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The influence of pore pressure gradients in soil classification during piezocone penetration test

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ABSTRACT

The standard cone penetration test (CPT) measures the resistance at the tip (q_c) during constant rate of penetration as well as the friction/adhesion along the sleeve (*fs*). The excess porewater pressures generated as a result of the penetration can also be measured by a piezometer/transducer (u_2) located immediately behind the cone (CPTU). The collected data help to identify several physical, hydraulic and mechanical properties of the soil layers. However, the main function of the test is soil classification. Classification has been done by using the q_c and f_s values at the early stages to be followed by incorporating the concept of soil behaviour type index I_c. Soil behaviour type (SBT) index calculates I_c and is generally calculated by normalised values of tip resistance and sleeve friction: *Q* and *F*, respectively. The porewater pressure component in the relationship is accounted for by the coefficient B_q. A clear distinction between the soil classes cannot be made due to limited coverage of the parameters employed. A new parameter "*i*" which contributes significantly to the classification process by the use of varying porewater pressure values Δu_w by depth is introduced in this paper to improve the value of I_c in the classification procedure.

1. Introduction

Cone penetration test can be done easily then most of the other in-situ tests and its results are reliable and repeatable. It can be said that a major advantage of this test is that CPT provides a continuous profile. The scope of this paper is to estimate soil class by using in-situ cone penetration test results. Several investigators have attempted to classify soils by using the test data. The early methods have employed q_c and f_s to prepare classification charts without attempting to correct these for overburden and porewater pressure (Begemann, 1965). Sanglerat et al. (1974) have asserted that the type of soil is a function of the tip resistance and the friction ratio R_f, where

$$R_f\% = \frac{f_s}{q_c}100 \quad (1)$$

and sand, silt and clayey soils were represented in separate closed polygons in their chart.

Schmertmann (1978) represented cone tip resistance (q_c) on a log and R_f on arithmetic axis to define the different zones. His chart differed from that of Begemann (1965) because sands are classified according to relative density and clays with their consistency. However, it is seen that fine grained soils are represented in limited bands of consistency that do not cover the whole spectrum. He emphasised that results from different regions may influence the shape of the chart due to factors such as sensitivity of the soils and their creep behaviour, roughness of the sleeve and the groundwater regime suggesting that it would be expedient to develop charts for local use.

Douglas and Olsen (1981) are the first investigators who attempted to include some of the USCS symbols in the q_c–R_f (log) chart. In addition, they incorporated properties such as liquidity index, sensitivity, earth pressure coefficient and void ratio. Their chart is the predecessor of the currently existing charts and its striking difference from that of Schmertmann is the concave upwards shapes of the lines separating soil zones.

Jones and Rust (1982) have subsequently initiated the use of a piezometer in the cone (CPTU), where the change of porewater pressures during penetration was measured. The chart they developed is based on readings of net cone tip resistance ($q_c-\sigma_{v0}$) versus excess pore pressure ($\Delta u = u_{max} - u_0$). This chart is unique because it comprises relative density and consistency values. Vermeulen and Rust (1995) have used this chart with minor changes to illustrate its use with a lot of data.

Robertson and Campanella (1983) modified the Douglas and Olsen (1981) chart and reported that mean grain size can be estimated by using the concentric circles. They also argued that measuring excess porewater pressures will improve the soil classification process.

Senneset and Janbu (1985) developed a classification system where a pore pressure coefficient B_q was defined. In addition to the use of q_t, tip resistance corrected for pore pressure u_2 was henceforth adopted.

$$q_t = q_c + u_2(1-a) \quad (2)$$

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a is the ratio of the cone base cross section and total cross section. B_q is thus defined as

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_v} \quad (3)$$

u_0 represents the hydrostatic pressure, u_2 the dynamic pore pressure measured immediately behind the cone, σ_v total stress at specified depth and q_t net cone tip resistance.

Robertson et al. (1986) used the expression for B_q to develop another classification chart where 12 zones were defined using the axes q_t–R_f (%) and q_t–B_q. Senneset et al. (1989) proposed a similar chart where B_q which is a function of corrected tip resistance q_t and u_2 with the difference that q_t axis was arithmetic. Additionally, the maximum tip resistance is limited to below 16 MPa.

Robertson (1990) made a critical appraisal of their 1986 charts and changed the labels of the axes to normalised sleeve friction (F)–normalised tip resistance (Q). The accompanying chart uses Q_t and B_q. The soil zones were reduced to 9 in this study. The F–Q chart is currently the most referred to where

$$Q = \frac{q_t - \sigma_v}{\sigma'_v} \quad (4)$$

$$F = \frac{f_s}{q_t - \sigma_v}. \quad (5)$$

Jefferies and Davies (1991) contested the Robertson (1990) charts claiming that two charts showing the relationship among Q, F and B_q is not essential. The chart was then modified by changing the B_q axis to $Q(1-B_q)$ to show all parameters in a single chart. It was then possible to express the influence of porewater pressure in the same chart. They claimed that such a grouping duly enlarged the zone for fine grained soils whilst no significant change emerged for sands.

Schneider et al. (2008) proposed using the ratio $\Delta u_2/u_0$ instead of B_q which may be more suitable for identifying clays, silts and sands. He claimed that soil behaviour is governed by dissipation of pore pressures that emerge during loading.

It can be deducted from above discussion that each parameter involved plays an important role to classify the soil. Generally, coarse grained soils give higher cone resistances (q_c) than the fine grained. On the other hand, friction ratio (R_f) is bigger for high plasticity soils. Robertson et al. (1986) are of the opinion that R_f gives more reliable results than q_c in general.

Other investigators (Zhang and Tumay, 1999; Cetin and Ozan, 2009) followed a different path to tackle the problem. They used probabilistic methods for soil characterisation and classification. Zhang and Tumay (1999) proposed a classification method to classify soil from CPT data by using statistical and fuzzy subset approaches. A continuous profile of the difference of having each soil type (silty, clayey, and sandy) can be obtained with this method. Cetin and Ozan (2009) proposed a simplified soil classification scheme based on probabilistic method. Cai et al. (2011) compared the CPT soil classification charts by using CPTU data obtained from clay deposits in Jiangsu Province, China. Researchers concluded that using only cone resistance and sleeve friction parameters to classify the soils with CPT gives less reliable results than using pore pressure ratio and net cone resistance.

2. Soil behaviour type index (i_c)

Efforts for understanding the response of soil to penetration have recently been directed to the study of soil behaviour type index I_c, a value that represents the dimensionless radii of the concentric circles in several publications.

