A preliminary attempt towards soil classification chart from total sounding

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ABSTRACT
Total sounding is an in-situ soil investigation tool that combines conventional rotary pressure sounding with rock control drilling. It is a quick method that can be used in most soil types. It's mainly used for preliminary characterization of soil layering and to identify location of bed rocks. In Norwegian geotechnical practice, total sounding is generally adopted as a standard method to start an in-situ soil investigation scheme. The main measurement in a total sounding is the penetration resistance force (in kN), which is used in defining soil layering. The main shortcoming of this measurement is its susceptibility to the increasing rod friction by depth. As a result this measurement is only used subjectively but still usually provides an important first time insight to the soil layering that are later verified with additional investigations. Thus, there is a need to systematically study measurements of total sounding for a better soil characterization and in a more objective way. The work is initiated in this study by deriving three parameters from the penetration resistance force: the smoothed normalized penetration pressure, the standard deviation of penetration force, and the gradient of the smoothed normalized penetration pressure. Then the relevances among these three parameters, and correlations between these parameters and grain size distributions are explored. This leads to a soil behaviour type chart, in which four general soil types including quick clay are distinguished. The soundness of the proposed chart is examined against the employed data, and later by being compared with two CPTU-based classification methods. The paper also discusses additional potential improvements that can be incorporated to the chart and more broadly to this sounding method to increase its usability for current geotechnical practice.

Keywords: total sounding, objective interpretation, soil behaviour type, classification chart, quick clay

1 INTRODUCTION

The total sounding is a rotary pressure sounding technique intended for all kinds of soil types. The method was developed in Norway through cooperation between the Norwegian Geotechnical Institute and the Norwegian Road Research Laboratory back in 1980s, with the purpose of combining rotary pressure sounding and bedrock control sounding into one operation (NGF, 1994). It is now established as the most used sounding method in Norway. The Swedish *rock soil total sounding* (JB totalsondering) is based on the Norwegian counterpart and is increasingly used in Sweden (Wister, S., 2010).

In the Norwegian geotechnical practice, a total sounding is generally adopted as a standard method to start an in-situ soil investigation scheme. The main use of total sounding is for a preliminary characterization of soil layering and to identify location of bed rocks. It provides a platform for planning of subsequent in-situ investigations such as CPTU (cone penetration test with pore pressure measurement), soil sampling and pore pressure measurements. The main measurement in a total sounding that is used in classifying soil layering is the penetration resistance force (in kN). This is used for a qualitative classification of soil behaviour. A main shortcoming in this measurement is its susceptibility to the influence of increasing rod friction by depth. The inaccuracy is especially remarkable in soft to medium firm soils as compared to CPTU (Sandven, R. et al., 2012).

However, given the fact that it is used extensively as a standard method in the practice, it is appealing to attempt to get more out of its measurements in an objective way and explore further extensions. Thus, this work is a preliminary attempt in that direction. The aim of this work is to quantitatively explore the potential of total sounding in soil classification, and evaluate its soundness against two classification methods based on CPTU. Laboratory data on physical and mechanical properties are used as references.

On this instance, it is worthwhile to mention that in Sweden Sofia W. (2010) correlated the penetration force of total sounding with tip resistance from CPTU in a simple manner, and proposed formulas for evaluating friction angle and elastic modulus out of the penetration force of total sounding.

2 SOME ASPECTS OF TOTAL SOUNDING

In principle, the soil firmness is a function of the penetration force. This concept is adopted in total sounding for a rough interpretation of soil types and layering. The limitations in accuracy of such use arise due to certain inherent aspects of the method such as where the penetration resistance measurements are performed, effect of friction along the rod and inclination of the drill.

Resistance is measured uphole (as opposed to at the tip such as CPTU). This means that all resistance in the system is included in the measured values, such as friction along the rods and resistance in the drill tower itself.

Water flushing is used to push the rod further down in firm layers as it reduces friction along the rods and drilling bit. However, it has been observed that, when flushing is enabled to penetrate through firm layers, it disturbs the relatively soft soil layers below, and gives recorded resistance much lower than in soils undisturbed by flushing. Thereafter, two similar soils may show different resistance depending on if flushing has been used above. It is also worthy to mention that under favourable soil condition the bore hole may not collapse and very limited friction could be expected (Fredriksen, F., 1997).

It is logical to assume that the total sounding results could be sensitive to change in rod direction while drilling. The drill tower direction may not be identical as the rod direction. This adds a lateral force to both the rod and the drill tower; and is often seen as abruptly increased resistance near the end of each 2-meter rod.

Considering the aforementioned aspects, one must take caution when interpreting results from total sounding.

It is well known by both geotechnical engineers and drilling operators that the fluctuations of the penetration force curve is descriptive of the coarseness of soil.

