Evaluation of undrained shear strength of Swedish fine-grained sulphide soils

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Abstract

In Swedish practice, there is a long tradition of evaluating undrained shear strength from fall-cone tests and field vane tests. During the last 20 years cone penetration tests have also become widely used. However, the results from all these test methods have to be evaluated using empirical factors. The factors generally used for Swedish clays are related to liquid limit and overconsolidation, but they are not applicable to all types of fine-grained soils and can often be improved by local calibration for the particular type of soil in the area of current interest. For this calibration, the results of direct simple shear tests and/or triaxial tests in the laboratory are normally used. This paper presents an evaluation for Swedish fine-grained sulphide soils, for which a general correction factor of 0.65 for field vane tests and fall-cone tests, a cone factor N c of 20.2 for cone penetration tests and a relation N c/σ ′ cu = (OCR ′ −0.2) of 0.28 have been found. No correlations were found between these empirical factors and the clay content, liquid limit or organic content, but a relationship was found between the overconsolidation ratio and both the cone penetration test and the field vane test. The sulphide soils in question are found in northern Sweden along the coast of the Gulf of Bothnia. They are mostly classified as organic silt or organic clay, which is normally silty.

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1. Introduction

A major task in geotechnical engineering is to establish geological and geotechnical models on the basis of empirical knowledge and a limited but sufficient number of tests. The geotechnical model forms a basis for idealized geomechanical models. For relatively young, saturated glacial and post-glacial fine-grained sediments, the main parameter in the ultimate limit state design or stability assessment of existing structures or slopes is the undrained shear strength (c u). However, c u is not a fundamental soil property but depends on factors such as the stress state, strength anisotropy, and strain rate, making it difficult to assess for failure domains where these factors vary. Advanced laboratory tests can be performed, but the number of tests may be extensive and costly. For most geotechnical applications, it is considered sufficient to evaluate strength parameters from in-situ soundings and relatively simple laboratory tests. Theoretical methods for the evaluation of c u from cone penetration tests (CPTs), field vane tests (FVTs) and fall-cone tests (FCs) on undisturbed samples have been developed (e.g. Teh and Houlbsy, 1991; Su and Liao, 2002; Morris and Williams, 1994, 2000; Houlbsy, 1982; Koumoto and Houlbsy, 2001). However, theoretical approaches generally suffer from a number of limitations making theoretical evaluations from different test methods difficult (e.g. Low et al., 2010; Casey and Germaine, 2013) and there is still a need for empirical correlations between test results and c u evaluated from well-defined reference tests. Like other empirical interpretation of geotechnical information, such correlations are still useful especially for low to moderate risk projects (Robertson, 2012).

Sulphide soils predominantly occur in tropical areas around the world but they also occur in the coastal areas around the Gulf of Bothnia in Sweden and Finland, Fig. 1a. These sulphide soils are fine-grained and have a relatively high organic content. According to Swedish practice, c u of inorganic clays is evaluated from CPT, FVT and FC through empirical relations according to Table 1. Sulphide soils have previously also been evaluated using these relations, but the results were then often inconsistent and differed from experience and more accurate determinations (Westerberg et al., 2005). Alternatively an empirical factor of 0.5, which is a conservative and lower boundary value for organic soils (Larsson, 1990), has been used for FCs and FVTs. There is thus a need for reliable correlations between a reference method and the commonly used CPT, FVT and FC.

The purpose of this study is to determine the relationships between c u evaluated from direct shear tests (DSSs) and results evaluated from CPTs, FVTs, FCs and the preconsolidation pressure (σ ′ pc) assessed from...
constant rate of strain tests (CRSs) of Swedish fine-grained sulphide soils. Results from five main sites were investigated, but results from three earlier investigations were also included in the analyses. The study was performed with the assumption that the evaluated \( c_u \) from DSSs can be considered as a reference value, which is common practice in Sweden. Many researchers have proposed empirical correlations related to various geotechnical parameters, and the results in this study were therefore analysed with respect to clay content, liquid limit (\( w_L \)), overconsolidation ratio (OCR), and organic content. The first three properties may affect the relations for inorganic clays and often also for organic soils.

