Correlation between cone penetration rate and measured cone penetration parameters in silty soils

Corrélation entre le taux de pénétration d'un cône et des mesures de paramètres de pénétration au cône dans les sols limoneux.

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ABSTRACT: This paper shows, how a change in cone penetration rate affects the cone penetration measurements, hence the cone resistance, pore pressure, and sleeve friction in silty soil. 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. When lowering the penetration rate, the soil pore water starts to dissipate and a change in the drainage condition is seen. In intermediate soils such as silty soils, the standard cone penetration rate may result in a drainage condition that could be undrained, partially or fully drained. However, lowering the penetration rate in silty soils has a great significance because of the soil permeability, and only a small change in penetration rate will result in changed cone penetration measurements. In this paper, analyses will be done on data from 15 field cone penetration tests with varying penetration rates conducted at a test site where the subsoil primary consists of sandy silt. It is shown how a reduced penetration rate influences the cone penetration measurements e.g. the cone resistance, pore pressure, and sleeve friction.

RÉSUMÉ: Dans cet article, on montre comment un changement dans le taux de pénétration d'un cône affecte les mesures de pénétration de cône, d'où la résistance du cône, la pression interstitielle et la friction manche en sol limoneux. Le taux normal de pénétration est de 20 mm/s, et il est généralement admis que la pénétration se produit dans de l'argile non drainée alors que la pénétration se produit dans le sable drainé. Lors de l'abaissement du taux de pénétration, l'eau interstitielle du sol commence à se dissiper et un changement de l'état de drainage est vu. Dans les sols intermédiaires, tels que les sols limoneux, le taux de pénétration de cône standard peut conduire à un drainage des conditions qui pourraient être non drainées, partiellement ou totalement déchargée. Cependant, l'abaissement du taux de pénétration dans les sols limoneux a une grande importance en raison de la perméabilité du sol et seulement un petit changement dans le taux de pénétration se traduira par des mesures de pénétration au cône changé. Dans ce document, les données de 15 essais sur le terrain de pénétration au cône, avec différents taux de pénétration menées sur un site d'essai où le premier sous-sol se compose de limon sableux, sont analysés. L'influence d'une réduction du taux de pénétration sur les mesures de pénétration d'un cône, par exemple la résistance du cône, la pression de pore, et la friction manchon, est démontrée.

KEYWORDS: Silt, CPT, penetration rate, cone resistance, pore pressure, sleeve friction, drainage, in situ testing.

1 INTRODUCTION

The Cone Penetration Test (CPT) is an in situ testing method that today's geotechnical engineers often make use of when determining soil parameters, and classifying soil type. The standard rate of penetration is 20 ± 5 mm/s, (ASTM 2007), and while the cone is pushed into the ground the cone resistance, (q_c), pore pressure (u_2), sleeve friction (f_s), and depth (d) are measured.

During the penetration, the pore water starts to dissipate, and the dissipation for sands occurs so quickly that the penetration appears as fully drained, whereas the dissipation happens over time for clays, for which reason the penetration is undrained in clays. For intermediate soil, such as silty soils, the penetration is somewhat in between; that is partially drained.

According to several researchers (Silva and Bolton 2005, Lehane et al. 2009, Kim et al. 2008, Schneider et al. 2008, Chung et al. 2006, House et al. 2001), the drainage is dependent on the soil permeability, compressibility and penetration rate. The soil permeability and compressibility are both connected to the soil type. However, the penetration rate is regardless of soil type 20 mm/s.

When the penetration rate is lowered, the pore water dissipates (change in drainage condition) which results in an increased cone resistance (Lehane et al. 2009, Kim et al. 2008, Chung et al 2006, House et al. 2001). For this reason, the largest cone resistance that could be obtained corresponds to a fully drained penetration. This effect has been shown by several researchers (Chung et al. 2006, House et al. 2001 and Randolph and Hope 2004) from laboratory tests in clay. Kim et al. (2008) also conducted laboratory as well as field cone penetration tests in cohesive soil and found that the soil behaves undrained for a penetration rate of 20 mm/s and partially drained for a penetration rate of 0.05 mm/s.

According to Poulsen et al. (2011a), the change in penetration rate and hence drainage condition has a greater impact in silty soils where the standard rate of penetration often induces a partially drained penetration.