Penetration force is indicative but could be deceiving when used alone as forces may come from other places in the system than the tip. Therefore a preliminary study is initiated by analysing some existing data aiming to (1) explore more indicative parameters from total sounding results; (2) investigate where the total sounding results may be misleading or ambiguous; (3) investigate if a quantitative soil behaviour type chart can be made, in a similar fashion as to those extensively used with CPTU (Robertson 1998).

3 CURRENT PRACTICE

3.1 Equipment and procedure

The total sounding equipment consists of a 57 mm diameter rock drilling bit, connected to hollow 45 mm “geo-rods”. The drilling bit has a hole with a spring-loaded steel ball, for flushing. The penetration rate is kept at 3 m/min and rotation rate 25 rev./minute or 50-70 rev./minute when boulder or rock is met (NGF, 1994). An illustration is given in Figure 1.

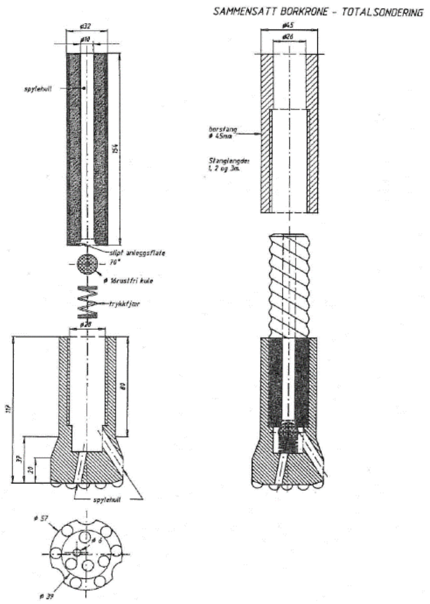

Figure 1 Total sounding drilling bit and rod (courtesy of NGF Pub. 9, 1994).

When encountering very firm layers, and penetration cannot be maintained at a desired rate, the operator can increase rotation rate. If this does not penetrate further hammering mode and flushing are enabled to facilitate drilling through firm soil or rock.

The total sounding system records the following data: depth (m), penetration force (kN), penetration rate in rock (sec/m), rotation rate (rev./sec), hammering and flushing (binary), flushing fluid pressure (kPa).

3.2 Interpretations of results

In Norway, the interpretations of total sounding results are done in accordance with Norsk Geoteknisk Forening (NGF) melding nr. 7 and nr. 9. However, considerable subjective judgement has to be involved. Smooth curves and low resistance indicate soft clays. Increasing fluctuations of the registration curve indicates larger fraction of coarse material. Also the overall trend of resistance force changing with depth gives an indication in relative stiffness. Sensitive soils have been observed to have a decreasing resistance with depth. Increased rotation rate indicates very firm soils and boulders. Enabled hammering together with recorded low resistance and constant low penetration rate imply the existence of bedrock, rather than boulders or very firm soils. Figure 2 shows a total sounding plot together with soil classifications.

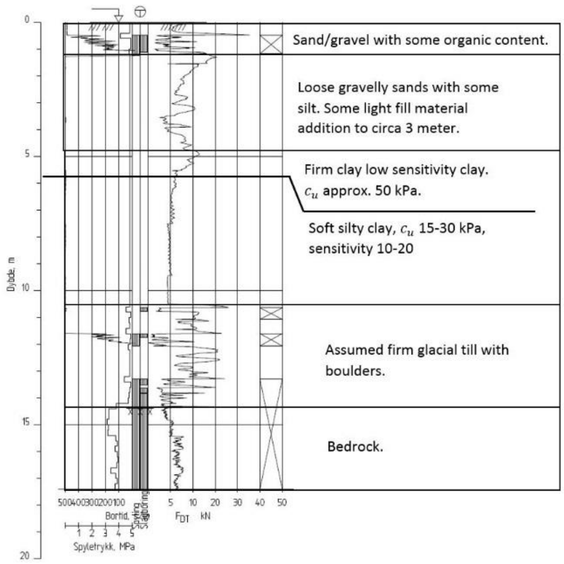

Figure 2 Example of a total sounding from Drammen. (Information of the first four layers are obtained from laboratory tests, while glacial till is speculated considering geological history of the site)

4 DATA SETS AND PROCESSING

4.1 Total sounding data

The total soundings, samplings and laboratory investigations carried out for road projects under the Norwegian Public Roads Administration (NPRA) Region South are used for study in this work. The data are gathered from 2011 to 2015 in counties Buskerud, Vestfold, Telemark and Aust-Agder. Figure 3 displays the geographic distribution of tests; number in circle indicates the number of data sets obtained from that site.

Cases where there has been no use of hammering, flushing and change of penetration rate have been chosen. Besides care was taken to include only data that are not close to rod changes, as abrupt resistance changes are often observed at those points.

