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Assessment and comparison of strength and stiffness parameters derived for normally consolidated sand using SPT and CPT

Évaluation et comparaison des paramètres de résistance et de rigidité du sol dérivés pour le sable consolidé normal à l'aide de SPT et CPT

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ABSTRACT: This case study compares different methods to assess the soil parameters of normally consolidated Late Glacial meltwater sand using Standard Penetration Test (SPT) and Cone Penetration Test (CPT). The density index, triaxial friction angle and oedometer modulus are assessed and compared for the Late Glacial meltwater sand using different methods presented in the literature for SPT and CPT. It is found that the density index estimated by SPT and the method presented in (German Institute for Standardization 1990) appear to give a fair estimate which tend to be slightly conservative in the uppermost layers. When comparing the triaxial friction angle estimated by SPT and CPT it is shown that the friction angles estimated from the CPTs decreases with depth, which is not the case for the friction angles estimated by the SPT data. It is found that (Dansk Standard 1984), (Schmertmann J.H. 1978) and (Stroud M.A. 1989) tend to give a mean value however rather low values and high-end values are encountered in the top and bottom of the layer, respectively. The number of methods for estimating the oedometer modulus using SPT and CPT in normally consolidated sands are few. Still, a good correlation between the E_{oed} estimated by SPT and CPT is found.

RÉSUMÉ : Cette étude de cas compare différentes méthodes pour évaluer les paramètres du sol du sable tardi-glaciaire normalement consolidé à l'aide du test de pénétration standard (SPT) et du test de pénétration au cône (CPT). L'indice de densité, l'angle de frottement triaxial et le module œdométrique sont évalués et comparés pour le sable tardi-glaciaire en utilisant différentes méthodes présentées dans la littérature pour le SPT et le CPT. On constate que l'indice de densité estimé par SPT et la méthode présentée dans (Institut allemand de normalisation 1990) semblent donner une estimation juste. En comparant l'angle de frottement triaxial estimé par SPT et CPT, il est montré que les angles de frottement estimés à partir des CPT diminuent avec la profondeur, ce qui n'est pas le cas pour les angles de frottement estimés par les données SPT. On constate que (Dansk Standard 1984), (Schmertmann J.H. 1978) et (Stroud M.A. 1989) tendent à donner une valeur moyenne. Les méthodes d'estimation du module oedométrique par SPT et CPT dans les sables normalement consolidés sont peu nombreuses. Néanmoins, une bonne corrélation entre l'Eoed estimée par SPT et CPT est trouvée.

KEYWORDS: Standard Penetration Tests, Cone Penetration Tests, normally consolidated sand

1 INTRODUCTION

In Denmark the Standard Penetration Test (SPT) is in general reduced to be an indicator of the strength and deformation parameters for sand because the field test is subject to great uncertainties and variations as the test results are influenced by the operating person. On the other hand, the Cone Penetration Test (CPT) is considered to be objective as the test is automated to a great extent. But how big is the difference between the test results and the derived parameters?

The purpose of the present article is to compare the strength and deformation parameters derived by different methods presented in the literature for SPT and CPT in order to evaluate the difference for normal consolidated Late Glacial meltwater sand.

2 TESTING PROGRAMME

2.1 *Site location*

The study is based on data from tests and recovered samples from a project site located east of the city Brande in the central part of Jutland, Denmark. The project area is situated on a relatively level terrain with ground elevations between approx. +51.0 to +51.2 m in vertical coordinate system Danish Vertical Reference frame of 1990 (m DVR90).

2.2 *Site investigation*

The study includes several exploratory boreholes with different purposes as stated in Table 1 and a distance between boreholes ranging from 5 to 70 meters. Generally the stratigraphy encountered in the exploratory holes is found to be quite similar.

In Table 1 the depths of the preformed boreholes are listed in meters below ground level (m bgl.) and levels.

Table 1. Summary of the site investigation.

Exploratory hole ID	*Purpose*	*Depth [m bgl.]*	*Level at base of borehole [m DVR90]*
BH01	*Core sampling*	87.2	-36.1
BH02	*MPM & SPT*	99.8	-48.7
BH03	*CPT/SPT*	84.3	-33.2
B3	*Geological identification & SPT*	25.0	+26.0
B6	*Geological identification & SPT*	10.0	+41.2
CPT130	*CPT*	13.6	+37.4
CPT131	*CPT*	8.1	+42.9
CPT132	*CPT*	*13.4*	*+37.7*
CPT142	*CPT*	*8.1*	*+43.1*

2.3 *Site conditions/geology*

Based on the site investigation presented in Table 1, the overall geological stratigraphic conditions can be described as a thin layer of topsoil (TS), under which Late Glacial (Lg) meltwater sand was encountered. The Late Glacial meltwater sand overlies Glacial deposits of clay, gravel and sandy silt, and below the Glacial deposits Miocene deposits are encountered at the base of the boreholes.

