Effect of drainage conditions on cone penetration testing in silty soils

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ABSTRACT
This paper discusses the challenges that occur when performing Cone Penetration Tests (CPT) in silty soil due to changes in drainage conditions. In this paper, CPT results from various papers and researchers are collected and interpreted. Results from cone penetrations tests with various penetration rates is analysed, and it is shown how the changes in drainage condition, caused by the change in penetration rate, affects the plot in the soil classification charts. In addition, the effect on changes in penetration rate is compared for clay and silt, respectively, where the silty soil is more susceptible towards change in penetration rate. A normalized penetration rate is implemented in order to compare various cone resistance results, and hence investigate the changes from undrained to partially drained and from partially drained to fully drained.

PRESENTACIONES TÉCNICAS
En este artículo son discutidas las dificultades que ocurren cuando se llevan a cabo Ensayos de Penetración Cónica (CPT) en suelos limosos debido a cambios en las condiciones de drenado. Los resultados de los Ensayos de Penetración Cónica de otros artículos e investigadores son recopilados e interpretados. Resultados de CPT's con varias velocidades de penetración son analizados y se muestra como los cambios en las condiciones de drenado causados por el cambio en el la velocidad de penetración afecta el diagrama en la clasificación del suelo. Adicionalmente, el efecto del cambio de la velocidad de penetración es comparado para arcilla y limos respectivamente, donde los suelos limosos son más susceptibles a cambios en la velocidad de penetración. Una velocidad de penetración normalizada es implementada con el fin de comparar varios resultados de resistencia del cono y así investigar los cambios de no-drenado a parcialmente drenado y de parcialmente drenado a completamente drenado.

1 INTRODUCTION

For several years Cone Penetration Test (CPT) has been widely used to determine soil classification and estimating geotechnical parameters. The cone is pushed into the ground at a constant rate while the cone resistance, sleeve friction and pore pressure are measured. The standard rate of penetration is 20 mm/s, and it is generally accepted that undrained penetration occurs in clay while drained penetration occurs in sand. In practice, CPT interpretations are based on empirical correlations between soil properties and CPT measurements (Lunne et al. 1997).

In intermediate soils, such as silty soils, standard cone penetration may vary from undrained to partially or fully drained conditions. This means that use of standard correlations developed for clean sand or clay will not work for soils where penetration takes place under partially drained conditions. This is why the behaviour of silt often is considered to be close to that of clean clays or sands, depending on its grain size distribution and clay content.

If the drainage condition in the design problem involves undrained loading, the cone penetration will presumably also be undrained, and the interpretation of the soil strength can be conducted in terms of undrained shear strength. Most design problems however, occur as drained in large time scales, which makes the soil strength interpretation more difficult in case the cone penetration process is partially drained or undrained.

Drainage conditions during cone penetration are mainly dependent of soil permeability and compressibility properties (Silva and Bolton 2005). According to several researchers (Lehane et al. 2009, Kim et al. 2008, Schneider et al. 2008, Chung et al. 2006, Silva and Bolton 2005, House et al. 2001) penetration rate also affects the drainage condition and the value of the cone resistance. The lower the penetration rate is, the more fully drained the penetration is and the higher the cone resistance becomes. In addition, at high rates of penetration the penetration is fully undrained and the cone resistance also increases due to viscous effects (Chung et al. 2006, House et al. 2001). However, the fact that the penetration rate affects the cone resistance, and hence the soil strength, was not taken into account at the time the CPT interpretations standards were developed.

In this paper a study on how the drainage condition affects the interpretation in silty soils will be given. The study will be given based on data collected from various papers and researchers which are subsequently processed by the author.

2 CLASSIFICATION OF SILTY SOIL ACCORDING TO CURRENT STANDARDS

Silt is well known as a soil that has a grain size that lies between clay and sand. However, to specify the exact classification of the silty soil is often difficult because the silt rarely is uniform.

When classifying soil, it is important to distinguish between different methods. In many parts of the world, the system called "Unified Soil Classification System"

(ASTM 2010) is used. This method bases the classification on the Atterberg Limits. According to ASTM (2010), silt is defined as soil passing the 75 µm sieve with a plasticity index, I_p, less than 4 % or if the plot of plasticity index versus liquid limit falls below the “A” line. Identifying silt according to the ASTM (2010) is complicated since in practice it is very difficult to determine the Atterberg Limits on silt. In addition, the ASTM (2010) does not describe how to distinguish between clayed silt and silty clay since the sub-classification is given in terms of percentages of soil mass retained on the 75 µm sieve, and not on the actual clay content, wherefore “clayed silt” does not exist according to the ASTM (2010).