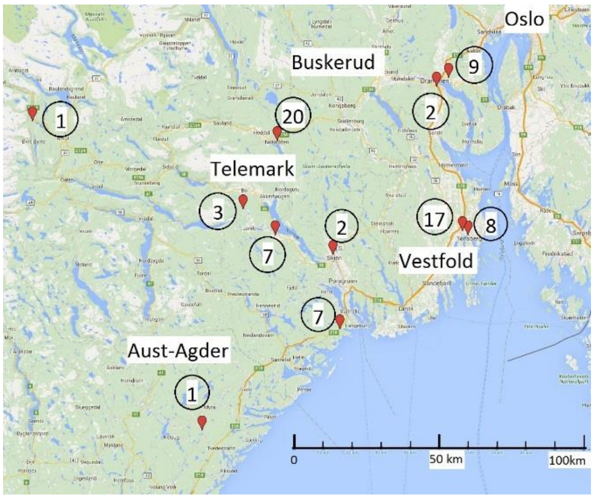

Figure 3 Geographic distribution of data sets (background map courtesy of Google.com).

4.2 Total sounding data processing

Analogous to CPTU, penetration force F_{dt} tends to increase with depth in most layers. For CPTU various normalization methods have been proposed to account for this influence as can be seen in work by Wroth (1984, 1988), Olsen (1984), Senneset and Janbu (1982), Douglas et al. (1985), Olsen and Farr (1986), Robertson (1989). In most of these approaches, the normalized cone resistance Q is computed by first subtracting overburden stress σ_{v0} from corrected tip resistance q_t and then dividing the remainder by the effective overburden stress σ'_{v0}. Sometimes different normalization methods and iterations are applied to account for different type of soil layers (e.g. Robertson, 2009). In that case Q is also dependent on sleeve friction f_s.

In current study, taking into account the available reading, a most straightforward normalization method has been adopted. Thus F_{dt} is first divided by σ'_{v0} and then divided by crossectional area of the drilling bit A to give the normalized pressure q_n as shown in Equation 1. Moreover, as soil unit weights and ground water level are only made available when laboratory investigations are performed and piezometer is installed, a uniform effective soil weight for all layers and ground water level at terrain surface are assumed to facilitate a fast interpretation right after total sounding is finished.

$$q_n = \frac{F_{dt}}{A \cdot \sigma'_{v0}} = \frac{F_{dt}}{A \cdot \gamma' \cdot z} \qquad (1)$$

where,

q_n is the normalized penetration pressure;

F_{dt} is the penetration force measured on the top of rod;

A is the cross-area of drilling bit, $A = 2.55 \times 10^{-3}\ m^2$;

σ'_{v0} is the effective overburden stress;

γ' is the average effective unit weight of penetrated soils (a value 8 kN/m^3 is taken for simplicity).

z is depth from terrain level.

The normalized penetration pressure q_n is further smoothened by a smoothening length then referred to as smoothened normalized penetration pressure and denoted as $q_{n,s}$. Besides, the gradient $dq_{n,s}/dz$ and the standard deviation of penetration force $std(F_{dt})$ within the smoothing length are also adopted. The fluctuation of penetration force F_{dt} instead of q_n or q_{ns} was found to offer better indication of soil grains composition.

A suitable length needed for smoothening q_n and calculating $dq_{n,s}/dz$ and $std(F_{dt})$ was chosen with these criteria met: (1) being small to keep resolution with depth; (2) including a reasonable amount of data in order to deliver stable results; (3) being robust for small changes of the length. In current study, 0.3 m appears to be suitable.

An example of the processed data is shown in Figure 4.