This present article addresses the Late Glacial meltwater sand encountered between level +50.6 m and +42.2 m with the following geological description stated in Table 2.

Table 2. Summary of the geological description of the Late Glacial meltwater sand addressed in this article.

Late Glacial formation	Material description
Meltwater SAND	Light/dark yellowish brown to light olive brown, fine to coarse, sorted to poorly graded, sl. silty to silty, sl. gravelly to gravelly, grains are angular to sub angular, non-calcareous

The groundwater monitoring installations demonstrate that the groundwater level encountered in the Late Glacial meltwater sand is +46.7 m.

3 METHODOLOGY

SPT and CPT were performed and compared for normal consolidated Late Glacial meltwater sand.

3.1 *Corrected SPT data, N_{60}*

The data from the SPTs have been corrected by use of correction factors according to (Danish Standard Foundations 2011) which also correspond to the correcting method in (The International Organization for Standardization 2004). The corrected SPT data is designated N_{60} and is obtained by the following expression (see Eq. 1):

$$N_{60} = \frac{E_r}{60} \cdot \lambda \cdot C_N \cdot N \tag{1}$$

Where E_r is the energy ratio of the specific test equipment (in this case 63 %), λ is the correction factor for energy loss due to the rod length, C_N is the correction factor for effective vertical stress due to the overburden of the soil in sand, N is the blow count in field per 0.3 meter and finally division by 60 adjusts the N-values to a reference energy ratio of 60 %.

The correction factor C_N varies depending on the effective vertical stress, σ'_v, and the type of consolidation; either normally consolidated or overconsolidated. Therefore, the effective vertical stress, σ'_v, has been calculated using the following: A water table at +46.7 m corresponding to the highest measured water level in the Late Glacial deposit and the unit weight, γ_{sat} /γ', of 18/10 kN/m^3 as no density tests have been performed for the late glacial meltwater sand. The Late Glacial deposit is considered to be normally consolidated as the stratum has not been covered with ice (glaciers). The corrected SPT data, N_{60}, is plotted in Figure 1.

Please note that the corrected SPT also can have the notation $(N_1)_{60}$ in which case the SPT is not corrected for energy loss due to the rod length, λ.

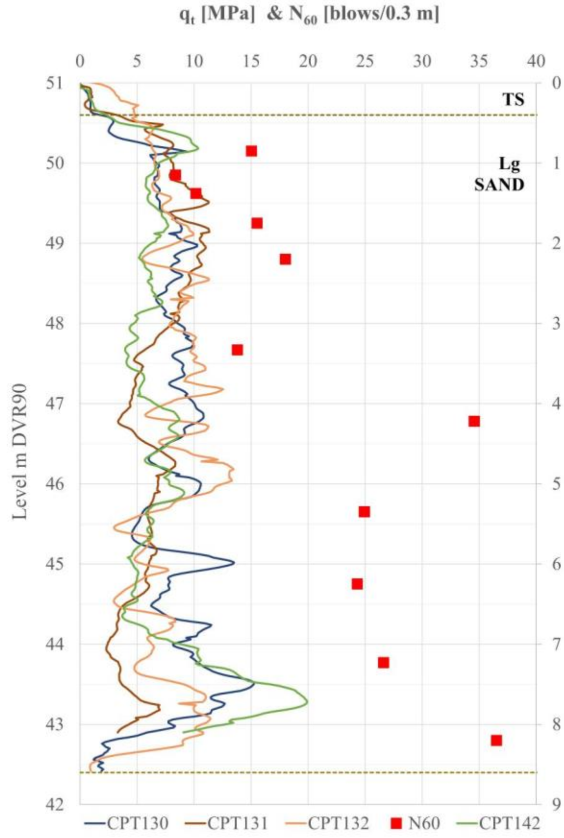

Figure 1. The corrected SPT data, N_{60}, and the corrected cone resistance, q_t, plotted as a function of level (m DVR90). TS stands for topsoil and Lg stands for Late Glacial.