Besides the ASTM standard, ISO 14688-1 (2002) is widely used. According to the ISO 14688-1 (2002), silt is defined as soil with a particle size between 63 µm and 2 µm. The classification of sand is based on the soil fraction predominating in terms of mass. For clay and silt, the classification is based on dry strength, dilatancy and plasticity. However, the classification is not evident but based on an individual estimation. In addition, the ISO 14688-1 (2002) does not describe how to distinguish between silty sand and sandy silt. For that reason, identifying silt according to the ISO 14688-1 (2002) is also very difficult.

From the above-mentioned, it is important to be aware that soil classified as silt in some parts of the world not necessarily classifies as silt in other parts. In addition, the classification is defined by a geological point of view and not geotechnical. This difference in classification can be important when interpreting CPT measurements. Therefore, there may be a need for another way to define the silt.

To avoid too many different and indefinable definitions, the silt will, in this paper, be classified in terms of percentages of sand, silt and clay. The soil is assumed to be classified as silt according to the percentages that can be seen in Table 1.

Table 1. The assumed classification of silt in terms of percentages of sand, silt and clay.

Soil type	Sand (%)	Silt (%)	Clay (%)
Silty sand	90-95	5-10	0
Sandy silt	10-25	75-90	0-5
Silt	0-10	80-100	0-10
Clayed silt	0-10	70-90	10-20
Silty clay	0-5	45-80	20-40

3 EFFECT OF PENETRATION RATE IN SATURATED SILTY SOILS

The standard rate of penetration is, regardless of soil type, 20 mm/s. Although the standard rate is 20 mm/s, the penetration is rarely constant due to soil inhomogeneity. Depending on the soil type, the penetration rate has a range of ±20 mm/s. An example of the variation of penetration rate is shown in Figure 1.

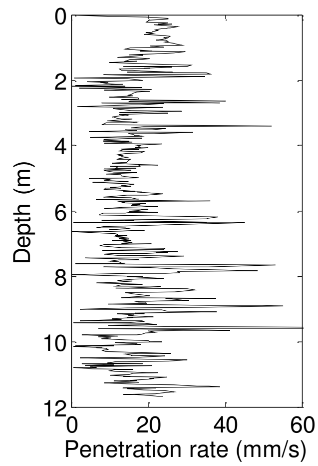

Figure 1. Range of penetration rate during CPT testing.

For sandy soil, this has no effect on the cone resistance since the penetration rate must be unrealistically high in relation to what is practically possible for causing partially drained penetration. Similarly, the penetration rate should be very low for clean clay to result in partially drained penetration. For soils consisting of silt particles, the standard penetration, however, may take place under partially drained conditions within the range of penetration rate.

When the penetration changes from undrained to drained, the cone resistance in normally consolidated soils increases by approximately three (House et al. 2001) to ten times (McNeilan and Bugno 1985).

3.1 Soil Classification

An advantage when using the Cone Penetration Test is the ability to classify the soil in situ without requirement of a laboratory test. However, the soil is then classified in terms of soil behaviour hence the measurements of cone resistance, q_t, sleeve friction, f_s, and pore pressure, u_2. The most widely used soil behaviour classification charts are developed by Robertson et al. (1986) by using q_t, B_q and R_f, where B_q and R_f is given by Equation 1 and Equation 2:

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \quad [1]$$

$$R_f = \frac{f_s}{q_t} \cdot 100\% \quad [2]$$

Because the classification charts were based on data obtained from CPT to depths less than 30 m, Robertson (1990) developed new classification charts by using normalized parameters, Q_t, B_q and F_r, where Q_t and F_r is given by Equation 3 and Equation 4:

$$Q_t=\frac{q_t-\sigma_{v0}}{\sigma'_{v0}} \quad [3]$$

$$F_r=\frac{f_s}{q_t-\sigma_{v0}}\cdot 100\% \quad [4]$$

According to Robertson (1990), the soil classifies as sandy silt to clayed silt when the pore pressure parameter, B_q, has a value between -0.4 and 0.5, a normalized friction ratio, F_r, between 0.3 and 5 % and a normalized cone resistance, Q_t, between 5 and 70.