2. Historical background

The FVT is traditionally used to determine \( c_u \) in many countries, e.g. Canada, USA, Japan, Norway, and Sweden. More recently, the CPT has also become widely used. In Sweden, the FC has been used in the laboratory for almost 100 years (SJ, 1922) and FVT has been used since the 1940s. Different reference methods have been used to calibrate empirical factors, e.g. the correction factors \( \mu \) for the evaluation of \( c_u \) from FCs and FVTs and the cone factors \( N_{kt} \) from CPTs. Ideally, the results from full-scale field tests and failures are used as references (e.g. Schwab, 1976; Larsson, 1980; Azzouz et al., 1983), but this is not usually possible and, in most cases, the correction must be based on results from reference tests in the laboratory. The results from triaxial tests and DSSs have been considered to be reliable and relevant (e.g. Larsson, 1980). The results from triaxial compression tests are relevant for the special case of active shear, whereas the results from DSSs are considered to be relevant for both direct shear in a horizontal plane and the average stress along a failure surface including approximately equal parts of active and passive shear (e.g. Ladd and Foott, 1974; Graham, 1979; Larsson, 1980; Ladd, 1991). DSSs are therefore often used as reference tests in Sweden.

The evaluation of \( c_u \) from FCs in Sweden has been revised many times over the years, mainly in connection with the introduction of new samplers yielding a better sample quality. When the Swedish standard piston sampler was developed in the 1950s (and finally finished in 1961), the FC was calibrated to yield the same \( c_u \) as the FVT (Hansbo, 1957). Empirical factors based on \( w_L \) were introduced by the Swedish Geotechnical Society, SFG, in 1960 (SGF, 1960). More recently, both types of tests have been calibrated against DSSs (Larsson et al., 2007b). The correction of measured strength from FVTs has been further developed including the relation between the in situ effective

### Table 1

<table>
<thead>
<tr>
<th>No</th>
<th>Equation</th>
<th>References and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( c_u = \mu \tau )</td>
<td>Larsson et al. (1984), Larsson et al. (2007b). For FC and FVT respectively, where ( \tau ) and ( \tau_v ) are the uncorrected values from FC and FVT.</td>
</tr>
<tr>
<td>2</td>
<td>( c_u = \mu \tau_v )</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( \mu = \left( \frac{w_L}{C_1} \right)^{0.45} \geq 0.5 )</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>( c_u = \left( \frac{\tau}{w_L} \right)^{0.45} \left( \frac{\tau_v}{w_L} \right)^{-0.15} )</td>
<td>Larsson et al. (1984), Larsson et al. (2007b). For uncased soils. In overconsolidated soils (OCR &gt; 1.3), a correction for OCR is included for FVT.</td>
</tr>
<tr>
<td>5</td>
<td>( c_u = \frac{\sigma_{cr}}{\tau} )</td>
<td>Larsson et al. (2007b). For CPT in normally consolidated soils.</td>
</tr>
<tr>
<td>6</td>
<td>( c_u = \frac{\sigma_{cr}}{\tau} \left( \frac{\tau}{\sigma_{cr}} \right)^{-0.2} )</td>
<td>Larsson et al. (1984), Larsson et al. (2007b). For CPT in overconsolidated soils (OCR &gt; 1.3).</td>
</tr>
<tr>
<td>7</td>
<td>( c_u = a \sigma_{cr} \left( OCR^{-1} \right)^{-1 - b} )</td>
<td>Larsson et al. (2007b). For ( \sigma_{cr} ) assessed from CRS. The factor ( a ) is dependent on the soil type and on the mode of shear. The factor ( b ) typically varies between 0.7 and 0.9.</td>
</tr>
<tr>
<td>8</td>
<td>( a = 0.125 \left( 0.205 w_L \right) / 1.17 )</td>
<td>Larsson et al. (2007b). Factor ( a ) for direct shear.</td>
</tr>
</tbody>
</table>
vertical stress $\sigma'_{v0}$ and $\text{OCR}$ (Morris and Williams, 1994; Aas et al., 1986; Chung et al., 2007, 2010, 2012), and OCR (Larsson and Åhnberg, 2003, 2005).