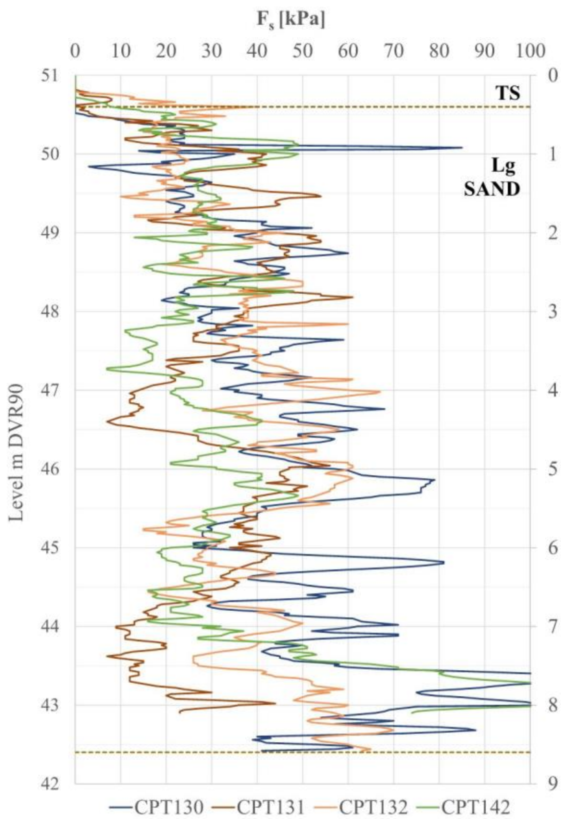

Figure 2. Sleeve friction, f_s, plotted as a function of level (m DVR90).

3.2 *CPT data*

It has been verified that the soil behavior interpretation of the CPTs is in accordance with the stratigraphy found in the geotechnical boreholes. The interpretation of the CPT data has been performed using the soil behavior type index, I_c, (Lunne T., Robertson P.K. & Powell J.J.M. 1997, expression 6.1 and Table 6.3).

The cone resistance corrected for pore pressure effects, q_t, the sleeve friction, f_s, and the pore pressure, u_2, are plotted in Figure 1, 2 and 3, respectively.

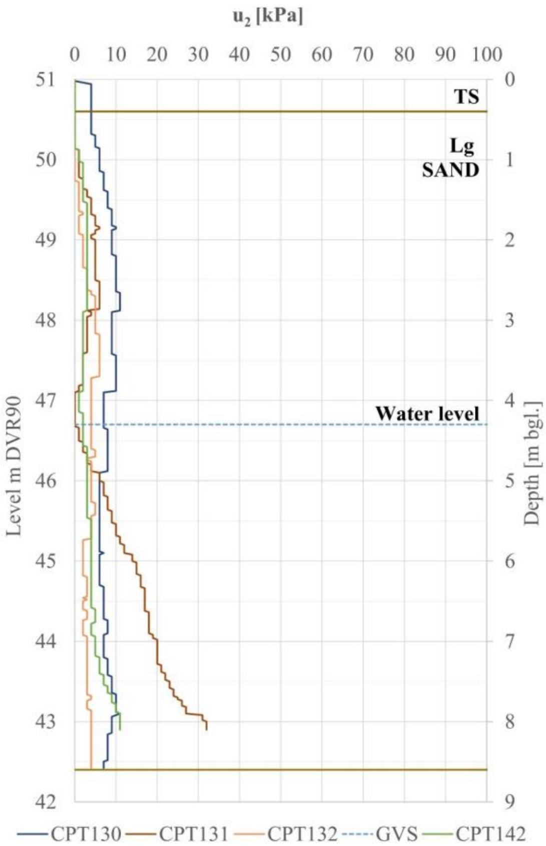

Figure 3. Pore pressure, u_2, plotted as a function of level (m DVR90).

3.3 *Soil Parameters*

The following parameters are assessed and compared using different methods presented in the literature for SPTs and CPTs: The density index (I_D), triaxial friction angle (φ'_{tr}) and oedometer modulus (E_{oed}). Please note, that the density index, I_D, is also designated the relative density, D_r.

4 COMPARISON & RESULTS

Below I_D, φ'_{tr} and E_{oed} are assessed and compared.

