Cone Penetration Testing 2018 – Hicks, Pisanò & Peuchen (Eds)
© 2018 Delft University of Technology, The Netherlands, ISBN 978-1-138-58449-5

Effect of piezocone penetration rate on the classification of Norwegian silt

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ABSTRACT: Interpretation of Cone Penetration Tests (CPTU) in intermediate soils is complex due to partially drained conditions during penetration. In order to gain more insight into the material behavior of silt during a CPTU, an intensive test program was carried out in the field and several soil samples were taken and analysed. In addition a set of tests were performed in the laboratory under controlled conditions using a mini-piezocone (Fugro miniature CPTU, owned by the University of Colorado). The aim is to develop an improved interpretation basis for the CPTU in intermediate soils. The present paper gives an overview over the results obtained and shows how a change in penetration rate affects the response of the CPTU-readings. The data have been plotted into existing soil classification charts and the results from the field and laboratory investigations are compared. The Schneider et al. (2007) chart seems promising in separating the results from the different rate tests.

1 INTRODUCTION

Cone penetration testing in silty soils is difficult due to partial drainage occurring during a standard penetration rate. The CPTU is generally carried out with a rate of 20 mm/s ± 5 mm/s according to the International Reference Test Procedure (IRTP) of the International Society of Soil Mechanics and Foundation Engineering (ISSMFE). Thereby one assumes to achieve fully undrained conditions for clayey soils and fully drained conditions for sandy soils (Lunne et al. 1997). However, in intermediate soils e.g. silts, partial drainage is likely to occur during a standard penetration rate, which may lead to over- or underestimation of the geotechnical soil parameters either using analysis tools developed for fully undrained or drained behavior.

Researchers have shown that the presence of partial drainage has significant influence on the corrected cone resistance (q_t), the pore pressure (u_2) and to some extent the sleeve friction (f_s). Most of the research has been carried out under controlled conditions in the laboratory using a calibration chamber or a centrifuge and varying the penetration speed of the advancing probe using either a cone or full flow probes (Stewart & Randolph 1991, Randolph & Hope 2004, Silva & Bolton 2005, Schneider et al 2007, Paniagua 2014). Up till now, only a few field studies have been reported in the literature, as for example by Kim et al. (2008), Martinez et al. (2016), Poulsen et al. (2013) and Holmsgaard et al. (2016).

There may be several reasons for the lack of research in the field. Usually silty soils consist of a mixture of both finer and coarser materials. They often appear as small layers or lenses which makes it difficult to obtain undisturbed samples and complicates the handling of the material in the laboratory. Moreover, the interpretation of the CPTU results are complicated due to the rather complex micro fabric of the soil, e.g. Sandven (2002).

In order to study and understand the penetration processes taking place during a CPTU in intermediate soils, an intensive field study has been carried out by the Norwegian University of Science and Technology (NTNU) on a silt site in Stjørdal, close to Trondheim, Norway. In total 25 CPTU's were conducted with penetration speeds varying between 0.5–200 mm/s using a standard 35.7 mm cone and measuring the pore pressure at the u_2 position directly behind the cone. Several dissipation tests were done at different depths of interest where the penetration is paused and the pore pressure development is logged over a certain time interval. High-quality 54 mm steel samples were taken and carefully examined in the laboratory.

In addition, a series of CPTU's were performed in the laboratory under controlled conditions using a Colorado minicone (diameter 12 mm) and a fully saturated silt specimen. The soil sample was built inside a Plexiglas cylinder (d = 100 mm) with an internally padded layer of neoprene in order to compensate for boundary effects. By using a slurry deposition method, a silt sample is built into the cylinder and an overburden pressure of 80 kPa was applied. The CPTU tests were performed using three different penetration rates: 0.06 mm/s, 6 mm/s and 50 mm/s, representing a slow, standard and fast penetration rate respectively, Paniagua (2014).

The paper gives an overview over the basic laboratory results obtained and shows CPTU curves for the different penetration rates. The results are plotted in selected existing soil classification charts and compared to the minicone results from the laboratory. The aim of the present paper is to show the influence of varying the rate of penetration in intermediate soils and how they affect the interpretation of the CPTU results. The analysis of the dissipation tests is not presented in this paper.

2 SITE DESCRIPTION

2.1 *Halsen, Stjørdal*

The research test site consists of a thick silt deposit which is situated in the Stjørdal valley about 35 km east of Trondheim in Norway. During the Quaternary period, the Scandinavian Peninsula was fully covered by a massive icecap. However several periods of warmer climate caused the icecap to retreat temporarily. During the last de-glaciation, rivers of melt-water transported clays and silts into the sea. These soils are representative for the Halsen test site where the thickness of the sediments may reach 200–300 m over bedrock. Clayey materials govern these deposits but in some parts due to increased or irregular water velocities, silts and fine sands are more dominant. This is typical for the Halsen test site where the fine sediments are dominated by silt, with layers and pockets of clay and coarse sand (Sandven 2002).

