Soil behaviour type from the CPT: an update

P.K. Robertson
Gregg Drilling & Testing Inc., Signal Hill, California, USA

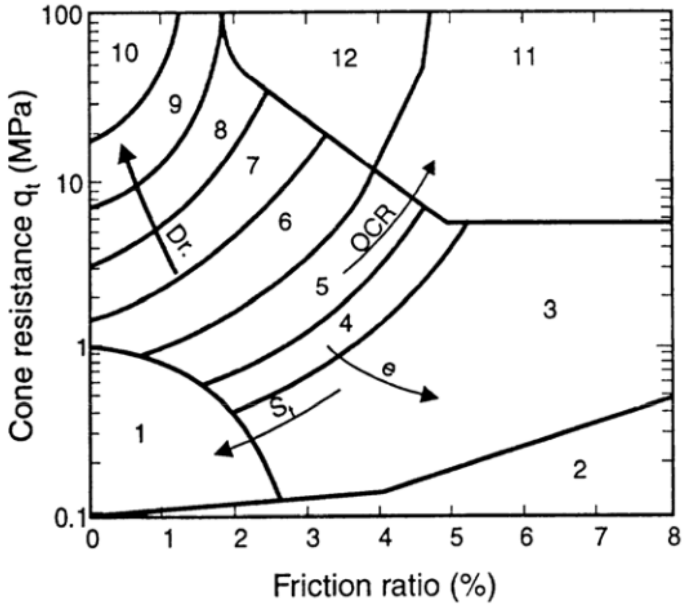
ABSTRACT: An initial application of CPT results is to evaluate soil type and soil stratigraphy. One of the more common CPT-based methods to estimate soil type is the chart suggested by Robertson et al (1986) based on cone resistance, q_c and friction ratio, R_f. Although newer charts have been developed based on normalized parameters, the simple chart based on q_c and R_f is still popular because it is easy to use and can be used in real-time during the CPT. This paper provides an update on the soil behaviour type charts based on basic CPT measurements of q_t and f_s. and proposes a new soil behaviour index for non-normalized CPT results.

1 INTRODUCTION

The electric Cone Penetration Test (CPT) has been in use for over 40 years. The CPT has major advantages over traditional methods of field site investigation such as drilling and sampling since it is fast, repeatable and economical. In addition, it provides near continuous data and has a strong theoretical background. These advantages have lead to a steady increase in the use and application of the CPT in many places around the world.

One of the major applications of the CPT has been the determination of soil stratigraphy and the identification of soil type. This has typically been accomplished using charts that link cone parameters to soil type. Early charts using q_c and friction ratio, R_f [where: $R_f = (f_s/q_c)100\%$] were proposed by Schmertmann (1978) and Douglas and Olsen (1981), but the chart proposed by Robertson et al. (1986) has become very popular (e.g. Long, 2008). The original Robertson et al (1986) chart based on q_t and R_f is shown in Figure 1. Although the chart is shown in terms of the corrected cone resistance q_t, it can be used equally well with uncorrected cone resistance, q_c, since the difference between q_c and q_t is small, except in soft fine grained soils that produce high penetration pore pressures.

The chart by Robertson et al (1986) uses the basic CPT measurements of q_c and f_s and has 12 soil types, whereas the chart by Robertson (1990) uses normalized parameters and has 9 soil types. The different soil types in each chart have sometimes created some confusion when comparing results. The advantage of the early Robertson et al (1986) chart was that it could be used in real-time to evaluate soil type during and immediately after the CPT, since it only requires the basic CPT measurements. Although the normalized charts of Robertson (1990) are considered more reliable because they use CPT parameters normalized in terms of effective stress, they can only be applied after the CPT during post-processing, since they require information on soil unit weight and groundwater conditions that are not available during the CPT. This paper provides an update to the early Robertson et al (1986) chart using non-normalized CPT results.



