} = 3.567x10^{-4}q_c+2.277R_f-8.200$	378	57.8 to 64
	(10) CL	$X_{CL}=5.00x10^{-4}q_c+1.544R_f-5.922$	170	58.3 to 75
	(11) CH	$X_{CH}=4.207x10^{-4}q_c+1.971R_f-7.659$	208	57.7 to 61.5

A soil of unknown type but of known q_c and R_f values maybe classified by substituting the q_c and R_f values in Equations. 1, 2 and 3. The soil is then allocated to the main soil group for which the greatest discriminant function numerical value was obtained. Once the soil main group is predicted, the same values of q_c and R_f are substituted in the discriminant subgroup functions pertaining to the specified main group. Equations 4 and 5 should be used if the main group is sandy soils whereas Equations 8 and 9 should be used for silty soils whereas Equations 10 and 11 are used for clayey soils. If the soil type was found to belong to the silty or clayey sand subgroup; then Equations 6 and 7 should be used to specify the correct soil type for which the greater discriminant value is obtained.

The accuracy of the method proposed by Al Attar was tested for 142 new samples by comparison of the soil types predicted using CPT data with actual descriptions based on soil classification test results made according to the USCS. The degree of success of each method and soil group or subgroup expressed as a percentage of the number of matching predicted samples to the total number of samples is given in Table 3.The overall average correct prediction was found to be in the range of 54.9 to 67.6% for all samples. It was concluded that the CPT method can be used to classify local sandy, clayey and silty soils with reasonable accuracy.

Zein [15] introduced major modifications to the original soil classification method to improve its accuracy by considering soil data made available from research works and site investigations conducted during the period from 1980 to 2003. A new grouping of soil types was considered by rearranging the database pertaining to 928 soil samples into the five main soil groups classified according to the USCS scheme terminology. The descriminant analysis approach was utilized to derive the mathematical functions given in Table 4 for the five soil groups to enable their type classification from CPT data. The units of q_c and R_f in Table 4 are MN/m^2 and % respectively.

To classify a soil sample of known qc and Rf the same procedure described earlier should be followed. To facilitate a fast and convenient profiling of the soil strata at any CPT point at a site, an excel computer software spreadsheet was developed to enable computations of the discriminant values for every penetration depth and give an indication of the consistency of clay soils and relative density of sandy soils.

Table 4: Modified CPT soil classification method based on discriminant analysis [15]

Soil Subgroup	USCS	Data size	Discriminant function
High plastic clays	CH	201	X1 = $0.35*q_c + 2.40*R_f + 8.31$
Low plastic clays	CL	152	X2 = $0.39*q_c + 1.87*R_f + 5.39$
Silty soils	ML/MH	184	X3 = $0.41*q_c + 1.73*R_f + 4.86$
Clayey and silty sands	SC/SM	257	X4 = $0.58*q_c + 1.59*R_f + 5.87$
Clean sands	SP/SW	134	X5 = $0.70*q_c + 1.12*R_f + 5.99$

4. USE OF CPT DATA FOR EVALUATION OF SOIL TYPE RELATED INDICES

Ismail and Gasmelseed [16] used CPT data for estimation of the consistency of cohesive soils which is normally described in terms such as soft, medium, stiff or hard. The soil relative consistency, C_r (also termed consistency index) is defined as the ratio of the liquid limit (LL) minus the water content (w) to the plasticity index (PI) i.e. $C_r = (LL - w)/PI$. The soils considered were classified as clays of low to high plasticity. The cone resistance qc expressed in kg/cm^2 were computed and plotted against the corresponding depths of Cr in a semi-log form using data from two main study areas. Some scatter of the data points was noticed in the plot; nevertheless, it was proposed that the Cr may be estimated from CPT data. The following empirical relationship was developed from regression analysis between qc and Cr for the combined data with a correlation coefficient of 0.82:

$$C_r = 0.6 \log q_c - 0.11$$

Using the relationships obtained between the two parameters, a method was proposed by the authors for the assessment of the soil relative consistency from CPT cone resistance as given in Table 5.

Table 5: Estimation of clay consistency from CPT data [16]

q^c (kg/m²)	**< 4**	**4 - 10**	**10 - 27**	**27 – 70**	**70 - 185**	**185 - 480**	**> 480**
C^r	< 0.25	0.25–0.50	0.50-0.75	0.75-1.0	1.0-1.25	1.25-1.50	> 1.50
Soil Description	Extremely soft	Very soft	Soft	Medium stiff	Stiff	Very stiff	Hard

Important information was incorporated in the method modified by Zein in 2003 to roughly evaluate the consistency of cohesive soils and relative density of cohesionless soils using the CPT cone resistance only. The relationships by Terzaghi and Peck [17] between the SPT N-value on one hand and the relative density and consistency parameters on the other were used in conjunction with empirical qc-N relationships developed by Zein [5] to define the consistency and relative density ranges given in Tables 6 and 7 for clay and sandy soils respectively. With this added feature the modified CPT based classification method may be used to predict the soil type and roughly evaluate some of the physical properties of local soils.

Table 6 Estimation of consistency of clay soils from CPT cone resistance

Consistency		**Very soft**	**Soft**	**Medium stiff**	**Stiff**	**Very stiff**	**Hard**
SPT N value		< 2	2 - 4	4 - 8	8 to15	15 to 30	>30
Equivalent q_c values MN/m²	CH	< 1.3	1.3 - 1.6	1.6- 2.1	2.1 - 2.9	2.9 - 4.7	> 4.7
	CL	< 1.4	1.4 - 1.7	1.7 - 2.4	2.4 - 3.6	3.6 - 6.0	> 6.0

Table 7 Estimation of relative density of sandy and silty soils from CPT cone resistance

Relative density		Very loose	Loose	Medium	Dense	Very dense
SPT N value		< 4	4 - 10	10 - 30	30 - 50	> 50
Equivalent q_c values in MN/m^2	ML/ MH	< 1.8	1.8 - 2.9	2.9 - 6.4	6.4 - 9.4	> 9.4
	SC / SM	< 1.9	1.9 - 3.2	3.2 - 7.2	7.2 - 10.5	> 10.5
	SP / SW	< 2.5	2.5 - 4.6	4.6 - 10.6	10.6 - 14.8	> 14.8

5. CONCLUDING REMARKS

Several studies have been undertaken by researchers to examine the CPT value in understanding and evaluation of Sudanese soils behavior with respect to aspects for which the method has proved to be useful and reliable worldwide. A great effort was made in these studies to collect relevant database for various soil types and conditions from sites located in different states of the country. Some conclusions may be drawn from the findings of the previous studies dealing with the use of CPT for the classification of local soils.

A soil classification method was developed by Zein in 1980 for local soils to enable prediction the nature of subsoil strata from the CPT results only. A soil sample of known cone resistance q_c and friction ratio R_f will be assigned to one of four main soil groups designated according the USCS scheme. Application of the method indicated that it has performed quite well for the classification of alluvial soils but showed little success for highly plastic clays and lateritic soils.

Further modifications have been introduced to refine the method and improve its reliability and accuracy. Important and useful information have been incorporated in the modified method to assess the consistency of cohesive and relative density of cohesionless soils.

A simple relationship was developed between CPT cone resistance and the relative consistency index of cohesive soils.

Due to the empirical nature of the soil classification methods based on the CPT developed in different countries further research is encouraged to examine their validity to local soils and arrive to a worldwide accepted method.

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