The soil behaviour classification charts developed by Robertson (1990) are the most commonly used. However, these charts do not take the significance of the penetration rate into account. Kim et al. (2006) tested the influence of penetration rate at two test sites. In one of the test sites, located on State Road (SR) 18 in Carroll County, Indiana, Kim et al. (2006) conducted CPTs with different penetration rates in two layers. A description of the two layers at the test site is shown in Table 2.

Table 2. Description of Test Site (SR 18). Data from Kim et al. (2006).

	Layer 1	Layer 2
Depth (m)	7.4-8.4	9.2-10.2
CPT rates (mm/s)	20, 3, 1, 0.2, 0.05	20, 1, 0.2, 0.1, 0.05
Clay (%)	24.0	11.1
Silt (%)	71.5	76.8
Soil classification	Silty CLAY	Clayed SILT
$c_v \cdot 10^{-6}$ (m^2/s)	0.467	5.82

The CPT results from Kim et al. (2006) plotted in the classification charts can be seen in Figure 2 and Figure 3. Zones 2 to 6 have been zoomed in on so as to make the results clearer. The results are only plotted in the B_q, Q_t chart since the sleeve friction does not give consistent results during cone penetration (Lunne et al. 1997). The matching soil behaviour type can be seen in Table 3.

The figures shows the influence of penetration rate when the penetration becomes partially drained. Layer 1 (Figure 2) is according to the chart (Robertson 1990) classified as clay for a penetration rate of 20 to 0.2 mm/s. However, when the penetration rate drops to 0.05 mm/s, the penetration becomes partially drained and the soil can be classified as clayed silt to silty clay. For layer 2 (Figure 3), the transition from undrained to partially drained occurs between a penetration rate of 1 and 0.2 mm/s. When the penetration rate drops to 0.05 mm/s, the soil is almost classified as silty sand to sandy silt. Furthermore, the figures illustrate that the clayed silt (Layer 2) is more susceptible to changes in penetration rate given that the transition from undrained to partially drained occurs within a smaller change in penetration rate.

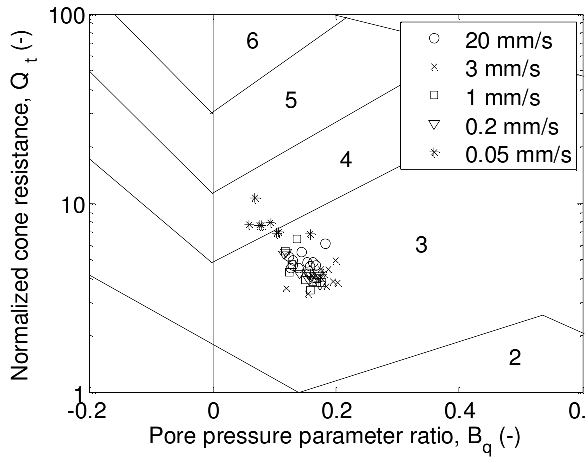

Figure 2. Location of Layer 1 – Silty CLAY on soil classification. Data from Kim et al. (2006).

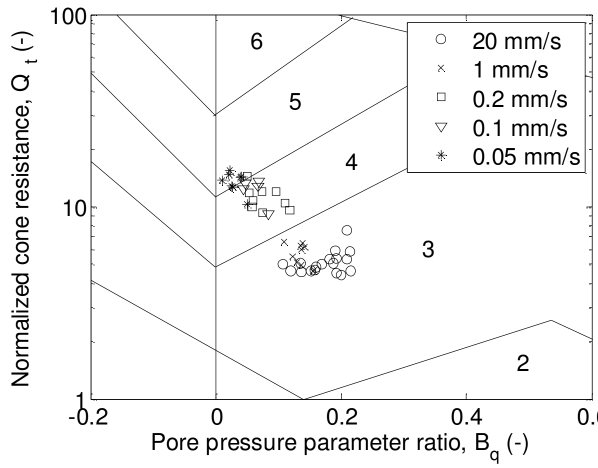

Figure 3. Location of Layer 2 – Clayed SILT on soil classification. Data from Kim et al. (2006).