Jefferies and Davies (1993) have demonstrated that the curves in the Robertson chart (1990) are indeed concentric circles. They developed a chart where the axes were labelled as $F-Q(1-B_q)$ and soil type behaviour index was formulised as

$$I_c = \sqrt{\left\{3 - \log\left[Q\left(1-B_q\right)\right]\right\}^2 + [1.5 + 1.3(\log F)]^2}. \quad (6)$$

The 1 value in the formula is apparently used to avoid a negative value in the process. It should be noted in Been and Jefferies (1992) that I_c includes a "+1" in the log term (Eq. (7)) and differs slightly from that defined in Jefferies and Davies (1993). The term $(1-B_q)+1$ in this expression has been devised to distinguish clays from silts.

$$I_c = \sqrt{\left\{3 - \log\left[Q\left(1-B_q\right)+1\right]\right\}^2 + [1.5 + 1.3(\log F)]^2} \quad (7)$$

However, Robertson and Wride (1998) adopted an alternate definition of I_c, which neglects the pore water pressure. They studied the evaluation of liquefaction potential with the CPT data where they expressed that the concentric arcs in the Robertson (1990) chart can be defined by the equation

$$I_c = \sqrt{[3.47 - \log Q]^2 + [1.22 + \log F]^2}. \quad (8)$$

Juang et al. (2003) also studied liquefaction potential where they used the variable q_{c1N} proposed by Robertson and Wride (1998), redefining the index as

$$I_c = \sqrt{[3.47 - \log q_{c1N}]^2 + [1.22 + \log F]^2} \quad (9)$$

$$q_{c1N} = \frac{q_c/100}{(\sigma'_v/100)^{0.5}} \quad (10)$$

where q_c: cone tip resistance and σ'_v: effective overburden stress with units of kPa.

Li et al. (2007) differ from former investigators because the powers under the square root were raised to 2.25 from 2 which deformed the arcs. The term for soil behaviour type index is accordingly changed to $I_{c,m}$

$$I_{c,m} = \sqrt{\left\{3.25 - \log\left[Q\left(1-B_q\right)\right]\right\}^2 + [1.5 + 1.3(1 + \log F)]^{2.25}}. \quad (11)$$

However, the author has determined using the data of this paper that, if $logF$ drops to below unity in Eq. (11), it becomes insoluble.

Robertson (1990) used the normalised values of tip resistance and the sleeve friction in his charts. Robertson (2010) stated that the use of their non-normalised values would not change the results noticeably, especially when the effective stress remains in the range 50–150 kPa thus defining a new index:

$$I_{SBT} = \sqrt{[3.47 - \log(q_c/p_a)]^2 + \left[1.22 + \log R_f\right]^2} \quad (12)$$

where q_c: cone tip resistance, p_a: atmospheric pressure (p_a: 1 bar = 100 kPa = 0.1 MPa) and R_f friction ratio (%).

Ku et al. (2010) compared the Been and Jefferies and the Robertson and Wride formulae. They found that I_c cut-off value between cohesionless (sand-like) and cohesive (clay-like) soils was 2.67 for the Robertson and Wride's expression. On the other hand, $I_c = 2.58$ was found to be the most suitable cut-off value by Been and Jefferies. The researchers compared their proposed limit for I_c values to distinguish clay like and sand like behaviour with B_q and $\Delta u_2/\sigma_0'$ to complement their findings. They showed that since penetration in sand-like soils does not generate excess pore pressures, $B_q \approx 0$. On the other hand, penetration in clay-like soils generates significant excess pore pressures, thus appreciable B_q values appear.

Table 1 summarises the approach adopted by several investigators in classifying soils based on the changing values of I_c. Slight differences among the values of soil behaviour type indices proposed by various researchers are easily discernible in this table.

An interesting observation when studying this table was made that no attempt has been made to classify soils in the charts directly using the symbols of the Unified or similar classification systems. The obvious reason is the difficulty in providing definite borders to the possible symbols because of the interactions among neighbouring zones.

3. Database

The first step in site investigation is to describe the soil profile by classifying the layers using two or four letter symbols. ASTM D 2487-93 (1994), BS 5930 (1981) and TS1500 (2000), a modified version of the British standard, are used for the purpose. No similar approach by the use of CPT data apart from Douglas and Olsen (1981) has been attempted so far.

This study has been conducted using the rich database obtained from Adapazari, Turkey, the site of the catastrophic earthquake in 1999. The data has been collected using a 200 kN acoustic CPTU machine. The data has been analysed during recent research projects [TUB.-104M387 (Önalp et al., 2007); TUB.-106M042 (Önalp et al., 2010)] with accompanying disturbed and undisturbed samples procured from boreholes drilled simultaneously with the CPT soundings in order that cone values can be correlated to the "traditional" data. At the same time, an amount of data of Adapazari soils from the Pacific Earthquake Engineering Research Center (PEER) web site (http://peer.berkeley.edu/publications/turkey/adapazari/) has been used in this study (Bray et al., 2001). The classification of the samples was performed according to TS1500 (2000) which is an extension of the USCS with the exception that the plasticity chart contains an intermediate zone (I) for liquid limits 35 to 50 as suggested by the BS plasticity chart. Table 2 illustrates the symbols used in the TS1500 (2000) whereas Table 3 depicts the similarities and the deviations among the three classification systems. On the other hand, the Robertson and other CPT soil classification charts classify the soil by using specific terms only and not by symbols.

A total of 990 samples from 135 boreholes were classified and their corresponding CPTU identities were compared. All sites are located in alluvial plain of Adapazari, Turkey. The top 50 m consist of sub-facies like point bar deposits (sands–fine sands), backswamps (clays–silts), abandoned channel deposits (sands and gravels), levees (silty sands), and crevasse splays (silts and fine sands) that are typical of the floodplains of large rivers (Bol et al., 2010; Bol, 2012). Consolidation tests were performed on 53 samples from the research area show that soils used in this paper are slightly overconsolidated ($OCR_{avg} \approx 3$).

Standard Penetration Test (SPT) is usually made at intervals of 150 cm in a borehole according to the Turkish standard. About 30 cm long soil samples are obtained in this test. In addition, about 30–40 cm undisturbed soil samples can be retrieved with UD samplers at different depths. CPTU soundings used for this paper provide data at intervals of 2 cm, so approximately 15 data points can be obtained for a single SPT or UD data point. At this stage, using only one CPT reading may be wrong, because 30 cm long soil sample from the SPT spoon is mixed and then tested for classification in laboratory. Therefore, q_c and f_s values were calculated for every data interval and a single average values were obtained for use in the I_c equation.

