Estimating in-situ soil permeability from CPT & CPTu

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ABSTRACT: Engineers often want to estimate profiles of soil permeability (hydraulic conductivity) as part of the site characterization process. Several methods have been proposed to estimate the coefficient of permeability (*k*) using CPT results. These methods are generally based on two approaches: (1) estimated soil type and (2) rate of dissipation during a CPTu dissipation test. This paper presents updated correlations to estimate the coefficient of permeability from CPT and CPTu dissipation test results. The proposed correlations are briefly evaluated with available published results.

1 INTRODUCTION

Geotechnical engineers and geologists often want to estimate profiles of soil permeability (hydraulic conductivity) as part of the site characterization process. Soil permeability can vary by up to ten orders of magnitude and can be difficult to both estimate and measure accurately. It is often considered that accuracy within one order of magnitude is acceptable. Most methods to measure soil permeability are slow and expensive and often subject to scale effects. During the initial stages of site characterization it is sometimes helpful to estimate soil permeability based on simple, inexpensive penetration tests, such as the cone penetration test (CPT). Several methods have been proposed to estimate the coefficient of permeability (*k*) using CPT results. These methods are generally based on two approaches: (1) estimated soil type and (2) rate of dissipation during a CPTu dissipation test.

The objective of this paper is to evaluate existing CPT-based methods to estimate soil permeability and to suggest updated correlations. The proposed new correlations are briefly evaluated using existing published records.

2 PERMEABILITY ESTIMATES BASED ON SOIL TYPE

Lunne et al (1997) suggested that soil permeability (*k*) could be estimated using the Soil Behaviour Type (SBT) charts proposed by either Robertson et al (1986) or Robertson (1990). A range of *k* values was suggested for each SBT. Table 1 shows the updated recommended range based on the Robertson (1990) normalized SBTn chart.

Table 1 Estimated soil permeability (*k*) based on normalized CPT soil behavior type (SBTn) by Robertson (1990) (Modified from Lunne et al., 1997)

SBTn Zone	SBTn	Range of *k* (m/s)	SBTn I_c
1	Sensitive fine-grained	$3x10^{-10}$ to $3x10^{-8}$	*NA*
2	Organic soils - clay	$1x10^{-10}$ to $1x10^{-8}$	$I_c > 3.60$
3	Clay	$1x10^{-10}$ to $1x10^{-9}$	$2.95 < I_c < 3.60$
4	Silt mixture	$3x10^{-9}$ to $1x10^{-7}$	$2.60 < I_c < 2.95$
5	Sand mixture	$1x10^{-7}$ to $1x10^{-5}$	$2.05 < I_c < 2.60$
6	Sand	$1x10^{-5}$ to $1x10^{-3}$	$1.31 < I_c < 2.05$
7	Dense sand to gravelly sand	$1x10^{-3}$ to 1	$I_c < 1.31$
8	*Very dense/ stiff soil	$1x10^{-8}$ to $1x10^{-3}$	*NA*
9	*Very stiff fine-grained soil	$1x10^{-9}$ to $1x10^{-7}$	*NA*

**Overconsolidated and/or cemented*

Manassero (1994) reported good results using Table 1 to estimate *k* values for quality control purposes in a slurry wall.

Jefferies and Davies (1993) identified that a Soil Behavior Type Index, I_c, could represent the SBT zones in the normalized CPT SBTn chart where, I_c is essentially the radius of concentric circles that define the boundaries of soil type. Robertson and Wride, (1998) and updated by Robertson (2009), modified the definition of I_c, as follows:

$$I_c = [(3.47 - \log Q_{tn})^2 + (\log F_r + 1.22)^2]^{0.5} \quad (1)$$

where:

$$Q_{tn} = [(q_t - \sigma_v)/p_a]\,(p_a/\sigma'_{vo})^n \quad (2)$$

$$F_r = [(f_s/(q_t - \sigma_{vo})]\ 100\% \quad (3)$$

q_t = CPT corrected total cone resistance
f_s = CPT sleeve friction
σ_{vo} = pre-insertion in-situ total vertical stress
σ'_{vo} = pre-insertion in-situ effective vertical stress
$(q_t - \sigma_v)/p_a$ = dimensionless net cone resistance, and,
$(p_a/\sigma'_{vo})^n$ = stress normalization factor
n = stress exponent that varies with SBT
p_a = atmospheric pressure in same units as q_t, σ_v and σ'_{vo}