Zone	*Soil Behavior Type*
1	*Sensitive fine grained*
2	*Organic material*
3	*Clay*
4	*Silty Clay to clay*
5	*Clayey silt to silty clay*
6	*Sandy silt to clayey silt*
7	*Silty sand to sandy silt*
8	*Sand to silty sand*
9	*Sand*
10	*Gravelly sand to sand*
11	*Very stiff fine grained**
12	*Sand to clayey sand**

** Overconsolidated or cemented*

Figure 1 SBT chart by Robertson et al (1986) based on CPT cone resistance, q_t, and friction ratio, R_f (where $R_f = (f_s/q_t)100\%$)

2 SOIL BEHAVIOUR TYPE (SBT)

Robertson et al (1986) and Robertson (1990) stressed that the CPT-based charts were predictive of Soil Behaviour Type (SBT), since the cone responds to the in-situ mechanical behavior of the soil and not directly to soil classification criteria based on grain-size distribution and soil plasticity (e.g. Unified Soil Classification System, USCS). Grain-size distribution and Atterberg Limits are measured on disturbed soil samples. Fortunately, soil classification criteria based on grain-size distribution and plasticity often relate reasonably well to in-situ soil behaviour and hence, there is often good agreement between USCS-based classification and CPT-based SBT (e.g. Molle, 2005). However, several examples can be given when differences can arise between USCS-based soil types and CPT-based SBT. For example, a soil with 60% sand and 40% fines may be classified as 'silty sand' (sand-silt mixtures) or 'clayey sand' (sand-clay mixtures) using the USCS. If the fines have high clay content with high plasticity, the soil behaviour may be more controlled by the clay and the CPT-based SBT will reflect this behaviour and will predict a more clay-like behaviour, such as 'clayey silt to silty clay' (SBT zone 5, Fig. 1). If the fines were non-plastic, soil behaviour will be controlled more by the sand and the CPT-based SBT would predict a more sand-like soil type, such as 'silty sand to sandy silt' (SBT zone 7, Fig 1). Very stiff, heavily overconsolidated fine-grained soils tend to behave more like a coarse-grained soil in that they tend to dilate under shear and can have high undrained shear strength compared to their drained strength and can have a CPT-based SBT in either zone 4 or 5 (Fig. 1). Soft saturated low plastic silts tend to behave more like clays in that they have low undrained shear strength and can have a CPT-based SBT in zone 3 (Fig. 1). These few examples illustrate that the CPT-based SBT may not always agree with traditional USCS-based soil types based on samples and that the biggest difference is likely to occur in the mixed soils region (i.e. sand-mixtures & silt-mixtures). Geotechnical engineers are often more interested in the in-situ soil behaviour than a classification based only on grain-size distribution and plasticity carried out on disturbed samples, although knowledge of both is helpful.

In general, the normalized chart (Robertson, 1990) provides more reliable identification of SBT than the non-normalized charts, although when the in-situ vertical effective stress is between 50 kPa to 150 kPa there is often little difference between normalized and non-normalized SBT. The term SBTn will be used to distinguish between normalized and non-normalized SBT.

3 MODIFIED NON-NORMALIZED SBT CHART

The early Robertson et al (1986) SBT chart was based on cone resistance, q_t (or q_c) on a log scale with friction ratio, R_f on a natural scale. Figure 2 provides an update of the chart in terms of dimensionless cone resistance, (q_c/p_a), where p_a = atmospheric pressure (p_a = 1 bar = 100 kPa = 0.1 MPa) and R_f (in percent), both on log scales to expand the portion where $R_f < 1\%$. The number of soil behaviour types has also been reduced to 9 to match the Robertson (1990) chart. Table 1 summarizes the unification of the 12 (Robertson et al.1986) SBT zones to match the 9 (Robertson, 1990) SBTn zones. Reducing the number of SBT zones in the non-normalized chart allows easier comparison between the normalized and non-normalized SBT's.

Table 1 Proposed unification between 12 SBT zones (Robertson et al, 1986) and 9 SBTn zones (Robertson, 1990)

SBT zone *Robertson et al (1986)*	**SBT_n zone** *Robertson (1990)*	**Proposed common SBT description**
1	1	*Sensitive fine-grained*
2	2	*Clay - organic soil*
3	3	*Clays: clay to silty clay*
4 & 5	4	*Silt mixtures: clayey silt & silty clay*
6 & 7	5	*Sand mixtures: silty sand to sandy silt*
8	6	*Sands: clean sands to silty sands*
9 & 10	7	*Dense sand to gravelly sand*
12	8	*Stiff sand to clayey sand**
11	9	*Stiff fine-grained**