Most of the measured data which are used in this study is digitised inside the probe (*Geotech CPT Classic Probe*) and then transferred acoustically (no cable down the hole) to the surface and the interface. This procedure makes the tests faster than tests that use cable probes. Because of this, changing the rods takes very little time, so this procedure provides a continuous profile for all test results (cone resistance—q_c, sleeve resistance—f_s and pore pressure—u_2). Sometimes, the readings drop to lower values whilst changing the probes generally at 1 m intervals. This interval however causes only one line of incorrect readings. The incorrect data have therefore been corrected before being used in calculations for this paper. It is interesting that pore pressure profile give less incorrect data than the others (q_c and f_s) exclusively in fine grained soils because excess pore pressures are generated around the cone cannot dissipate in sufficiently short time.

Table 2 lists the distribution of the soil classes identified. The position of the soils in the plasticity chart detected is illustrated in Fig. 1a. It can be seen from here that silts of high plasticity were seldom encountered. Those samples on which hydrometer test was performed are plotted on the USBR Feret diagram in Fig. 1b.

In order to compare the classified soils with those identified by CPTU it was necessary to represent the USCS symbols by digits in the database. A range of 1 to 7 was adopted where decreasing plasticity and increasing mean grain size were appointed different digits naming them soil class number (*SCN*). Samples such as MH silts and gravels were represented in groups with similar properties due to their scant occurrences. These soil groups are given in Table 4.

4. Dynamic porewater pressure gradient (*i*)

One gets the impression, upon reviewing the existing work on classification by CPTU that several attempts have been made but the final solution still evades the researcher. The developments in the derivation of the formula for I_c indicates that some further refinements are still needed. The author believes that the next step should be to minimise the incursions of neighbouring zones in the classification chart in order that each group is identified in the USCS in a single zone rather than the soil behaviour type (*SBT*). This issue is still awaiting further development.

It was noticed during examination of the depth-porewater pressure diagrams that the u_2 values exhibit positive gradients ($+i$) in clayey soils whereas ($-i$) gradients were apparent for clays of low plasticity, silts and dense sands (Figure 2). The gradients also show

Table 1
Soil behaviour type indices (*SBT*) proposed by several investigators.

Soil behaviour type, *SBT*	Zone	Robertson and Wride (1998)	Jefferies and Davies (1993)	Been and Jefferies (1992)
Organic soils—peat	2	$I_c>3.60$	$I_c>3.22$	$I_c>3.22$
Clays	3	$2.95<I_c<3.60$	$2.82<I_c<3.22$	$2.76<I_c<3.22$
Silt mixture—clayey silt to silty clay	4	$2.60<I_c<2.95$	$2.54<I_c<2.82$	$2.40<I_c<2.76$
Sand mixture—silty sand to sandy silt	5	$2.05<I_c<2.60$	$1.90<I_c<2.54$	$1.80<I_c<2.40$
Sands—clean sand to silty sand	6	$1.31<I_c<2.05$	$1.25<I_c<1.90$	$1.25<I_c<1.80$
Gravelly sand	7	$I_c<1.31$	$I_c<1.25$	$I_c<1.25$

Table 2
Soil classification symbols according to TS1500/2000 and numbers of samples tested.

Symbol	Identification	Sample#
CH	High plasticity clay	182
CI	Moderate plasticity clay	218
CL	Low plasticity clay	63
MH	High plasticity silt	6
MI	Moderate plasticity silt	65
ML	Low plasticity silt	255
SW (GW)	Well graded sand (gravel)	4 (0)
SP (GP)	Uniform sand (gravel)	15 (2)
SM (GM)	Silty sand (gravel)	113 (1)
SC (GC)	Clayey sand (gravel)	0 (0)
SP-SM (GP-GM)	Uniform silty sand (gravel)	41 (2)
SW-SM (GW-GM)	Well graded silty sand (gravel)	20 (3)
SP-SC (GP-GC)	Uniform clayey sand (gravel)	0 (0)
SW-SC (GW-GC)	Well graded clayey sand (gravel)	0 (0)

Table 3
Differences in engineering classifications of soils.

Standard➔	ASTM D 2487-93 (1994), 2000d (USCS)	BS 5930 (1981)	TS1500 (2000)
Limit between coarse and fine grained soils is	75 μm	63 μm	75 μm
Limit between sands and gravels is	4.75 mm	2 mm	2 mm
Limit between silts and clays is	–	2 μm	2 μm
Classes coarse grained soils if	More than 50% by dry weight of the test specimen is retained on the 75-μm sieve	More than 65% by dry weight of the test specimen is retained on the 63-μm sieve	More than 50% by dry weight of the test specimen is retained on the 75-μm sieve
Coarse grained group symbols are	Same as TS1500	Different from the others	Same as USCS
Plasticity chart for fine grained soil separates	Low (L: w_L<50) and high (H: w_L>50) plasticity soils	Low (L: w_L<35), intermediate (I: 35–w_L–50), high (H: 50–w_L–70), very high (V: 70–w_L–90) and extremely high (E: w_L>90) plasticity soils	Low (L: w_L<35), intermediate (I: 35–w_L–50) and high (H: w_L>50) plasticity soils

sharp changes as the cone penetrates different layers. This change has prompted the author to investigate whether these changes in the gradients were indications of different physical properties such as consistency and grain size. This would suggest the use of the values of pore pressure gradients i along a depth corresponding to a laboratory sample, thus defining the gradient

$$i = \frac{\Delta u_2}{\Delta \sigma_0} = \frac{u_{2_{z2}} - u_{2_{z1}}}{\left(\sigma_{0_{z2}} - \sigma_{0_{z1}}\right)} \tag{13}$$

where u_{2z2} and u_{2z1} are the porewater pressures corresponding to depths z_2 and z_1 and σ_{0z2} and σ_{0z1} are the calculated total stresses at depths z_2 and z_1 respectively.

Fig. 2 shows a sounding profile from coordinates N40.78353; E030.40736 performed in downtown Adapazari with code CTOR15. The gradients "i" are indicated on the u_2 diagram with the corresponding soil classes determined by TS1500 (2000) in the laboratory.