Values of $\text{OCR}$ evaluated from DSSs have also been used for the calibration of $N_k$ used to derive $\text{OCR}$ from measured net cone resistance ($q_{net}$) assessed from CPTs (e.g. Larsson and Mulabdic, 1991; Larsson and Åhnberg, 2003, 2005). For inorganic clays in Sweden, the relation between $\text{OCR}$ and $q_{net}$ ($q_{net} = q_t - \sigma'_{v0}$), where $q_t$ is total cone resistance and $\sigma'_{v0}$ is total overburden pressure, has been found to be dependent on $w_L$ and OCR, as proposed by Larsson and Åhnberg (2003, 2005), Table 1.

Strain rate, creep, yield stresses, and anisotropy affect the results from FVTs as well as from CPTs (e.g. Chung et al., 2007; Larsson et al., 2010). However, as long as the tests are performed at a standard shear rate and with a standard mode of shear, the evaluation inherently takes these effects into account.

The assessment of $\text{OCR}$ from $\sigma'_{c}$, also requires an empirical factor taking into account several parameters such as the shear rate, the mode of shear, and the type of soil material. It is commonly suggested that $\text{OCR}$ is related to $\sigma'_{c}$ and OCR (e.g. Ladd and Foott, 1974; Jamiolkowski et al., 1985; Larsson and Åhnberg, 2003), Table 1.

Organic soils are usually included in the common evaluation methods for fine-grained soils (e.g. Bihs et al., 2010; Bajda and Skutnik, 2010; Mlynarek et al., 2006; Lechowicz and Szymanski, 2001). However, experience and a more general investigation of the behaviour of organic soils (e.g. Larsson, 1990) have shown that some organic soils and particularly sulphide soils often do not fit into this pattern. Schlu et al. (2010) have proposed new shear rate dependent factors of FVT to evaluate $\text{OCR}$ of organic mud. However studies related to organic soils are considerably fewer than those

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**Fig. 2.** Soil properties, stresses, net cone resistance and uncorrected strength at the sites: a) Gammelgården, b) Sunderbyn, c) Hjoggböle, d) Västerslätt and e) Umeå bangård.
on inorganic soils, and site-specific correlations are needed for organic soils (Saye et al., 2013).

3. Methods

The test results from the FCs, the FVTs, the CPTs, and CRSs were compared to values of \(c_u\) obtained from DSSs on soil samples taken at the test sites. The samples were taken with a Swedish standard piston sampler (SGF, 1996). Empirical factors \(\mu, N_k, a\) fitting the relations stated in Table 1 were assessed from these comparisons. The results were then analysed in order to investigate the occurrence of correlations between these empirical factors and the properties clay content, \(w_c\), OCR, and organic content.

At the sites, CPTs and FVTs were performed in situ and laboratory tests in the form of DSSs, FCs, and CRSs (in order to determine \(\sigma'_c\)) were made on undisturbed samples taken at the sites. All tests were made according to Swedish standard practice (SS 027125, 1991; SS 027126, 1991; SGF, 1993a, 1993b; SGF, 1996, and SGF, 2004). Swedish routine testing on clay samples, to determine bulk density \(\rho\), natural water content \(w_h\), \(w_l\) and sensitivity \(S_t\), and soil type classification was also performed. The organic content was determined by analyses of the total organic carbon content (TOC), and the total sulphur and total iron contents were also determined.