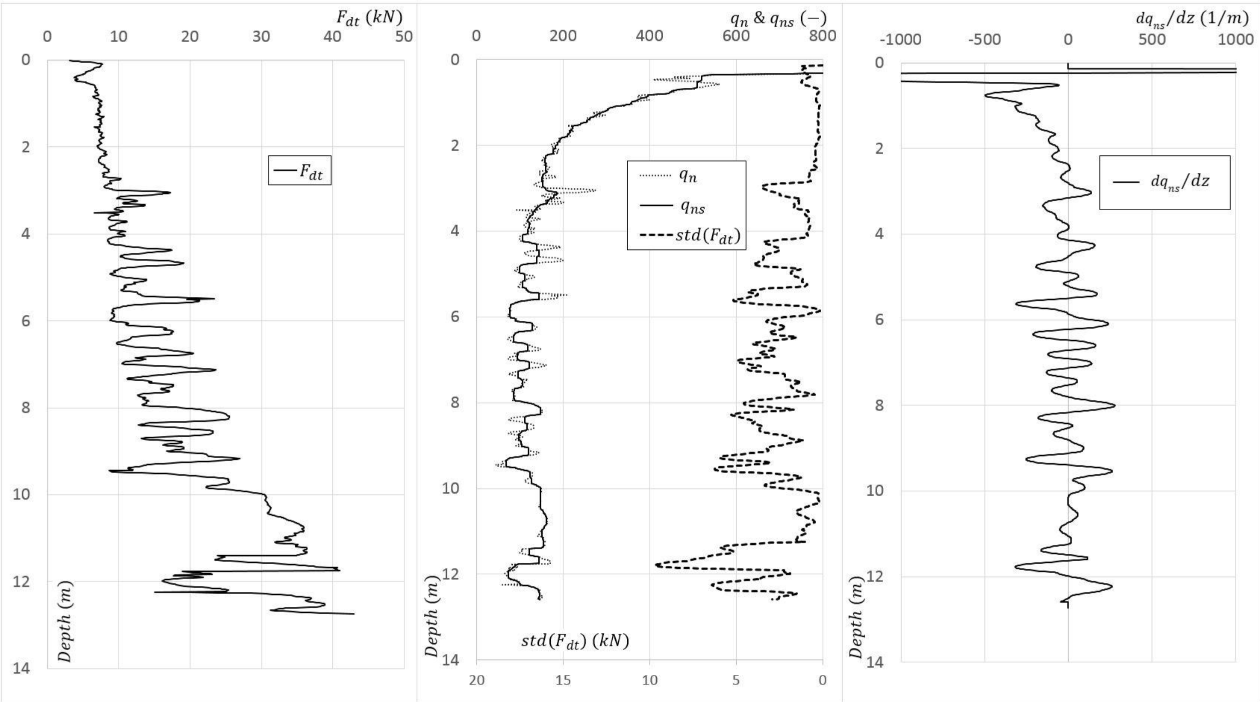

Figure 4 An example of processed data.

4.3 Laboratory data

Grain size analysis has been performed for the chosen sites, and later provides basis for soil classification. The undisturbed and remoulded shear strengths (c_u *and* c_{ur}) of fine-grained soils and subsequent sensitivity S_t were obtained from the falling cone tests.

5 RESULTS

5.1 Possible correlations among the parameters and soil fractions

In attempt to examine the dependence or independence of parameters q_{ns}, $dq_{n,s}/dz$ and $std(F_{dt})$, each two of them has been plotted below (Figure 5). In all three plots, most data points cluster near the origin and some others randomly farther distributed. No simple or decisive relationships could be identified.

An attempt has also been made to correlate the parameters q_{ns}, $dq_{n,s}/dz$, and $std(F_{dt})$ to grain size distribution in terms of fractions of sand or gravel (f_s), silt (f_{si}) and clay (f_c) by weight (Figure 6).

Having x-axis adapted in logarithmic scale, these three parameters fail to offer accurate predictions of soil type in terms of fractions of specific soil grains. Nevertheless, comparatively q_{ns} and $std(F_{dt})$ have demonstrated better convergence of data than $dq_{n,s}/dz$. Though considerable scattering exist, q_{ns} greater than 100 and $std(F_{dt})$ over 1.0 are likely to indicate sands or gravels.

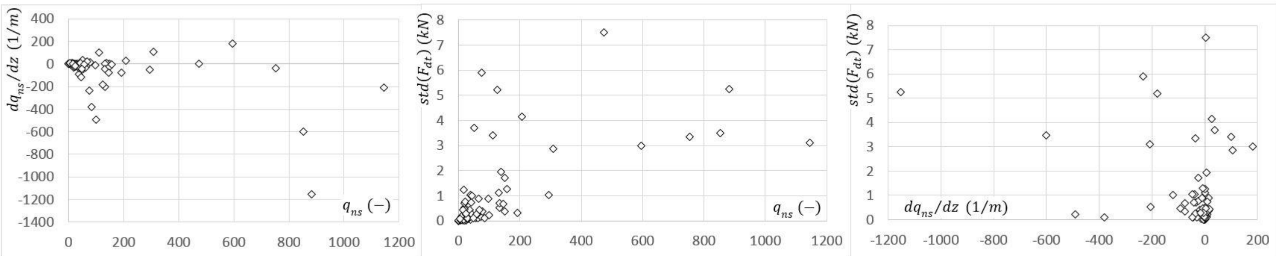

Figure 5 Correlations among q_{ns},$dq_{n,s}/dz$ *and* $std(F_{dt})$.