Significant drops in the values of i are observed as the cone passes from an impermeable layer to a permeable one. This is believed to emanate from relative rigidity of different layers of soils. Excessive bigger or smaller i gradient values may erroneously be obtained in the transition zones, if calculated for every CPT data interval. Generally, i gradient suddenly drops to lower values whilst crossing from impermeable layers (clays) to permeable layers (sands and gravels). Calculating i values at such transition zones may lead to significant errors. Sudden drops that occur at these boundaries are not considered within the scope of the study. i tendencies are taken into account at the zones where CPTU pore pressure diagram shows a continuous decline or increment in a homogeneous layer. Q and F values have been obtained by using its average values, but i values of a certain depth interval should be calculated by

Table 4
Soil class numbers (SCN).

Soil class ➔	CH or MH	CI	MI	CL	ML	SM or SW-SM	SP, SP-SM or Gravels
Soil class number (SCN) ➔	1	2	3	4	5	6	7

using start and end values of pore pressures and total stress. For example, i value of 3.84–4.28 m sample in Fig. 2 is calculated as 2.020 (u_{2z2} = 0.049 MPa, u_{2z1} = 0.033 MPa, σ_{z2} = 0.07704 MPa and σ_{z1} = 0.06912 MPa with ρ_{avg} = 18 kPa).

Since consistency is the characteristic property for cohesive soils as opposed to grain size and its distribution in coarse grained soils, parameter i would have to reflect those properties. To represent these values, the liquid limit values (w_L) and the mean grain sizes (D_{50}) were selected and their correlation with the gradient i was investigated.

A parallel comparison was performed with the currently used parameter B_q (Figure 3a and b). It can be seen from here that a correlation between B_q and liquid limit (w_L) cannot be established. Similar finding is true for the B_q–D_{50} diagram. Further, B_q was found to be equal to zero in cases where D_{50} is smaller than 0.10 mm, implying that B_q is insensitive to increases in particle size. Similarly, B_q shows significant scatter in fine grained soils with mean grain sizes below 0.10 mm.

The relationship of i with liquid limit and mean grain size are illustrated in Fig. 3. i indicates positive values for w_L>34 but it drops to below zero for liquid limits smaller than 34. Similarly, a reliable relationship between i and the mean grain size has been detected. The parameter i assumes negative values for D_{50}<0.02 mm whereas it rises to positive zone for mean grain sizes greater than 0.02 mm. This is an indication that although the relationship between B_q and

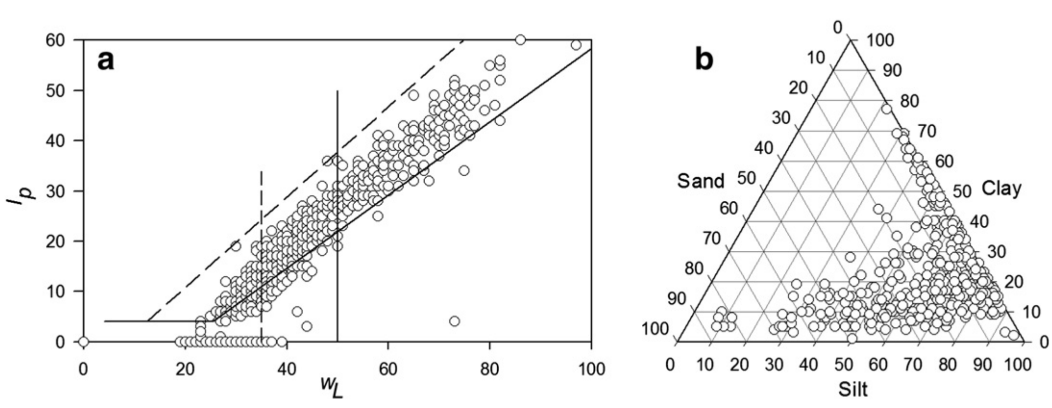

Fig. 1. The position of the soil samples in the database on a) TS-1500 plasticity chart and b) USBR triangle.

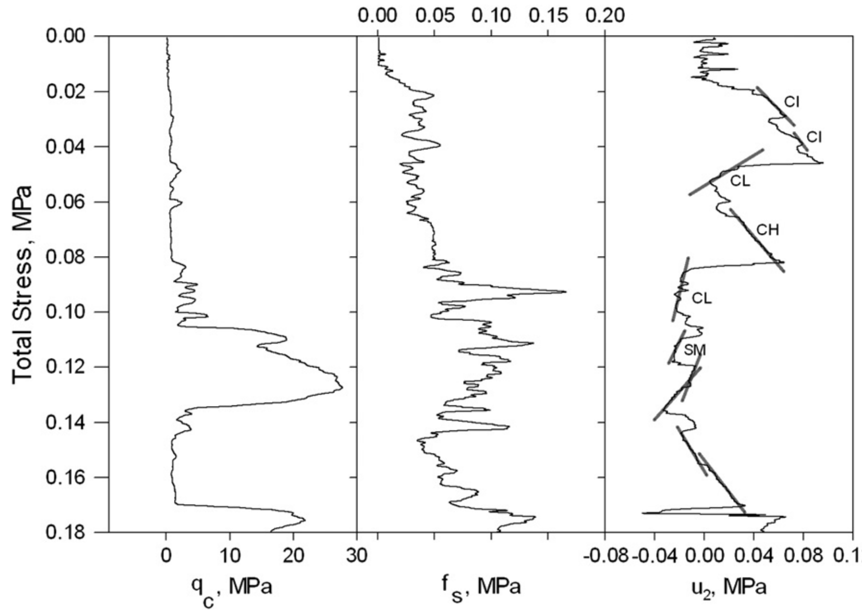

Fig. 2. Sounding profile of CTOR15 site and '*i*' gradients for laboratory sample depths.

w_L–D_{50} is not clearly reflected in the plots, one is able to state that *i* increases with increasing liquid limit and decreases as mean grain size increases.

5. Multiple linear regression analysis, *MLR*

Multiple linear regression analysis (*MLR*) was implemented to see the contribution of *i* to the classification process done with variables *Q*, *F*, q_{c1n}, and B_q derived from the CPTU data. This would enable the investigator to establish the relationship by evaluating the worthiness of dependent variables w_L, I_p, D_{50}, *%Clay* and *SCN* in order to see which parameter is to be included in the final solution. Accordingly, every dependent variable (w_L, I_p, D_{50}, *%Clay*, and *SCN*) was incorporated in the *MLR*.

The results of the analyses performed have been presented in Table 5. The model equation estimating the dependent variable and its *coefficient of determination—R^2* as well as the *correlation coefficient—R* can be seen in the table. It is seen that the parameter *i* contributes more to the solution of the problem than B_q, indicating that the gradient is more effective in identifying the physical properties. Since there is no alternative to *F*, it has been included in all the equations. In addition, it was found that *Q* or q_{c1N} proposed by Juang et al. (2003) does not contribute to the solution significantly.