4.1 *Density index, I_D*

The density index, $I_{D,SPT}$, is assessed by SPT data and the expression provided in (German Institute for Standardization 1990) (see Eq. 2), as the expression is suitable for sand with a uniformity coefficient $C_u \leq 3$ and the Late Glacial meltwater sand is described as sorted to poorly graded.

$$I_{D,SPT} = \begin{vmatrix} 0.10 + 0.385 \cdot \ln(N_{60}) & \textit{above water table} \\ 0.18 + 0.37 \cdot \ln(N_{60}) & \textit{under water table} \end{vmatrix} \quad (2)$$

Combining CPT data and an expression from (Lunne T. & Christoffersen H.P. 1983) an estimate of the density index, $I_{D,CPT}$, for normal consolidated sands can be calculated (see Eq. 3). The expression was proposed by (Schmertmann J.H. 1978) and modified by (Lunne T. & Christoffersen H.P. 1983) based on a comprehensive database for sands mainly from large scale calibration chamber tests performed at several institutions. Eq. 3 is suitable for fine to medium normal consolidated uniform sand.

$$I_{D,CPT} = \left(\frac{1}{2.91}\right) \cdot ln\left(\frac{q_c}{61 \cdot \sigma'_{v0}{}^{0,71}}\right) \quad (3)$$

In Eq. 3 σ'_{v0} is the effective in-situ stress and q_c is the cone resistance. Furthermore, for normally consolidated uncemented and unaged sands (Jamiolkowski M., Ladd C.C., Germaine J.T. & Lancellotta R. 1985) suggested the expression in Eq. 4.

$$I_{D,CPT} = -98 + 66 \cdot \log_{10} \frac{q_c}{(\sigma'_{v0})^{0.5}} \quad (4)$$

The estimated I_D by use of Eq. 2 to Eq. 4 is plotted against the levels in Figure 4 for the Late Glacial meltwater sand.

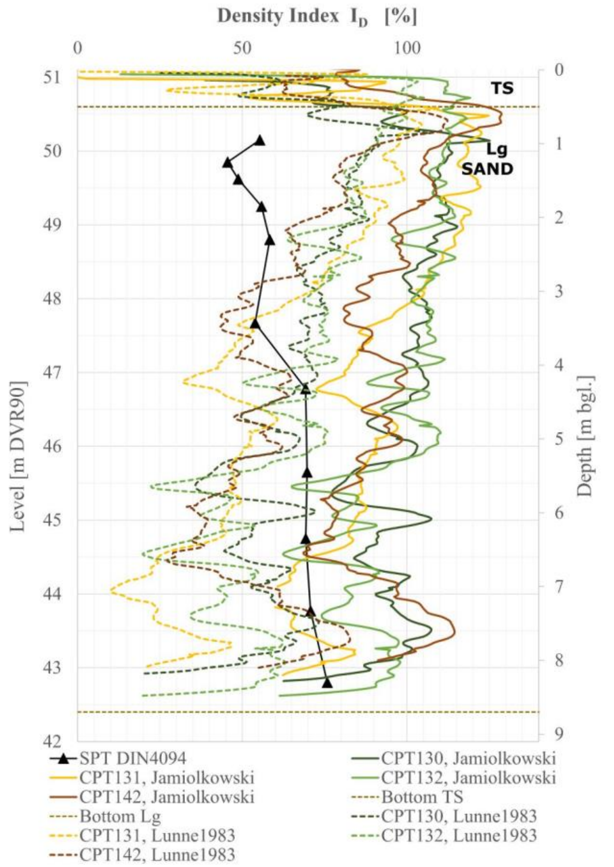

Figure 4. Density index, I_D, plotted as a function of level (m DVR90) and depth below ground level (m bgl.).

Based on Figure 4, Eq. 4 (Jamiolkowski M., Ladd C.C., Germaine J.T. & Lancellotta R. 1985) overestimate the density index, I_D, as it by definition can't be more than 100 %.

When comparing the I_D estimated by SPT and the expression given by (German Institute for Standardization 1990) and the I_D estimated by CPT and the expression by (Lunne T. and Christoffersen H.P. 1983), the I_D values seem to be contradictory until about 3 m bgl. showing no tendency for the I_D. Below level +46.7 m DVR90, corresponding to the recorded water level, the I_D estimated by SPT turns to a mean of the CPT values.

Therefore, the method presented in (German Institute for Standardization 1990) and Eq. 2 appear to give reliable values of the density index but tend to be conservative in the uppermost part of the layer.