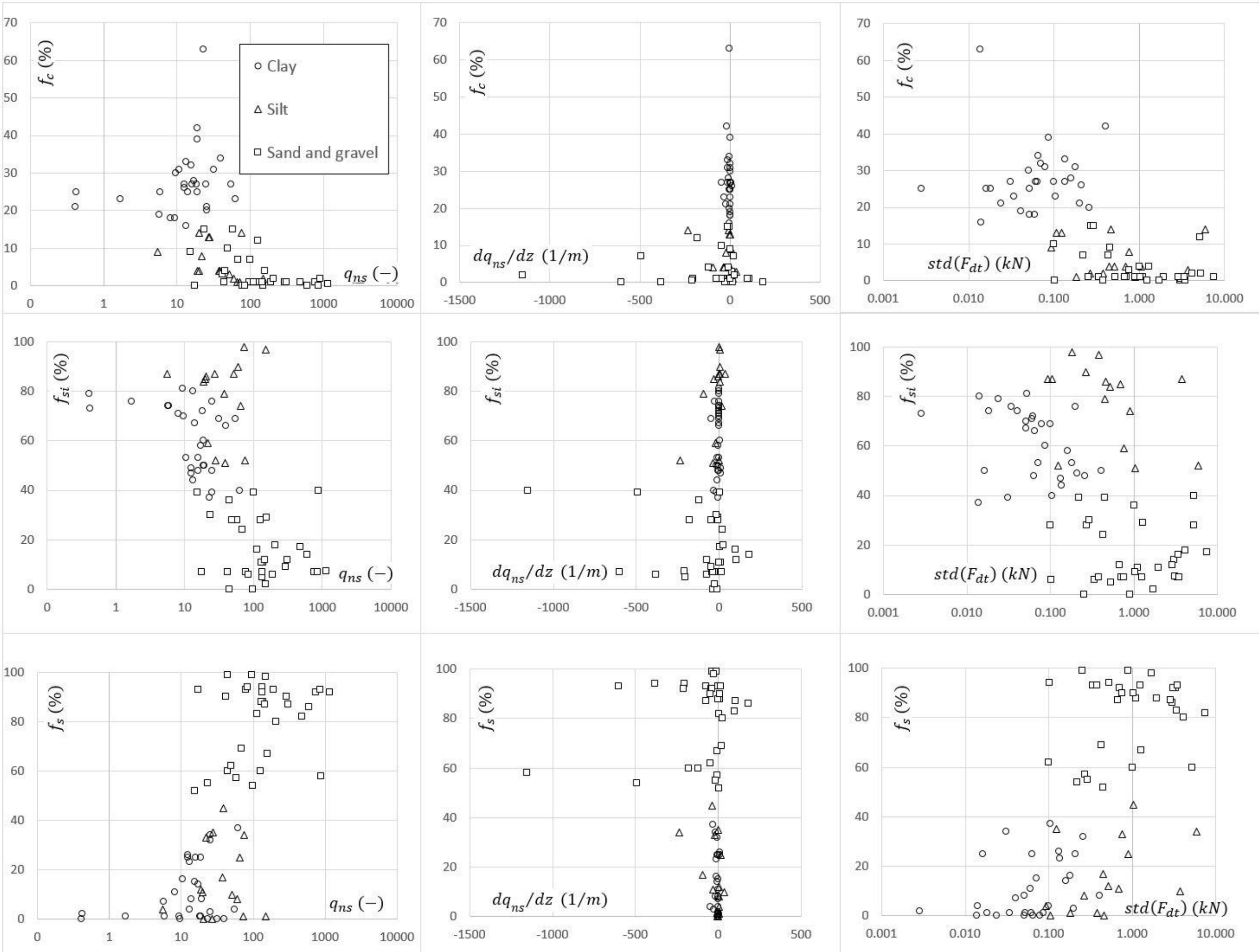

Figure 6 Correlations between q_{ns},$dq_{n,s}/dz$ and $std(F_{dt})$ and grain size distribution.

5.2 *Soil type chart*

The proposed classification is based on the mechanical response of soils, in a similar fashion as CPTU soil behaviour classification charts. The reference soils are classified by grain size analysis, which disregards several mechanical aspects such as friction angle, overconsolidation ratio (OCR) and water content. Despite this inconsistency, current classification based on grain size analysis is being regarded as identical to classification that incorporates comprehensive soil behaviours.

According to Figure 6, parameters $q_{n,s}$, $dq_{n,s}/dz$ and $std(F_{dt})$ cannot be expected to deliver accurate classifications of soil based on grain size distributions but offer a guide of soil behaviour type. Besides $q_{n,s}$ and $std(F_{dt})$ have demonstrated more distinctive relevances to soil type than $dq_{n,s}/dz$.

Having all data plotted against $q_{n,s}$ and $std(F_{dt})$ in Figure 7, the data points are found confined in a band in which $std(F_{dt})$ tends to increase with increasing $q_{n,s}$. Within the band, three zones as separated by shaded transition areas could be distinguished.

In the lower-left zone are all clay-type soils located though very few points of silt and sand can be seen near the boundary. In case of specific soil type, clays cluster closely, while silty sandy clays and silty clays distribute sparsely. In the transition area between clay and silt, a handful of all three general types of soil exist.