Since the aim of this paper is to estimate the group of soils using the CPTU data, a more detailed study of soil class number (*SCN*) has been implemented.

Initially, the *Q* and *F* values have been included in the *multiple linear regression analysis* (*MLRA*) to reach at the soil class number, *SCN*. Thus

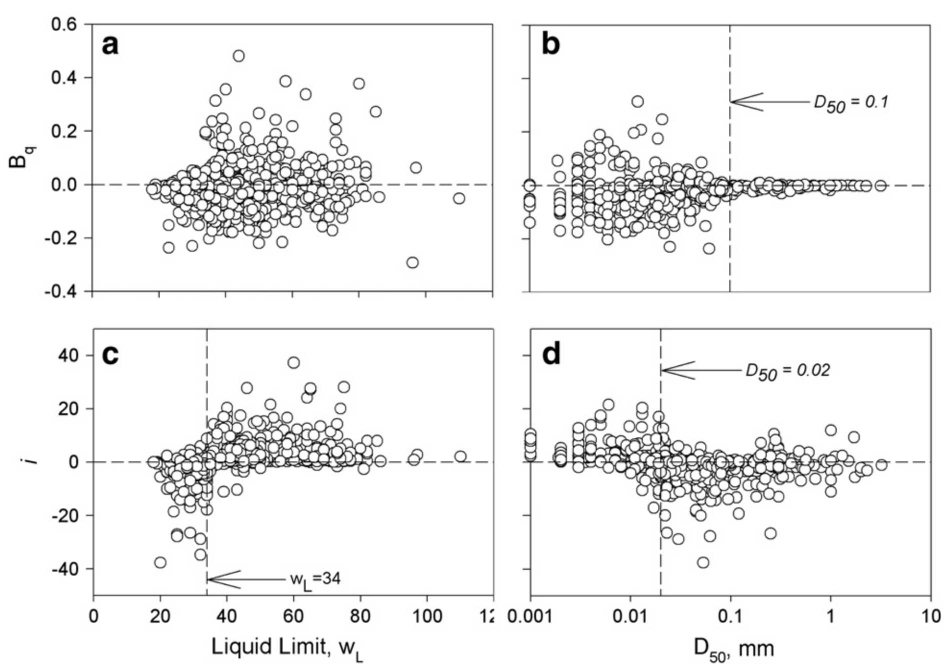

Fig. 3. The relationship of parameters *i* and B_q with liquid limit, mean size (w_L: 803 data, D_{50}: 597 data).

Table 5
Contribution of parameters F, Q, q_{c1N}, Bq and i in the estimation of physical properties of soils.

No	Dependent variable	Independent variables					Model	R	R^2	SEE
		Q	F	q_{c1N}	$(1-B_q)$	$(1-0.01i)$				
1	w_L	x	x				$w_L = 31.481 + (3.942F) - (0.0807Q)$	0.726	0.527	10.126
2	w_L	x	x		x		$w_L = 24.965 + (4.010F) - (0.0781Q) + (6.102(1-B_q))$	0.727	0.528	10.121
3	w_L	x	x			x	$w_L = 70.132 + (3.736F) - (0.0531Q) - (39.212(1-0.01i))$	0.741	0.550	9.886
4	w_L		x	x		x	$w_L = 70.213 + (3.752F) - (0.0704q_{c1N}) - (39.359(1-0.01i))$	0.742	0.550	9.883
5	Ip	x	x				$\mathrm{Ip} = 12.122 + (3.363F) - (0.123Q)$	0.667	0.444	9.503
6	Ip	x	x		x		$\mathrm{Ip} = 9.239 + (3.396F) - (0.122Q) + (2.678(1-B_q))$	0.667	0.445	9.509
7	Ip	x	x			x	$\mathrm{Ip} = 48.513 + (3.336F) - (0.0820Q) - (38.265(1-0.01i))$	0.682	0.465	9.330
8	Ip		x	x		x	$\mathrm{Ip} = 48.836 + (3.341F) - (0.124q_{c1N}) - (38.388(1-0.01i))$	0.682	0.465	9.330
9	D_{50}	x	x				$D_{50} = -0.0949 + (0.0139F) + (0.00222Q)$	0.765	0.586	0.183
10	D_{50}	x	x		x		$D_{50} = -0.291 + (0.0148F) + (0.00225Q) + (0.187(1-B_q))$	0.766	0.587	0.183
11	D_{50}	x	x			x	$D_{50} = 0.0753 + (0.0120F) + (0.00222Q) - (0.165(1-0.01i))$	0.766	0.587	0.183
12	D_{50}		x	x		x	$D_{50} = 0.0999 + (0.00617F) + (0.00248q_{c1N}) - (0.157(1-0.01i))$	0.733	0.537	0.194
13	$C\%$	x	x				$C\% = 16.642 + (3.477F) - (0.0782Q)$	0.581	0.338	11.696
14	$C\%$	x	x		x		$C\% = -0.150 + (3.587F) - (0.0724Q) + (15.818(1-B_q))$	0.585	0.342	11.666
15	$C\%$	x	x			x	$C\% = 70.790 + (2.980F) - (0.0542Q) - (53.793(1-0.01i))$	0.623	0.388	11.258
16	$C\%$		x	x		x	$C\% = 71.643 + (3.057F) - (0.0623q_{c1N}) - (55.179(1-0.01i))$	0.620	0.385	11.284
17	$FC\%$	x	x				$FC\% = 82.034 + (2.905F) - (0.229Q)$	0.851	0.724	16.068
18	$FC\%$	x	x		x		$FC\% = 66.747 + (3.033F) - (0.227Q) + (14.564(1-B_q))$	0.852	0.725	16.045
19	$FC\%$	x	x			x	$FC\% = 115.496 + (2.596F) - (0.229Q) - (32.728(1-0.01i))$	0.853	0.728	15.965
20	$FC\%$		x	x		x	$FC\% = 115.205 + (2.728F) - (0.275q_{c1N}) - (33.449(1-0.01i))$	0.857	0.735	15.766
21	SCN	x	x				$SCN = 4.509 - (0.505F) + (0.00784Q)$	0.858	0.736	1.020
22	SCN	x	x		x		$SCN = 6.241 - (0.520F) + (0.00760Q) - (1.650(1-B_q))$	0.860	0.739	1.014
23	SCN	x	x			x	$SCN = -3.085 - (0.435F) + (0.00774Q) + (7.428(1-0.01i))$	0.885	0.783	0.926
24	SCN		x	x		x	$SCN = -3.068 - (0.441F) + (0.00920q_{c1N}) + (7.455(1-0.01i))$	0.884	0.782	0.927

the equation on line 21 in Table 5 which considers F and Q exclusively appears in the form

$$SCN = 4.509 - 0.505 \times F + 0.008 \times Q \quad \left(R^2 = 0.736\right). \tag{14}$$