4.2 *Triaxial friction angle, φ_{tr}*

In Denmark it is common practice to distinguish between the plane friction angle, φ'_{pl}, and the triaxial and thus axisymmetric friction angle, φ'_{tr}, for cohesionless soils. Below the triaxial friction angle is addressed.

The triaxial friction angle has been estimated based on SPT data and four different methods; (Dansk Standard 1984), (Stroud M.A. 1989), (Schmertmann J.H. 1978) and (Peck R.B., Hanson W.E. & Thornburn T.H. 1953) as presented below and in Figure 5.

The empirical expression cf. (Dansk Standard 1984) (see Eq. 5) can be applied for sand with relatively angular grains when estimating the peak triaxial friction angle applying the uniformity coefficient, C_u, and the density index, I_D. In (Eq. 5) the relation between the plane friction angle and the triaxial friction stated in (Danish Standard Foundations 2021) has been inserted. If the grains are rounded or the silt content of the deposit is 10% or higher, the friction angle in (Eq. 5) must be reduced accordingly; -2° for 10 % silt content, -5° for 20 % silt content and -3° if the grains are rounded.

$$\varphi'_{tr} = \frac{1}{(1+0.1\cdot I_D)}\left(33^o - \frac{3}{C_u} + \left(15 - \frac{4}{C_u}\right)\cdot I_D\right) \quad (5)$$

In this case study the grains in the Late Glacial meltwater sand are described as angular to sub angular and therefore, the friction angle is not reduced by -3°. Please note that the shape of the grains was only described in one (BH01) of the five relevant boreholes. As the stratigraphy encountered in all the boreholes was found to be quite similar this description of the grains was applied as prerequisite for all boreholes.

A comparable method is described in (Stroud M.A. 1989) whereas a relation between the peak triaxial friction angle, φ'_{tr}, and the number of blows, N_{60}, is proposed based on a critical state value of the friction angle of 33^0. (Stroud M.A. 1989) points out that this relation is very sensitive to the value of the friction angle of critical state, φ'_{cv}, and plots a relation between φ'_{cv} and particle shape. (Stroud M.A. 1989) highlights the typical values for φ'_{cv} as presented in Table 3.

Table 3. Values of critical state friction angle, φ'_{cv}, in relation to particle shape cf. (Stroud M.A. 1989).

	Particle shape	φ'_{cv}
Uniformly graded	Rounded	30°
	Sub rounded/ Sub angular	32°
	Angular	34°
	Very angular	36°
Well graded	Sub rounded	36°
	Angular	38°

Based on this, the critical state friction angle, and thus the friction angle, should be reduced by -2° to -4° if the grains are rounded (instead of angular) in the same way as in (Dansk Standard 1984). Although (Stroud M.A. 1989) will lead to higher friction angles as the "origin" friction angle of critical state for angular grains (as well as sub rounded/sub angular) is higher than the one in Eq. 5 by (Dansk Standard 1984) as $\frac{1}{(1+0.1\cdot I_D)}33° \approx \frac{33^0}{1.1} \approx 30^0$.

In contradiction to Eq. 5 by (Dansk Standard 1984) the friction angle in (Stroud M.A. 1989) should be increased by up to 5° if the sand is well graded and has angular grains. In this study the critical state friction angle for the Late Glacial meltwater sand is assumed to be $\varphi'_{cv} = 33^0$as a mean of φ'_{cv} for angular and sub angular grains.

(Schmertmann J.H. 1978) proposed a relation between the triaxial peak friction angle, the density index, the grading and the grain size. This relation is limited to the depth of an effective overburden stress $\sigma'_v \leq 150$ kPa corresponding to a depth of around 17 m bgl. at the case study location. The Late Glacial meltwater sand is assumed to comply with the assumptions by (Schmertmann J.H. 1978) for "fine sand" because the silt content generally is rather high at the location. The alternatives are *medium sand, coarse sand, gravel* and *gravel-sand-silt* whereas the latter is considered to relate to till material. The Late Glacial meltwater sand is classified as sorted to poorly graded. When estimating the triaxial friction angle using (Schmertmann J.H. 1978) the soils are classified as *uniform*, which was found more suitable than the alternative classification *well-graded*. Please note that the peak triaxial friction angle estimated from (Schmertmann J.H. 1978) is also proposed as a method for estimating the friction angle in (Danish Standard Foundations 2011) and by (US Army Corps of Engineers 1993).

(Peck R.B., Hanson W.E. & Thornburn T.H. 1953) proposed a relationship between the relative density, N_{60} and the friction angle for normal consolidated, NC, sands. The friction angle is a peak triaxial angle.