Robertson (2009) provided a detailed discussion on stress normalization and suggested the following updated approach to allow for a variation of the stress exponent (n) with both SBTn I_c (soil type) and stress level using:

$$n = 0.381\,(I_c) + 0.05\,(\sigma'_{vo}/p_a) - 0.15 \quad (4)$$

where $n \leq 1.0$

The range of I_c values for each SBTn zone are included in Table 1. Figure 1 shows the updated Robertson (1990) SBTn chart in terms of Q_{tn}- F_r with the I_c boundaries. The concept of a SBTn index I_c only applies to soils that plot down the center of the chart in regions 2 to 7.

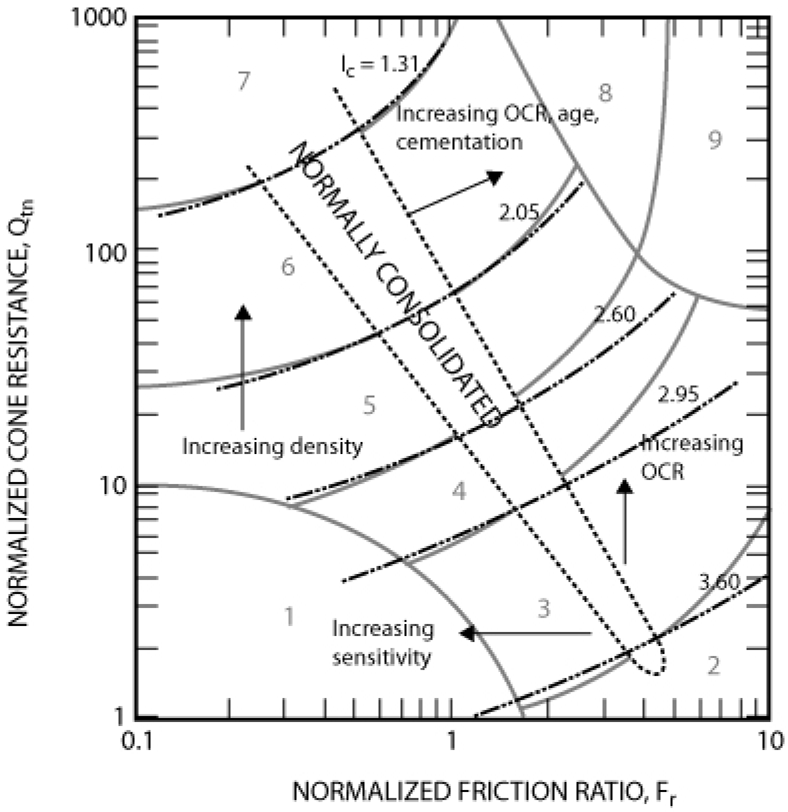

Figure 1. Updated normalized SBTn chart showing contours of I_c

It is well recognized that the normalized cone resistance decreases and the SBTn I_c increases as a soil becomes more fine-grained, due to the increasing compressibility of fine-grained soils compared to coarse-grained soils. This was identified by Robertson (1990) where the normally consolidated region on the CPT SBTn chart extends down the chart (see Figure 1), i.e. as soil becomes more fine-grained the normalized cone resistance (Q_{tn}) decreases and F_r increases. Cetin and Ozan (2009), and others, have also shown that as I_c increases the soils become more fine-grained. Hence, as I_c increases the soil permeability (k) generally decreases.