It is possible using this equation to guess the soil group with a coefficient of correlation of $R^2 = 0.736$. The soil groups (SCN_{MLR}) obtained in the regression analysis have been subjected to statistical analysis. The results are shown in Fig. 4a as box-plots. The minimum and the maximum values for each group have been plotted in the first, second and the third quartiles (Q_1; *median*—Q_2; Q_3). The difference between the third and the first quartiles (*interquartile range*, $IQR = Q_3 - Q_1$) as well as the spread of each group can be observed from the plots. The scatter of each class of soil (SCN_{LAB}) is seen to cover a large area (SCN_{MLR}).

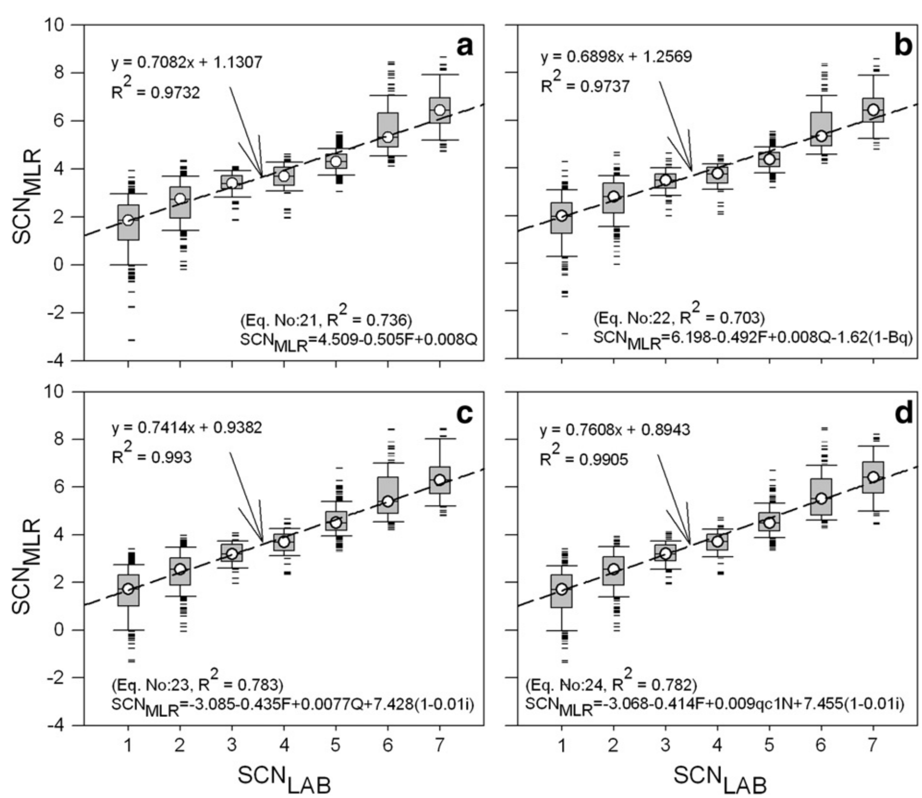

Fig. 4. Statistical analyses for the soil class numbers determined by the equations of regression.

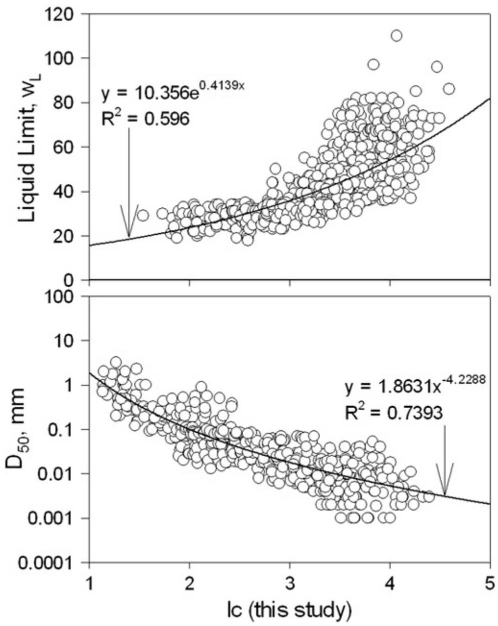

Fig. 5. The relationship of I_c with liquid limit and mean size.

Subsequently a linear tendency curve was drawn through the median value of each class of soil and the correlation coefficients shown in Fig. 4a. It must be pointed out however that the high values of the correlation coefficients obtained by constructing a curve through the median values of each SCN_{MLR} group may be misleading. Because in reality whilst the SCN_{LAB} is a singular value the SCN_{MLR} represents an interval represented by a median. It is reasoned that the high correlation coefficients in estimating the soil groups indicate the success of the equation used.

The operation was repeated by using the equations shown on lines 22, 23 and 24 of Table 5. The correlation coefficients of the mean values have also been calculated. The influence of B_q was evaluated in Fig. 4b and that of gradient *i* in Fig. 4c. It is found that B_q frequently used in current practice has actually no influence whereas *i* contributes significantly to the solution as indicated by the rising value of the correlation coefficient.

Fig. 4d illustrates the values obtained by substituting q_{c1N} in lieu of *Q* into the equation. It was decided to use the *F*, *Q* and *i* values instead of q_{c1N} because the coefficients of correlation were found to be markedly low when q_{c1N} was used. However, it must be stated that this drop was found to be insignificant, attested by the similarities of the coefficients in the equations.

Table 6
Correlation analyses results between I_c and physical properties.

Dependent variable➔	Class	%FC	D_{50}	w_L	I_P	%C
Correlation equation form➔	Class = $a \cdot I_c + b$	$FC = a \cdot Ln(I_c)^{-b}$	$D_{50} = a \cdot e^{b.Ic}$	$w_L = a \cdot e^{b.Ic}$	$I_P = a \cdot e^{b.Ic}$	$C = a \cdot I_c^{-b}$
Jefferies and Davies (1993)	0.813	0.733	0.711	0.566	0.483	0.383
Been and Jefferies (1992)	0.812	0.733	0.710	0.567	0.485	0.383
Robertson and Wride (1998)	0.808	0.768	0.731	0.528	0.444	0.371
Juang et al. (2003)	0.805	**0.774***	0.736	0.536	0.446	0.367
Li et al. (2007)	0.816	0.731	0.713	0.577	0.490	0.382
Robertson (2010)	0.760	0.766	0.708	0.471	0.346	0.326
This study	**0.840***	0.751	**0.738***	**0.596***	**0.513***	**0.392***

* The biggest value of the column.