Table 3. Soil behaviour type corresponding to the zones in the soil classification charts. Robertson (1990).

Zone	Soil behaviour type
2	Organic soils-peats
3	Clays-clay to silty clay
4	Silt mixtures; clayey silt to silty clay
5	Sand mixtures; silty sand to sandy silt
6	Sands; clean sands to silty sands

Kim et al. (2006) also conducted oedometer tests, to estimate c_v for the two layers, which can be seen in Table 2. The fact that c_v is smaller for layer 1 than layer 2 also emphasizes that the change in drainage condition is observed for a lower penetration rate than for layer 2.

3.2 Variation of q_t, u_2 and f_s with penetration rate

The simplest way to examine whether the penetration is undrained, partially drained or fully drained, is by plotting the cone resistance, sleeve friction and pore pressure against the penetration rate. The effect of the penetration rate on q_t for the two layers is shown in Figure 4.

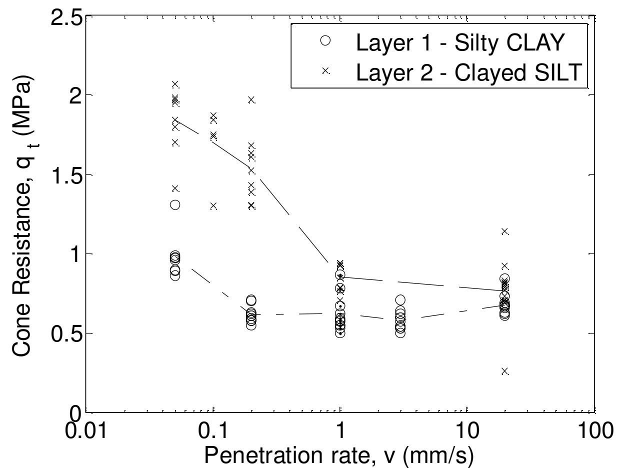

Figure 4. Effect of penetration rate on q_t. Data from Kim et al. (2006).

The figure shows how the cone resistance is dependent on the penetration rate, and hence the drainage condition. For layer 2, the cone resistance is almost constant for a penetration rate between 20 and 1 mm/s, whereas for a penetration rate below 1 mm/s, the cone resistance increases significantly due to change in drainage conditions. For layer 1, however, the cone resistance is constant for a penetration rate between 3 and 0.2 mm/s, while only a small increase in cone resistance is seen for a penetration rate below 0.2 mm/s. For a penetration rate above 2 mm/s, the cone resistance also increases due to viscous effects. Cone resistance is directly related to the undrained shear strength, which increases with increasing loading rate (Chung et al. 2006, House et al. 2001, Roy et al. 1982).

Considering the change in cone resistance (Figure 4), the transition from undrained to partially drained occurs at a penetration rate of 0.2 mm/s for layer 1 and 1 mm/s for layer 2, which is in accordance with the results shown in Figure 2 and Figure 3. This emphasizes that the change in drainage condition is dependent on the soil type, and that silt is more susceptible towards changes in penetration rate. The effect on penetration rate on the pore pressure, u_2, and sleeve friction, f_s, is shown in Figure 5 and Figure 6. Once again, the clayed silt is more susceptible to changes in penetration rate. For the silty clay, the pore pressure is almost constant at a penetration rate form 20 mm/s to 0.2 mm/s, after which the pore pressure drops indicating incipient drainage. For the clayed silt, however, the drainage begins at a penetration rate of 1 mm/s. According to Lunne et al. (1997) the sleeve friction does not give consistent results during cone penetration. In Figure 6, it seems like a correlation exists between the sleeve friction and penetration rate for the clayed silt layer. However, Figure 4 and Figure 5 indicate that the transition from undrained to partially drained occur between a penetration rate of 20 and 1 mm/s, which is not the case for the sleeve friction in Figure 6.