This paper analyses data from 15 field cone penetration tests conducted with a penetration rate varying from 60 to 0.5 mm/s. Only a short description of the method for the cone penetrations tests will be given. The results and the interpretation of how a change in the penetration rate affect the measured parameters, hence the cone resistance, pore pressure, and sleeve friction will be given.

2 DESCRIOTION OF EXEPERIMENTAL PROGRAM

The aim of the research is to examine how a change in the cone penetration rate affects the measured cone penetration parameters when conducting cone penetration tests (CPT). The research was carried out at a test site located in the northern Jutland in Denmark, more specifically at a field near the town Dronninglund.

2.1 *Test site soil stratigraphy*

The soil stratigraphy was at the test site identified by means of two geotechnical boring results. In addition, soil samples were collected and laboratory tests were executed in order to classify the soil. Both test results show that the subsoil consists of sandy silt with clay stripes from approx. 4.5 to 11.4 m below ground level. Above 4 m, the soil consists of silty sand, and below 11 m the soil consists of clay with sandy silt stripes. In addition, the groundwater was encountered at approximately 0.2-0.6 m below the ground level. Generally, the soil is much layered and inhomogeneous which makes the soil difficult to classify. However, in Poulsen et al. (2012a), the soil was overall classified as sandy silt with clay stripes.

2.2 *Cone Penetration Tests*

In order to examine how a change in the cone penetration rate affects the measurements, various cone penetration tests have been conducted. A total of 15 CPTs with five different penetration rates were conducted; these were 60, 20, 5, 1, and 0.5 mm/s. All CPTs were conducted with a distance of approximately 3 m. This was done to make sure that the drainage of each CPT would not affect the drainage of the other CPTs. The location of the 15 CPT's can be seen in Figure 1.

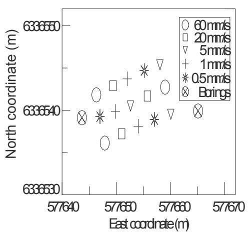

Figure 1 Location of the 15 CPTs with penetration rates of 60, 20, 5, 1 and 0.5 mm/s. The coordinates are given UTM coordinates.

During the execution of the CPT's, the cone resistance, (q_c), pore pressure (u_2), sleeve friction (f_s), depth (d), and the penetration rate (v) were measured. A more detailed description of the test site, experimental programme and the validity of the tests can be found in Poulsen et al. (2012b).

Because of the layered and inhomogeneous soil, the measured CPT parameters are very fluctuating and hence difficult to interpret. As a result, the data has been smoothed for every 50 cm, which was concluded acceptable in Poulsen et al. (2012b).

3 EFFCT OF PENETRATION RATE IN SILT LAYER

The soil layer classified as sandy silt with clay stripes was located between 4.5 to 11.4 m below ground level. Only this layer has been analysed since it is considered to be the silt layer where the effect of the penetration rate is clearest. As a result, the following graphs only contain results from 4.5 to 11.4 m.

In the following, it is analysed how a change in cone penetration rate affects the measured cone resistance, pore pressure and sleeve friction respectively. As described in Poulsen et al. (2012b), the soil layer consists of many stripes, which gives a very fluctuating result for the measured cone penetration parameters. In order to clearly visualise the effect of a change in the penetration rate, only the penetration rates of 60 and 0.5 mm/s have been included. This is done as it is the extreme points corresponding to undrained and fully drained that are of interest, and the penetration rates of 60 and 0.5mm/s are closest to these conditions. Consequently, the data from the CPTs conducted with a penetration rate of 20, 5 and 1 mm/s have been excluded in the figures.

3.1 *Pore pressure*

In Figure 2, the smoothed pore pressure from 4.5 to 11.4 m for the CPTs conducted with a penetration rate of 60 and 0.5 mm/s can be seen.

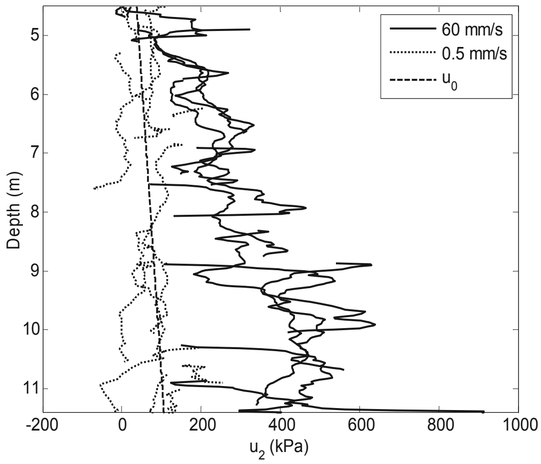

Figure 2. Comparison of the smoothed pore pressure conducted with a penetration rate of 60 and 0.5 mm/s. The figure contains results from 3 CPTs test for each penetration rate. The plotted u_0 is an average value.