Table 7
Soil classes identified by I_c values.

Zone	I_c	Soil class
1	$I_c < 1.4$	SP or gravels
2	$1.40 < I_c < 1.8$	SW-SM or SP-SM
3	$1.80 < I_c < 2.45$	SM or ML
4	$2.45 < I_c < 2.9$	CL or ML
5	$2.90 < I_c < 3.48$	CI-MI or CL
6	$3.48 < I_c < 4$	CH or CI
7	$I_c > 4.00$	CH

6. Derivation of the formula for soil type behaviour index

This part of the paper gives an account of the derivation of the formula for the determination of the soil class where parameter *i* was also employed. Since apart from Li et al. (2007) all investigators used a circular form to define the soil type behaviour index I_c as ($a^2 = b^2 + c^2$), its use was preferred in this study. The equation used to identify standard soil groups in this study was therefore adopted as

$$I_c = \sqrt{\{3.47 - 0.9\log[Q(1-0.01i)]\}^2 + \{1.4 + 2[\log F/(1-0.01i)]\}^2}. \quad (15)$$

Fig. 5 shows the relationships between the liquid limit, median size and the soil type behaviour index. It can be seen that the liquid limit increases as I_c increases, but the mean grain size drops.

The physical properties of the soils were subjected to correlation analyses to test the validity of the equation. Table 6 summarises the results where all the available formulae were evaluated. This table also shows the most applicable form of the function such as linear, exponential, and logarithmic. Coefficients of determination, R^2 obtained in the correlation analyses listed in this table indicate that the percent fines were predicted at about the same sensitivity as the other formulae, whereas it was superior in the prediction of all other parameters.

A study of the results in Table 7 reveals another important conclusion: All the proposed equations are able to predict percent fines and the median sizes with sufficient accuracy. Fig. 6′ depicts a histogram where the results published by Jefferies and Davies (1993) as well as Robertson and Wride (1998) are compared with the findings of this study. However, their efficacy in guessing the liquid limit, plasticity index and clay content can be said to be less pronounced. In addition, because the proposed *i* parameter is affected significantly by the plasticity of soil, the parameter *i* increases positively with increasing

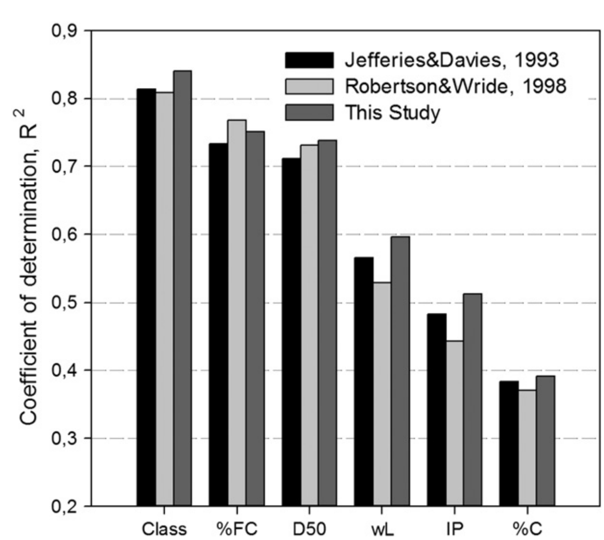

Fig. 6. Correlation analysis results between soil physical properties and I_c formulae.

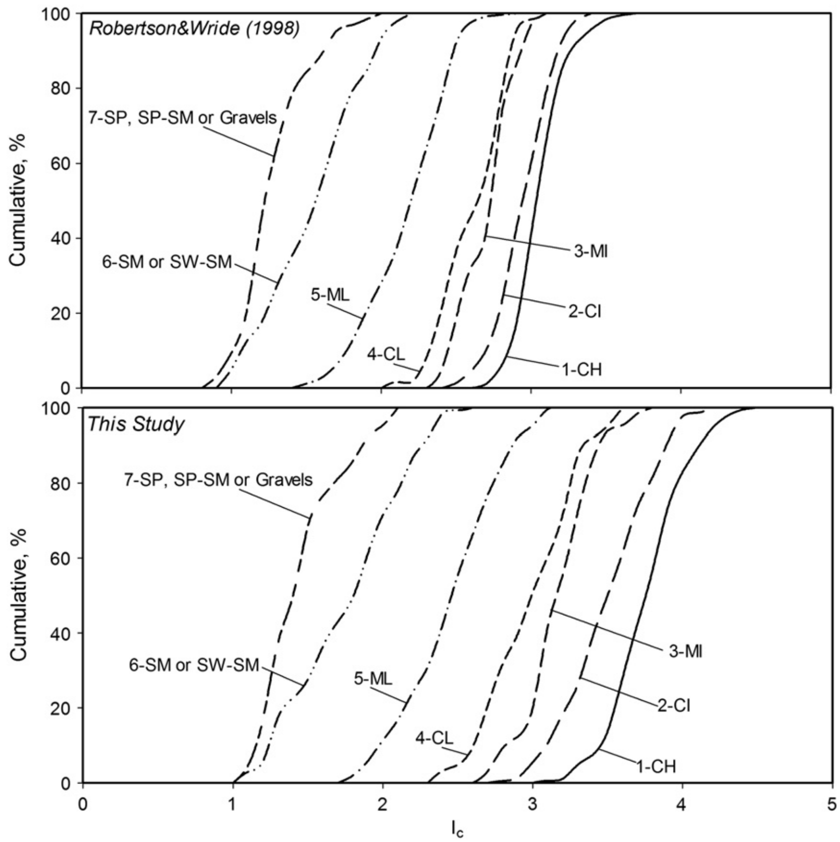

Fig. 7. Cumulative diagrams of soil classes.

plasticity. It can also reflect dilation property of non-plastic silts by showing negative tendency.

Almost all previous researchers have proposed the use of I_c in estimating the type of soil. The cumulative sums of the values by previous investigators have been plotted (Figure 7). As can be observed from the cumulative graph (Figure 7a) of the frequently used Robertson and Wride (1998) formula the curves for fine grained soils approach each other, obscuring the possibility to distinguish neighbouring zones, especially for CH-MH, CI-ML and CL. Since sampling is not possible during CPTU, the major disadvantage of the test, the formula proposed in this paper may be considered to make a contribution to the solution as reflected in Fig. 7b. The use of the formula helps separate the overlapping curves to a certain extent.