Grain size distributions have been determined and Figure 1 shows a summation plot of some of the test results including one test from the Vassfjellet silt. It is common Norwegian practice to use the recommendations made by the Norwegian Geotechnical Society (NGF) in order to classify the soil type NGF (2011). Herein the soil is defined as SILT if more than 45% of the grains are between 0.002 mm and 0.06 mm and less than 15% is clay (< 0.002 mm).

As can be seen from Figure 1, most of the soil from the Halsen test site consists of either sandy or clayey SILT with an average silt content of 55% and the majority of the particles falling into the coarse silt spectrum (e.g. 0.02–0.06 mm). The average soil grain density is about 2.66 g/cm^3. The soil gradation is middle to poorly graded with an average coefficient of uniformity of C_u = 17 which is defined as the ratio of d_{60} over d_{10}.

Figure 2 shows basic laboratory results for the Halsen test site. The water content varies between 20% and 35% with an average value of about 25%. Measurements of the bulk density are around 2.1 g/cm^3 on average. The distribution of the falling cone (fc) shear strength over depth shows a rather varied behavior with minimum values of

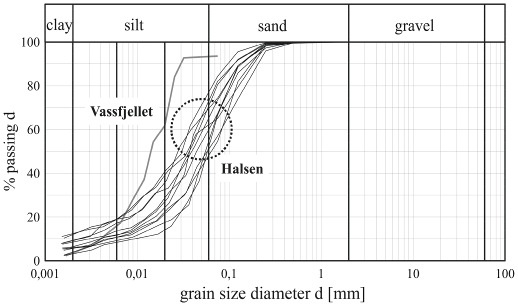

Figure 1. Grain size distribution: Halsen-Stjørdal and Vassfjellet.

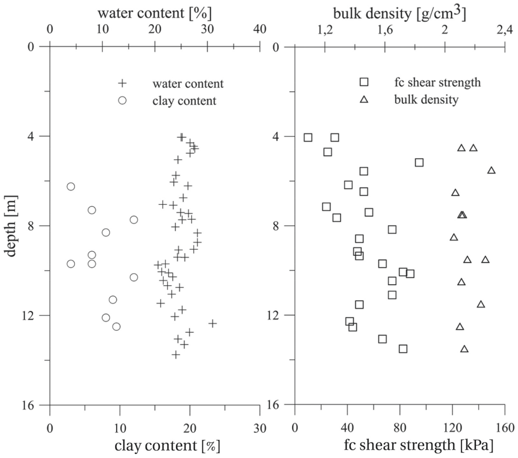

Figure 2. Overview over basic soil parameters.

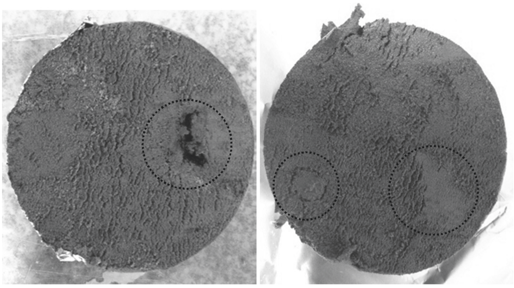

Figure 3. Cross section of soil specimen from 7.5 m, Halsen.

20 kPa and maximum values of 95 kPa. The distribution of the clay content over the depth shows an increase of clay content with depth.

In general, there is little evidence of soil properties varying with depth. Findings from the laboratory reflect the natural variation of the silty soil and underline the challenges in handling and characterizing these soils in the laboratory and in the field. Figure 3 shows a cross section of a sample from 7.5 m depth opened in the laboratory. The sand and clay lenses, which in this case seem to form vertical columns rather than horizontal layers, are clearly visible as well as cracks and holes inside and along the sample.

The laboratory results underline the geological history of the test area. To ensure the highest possible sample quality, all samples taken in the field have been analyzed within 24 hours of sampling time. The focus of the present project was on the silt layer between 4 m and down to more than 13 m. The ground water table is located at about 2.8 m which fits well with the findings from Sandven (2002).

2.2 *Vassfjellet*

The silt, which has been used in the laboratory study by Paniagua (2014), is from Vassfjellet, Klæbu, Norway, south of the Trondheim. The soil consists of a combination of glacier river deposits and peat. Due to its low cohesion, it was impossible to obtain undisturbed samples. Therefore disturbed samples were taken and rebuilt in the laboratory by a slurry deposition method.