The estimated triaxial friction angle based on SPT data and (Dansk Standard 1984), (Stroud M.A. 1989), (Schmertmann J.H. 1978) and (Peck R.B., Hanson W.E. & Thornburn T.H. 1953) are plotted as a function of level at Figure 5.

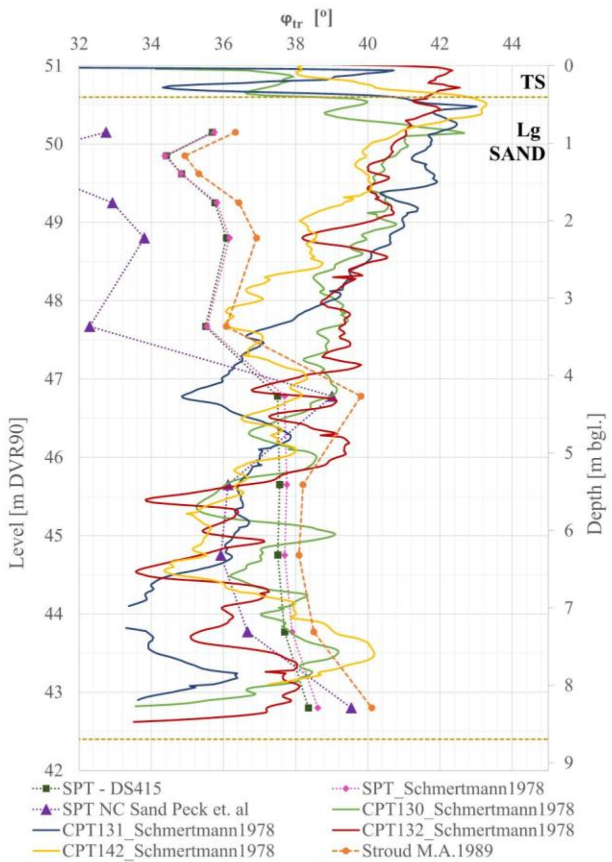

Figure 5. Estimated peak triaxial friction angle for the Late Glacial meltwater sand.

With regards to the CPTs, the peak triaxial friction angle is also estimated based on four CPT profiles and the method presented by (Schmertmann J.H. 1978). The calculated peak triaxial friction angles of the CPTs are presented in Figure 5 for the Late Glacial meltwater sand together with the triaxial friction angle estimated by the SPT.

Based on Figure 5, the peak triaxial friction angles estimated from the CPTs decreases with depth below ground level which comply with the findings in (Bolton M. D. 1986) and (Been K. & Jefferies M. G. 1985) describing that the friction angle decreases with increasing stress state. The same relation cannot be found for the estimated friction angles by use of SPT which is supported by the fact that (Dansk Standard 1984) do not take into account the relation between the friction angle and the stress state.

Between ground level and level +47 m DVR90 the friction angles estimated by use of the method (Peck R.B., Hanson W.E. & Thornburn T.H. 1953) with the SPT data are found to be relatively low.

The peak triaxial friction angle estimated by the SPTs and the expressions by (Dansk Standard 1984), (Schmertmann J.H. 1978) and (Stroud M.A. 1989) tend to give a mean value throughout the dept of the layer despite lower values in the top and high-end values in the deepest. It is noted that the methods (Dansk Standard 1984) and (Schmertmann J.H. 1978) lead to coinciding values based on the SPT.

4.3 *Oedometer modulus, E_{oed}*

(Stroud M.A. 1989) as reported in (Clayton C.R.I. 1995) suggests that for both normally consolidated and overconsolidated granular deposits, a reasonable approximation of the effective Young's Modulus for settlement calculation may be given by Eq. 6.

$$\frac{E'}{N_{60}} = 1 \quad [MPa] \tag{6}$$

According to (Clayton C.R.I. 1995) E'/N_{60} may rise to 2 MPa for normally consolidated sands while for overconsolidated materials the value of this ratio could be increased even more. Consequently, applying E'/N_{60}=1 MPa for normally consolidated sand is expected to be rather conservative. The effective Young's Modulus, E', estimated from the SPT data corresponds to an effective Young's Modulus at in-situ stress σ'_{v0}.