The zone to the upper-right is dominated by sand-type soils with one exception of silt. Manifested by gravely sand, data sets in this zone are highly scattered if plotted with linear x-axis.

Another zone confined in the middle sees the majority of silts, but also have considerable number of sandy soils randomly mixed.

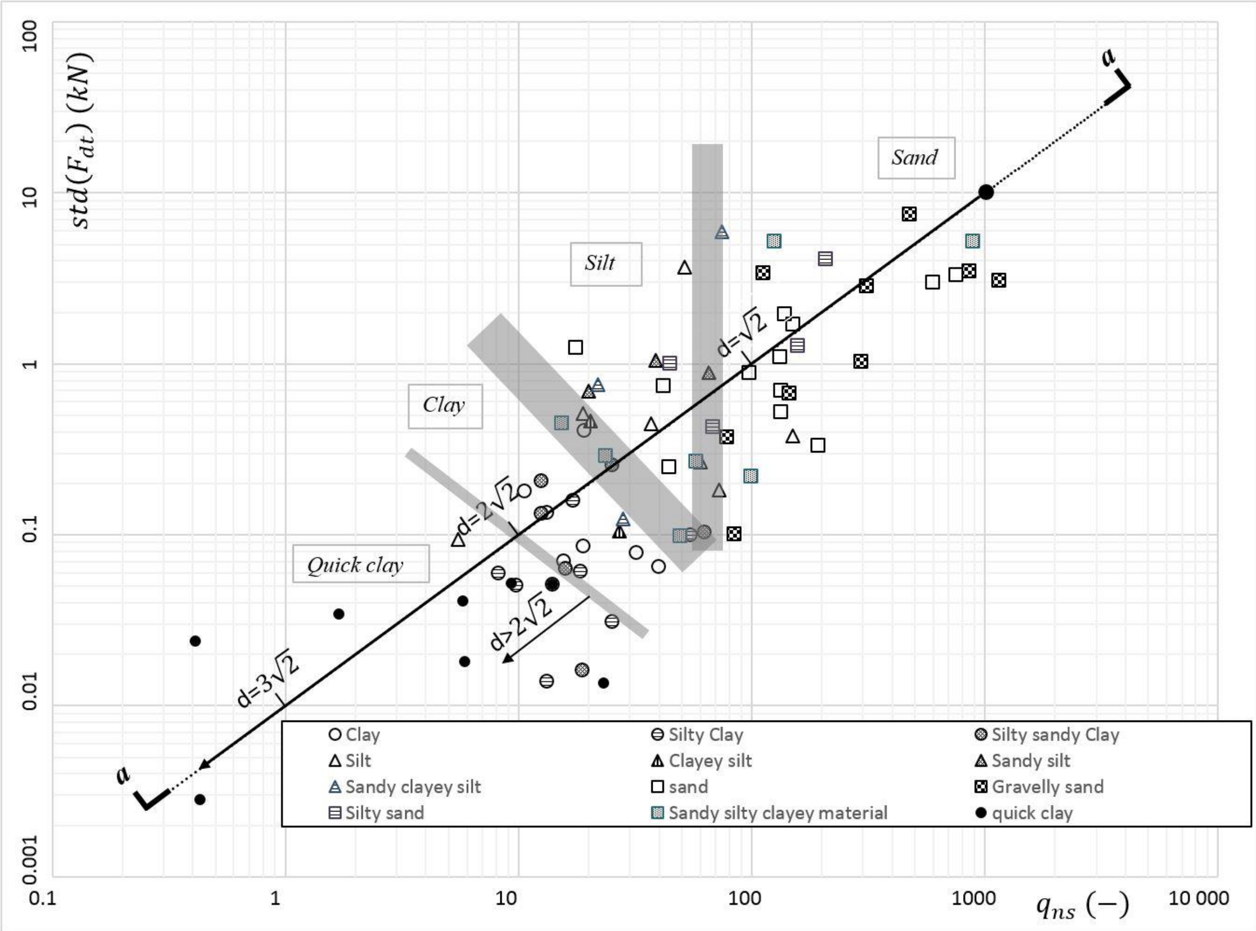

Figure 7 Soil behaviour type chart.

One of the most important soil parameters that has been studied in connection of CPTU interpretation is the undrained shear strength of soils (c_u) (Kjekstad et al. 1978; Lunne and Kleven 1981: Aas et al.1986; and Senneset et al. 1982, and Karlsrud et al., 2005). A common trend with these extensive studies is that there exists a correlation between c_u and excess pore pressure Δu or corrected cone resistance q_t. In present study of total sounding the relevances of remoulded undrained shear strength c_{ur} and sensitivity S_t to parameters $q_{n,s}$ and $std(F_{dt})$ were also explored.