* *Overconsolidated or cemented*

Jefferies and Davies (1993) identified that a Soil Behaviour Type Index, I_c, could represent the SBTn zones in the normalized chart where, I_c is essentially the radius of concentric circles that define the boundaries of soil type. Robertson and Wride, (1998) modified the definition of I_c to apply to the Robertson (1990) $Q_t - F_r$ chart. When the non-normalized SBT chart is presented on log-log scales (Figure 2) the boundaries are also essentially concentric circles and a non-normalized Soil Behaviour Type Index, I_{SBT} can also be defined by:

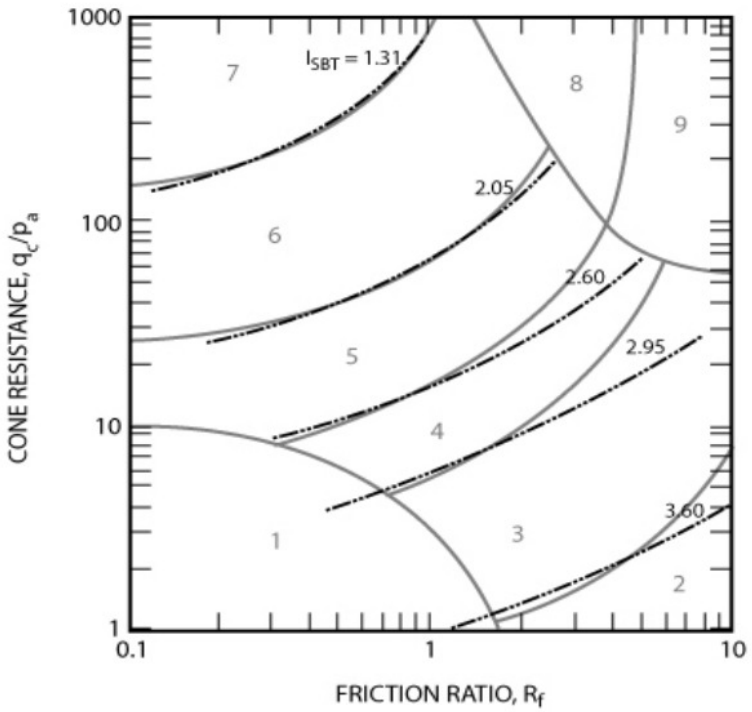
$$I_{SBT} = [(3.47 - \log(q_c/p_a))^2 + (\log R_f + 1.22)^2]^{0.5} \qquad (1)$$

where:
q_c = CPT cone resistance (or corrected cone resistance, q_t)
R_f = friction ratio = $(f_s/q_c)100\%$
f_s = CPT sleeve friction

The non-normalized SBT index (I_{SBT}) is essentially the same as the normalized SBTn index (I_c) but only uses the basic CPT measurements. In general, the normalized I_c provides more reliable identification of SBT than the non-normalized I_{SBT}, but when the in-situ vertical effective stress is between 50 kPa to 150 kPa there is often little difference between normalized and non-normalized SBT.

4 EXAMPLE

Figure 3 shows an example CPTu profile at a site with about 8m of very soft, essentially normally consolidated clay, overlying stiff, overconsolidated silty clay, with occasional thin sand layers, to a depth of about 18m. Underlying the stiff silty clay is dense sand to a depth of about 30m. The piezometric profile is approximately hydrostatic with groundwater at a depth of about 3m. Figure 3 presents the measured CPTu parameters in terms of cone resistance (q_t), friction ratio (R_f) and pore pressure (u_2), as well as the profiles of non-normalized SBT index (I_{SBT}) and the SBT descriptions, based on the chart shown in Figure 2. The SBT zones are colour coded to aid in visual representation (Geologismiki, CPeT-IT). The pore pressure sensor appears to have lost saturation when passing through the thin dense sand layer at 12m, but regained saturation again at a depth of about 17m.



Zone	Soil Behaviour Type (SBT)
1	*Sensitive fine-grained*
2	*Clay - organic soil*
3	*Clays: clay to silty clay*
4	*Silt mixtures: clayey silt & silty clay*
5	*Sand mixtures: silty sand to sandy silt*
6	*Sands: clean sands to silty sands*
7	*Dense sand to gravelly sand*
8	*Stiff sand to clayey sand**
9	*Stiff fine-grained**

* *Overconsolidated or cemented*

Figure 2. Updated non-normalized SBT chart based on dimensionless cone resistance, (q_c/p_a) and friction ration, R_f, showing contours of I_{SBT}

Figure 4 presents the normalized CPTu parameters as defined and updated by by Robertson (2009), as well as the profiles of normalized SBT index (I_c) and the SBTn descriptions, base on Table 1. Figures 3 and 4 show that there is little difference between the soil behavior type interpretation for this example profile.