The soil consist of a non-plastic, medium to coarse silt with a silt content of 92% and a clay content of 2.5%, see Figure 1. The silt from Vassfjellet is less sandy and clayey than the silt from the Halsen site. The soil grain density is 2.46 g/cm^3 and the organic content is lower than 2%. A maximum dry density of 1.57 g/cm^3 is obtained at 22% optimum water content and 95% saturation.

3 OVERVIEW OVER EXISTING SOIL CLASSIFICATION CHARTS

Soil classification charts, or more correctly soil behavior charts have been established since approximately 1965. It has to be stated that the application of these charts does not give accurate predictions of the soil type in terms of grain size distribution, but it is an indicator for the behavior of the present soil. Robertson (1990) stated that the classification charts are global and should only be used as a guide to define soil behavior. The general idea is that sandy soils usually generate high cone resistance and low friction ratios, whereas clayey soils have low cone resistance and high friction ratios (Lunne et al. 1997 and Robertson et al. 1986).

Ideally, all three measured parameters during a CPTU should be combined in order to achieve more reliable soil classification. Nevertheless, researchers are aware of the fact that the measured sleeve friction is often the less accurate and less reliable parameter of the three (for measurements below the groundwater table). In order to overcome the problems with the sleeve friction, Wroth (1984) and Senneset and Janbu (1985) were one of the first researchers to introduce the pore pressure parameter ratio B_q:

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_{v0}} \tag{1}$$

where u_2 = measured pore pressure, u_0 = in-situ pore pressure, q_t = corrected cone resistance and σ_{v0} = total overburden stress. The original classification chart by Senneset & Janbu (1985) included the q_t against B_q whereas Senneset et al. (1989) revised the chart and used the normalized cone resistance Q_t according to Equation 2 instead of q_t.

The most widely used charts have been suggested by Robertson et al. (1986), which are based on either B_q or friction ratio versus q_t. In total 12 different soil behavior types were categorized to describe the different behavior and give a first indication of the drainage condition during cone penetration. Robertson (1990) later modified the existing charts to overcome issues related to CPTU soundings in greater depths (>30 m) by normalizing the q_t and the friction ratio F_r in the following way (see Equation 2 and 3)

$$Q_t = \frac{q_t - \sigma_{v0}}{\sigma'_{v0}} \tag{2}$$

$$F_r = \frac{f_t}{q_t - \sigma_{v0}} \tag{3}$$

where σ'_{v0} = effective vertical stress and f_t = corrected sleeve friction. Eslami & Fellenius (1997) established a classification chart used for pile design by applying data from more than 100 case histories in various soil conditions. The chart uses non-normalized parameters such as the effective cone resistance q_e ($q_e = q_t - u_2$) versus the measured friction f_t and divides the soil types into five different classes.

More recent developments are described by Schneider et al. (2008) where the classification charts are based on Q_t versus $\Delta u/\sigma'_{v0}$ and Q_t versus B_q to take into account the effects of partial consolidation and yield stress ratio. Robertson (2013) developed a revised version of the Robertson (1990) chart where it is possible to distinguish between drained and undrained penetration as well as contractive and dilative penetration behavior.

4 CPTU RESULTS

4.1 *Halsen, Stjørdal*

Several CPTU soundings are carried out at the Halsen test site between 4 to 14 m. Due to a very stiff and coarse top layer, it was decided to predrill the first 4 m. Different rates of penetration have been used, but only one group of tests has been selected for the present paper: the slow test with an average penetration rate of about 0.5 mm/s representing drained conditions, the standard test at 20 mm/s and the fast test with a penetration rate of 200 mm/s corresponding to an undrained penetration. In order to facilitate the interpretation of the CPTU results, the recordings have been smoothened by applying a moving average over a measuring interval of 100 mm, similar to Holmsgaard et al. (2016).

Figure 4 shows the measured q_t, u_2 and f_s results for some of the tests carried out at Halsen. Between 4 to 14 m the soil consist of a rather coarse sandy silt layer with an average cone resistance at standard penetration rate of about 1,5 MPa and pore pressure values varying around the hydrostatic level at standard penetration rate. Below 12 m, the clay content increases resulting in a lower cone resistance and higher positive excess pore pressures exceeding the hydrostatic level when penetrating the cone at 20 mm/s (see also Figure 2).

The CPTU results pick up the different layering of the soil deposit rather precisely. The measured sleeve friction values are somewhat more scattered than the cone resistance and the pore pressure. Nevertheless, slightly higher friction values are observed during a slower penetration process. As stated by Lunne et al. (1997), the friction measurements have to be used with care due to less reliability.