Figure 2 shows the range of k values from Table 1 as a function of I_c

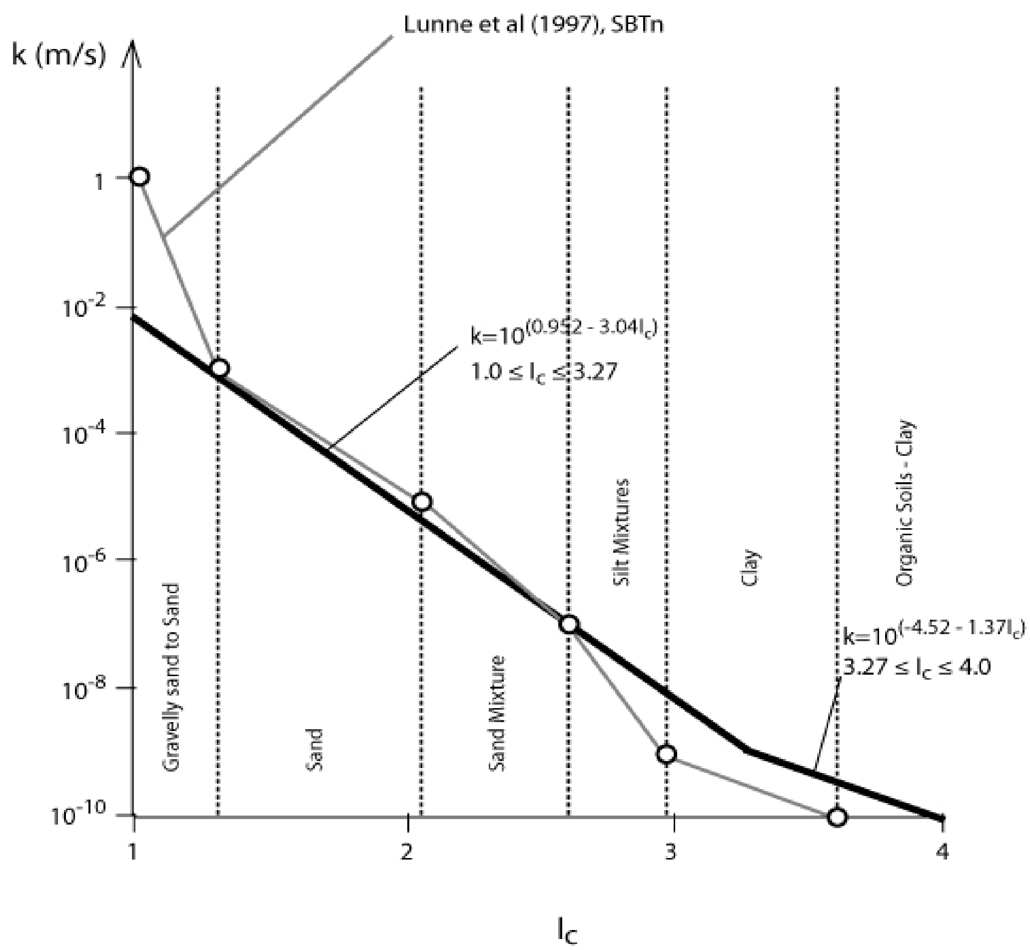

Figure 2. Suggested variation of soil permeability (k) as a function of SBT I_c

The proposed relationship between soil permeability (k) and SBT I_c, shown in Figure 2, can be represented by:

When $1.0 < I_c \leq 3.27$ $\quad k = 10^{(0.952 - 3.04\, Ic)}$ m/s (5)

When $3.27 < I_c < 4.0$ $\quad k = 10^{(-4.52 - 1.37\, Ic)}$ m/s (6)

Equations 5 and 6 can be used to provide an approximate estimate of soil permeability (k) and to show the variation of soil permeability with depth from a CPT sounding. Since the normalized CPT parameters (Q_{tn} and F_r) respond to the mechanical behaviour of the soil and depend on many soil variables, as illustrated schematically in

Figure 1, the suggested relationship between k and I_c is approximate and should only be used as a guide.

3 PERMEABILITY ESTIMATES BASED ON CPTU DISSIPATION TEST

The estimated soil permeability based on soil type will be approximate, but generally within the correct order of magnitude. For improved estimates, pore pressure dissipation tests should also be performed in soil layers defined by the CPTu. The dissipation of pore pressures during a CPTu dissipation test is controlled by the coefficient of consolidation in the horizontal direction (c_h) which is influenced by a combination of the soil permeability (k_h) and compressibility (M), as defined by the following:

$$k_h = (c_h\, \gamma_w)/M \tag{7}$$

where: M is the 1-D constrained modulus and γ_w is the unit weight of water, in compatible units.

Schmertmann (1978), Parez and Fauriel (1988) and Robertson et al (1992) suggested methods to estimate soil permeability (k) using the time for 50% dissipation (t_{50}) from a CPTu dissipation test. These simplified relationships are approximate, since the relationship is also a function of the soil compressibility (M), as shown in equation 7. An alternate and better approach is to estimate the coefficient of consolidation from a dissipation test then combine this with an estimate of the soil compressibility (M) to obtain an improved estimate of the soil permeability (k).