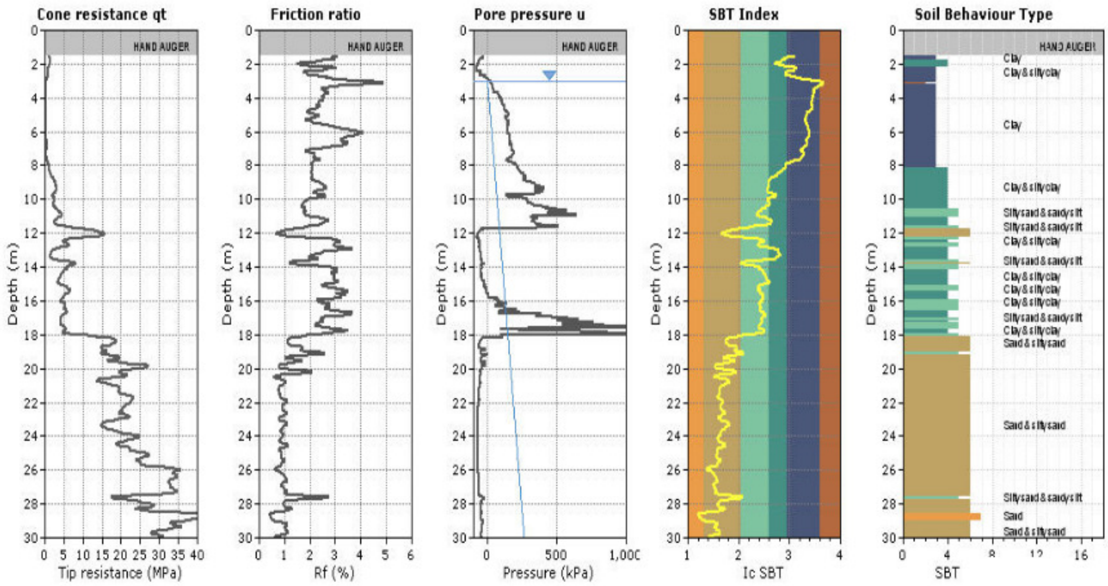


Figure 3 Example CPTu profile to illustrate non-normalized SBT and SBT Index, I_{SBT}