Several researchers have observed similar trends for the cone resistance, i.e. increasing cone resistance values with decreasing penetration speed. This can be explained by partial consolidation effects occurring in front of the advancing cone during a slower penetration rate and allowing the pore pressure to dissipate and hence the cone resistance to increase (Kim et al. 2008 and Schneider et al. 2007). The drainage conditions during penetration change from drained (slow penetration) to partially drained (medium penetration rate) to undrained (fast penetration).

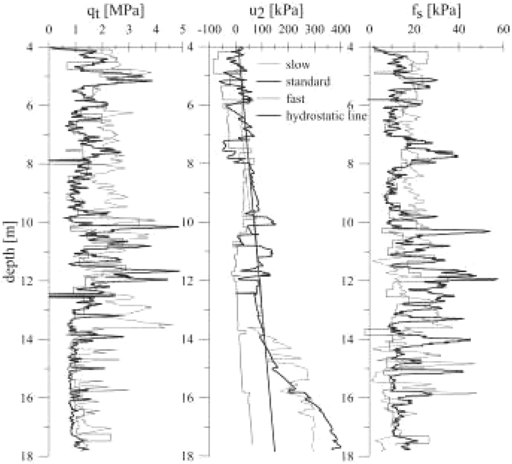

Figure 4. CPTU results Halsen (not smoothed).

However, at Halsen the measured pore pressure profiles show opposite trends. During an increased penetration rate the pore pressure decreases and develops high negative values. During the slow rate a drained penetration is assumed by measuring almost hydrostatic pore pressures and a high cone resistance. Increasing the penetration rate leads to an increase in negative excess pore pressure. The measured pore pressure u_2 during a CPTU consists of the in situ pore pressure u_0 and the excess pore pressure Δu_2. The measured Δu_2 can further be separated into the following quantities (see Equation 4, Burns & Mayne 1998)

$$u_2 = u_0 + \Delta u_{2,oct} + \Delta u_{2,shear} \tag{4}$$

where $\Delta u_{2,oct}$ = mean octahedral normal stress component and $\Delta u_{2,shear}$ = shear component of the measured pore pressure (Wroth 1984, Baligh & Levadoux 1986 and Schneider et al. 2007). Shear induced pore pressures can have a significant effect in OC (over consolidated) clays and sandy silts, due to high negative shear occurring in the zone of intense shearing next to the penetrating cone. Further away from this zone the mean octahedral normal stress component dominates, resulting in larger positive excess pore pressures (Schneider et al. 2007).

Furthermore, the data has been applied to some of the soil classification charts discussed in this paper. The focus is on the 4 m thick sandy silt layer that is present between 4 to 8 m. Friction based classification diagrams have not been considered due to the scattered and rather less reliable results as described above.

The top line of Figure 5 shows the Halsen CPTU data (from left to right) plotted into the Senneset et al. (1989), Robertson (1990) and the Schneider et al. (2008) chart. The Senneset et al. (1989) chart defines the soil as a stiff clay-silt or a loose sand for all penetration rates. Robertson (1990) plots the data mostly into zone 4 and 5, which are defined as silt and sand mixtures. The results for the slow tests are plotted completely in the sand mixture zone, consistent with a drained penetration. The Schneider et al. (2008) diagram shows the most distinct classification where the data is plotted mostly into zone 3 corresponding to transitional soil behavior. Nevertheless results for the slow penetration test are plotted mostly in zone 2 which is defined as a drained sand.

4.2 *Vassfjellet*

Figure 6 shows the CPTU results for the tests carried out in the laboratory for the Vassfjellet silt including three different penetration rates (Paniagua 2014).

The cone resistance shows the highest values during the fast penetration and the lowest results for the slow penetration, i.e. opposite to the Halsen test results. In contrast to the cone resistance, pore pressure values increase with increasing penetration rate, e.g. developing high negative excess pore pressure values at the fastest penetration rate, i.e.

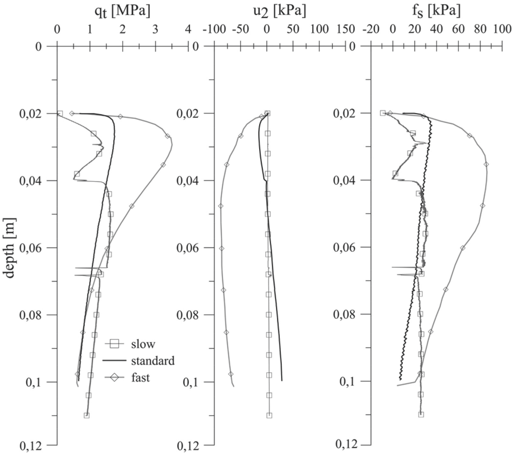

Figure 6. CPTU results Vassfjellet.