Inspired by the soil behaviour type index I_c introduced by Robertson (1998), which behaves as radius and delineates the boundaries of soil behaviour type zones, and the fact that all present data points congregate in a band, it becomes natural to study the trend of c_{ur} and S_t along the band. Therefore a line (a-a) going through the data points is chosen and defined in equation 2. Later these points are projected to line a-a, and distances are measured starting from a reference point (1000, 10) to the projected points. Then the S_t and c_{ur} information mainly of clay-type soils are plotted against their projection distance d_p (Equation 3) as shown in Figure 8.

$$\log\big(std(F_{dt})\big) = \log(q_{ns}) - 2 \qquad (2)$$

$$d_p = \sqrt{\left[\log\left(\frac{q_{ns}}{1000}\right)\right]^2 + \left[\log\left(\frac{std(F_{dt})}{10}\right)\right]^2 - 0.5\left[\log\left(\frac{q_{ns}}{100 std(F_{dt})}\right)\right]^2} \qquad (3)$$

It can be seen that S_t rises with increased d_p while c_{ur} is inclined to decrease. In spite of considerable scattering, $d_p > 2\sqrt{2}$ is potentially to suggest the existence of quick clay, which requires $S_t > 30$ and $c_{ur} < 0.5\ kPa$.

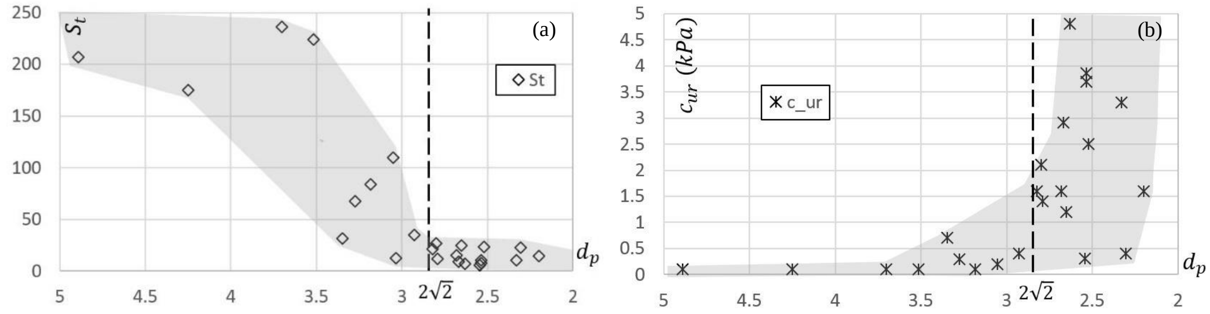

Figure 8 Sensitivity (a) and remoulded shear strength (b) on projection line a-a (in Figure 7).

6 EVALUATION AND COMPARISON

6.1 Evaluation based on employed data

Soil type zones in the proposed chart are examined against all data points that were employed in producing this chart in Figure 7. Results are shown in Table 1. Values in every row explain the fact that the number of data points of each soil type decided by grain size analysis is distributed over multiple zones of the chart. Underlined numbers in the table signify the dominance of good or acceptable correspondence, and thus sound predictions.

Compared with current practice of total sounding interpretation, this chart provides more insights into soil types. The major advantages are summarised as:

- Clay-type soils could be differentiated from silts, which is difficult before performing laboratory tests as only penetration force is interpreted in current practice.
- One could imply the existence of sand or gravel type soils with considerable confidence if data points lie in the upper-right zone.
- It turns out to be ambivalent when silt or mixture of silt and sand are encountered.
- Identification of quick clay is made promising when d_p is found exceeding $2\sqrt{2}$.

However, as the analysed database is not sufficiently large, the boundaries of zones could be altered, and the specific areas for transitional soil types could be delineated after the inclusion of more data.

Table 1 Evaluation of the soundness of the proposed chart.

results from laboratory	predicted results by present study					
	sand or gravelly sand	transition sand-silt	silt	transition silt-clay	clay	quick clay
gravelly sand	9	2				
sand	8	1	3	1		
silty sand	2	3	1			
sandy silty clayey material	2	1	1	3		
sandy silt	1	2				
sandy clayey silt		1	1	3		
silt	1	1	3	1	1	
clayey silt				1	1	
silty sandy clay				2	4	
silty clay				1	2	5
clay			1	1	10	
quick clay*						8

* silty clays that behaviour as quick clay are counted here.

6.2 Comparison with other classification methods

Site investigations performed in five sites that involve both total sounding and CPTU, together with laboratory test results makes it possible to evaluate the accuracy of the predictions of present chart against several other classifications.