In the DSSs, the test specimens were consolidated for 0.85 \(\sigma'_c\) followed by unloading to the in situ stresses before they were sheared in undrained conditions. This is the normal procedure in Sweden, to reconsolidate the samples and to avoid seating errors without the risk of increasing the strength of the samples. The DSSs were conducted at room temperature (about +20 °C), and evaluated according to Swedish standard (SS 027127, 1991), and \(c_u\) was evaluated as the shear stress at an angle of distortion of 0.15 rad (unless a peak-value was obtained at a lower shear strain). The limit of 0.15 rad is in accordance with Swedish practice. In Sweden, CRSs are performed according to SS 027126 (1991). The normal rate of compression of the 20 mm high test specimen is 0.6%/h, but the rate is decreased in cases where the pore pressure at the undrained end exceeds 15% of the applied vertical pressure and it may be increased if the pore pressure is too low to evaluate the permeability and coefficient of consolidation.

### Table 2

Properties and classified soil types for the sulphide soils at the sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Gammel-gården</th>
<th>Sunderbyn</th>
<th>Hjoggböle</th>
<th>Västerslätt</th>
<th>Umeå bangård</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main investigated depth (m)</td>
<td>2–12</td>
<td>2–5</td>
<td>2–5</td>
<td>2–10</td>
<td>2–8</td>
</tr>
<tr>
<td>OCR</td>
<td>(\approx 8)</td>
<td>(\approx 10)</td>
<td>(\approx 14)</td>
<td>4–11</td>
<td>(\approx 9)</td>
</tr>
<tr>
<td>Classified soil type</td>
<td>Organic sulphide clay/clayey sulphide gyttja</td>
<td>Organic sulphide clay</td>
<td>Organic sulphide clay/organic sulphide silt</td>
<td>Organic sulphide silt (and as organic sulphide clay below 10 m depth)</td>
<td>Organic sulphide silt</td>
</tr>
</tbody>
</table>
4. Sulphide soils and test sites

4.1. General properties of sulphide soils

Sulphide soils are common along the coast of the Gulf of Bothnia, i.e. in the north-eastern parts of Sweden over a distance of about 900 km and also in the north-western parts of Finland, Fig. 1a. These sulphide soils were formed during the last 8000 years, as fine-grained sediments settled at river mouths and at areas near the coast in brackish/fresh water, where the environment was deficient in oxygen (Mácsik, 1994). The environment prevented a complete decomposition of the organic material and iron monosulphide (FeS) and pyrites (FeS₂) were formed. Sulphide soils generally consist of organic matter and iron sulphides in addition to clay and silt particles (Pusch, 1973; Larsson, 1990). According to the Swedish classification, a soil is designated as an inorganic mineral soil when the organic content is less than 2%, as an organic mineral soil when it is between 2 and 6%, as a mineral organic soil when it is 6–20%, and as an organic soil when it is 20% or higher (Karlsson and Hansbo, 1984). The investigated sulphide soils were classified from organic silt to organic clay and, in cases with higher organic contents, as silty gyttja or clayey gyttja. Sulphide soils found in other parts of the world may differ in origin, deposition and composition from the sulphide soils found along

Fig. 3. Plots of $c_{u,DSS}$ versus data obtained from a) FCs, b) FVTs, c) CPTs, d) CPTs with correction for OCR and e) $\sigma'_c$ from CRS.
the Gulf of Bothnia, and the mechanical properties, including the empirical factors suggested in the present study, may therefore differ.

Typical ranges for some properties of the sulphide soils found in Sweden around the Gulf of Bothnia are: total sulphur content 0.1–2% of dry weight; total content 2–7% of dry weight; $w_g = 50–150\%$; and $\rho = 1.3–1.7$ t/m$^3$. Typically $c_u$ is 10–20 kPa. Sulphide soils are in general very compressible and show significant creep behaviour. The organic matter and iron sulphides are believed to contribute to the open structure of the material, hence; the relatively low $\rho$ and high $w_N$.

$N$-values are typically 5–150%; and $\rho = 1.3–1.7$ t/m$^3$. Typically $c_u$ is 10–20 kPa. Sulphide soils are in general very compressible and show significant creep behaviour. The organic matter and iron sulphides are believed to contribute to the open structure of the material, hence; the relatively low $\rho$ and high $w_N$.