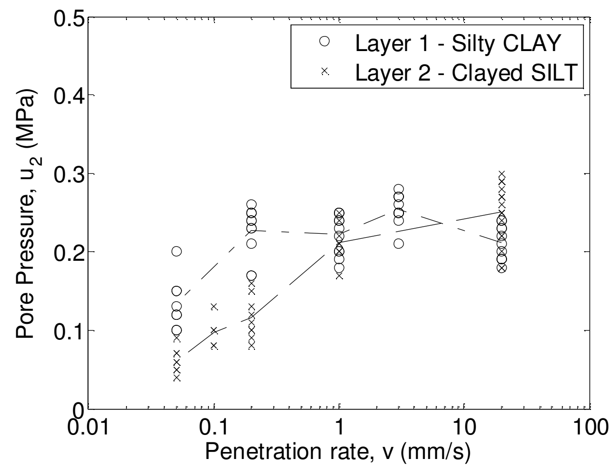

Figure 5. Effect of penetration rate on u_2. Data from Kim et al. (2006).

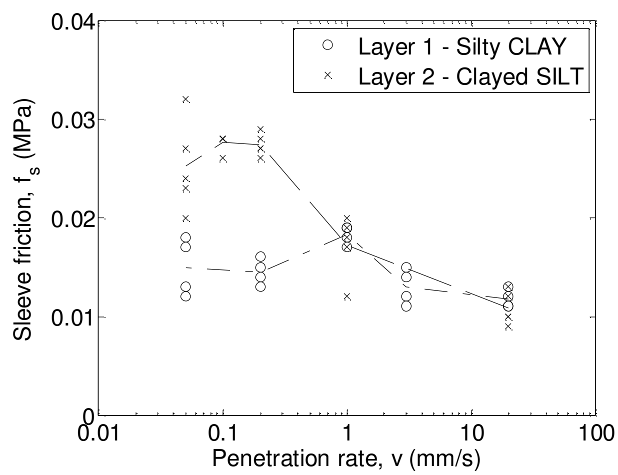

Figure 6. Effect of penetration rate on f_s. Data from Kim et al. (2006).

3.3 Normalized penetration rate

Data from different soils and with various cone diameters may be compared by using a non-dimensional/normalized penetration rate defined by Finnie and Randolph (1994) and House et al. (2001) given in Equation 5:

$$V=\frac{v\cdot d}{c_v} \qquad [5]$$

where v is the cone velocity, d is the cone diameter, and c_v is the coefficient of consolidation. The expression using the normalized penetration rate is nevertheless mostly used for clayed soils. Figure 7 shows the cone and T-bar resistance normalized with respect to the minimum resistance q_{min} (undrained resistance) measured in centrifuge tests (House et al. 2001, Chung et al. 2006).

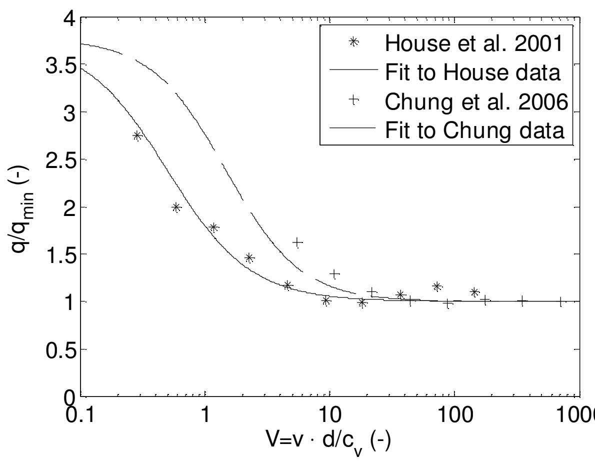

Figure 7. Effect on normalized penetration rate on T-bar resistance (House et al. 2001) and cone resistance (Chung et al. 2006).

The T-bar penetrometer is a "full-flow" device which has an end area that is much larger than that of the cone. It is often used in very soft sediments found offshore, because it should provide the basis for obtaining absolute estimates of the shear strength directly from the measured penetration resistance (Lehane et al. 2009, Randolph et al. 2005). The failure mode is different for the T-bar and cone, for which reason the transition from undrained to drained cannot be directly compared. However, the T-bar resistance can still be used to show the tendency.

Centrifuge tests conducted by Randolph and Hope (2004) show a similar tendency. The data in Figure 7 is fitted by the expression given in Equation 6 (Chung et al. 2006):

$$\frac{q}{q_{ref}} = a + \frac{b}{1 + c \cdot V^m} \qquad [6]$$

where q is the bearing resistance at any rate, q_{ref} is a reference bearing resistance equivalent to an undrained resistance, V is the normalized penetration rate, and a, b, c and m are constant. The value of the constant for the fitted data in Figure 7 is shown in Table 4.