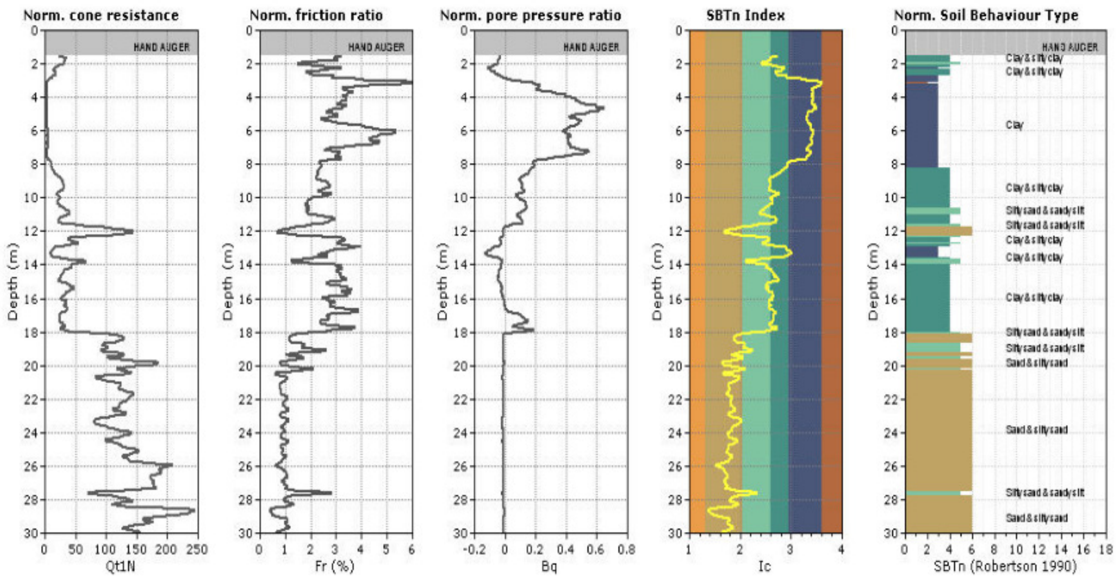
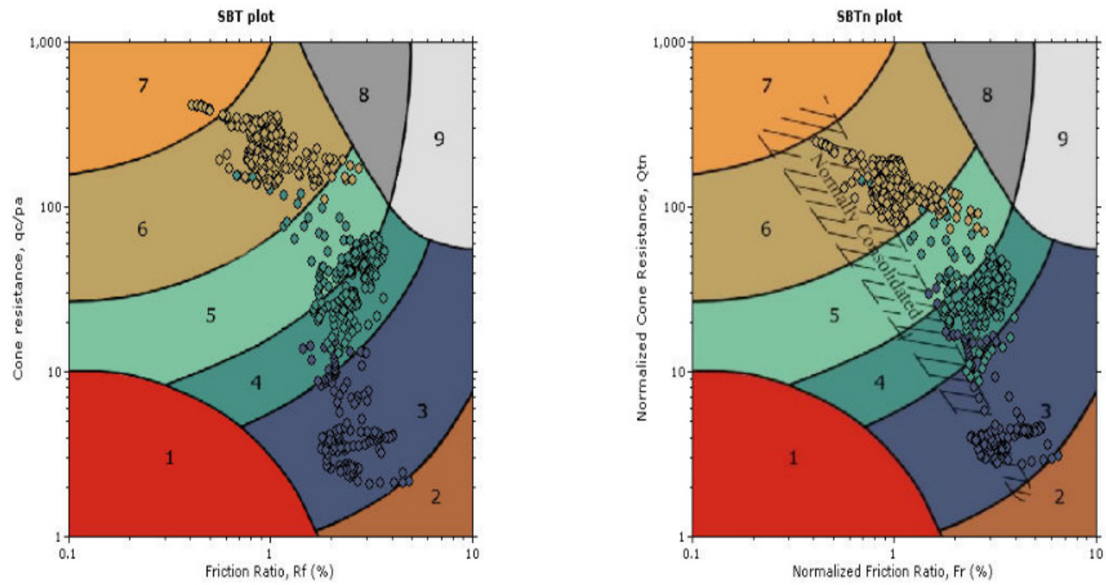


Figure 4 Example CPTu profile to illustrate normalized SBT and SBT Index, I_c

Figure 5 shows the CPT data plotted on both the updated non-normalized SBT chart and the normalized SBTn (Robertson, 1990) chart. Each layer is represented by different colour data points to aid identification. Figure 5 shows that the CPT data are more closely clustered on the normalized charts, as expected, but that both charts provide similar interpretation of soil behaviour type. Note that the "normally consolidation" region suggested by Robertson (1990) can only been shown on the normalized SBT chart, since a similar region is only valid on the non-normalized chart when the effective overburden stress is close 1 atmosphere (i.e. ~100kPa).



(a) (b)

Figure 5 Comparison between (a) updated non-normalized SBT and (b) normalized SBTn (Robertson, 1990) for the CPTu profile shown in Figure 3

5 SUMMARY

One of the major applications of the CPT has been the determination of soil stratigraphy and the identification of soil type. This has typically been accomplished using charts that link cone parameters to soil type. This paper has presented an update to the Robertson et al (1986) chart to aid in comparison with the normalized chart suggested by Robertson (1990). A new non-normalized soil behavior type index (I_{SBT}) has also been proposed that uses the basic non-normalized CPT results. The non-normalized SBT index (I_{SBT}) is essentially the same as the normalized SBTn index (I_c), suggested by Robertson and Wride (19898) but only uses the basic CPT measurements. In general, the normalized I_c will provide more reliable identification of SBT than the non-normalized I_{SBT}, but when the in-situ vertical effective stress is between 50 kPa to 150 kPa there is often little difference between normalized and non-normalized SBT. The normalized soil behaviour type chart and SBTn index (I_c) is recommended for later post-processing of CPT results, but the non-normalized chart and SBT index (I_{SBT}) can be helpful for real-time data processing and interpretation. An example CPTu profile is presented to illustrate the comparison between non-normalized and normalized CPTu results.

6 ACKNOWLEDGMENTS

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