The simplified relationship presented by Robertson et al (1992), based on the work of Teh and Houlsby (1991), for the coefficient of consolidation in the horizontal direction (c_h) as a function of the time for 50% dissipation (t_{50}, in minutes) for a 10 cm^2 cone can be approximated using:

$$c_h = (1.67\text{x}10^{-6})\; 10^{(1 - \log t_{50})} \qquad \text{m}^2/\text{s} \tag{8}$$

For a 15cm^2 cone, the values of c_h are increased by a factor of 1.5.

Robertson (2009) recently updated the correlation to estimate 1-D constrained modulus (M) using:

$$M = \alpha_M\, (q_t - \sigma_{vo}) \tag{9}$$

when $I_c > 2.2$:

$$\alpha_M = Q_{tn} \qquad \text{when } Q_{tn} \leq 14$$
$$\alpha_M = 14 \qquad \text{when } Q_{tn} > 14$$

Note that, in fine grained soils, where n = 1.0, $Q_{tn} = Q_t = (q_t - \sigma_{vo})/\sigma'_{vo}$.

Combining equations 7, 8 and 9 in compatible units (i.e. net cone resistance, $(q_t - \sigma_{vo})$ in kPa and $\gamma_w = 9.81$ kN/m^3) it is possible to develop contours of k versus t_{50} for various values of Q_{tn} and σ'_{vo}, as shown on Figure 3.

