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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

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_v} \tag{3}$$

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

$$Q = \frac{q_t - \sigma_v}{\sigma'_v} \tag{4}$$

$$F = \frac{f_s}{q_t - \sigma_v}. \tag{5}$$

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

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

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.

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

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

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

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

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

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

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 $I_{c,m}$

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

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:

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

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.