Table 4. Constants derived from the fitted data. (House et al. 2001, Chung et al. 2006).

Characteristics	*a*	*b*	*c*	*m*
T-bar: House et al. 2001	1.00	2.77	2.47	1.30
Cone: Chung et al. 2006	1.00	2.77	0.57	1.45

When normalising the bearing resistance by a reference resistance corresponding to fully undrained, the sum of a and b can be considered as the ratio of drained to undrained resistance. For silt, however, it is difficult to be certain that the minimum reference resistance corresponds to fully undrained condition, particularly when conducting penetration test in the field. In addition, choosing the resistance equivalent to the lowest penetration rate can result in using a bearing resistance affected by viscose effects. The bearing resistance results in Figure 7 are, furthermore, obtained from centrifuge tests, which often are associated with scaling errors, e.g. particle size scale effects (Taylor 1995). It, therefore, questions the centrifuge tests comparability to cone penetrations tests in the field.

The field cone resistance results from Kim et al. (2006) normalized by the initial vertical effective stress, σ'_{v0}, are shown in Figure 8.

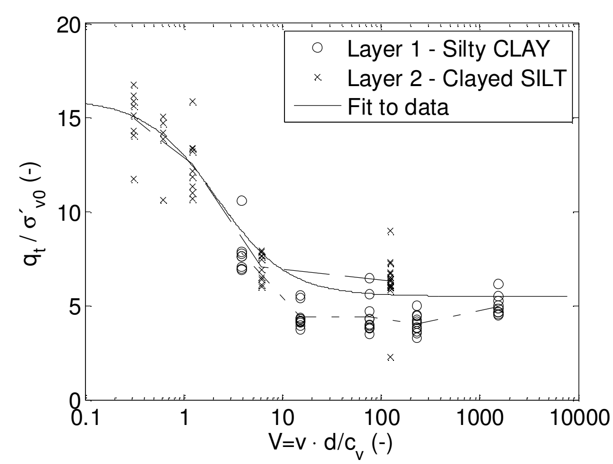

Figure 8. Variation of normalized cone resistance versus normalized penetration rate. Data from Kim et al. (2006).

When normalizing the cone resistance by the initial vertical effective stress, the two layers are coinciding. In practice, it is also simpler to normalize the data by the effective stress. The data are fitted to equation 6, with the constants a = 5.5, b = 10.5, c = 0.4, and m = 1.2. The curves in Figure 8 show that the transition from undrained to partially drained, occurs at a normalized penetration rate at V=15. Figure 9 shows the excess pore pressure normalized by the initial vertical effective stress versus the normalized penetration rate. The data can be approximated reasonably to two linear lines. The figure emphasize that the transition from undrained to partially drained occur at V=15.

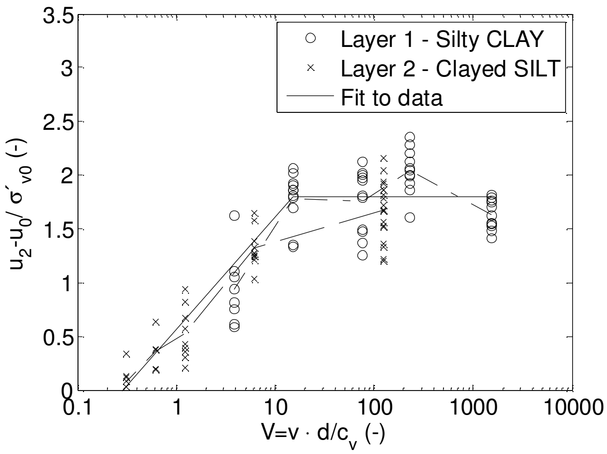

Figure 9. Variation of normalized excess pore pressure versus normalized penetration rate. Data from Kim et al. (2006).

3.4 Drained or undrained

Some researchers have given an estimate on when the penetration changes from undrained to drained. However, most of the research has been conducted on clayed soil. Kim et al. (2008) stated that with a standard cone diameter at 35.7 mm and standard penetration rate at 20 mm/s, the penetration is considered to be undrained for a $c_v < 7.1 \cdot 10^{-5}$ m^2/s, and drained for a $c_v > 1.4 \cdot 10^{-2}$ m^2/s. The transition from undrained to drained is also given in terms of permeability, *k*, where undrained penetration occur for $k < 10^{-9}$ - 10^{-8} m/s, and drained penetration occur for $k > 10^{-6}$ - 10^{-5} m/s (McNeilan and Bugno 1985). Most researchers have listed the transition from undrained to drained in terms of the normalized penetration rate, *V*, which can be seen in Table 5 for the cone, and Table 6 for the T-bar.