Based on the estimated Young's Modulus, the Oedometer Modulus can be derived using Eq. 7 and the Poisson's ratios, ν, which for the Late Glacial meltwater sand in this case study is evaluated to have a mean value of 0.28. Poisson's ratio is estimated by use of the expression for at rest earth pressure, K_0, in (Eq. 8) stated in (Danish Standard Foundations 2007) (taking OCR = 1), and subsequently the theory of elasticity has been applied cf. Eq 9. When estimating the at rest earth pressure the friction angle estimated by the SPT data and the expressions (Dansk Standard 1984), (Schmertmann J.H. 1978) and (Stroud M.A. 1989) have been applied.

$$E_{oed} = \frac{(1-\nu)E'}{(1-2\nu)(1+\nu)} \tag{7}$$

$$K_0 = (1 - \sin\varphi'_{tr}) \cdot OCR \tag{8}$$

$$\nu = \frac{K_0}{1+K_0} \tag{9}$$

In Figure 6 the oedometer modulus is plotted as a function of level applying Eq. 6 and subsequently Eq. 7.

(Lunne T., Robertson, P.K. & Powell J.J.M. 1997) have reviewed available calibration chamber tests and recommend the estimation of the drained constrained modulus M = E_{oed} stated in Eq. 10 for unaged and uncemented sands using CPT.

$$\begin{aligned} E_{oed} &= 4q_c && for\ q_c < 10\ MPa \\ E_{oed} &= 2q_c + 20\ MPa && for\ 10\ MPa < q_c < 50\ MPa \\ E_{oed} &= 120\ MPa && for\ q_c > 50\ MPa \end{aligned} \tag{10}$$

The application of Eq. 6 to Eq. 10 is plotted in Figure 6 for the Late Glacial meltwater sand. Generally, only a few methods exist for estimating the oedometer modulus from SPT and CPT in normal consolidated sands. Nevertheless, a good correlation between the E_{oed} estimated from SPT and the E_{oed} estimated from CPT is found. It seems that the method reported in (Clayton C.R.I. 1995) is not conservative (as indicated by (Clayton C.R.I. 1995)) but gives a rather good estimate for the oedometer modulus when comparing the results with the ones of the CPT and (Lunne T., Robertson, P.K. & Powell J.J.M. 1997).

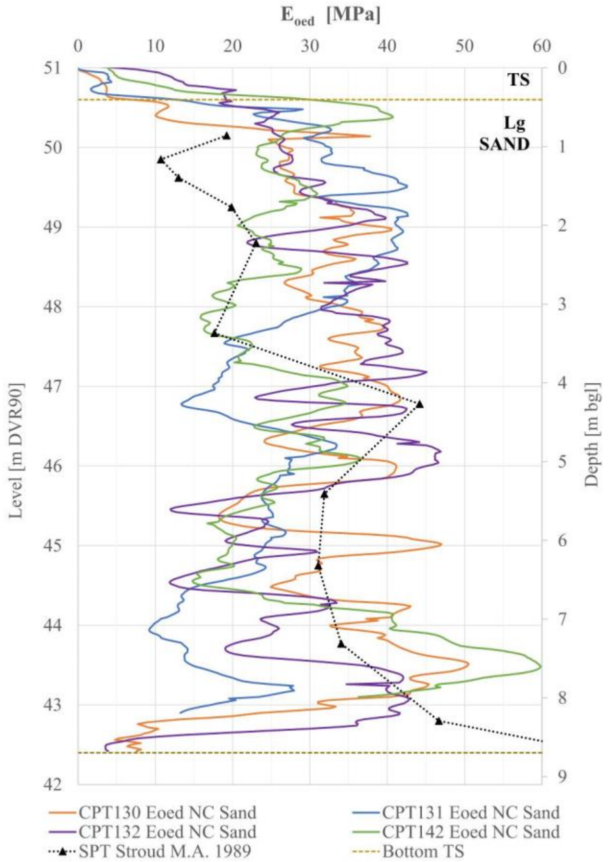

Figure 6. Estimated oedometer modulus based on Eq. 6 to Eq. 8 for the Late Glacial meltwater sand.

5 DISCUSSION AND FURTHER INVESTIGATION

The I_D estimated by SPT slightly increases with depth whereas the I_D estimated by CPT tends to decrease with depth (see Figure 4). Above level +48 m DVR90 the I_D by SPT is lower than the I_D by CPT, whereas the I_D estimated by SPT turns to a mean of the CPT values below level +46.7 corresponding to the recorded water level. As both the I_D estimated by SPT and CPT take the water level into account, and thus the change in effective in-situ stress, σ'_{v0}, the expressions for estimating the I_D above the water level must be studied further as no tendency between the I_D's by SPT and CPT was found.