Figure 2 shows that changing the penetration rate from 60 to 0.5 mm/s results in a decreased pore pressure. This is because the drainage conditions change when the penetration rate is decreased. From Figure 2, it seems as though the CPT conducted with a penetration rate of 0.5 mm/s corresponding to fully drained penetration, since the measured pore pressure is close to or equivalent to u_0.

However, it is not possible to conclude if the CPT conducted with a penetration rate of 60 mm/s corresponds to undrained or partially drained penetration. Nevertheless, by lowering the penetration rate, the penetration changes from undrained or partially drained to fully drained, which results in a lower pore pressure.

3.2 *Cone resistance*

In Figure 3, the smoothed cone resistance from 4.5 to 11.4 m for the CPTs conducted with a penetration rate of 60 and 0.5 mm/s can be seen.

Figure 3 likewise shows that changing the cone penetration rate from 60 to 0.5 mm/s results in a change in the cone resistance. However, a decreased penetration rate results in an increased cone resistance. The changes observed in the cone resistance are like the pore pressure caused by changes in drainage conditions where the penetration changes from undrained or partially drained to fully drained. This results in a higher cone resistance.

3.3 *Sleeve friction*

In Figure 4, the sleeve friction from 4.5 to 11.4 m for the CPTs conducted with a penetration rate of 60 and 0.5 mm/s can be seen.

Contrary to the pore pressure and cone resistance, Figure 4 does not show any correlation between the sleeve friction and cone penetration rate.

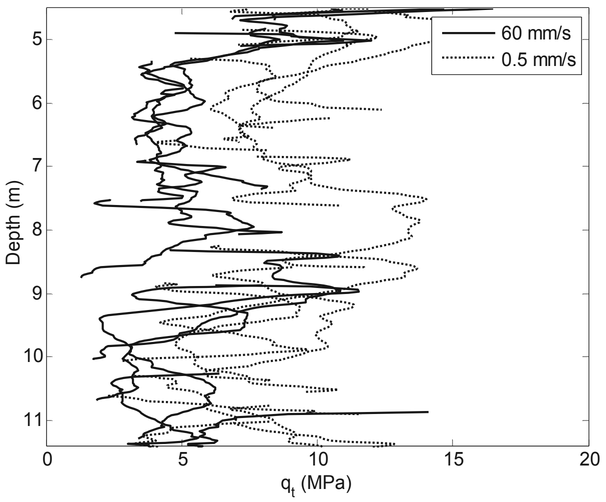

Figure 3 Comparison of the smoothed cone resistance conducted with a penetration rate of 60 and 0.5 mm/s. The figure contains results from 3 CPTs test for each penetration rate.

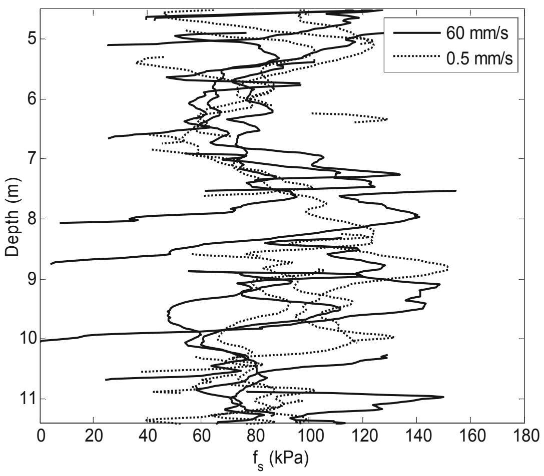

Figure 4. Comparison of the smoothed sleeve friction conducted with a penetration rate of 60 and 0.5 mm/s. The figure contains results from 3 CPTs test for each penetration rate.

4 CORRELATION BETWEEN PENETRATION RATE AND MEASURED PARAMETERS

The order of the change in the cone penetrations parameters that can be anticipated is however difficult to read from Figure 2, Figure 3 and Figure 4. As a result, the mean value of the entire silt layer from all CPTs (CPTs with penetration rate of 60, 20, 5, 1 and 0.5 mm/s) can be plotted in a semi logarithmic plot. This has been done for the sleeve friction in Figure 5.