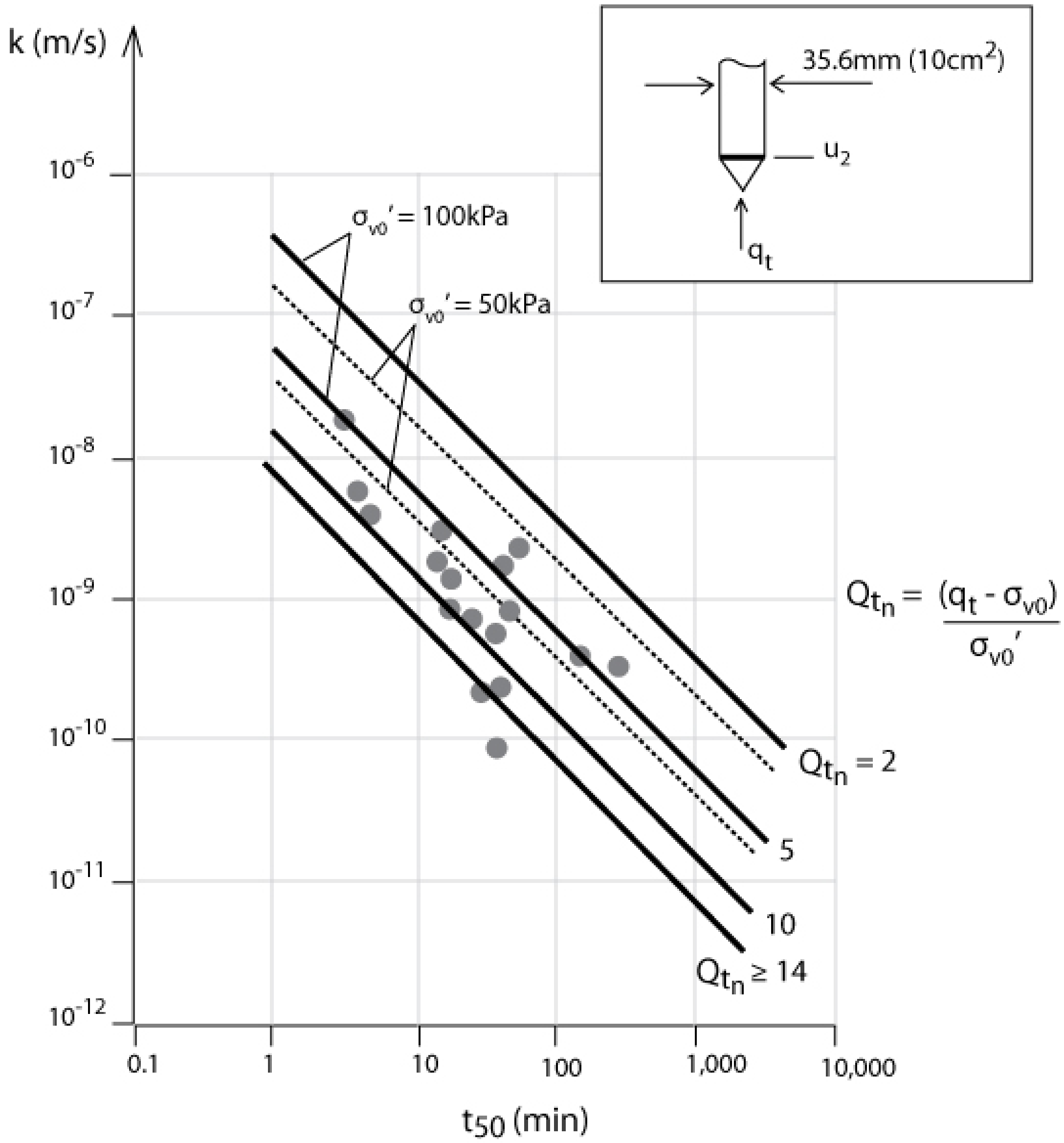

Figure 3. Proposed relationship between CPTu t_{50} (in minutes) and soil permeability (k) and normalized cone resistance, Q_{tn}.

The relationship shown in Figure 3 can be applied to data from standard 10 cm^2 and 15 cm^2 cones pushed into soft to stiff, fine-grained soils, where the penetration process is essentially undrained.

Robertson et al (1992) also presented a summary of CPTu data where laboratory derived values of horizontal coefficient of permeability results were also available and these are included on Figure 3. Sites where normalized cone resistance values were also available confirm that the observed scatter in test results is due to the variation in soil stiffness reflected in the normalized cone resistance.

4 PARTIALLY DRAINED PENETRATION

The degree of consolidation during cone penetration depends on the penetration rate (v), cone diameter (d_c), and the coefficient of consolidation of the soil (c_h) (Finnie and Randolph, 1994). These factors can be used to obtain a normalized, dimensionless penetration rate, V:

$$V = v\, d_c/c_h \tag{10}$$

According to a number of researchers (e.g. Finnie and Randolph, 1994, Chung et al., 2006, Kim et al., 2008) the transition from fully undrained to partially drained conditions is approximately when V ~ 10. Therefore, for CPT using a standard 10 cm^2 cone carried out at the standard rate of 20 mm/s, undrained penetration can be expected in soils with c_h values less than about 7×10^{-5} m^2/s. Because of the offsetting effect of rate-dependence shear strength, Kim et al (2010) showed that the cone resistance is unchanged for V > 1, which corresponds to a $c_h \sim 7 \times 10^{-4}$ m^2/s. Based on the relationship between t_{50} and c_h, (equation 8) this corresponds to a $t_{50} < 0.5$ min (30 sec). Hence, a simple method to evaluate if CPT penetration is occurring undrained or partially drained is to perform a dissipation test. If $t_{50} > 30$ seconds, cone penetration for either a 10 cm^2 or 15 cm^2 cone is likely undrained and the measured cone resistance can be used to estimate undrained shear strength. If $t_{50} < 30$ seconds, the measured cone resistance may be slightly high due to partial drainage. This is consistent with the observation made by Robertson et al (1992).

5 SUMMARY

Updated correlations are presented to estimate the coefficient of permeability (*k*) from either CPT or CPTu results. Estimates based on soil behavior type (SBT) can be used to provide an approximate estimate of soil permeability (*k*) and to show the likely variation of soil permeability with depth from a CPT sounding. Improved estimates can be made by performing dissipation tests and recording the time for 50% dissipation, t_{50}. The updated relationship based on t_{50} incorporates the variation in soil stiffness reflected in the normalized cone resistance.

A simple method to evaluate if CPT penetration is occurring undrained or partially drained is to perform a dissipation test. If $t_{50} > 30$ seconds, cone penetration is likely undrained and the measured cone resistance can be used to estimate undrained shear strength. If $t_{50} < 30$ seconds, the measured cone resistance may be slightly high due to partial drainage.

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