The empirical expression cf. (Dansk Standard 1984) (see Eq. 5), is a method which is widely applied when estimating the triaxial friction angle for Danish sand material. Nevertheless, in practice many Danish geotechnical engineers reduce the estimated triaxial friction angle from Eq. 5 further, which based on the findings in this article is too conservative. It is found that the expression in (Dansk Standard 1984), (Schmertmann J.H. 1978) and (Stroud M.A. 1989) tend to give a mean value despite lower values in the top and high-end values in the bottom.

(Dansk Standard 1984) do not include the relation between the friction angle and the stress state which is out most relevant and should be investigated.

(Dansk Standard 1984) and (Stroud M.A. 1989) state that the friction angle should be reduced by -2° to -4° if the grains are rounded. Therefore the geologists or geotechnical engineers' description of the grains are of great importance. It can be discussed if it is reasonable that the often subjective decision by a geologist of whether the grains are rounded or angular should haves an impact of the friction angle of up to 3°.

The method presented by (Lunne T., Robertson, P.K. & Powell J.J.M. 1997) for estimating the oedometer modulus, E_{oed}, (Eq 10) is frequently used among Danish geotechnical engineers. Figure 6 shows that this expression then to give mean value when relating to the E_{oed} estimated by SPT which shows a bigger variation. Nevertheless, the number of methods for estimating the oedometer modulus with SPT and CPT data in normal consolidated sands are few and further studies is recommended.

6 CONCLUSIONS

In this article, normally consolidated Danish Late Glacial meltwater sand described as *fine to coarse, sorted to poorly graded, sl. silty to silty, sl. gravelly to gravelly, grains are angular to sub angular, non-calcareous* was assessed with SPT and CPT data.

The following parameters were studied and compared using different methods presented in the literature for SPTs and CPTs: The density index (I_D), the triaxial friction angle (φ'_{tr}) and oedometer modulus (E_{oed}).

The density index, I_D, was estimated by SPT data and the expression in (German Institute for Standardization 1990) as well as CPT data and the expressions proposed by (Lunne T. & Christoffersen H.P. 1983) and (Jamiolkowski M., Ladd C.C., Germaine J.T. & Lancellotta R. 1985).

It was found that the expression proposed by (Jamiolkowski M., Ladd C.C, Germaine J.T. & Lancellotta R. 1985) overestimates the density index, I_D, as it by definition can't be more than 100%.

The expressions for estimating the I_D above the water level must be studied further as no tendency between the I_D's by SPT and CPT was established. However, the method presented in (German Institute for Standardization 1990) appears to give mean values that can be applied as a fair estimate throughout the depth tending to slightly underestimate the I_D in the uppermost layers.

The triaxial friction angle was estimated based on SPT and four different methods presented in the literature; (Dansk Standard 1984), (Stroud M.A. 1989), (Schmertmann J.H. 1978) and (Peck R.B., Hanson W.E. & Thornburn T.H. 1953). Furthermore, the triaxial friction angle was also estimated based on four CPT profiles and the method presented by (Schmertmann J.H. 1978).

Based on the data presented in this paper, it was determined that the friction angles estimated from the CPTs decrease with depth, which complies with the findings in (Bolton M. D. 1986) and (Been K. & Jefferies M. G. 1985). Contrary this is not the case for the friction angles estimated by the SPT data.

In general, it was found, that (Dansk Standard 1984), (Schmertmann J.H. 1978) and (Stroud M.A. 1989) tend to give a mean value, however, rather low values were encountered in the uppermost part of the layer and high-end values were achieved in the lowermost part of the sand layer. A relation between the stress state (and thus the depth below ground level) and the friction angle estimated by (Dansk Standard 1984) and (Stroud M.A. 1989) should be subject for further investigation.

In terms of the oedometer modulus, a good correlation between the E_{oed} estimated with SPT data and CPT data was found. It seems that the method reported in (Clayton C.R.I. 1995) is not conservative (as indicated by in (Clayton C.R.I. 1995)) but gives a rather good estimate for the oedometer modulus when comparing the results with the ones of the CPT and (Lunne T., Robertson, P.K. & Powell J.J.M. 1997).

The number of methods for estimating the oedometer modulus with SPT and CPT data in normal consolidated sands are few and further studies is recommended.

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