Just as Figure 4, Figure 5 does not show any correlation between the mean sleeve friction and the mean penetration rate. According to Lunne et al. (1997) the sleeve friction does not give consistent results during cone penetration. The results shown in Figure 4 and Figure 5 substantiate this, for which reason caution must be taken when using the sleeve friction to analyse CPT data.

The mean value for the pore pressure and cone resistance plotted against the mean penetration rate in a semi logarithmic plot is seen in Figure 6 and Figure 7. It can be seen that a correlation between the pore pressure and the penetration rate (Figure 6) and cone resistance and the penetration rate (Figure 7) exist.

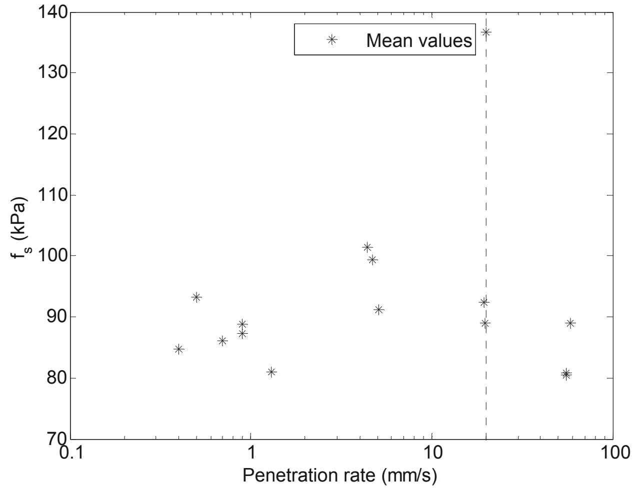

Figure 5. The mean sleeve friction plotted against the mean penetration rate from 4.5 to 11.4 m below ground level. No correlation seems to exist. The standard rate of penetration of 20 mm/s has been marked with a dotted line.

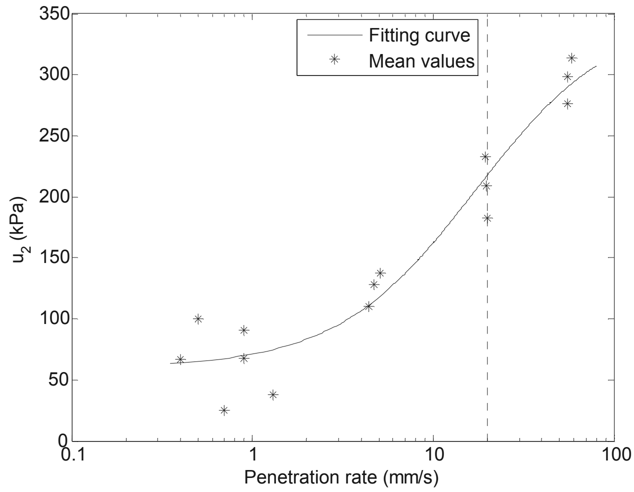

Figure 6. Correlation between the mean pore pressure and the mean penetration rate from 4.5 to 11.4 m below ground level. The standard rate of penetration of 20 mm/s has been marked with a dotted line.

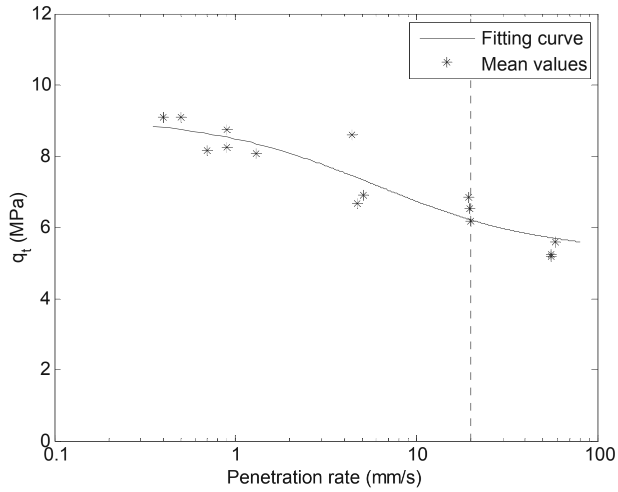

Figure 7. Correlation between the mean cone resistance and the mean penetration rate from 4.5 to 11.4 m below ground level. The standard rate of penetration of 20 mm/s has been marked with a dotted line.