This effect can best be realised by studying the relative frequencies of the class numbers (*SCN*) 1, 3, 5 and 7 obtained by this formula and that proposed by Robertson and Wride (1998) in Fig. 8. The distribution

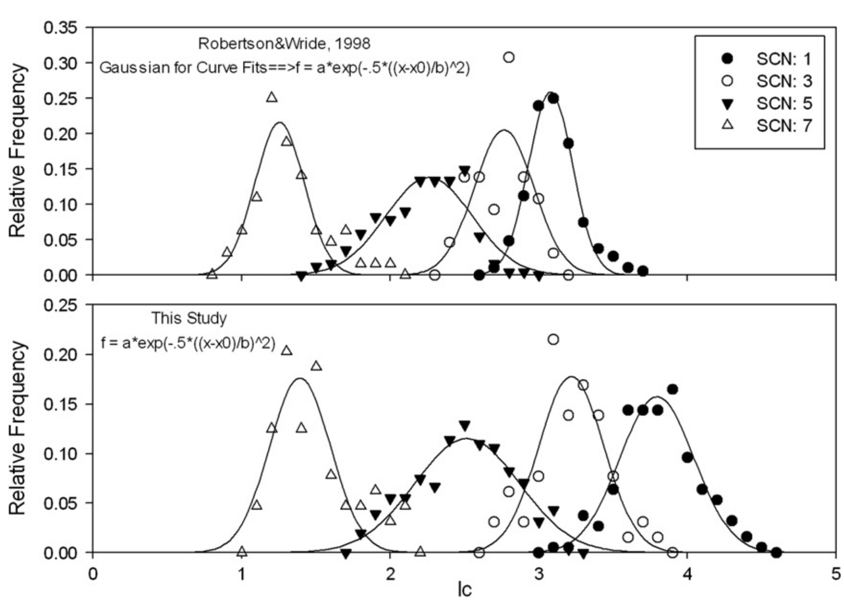

Fig. 8. Relative frequency diagrams of soil class numbers (*SCN*).

of the relative frequencies for each class has best been fitted into Gaussian distribution. A clear distinction is obvious especially for fine grained soils with $I_c > 2.5$. Although a definite distinction of different classes has still not been achieved, it is believed that the errors have decreased considerably.

The results of analysis for the distribution of I_c intervals obtained by the proposed formula 15 have been summarised in Table 7. It is seen that all soils with $I_c > 4$ belong to the class CH. The soils within the interval 3.48 and 4 are predominantly clays of high and intermediate plasticity sometimes covering CL clays as well, whereas low plasticity clays and silts appear in the band 2.45–2.90. The interval 1.80–2.45 contains non-plastic silts and silty sands. Sands with double symbols with fines content 5–12% fall into the 1.40–1.80 zone. Uniform sands and gravels are in the zone where I_c is smaller than 1.40. Table 7 shows that soils with symbol ML plot in Zone 3 as well as Zone 4. Similarly, Ku et al. (2010) have demonstrated that whilst soils with symbols ML and CL-ML (USCS) show appreciable increases in pore water pressures (i.e. high B_q values) the rest do not behave in the same fashion. Accordingly, ML and CL-ML plot above as well as below the I_c value that separates sand-like and clay-like soils.

It is hereby proposed that the classification showing the boundaries of soil behaviour type index in Table 7 is carried out as shown in Fig. 9. Additionally, the corresponding zone to those presented in the table is shown in the graph. One can also see on this figure the zones where soil classes of Fig. 2 at different depths were plotted. The value $I_c = 4.6$ was determined to be the upper limit to which classification points can extend. Another finding is that all points are limited to within the concentric circles where upper and lower bound curves are defined. The equation for the limiting curves can be given by the following equation:

$$I_B = \sqrt{\{0.2 + \log[Q(1-0.01i)]\}^2 + \{1.4 + 1.3[\log F/(1-0.001i)]\}^2}. \quad (16)$$

The values I_B have been calculated as 1.6 and 3.2 for the upper and lower bounds respectively.

7. Discussion and conclusions

This paper is about the prediction of soil classes assigned by laboratory through the use of data collected during a cone penetration test. A comprehensive evaluation of the existing knowledge available in the literature has been carried out and a new parameter to perform the analysis is proposed. The parameter i representing the porewater pressure gradients along the soil profile during cone penetration is a dimensionless number describing the changes in pore water pressures during flight. The parameter i increases with the increasing liquid limits and it drops as grain size increases. Furthermore, it was found that silty soils that exhibit dilative character assume appreciable $-i$ values.

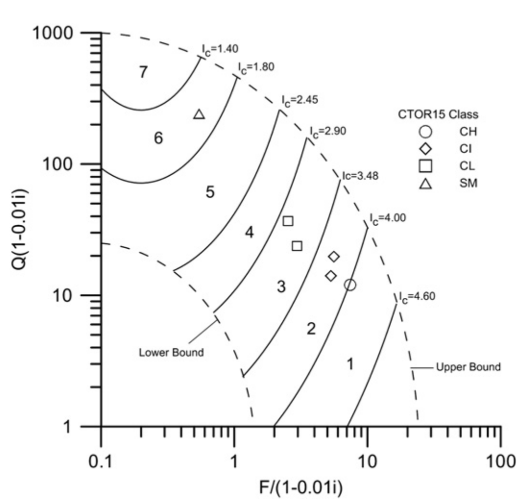

Fig. 9. Classification of soil classes from CPTU data.

A new chart with seven zones for classification of soils has been developed. The new soil type behaviour index proposed has been instrumental for the purpose. The new I_c shows CH type clays when it is bigger than 4. Clays of high and intermediate plasticity are located in the interval 3.48–4.00. Data for clays of low plasticity and silts are placed within $I_c = 2.45$–2.90. Sands with double symbols (SW-SM/SP-SM) are located in the narrow band 1.40 to 1.80, whereas uniform sands and gravels are in the zone $I_c < 1.40$.

Although it cannot be claimed that the new equation is able to differentiate soils of different classes precisely, an improvement over previous equations has been achieved. It would not be wrong to say that the i parameter that is introduced in the context of this study will help to understand other physical, mechanical and hydrological properties of soils. Its contribution may be more meaningful in the study of consolidation and hydraulic features. The next step in the study will be to compare the information in the database whether they are in agreement with the test results from consolidation, shear strength and hydraulic conductivity.

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