The soil behaviour type chart proposed by Robertson (1998, 2009) and the classification method developed in Swedish Geotechnical Institute (SGI) (Larsson, R., 2007) are adopted for comparison. In the chart by Robertson, the normalized tip resistance Q_m, the normalized friction F_r and the soil behaviour type index I_c altogether define 9 soil behaviour type zones. Using similar parameters $(q_t - \sigma_{v0})/\sigma'_{v0}$ and $f_t/(q_t - \sigma_{v0})$, SGI's chart characterizes three general soil types: clay/organic soil, silt and sand. As for silt and sand, plural subtypes are defined in light of varying firmness, which fact makes itself distinct from Robertson's chart.

Table 2 Comparison with other classification methods

site	depth (m)	q_{ns} $(-)$	$std(F_{dt})$ (kN)	soil type: based on Lab. investigation	soil type: based on total sounding: present study	soil type: based on CPTU: Robertson (1998, 2009)	soil type: based on CPTU: SGI method
Fv32 Gimlevegen – Augestadvegen. Hovenga borehole 101	3.2-4.0	46.69	1.42	sand	silt	sand/silty sand	silt/sand
	5.2-6.0	19.73	0.31	sand	silty clay/clayey silt	silt/clayey silt	clay
	9.2-10 .0	13.18	0.41	clayey sandy silt	silty clay/clay	silt/clayey silt	silt
	16.2-17.0	6.67	1.10	clayey sandy silt (quick)	silty clay/clayey silt	sensitive soil	clay
	29.2-30.0	3.85	0.60	silty clay (quick)	clay	clay	clay
	38.2-39.0	8.73	5.08	silty clay	silt		
Fv415 Ubergsmoen borehole 1002	2.0-3.0	59.79	0.63	sand (humus)	silty sand/sandy silt	sand/silty sand	silt
	4.0-5.0	245.63	4.47	gravelly sand	sand		
	6.0-7.0	145.21	2.55	gravelly sand	sand		
Fv308 Kjelle-Barkåker borehole 1104	7.2-8.0	14.05	0.39	silty clay	clay/silty clay	clay/silty clay	clay
	8.2- 9.0	11.94	0.08	clay	clay	clay/silty clay	clay
	9.2- 10.0	12.74	0.37	clay	clay	clay/silty clay	clay
E 18 Skjeggestad bru, borehole b2	5.0- 5.8	52.15	0.28	silty clay	silt	silt/clayey silt	silty clay
	7.0- 7.8	37.30	0.69	silty clay	silt	clay	clay
	10.0- 10.8	36.03	0.17	clay	silty clay/clayey silt	clay	clay
E 18 Skjeggestad bru, borehole G5	2.2- 3.0	23.39	0.10	silty clay	clay	clay	clay
	5.2- 6.0	11.65	0.11	clay	clay	clay	clay
	9.2- 10.0	10.33	0.24	silty clay	clay	quick clay	clay
	11.2-12.0	9.77	0.37	quick clay	clay	quick clay	clay

Through comparison (Table 2), some significances could be drawn as below.

- Compared with laboratory results, present predictions exhibit satisfactory consistency and accuracy.
- Present method is capable of predicting more soil types as the drilling bit is adaptive in penetrating through firm materials such as gravels and boulders, while the penetrometer of CPTU sounding is highly susceptive to coarse and firm soils.
- Deviation of prediction by present method is more noticeable when data points fall into the zone of silt.
- Predictions of present study seem to closely resemble the results by classification chart of Robertson (1998, 2009).

7 CONCLUSIONS

In this study, a preliminary normalization method to account for depth influence is introduced for penetration force of total sounding. Later the normalized penetration pressure and the standard deviation of penetration force were applied in bringing a new soil classification chart in which the separation of four general soil types are made prominent. However, noticeable ambiguity remains in determining detailed soil type especially when silt is involved.

Facilitated by the projection distance, sensitivity and remoulded shear strength of clays are found to demonstrate distinct trends along the data points band. A threshold is thus made possible to identify the presence of quick clay. Nevertheless, extensive data points are needed to improve the proposed classification chart. Through comparison with two CPTU-based classification methods, present classification is proved to be satisfactorily consistent and accurate.

By far factors like sleeve friction, inclination of rods have not been taken into considerations. And ground water level and soil unit weights have been assumed for the sake of simplicity. Additionally, the soil types referred merely express the grain size distributions; other essential information like the mechanical properties, void ratio or OCR were not incorporated.

Regarding the future work, extensive study can be foreseen. For instance, the effects of recording penetration force and torque at the tip could be explored. Also the drilling rate of total sounding could be tuned the same as CPTU in order to extract certain correlation between the two, and enable the predictions of soil unit weight, friction angle and deformation characteristics out of total sounding.

Considering that data of this study has been collected in the south region of Norway, great caution should also be paid when the chart is to be used in other areas.

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