The correlations appear to be linear, however this cannot be true since there must exist an upper and lower boundary for the cone resistance and pore pressure corresponding to fully drained and fully undrained. The mean values can instead be fitted by an expression from Chung et al. (2006), which has been modified by Poulsen et al. (2012b). The expression is given in (1) and (2)

$$u_2 = a_u + \frac{b_u}{1 + c_u \cdot \frac{v}{v_{ref}}^{m_u}} \quad (1)$$

$$q_t = a_q + \frac{b_q}{1 + c_q \cdot \frac{v}{v_{ref}}^{m_q}} \quad (2)$$

where u_2 is the pore pressure (kPa), q_t is the cone resistance (MPa), v is the penetration rate (mm/s), v_{ref} is the reference penetration rate equal to 20 mm/s and a_u, b_u, c_u, m_u, a_q, b_q, c_q, and m_q are fitting constants.

The value of a corresponds to undrained penetration, whereas $a + b$ corresponds to a fully drained penetration. From Figure 6 and Figure 7, it is not possible to see when the penetration is undrained or fully drained from the mean values. For this reason, the constants a and b must be assumed. However, in Figure 2 the penetration is close to fully drained for a penetration rate of approximately 0.5 mm/s. This gives an estimate of the constants $a_u + b_u$ and $a_q + b_q$. The value of the other constants can be seen in Table 1, and the fitting curves for the pore pressure and cone resistance can be seen in Figure 6 and Figure 7.

Table 1. Derived value for fitting constants.

	a	*b*	*c*	*m*
Pore pressure, *u*	350	-290	1.2	1.1
Cone resistance, *q*	5.3	3.8	3.1	0.9

By lowering the penetration rate so that the penetration occurs as drained, the cone resistance increases. This can be expressed as (3) (Poulsen et al. 2012b):

$$q_{t,drained} = \xi \cdot q_{t,20\,mm/s} \quad (3)$$

Where $q_{t,drained}$ is the cone resistance corresponding to drained penetration (MPa), $q_{t,20\,mm/s}$ is the measured cone resistance determined with a penetration rate of 20 mm/s (MPa), and ξ is a coefficient of drainage. The coefficient of drainage, ξ, can for the Dronninglund silt be set to 1.0-1.7 depended on whether $q_{t,20\,mm/s}$ is undrained (ξ =1.7), fully drained (ξ =1.0), or how close to fully drained it is.

5 CONCLUSIONS

This paper has shown how a change in the penetration rate affects the measured cone penetration parameters in silty soil. When using cone penetration tests (CPT) with the standard rate of penetration of 20 mm/s, the penetration will appear as fully drained in sandy soils and undrained in clayed soils. However, for silty soils the standard rate of penetration of 20 mm/s results in a partially drained penetration. In order to examine which affect a changed penetration rate has in silty soils on the measured cone penetration parameters (cone resistance, pore pressure, and sleeve friction), 15 CPTs with varying penetration from 60 to 0.5 mm/s have been conducted.

Results from the cone penetration tests conducted with a penetration rate of 60 and 0.5 mm/s were compared for the cone resistance, pore pressure and sleeve friction. It was shown that both the pore pressure and cone resistance gave different results for a penetration rate of 60 and 0.5 mm/s. The pore pressure measured with a penetration rate of 0.5 mm/s corresponded to drained penetration, which resulted in the highest cone resistance. For the sleeve friction, no correlation was seen.

In addition, a correlation between the mean pore pressure and mean penetration rate, and mean cone resistance and mean penetration rate was however seen when plotting the mean penetration rate in a semi logarithmic plot.

Compared to the normal penetration rate of 20 mm/s, a decrease in the penetration rate leads to an increase in the cone resistance due to drainage. The increase can be expressed by a coefficient of drainage, ξ , that is equal to 1.0 for fully drained penetration and 1.7 for undrained penetration. The increase depends on whether the normal penetration rate of 20 mm/s has been conducted under undrained, partially drained or fully drained conditions.

For that reason, it can be concluded that a correlation between the cone penetration rate and the cone resistance and pore pressure exists. It is an important factor that the cone resistance is dependent on drainage condition and consequently the penetration rate. Particularly if a project requires knowledge of both the undrained soil parameters and the drained soil parameters. In this case, it can be useful to know when the penetration is partially drained and how to convert it to a fully drained penetration or undrained penetration.

6 ACKNOWLEDGEMENTS

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