Table 5. Transition from undrained to drained for cone.

Undrained	Drained	Test type	Reference
V>30	V<0.01	Centrifuge	Finnie and Randolph (1994)
V>30	-	Centrifuge	Randolph and Hope (2004)
V>30	-	In situ	Kim et al. (2008)
V>10	V<0.05	Calibration chamber	Kim et al. (2008)

Table 6. Transition from undrained to drained for T-bar.

Undrained	Drained	Test type	Reference
V>10	V<0.1	Centrifuge	House et al. (2001)
V>10	-	Centrifuge	Randolph and Hope (2004)
V>3-12	V<0.05	Centrifuge	Lehane et al. (2009)

The transition from undrained to drained condition is almost identical for the T-bar. However, for the cone there is some disagreement. The main reason for this difference is the test type. The majority of the tests are conducted in a centrifuge, which almost gives identical results. In addition, Table 5 shows that further research on in situ test is needed to clarify the transition from undrained to drained penetration. In general, there is an agreement that the penetration rate is of great importance to the drainage condition. Figure 10 shows a schematic diagram of the influence of the penetration rate on normalized cone resistance and pore pressure.

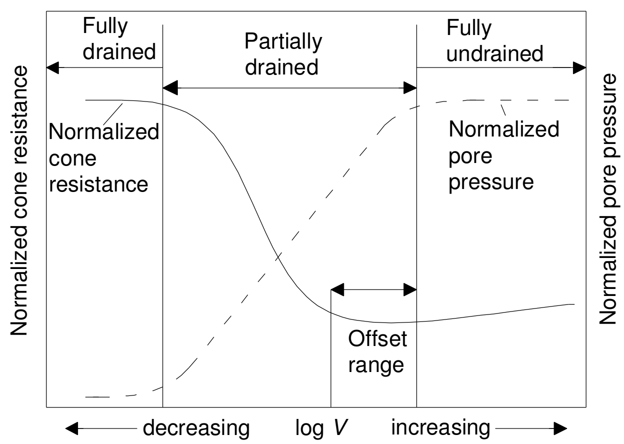

Figure 10. Simplified sketch of the effect of penetration rate on normalized cone resistance and pore pressure (Kim et al. 2006).

In Figure 10, the boundaries between drained, partially drained, and undrained are represented by a vertical line. By plotting the normalized cone resistance and pore pressure against a normalized penetration rate, it is possible to determine whether the soil is drained, partially drained or undrained during the standard penetration rate at 20 mm/s. Due to viscose effects (Chung et al. 2006, House et al. 2001, Roy et al. 1982), when observing the normalized cone resistance, the transition from undrained to partially drained is not clearly defined. The "partially drained" zone, therefore, includes an offset range where the drainage may seem to be undrained. However, when observing the normalized pore pressure, the transition from undrained to partially drained is more clearly defined.

4 SET-UP BETWEEN PUSHES

As described above, the order of drainage is of great important of the cone resistance. However, it is not only changes in penetration rate that can cause a transition from undrained to partially drained penetration.

McNeilan and Bugno (1985) showed how the set-up between CPT pushes also can cause changes in drainage condition. McNeilan and Bugno (1985) used a cone where data was acquired in 0.91 m increments, and due to set-up between each increment, a delay time of 2 to 5 min occurred. This delay time, therefore, allows the excess pore pressure to dissipate. Figure 11 shows the interruption in the CPT due to set-up in four different soils classified by McNeilan and Bugno (1985) as clayed silt, silt, slightly sandy silt, and very sandy silt.