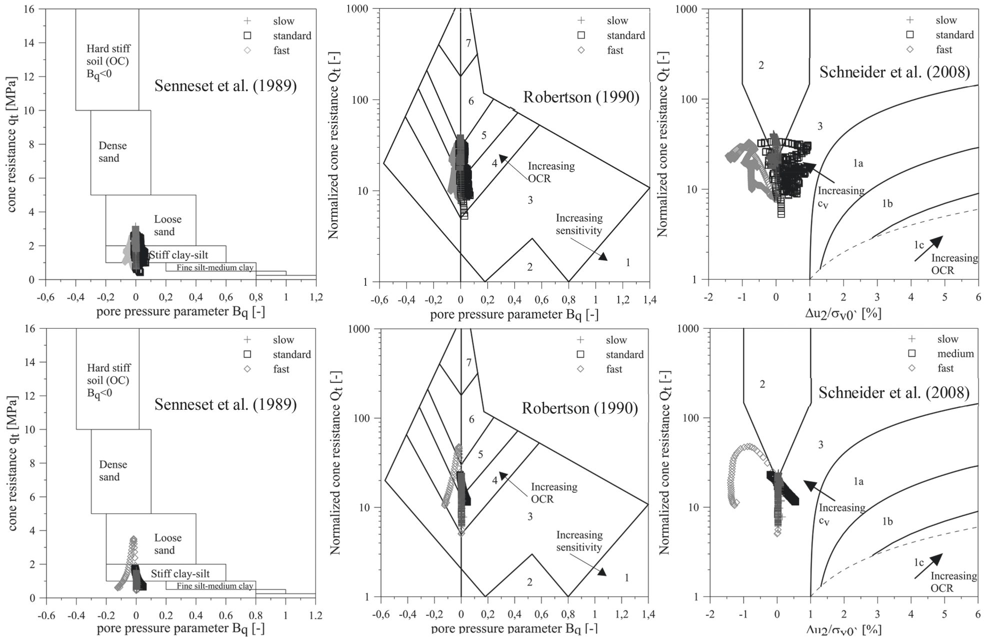

Figure 5. Soil classification charts: Halsen (top) and Vassfjellet (bottom).

similar to the results from the Halsen test site. The sleeve friction values show a similar trend as the cone resistance, e.g. high values for fast penetration and lower values for the slow penetration rate.

The bottom row of Figure 5 shows the results for the Vassfjellet silt plotted into three different soil classification charts. The Senneset et al. (1989) chart classifies the data as silt or stiff clay for the standard and fast rate whereas the data for the slow test are plotted more towards the loose sand—soil behavior. Robertson (1990) defines the soil for all three penetration rates as silt and sand mixture. Schneider et al. (2008) plots the data data into the transitional zone showing an increasing coefficient of consolidation for the increasing penetration rate, Paniagua & Nordal (2015).

5 CONCLUSIONS

The present paper gives an overview over the results obtained during variable rate CPTU tests in silty soils both in the laboratory and in the field. The results show how varying the rate of penetration effects the CPTU readings and hence the degree of drainage and the classification of the soil behavior.

Overall, during a slow penetration, the results for the Halsen test site show a contractive penetration behavior, e.g. developing high cone resistance values and close to hydrostatic pore pressures. In contrast the fast penetration tests show lower cone resistance values and high negative excess pore pressures which corresponds to a more dilative soil behavior. This can be explained by the influence of the dilative behavior giving a shear induced pore pressure component during fast penetration which results in a zone of intense shearing next to the CPTU device.

The results from the laboratory study also show a dilative penetration behavior. During a slow penetration the cone resistance is low and the pore pressures are close to the hydrostatic level. Increasing the penetration rate leads to an increase in penetration resistance and an increase in negative excess pore pressure.

Plotting the CPTU results from the Halsen test site and Vassfjellet silt onto the different soil classification charts shows a general agreement of classifying the soil as transitional and intermediate. In particular the Schneider et al. (2007) chart seems to be promising and support the use of different penetration rates allowing one to make conclusions about the degree of drainage during penetration for identifying silts.

The results show a clear rate dependency of the measured parameters and hence emphasize the need of extended research in the interpretation field of intermediate soils. Further field tests are necessary to gain more insight into the understanding of intermediate soil behavior during a CPTU and an improvement of the interpretation methods is necessary in order to increase the accuracy of developed engineering soil parameters.

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