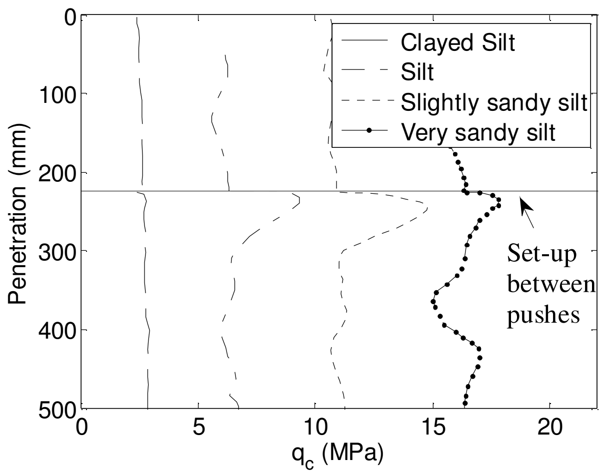

Figure 11. Example of the influence of setup between pushes (McNeilan and Bugno 1985).

The figure shows how the cone resistance temporarily increases at the start of a new push. However, the increased resistance at the start of the push diminished with increasing penetration, which typically occurred after about 76 mm of penetration (McNeilan and Bugno 1985).

As shown in Figure 11, the influence of the set-up is significantly larger in the silt and slightly sandy silt than in the clayed silt and sandy silt. In the clayed silt, the influence of the set-up is negligible because of a low permeability, hence the penetration is undrained and the excess pore pressure is not able to dissipate. In the very sandy silt, the permeability is so high that only very little excess pore pressure is generated, hence dissipation during set-up is very little. In soils with intermediate permeability, such as silt and the slightly sandy silt, penetration is partially drained. During penetration, excess pore pressure is generated, and during the set-up stop of 2 to 5 min., it is also able to dissipate, which causes a temporally increase in cone resistance.

Therefore, when conducting cone penetration tests in silty soils, large variations in the cone resistance can be observed due to set-up interruptions. The variation in cone resistance will dependent on the soil type and the delay time of the set-up.

5 CONCLUSION

This paper has discussed the problems concerning drainage conditions when interpreting CPT results in silty soils. The soil data has been collected and a subsequent processing of the collected data has been conducted by the author. Silt is a well-known soil that has a grain size between clay and sand. However, in reality the soil is almost never uniform, wherefore a classification is often difficult. Two of the currently most used standards do not agree on the definition and classification of silt. They do not provide an accurate definition of silt and additionally, the classification is defined by a geological point of view and not on the basis of geotechnical soil behaviour. Even when using the current soil classification charts, problems arise when classifying the silt since the classification is dependent on drainage condition. The silty soil can consequently be interpreted as clay or sand if the drainage is respectively undrained or fully drained.

When conducting CPT with the standard penetration rate of 20 mm/s, the penetration occurs as undrained for clayed soils, contrary to sandy soil where the penetration occurs as fully drained. In silty soils, however, the penetration can be partially drained. In general, the drainage condition in silty soil is dependent on the applied CPT, penetration rate and the soil coefficient of consolidation or soil permeability. Therefore, when conducting cone penetration tests in silty soils it is important to be aware whether the penetration is undrained, partially drained or fully drained, since the measured cone resistance, sleeve friction and pore pressure vary with the drainage condition. Especially the cone resistance increases when the penetration rate decreases and the drainage goes from undrained to fully drained, which can be very important if the design problem causes drained loading. By implementing a normalized penetration rate, it should be possible to compare various cone resistance results, and hence determine the transition from undrained to fully drained.

In order to examine the effect on changes in penetration rate, most researchers have, to this point, conducted rate dependent test in a centrifuge or calibration chamber in the laboratory. These tests can not necessarily be applied to the field. The interpretation of field tests is also, however, more difficult because of inhomogeneous soil stratigraphy. In addition, conducting rate dependent CPT tests in the field and reducing the penetration rate right down to about 0.01 mm/s can be very difficult.

When pushing the cone into the soil, a set-up stop occurs every time a new rod is needed. During this stop, the excess pore pressure starts to dissipate. In clay and sand, this set-up stop has no effect, although in silty soil the dissipation causes an increase in cone resistance in the subsequent push.

When interpreting CPT in silty soil, the measured cone resistance may vary which can be interpreted as layered and inhomogeneous soil, but the variation in the measured cone resistance could also be caused by changes in penetration rate or set-up stops.

The change in drainage conditions due to various penetration rates is mostly examined for clay. For silt, however, a change in penetration rate presumably has a greater significance. It is, therefore, necessary to conduct more cone penetration tests in silt and it is important that the entire silt spectrum is investigated.

ACKNOWLEDGEMENTS

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