4.2. Test sites

Investigations were performed at five sites within a distance of about 350 km along the north-eastern coast line of Sweden, from Kalix in the north to Umeå in the south, Fig. 1b. The properties of the tested soils vary but their geological histories are similar. The sites are designated, with the nearest city in parentheses, Gammelgården (Kalix), Sunderbyn (Luleå), Hjoggböle (Skellefteå), Västerslätt (Umeå) and Umeå bangård (Umeå), Fig. 1b. Gammelgården is located in sloping terrain in the Kalix river valley, whereas Sunderbyn is located in an area with level ground in the Luleå river valley, close to Road 97. The Hjoggböle site is located in a slightly inclined terrain near Road 364, far from any river, and the Västerslätt and Umeå bangård sites are located in an area with a level ground surface in the Umeå river valley, about 1 km apart.

4.3. Geotechnical soil properties

4.3.1. General soil properties

A selection of results from the site investigations of the sulphide soils found at the five sites is presented in Fig. 2, where the soil properties $\rho$, $w_g$, $w_l$, organic content, iron content and sulphur content are presented. Vertical preconsolidation pressures ($\sigma_{vc}$) assessed from CRSs, $\sigma_{vo}$, $q_{net}$, $\tau_c$, $\tau_v$ and $c_u$ assessed from DSSs are also included. Table 2 shows the soil classification for the five sites.

Variations in the properties with depth at the site are generally quite large and the properties may also vary at a given depth due to the varved stratification. As seen in Fig. 2, the values of $\rho$ and $w_N$ are influenced by the organic content, a high organic content giving rise to a low value of $\rho$ and a high value of $w_N$. The iron content and sulphur content together are generally slightly higher than the organic content.

At the five sites, the soil is overconsolidated with respect to $\sigma_{vo}$ throughout the soil profiles, the lowest OCR ($=\sigma_{vc}/\sigma_{vo}$) being 1.1–1.2 at Gammelgården and the highest being 6.7 at Hjoggböle. The trends for $\sigma_{vc}$ and $\sigma_{vo}$ with depth vary between the sites, the highest OCR values of about 3–6 being in the upper parts of the soil profiles. When the CRS results are compared with the criteria for the evaluation of sample disturbance proposed by Lunne et al. (1997), the results range from “very good to excellent” to “good to fair”. The rate of compression in the CRSs varied between 0.6 and 1.3%/h.

4.3.2. Strength data

At all the sites except Hjoggböle, the $c_u$ values obtained from the DSSs ($c_u$, DSS) are significantly lower than the corresponding values of $\tau_c$ and $\tau_v$, and the variations of these properties with depth are similar at each site. The variation of $q_{net}$ with depth is similar to that of $c_u$.

![Fig. 4. Evaluated $c_u$,DSS/$\tau_c$ from FCs as functions of a) clay content, b) $w_g$, c) organic content, and d) OCR.](image-url)
from the DSSs at the five sites. The $c_u$ value was evaluated as the shear stress at an angle of distortion of 0.15 rad for most of the DSSs. For a few tests, a peak-value was obtained at a distortion angle of between 0.10 and 0.15 rad.

5. Results and discussion

In Fig. 3, $\tau_c$, $\tau_v q_{\text{net}}$ (with and without correction for OCR), and $\sigma'$, OCR$^{0.2}$ are plotted against corresponding values of $c_{u,DSS}$. In each diagram, the best fit linear regression lines (black lines) are presented together with the upper and lower 95% confidence intervals for these regression lines (dashed lines, assuming Student's t distributions) and with $\rho_c$ as the coefficient of correlation. Taking the averages of all data points for each method, $c_{u,DSS}/\tau_c = 0.65$ was obtained for the FCs, $c_{u,DSS}/\tau_v = 0.65$ for the FVTs, $q_{\text{net}}/c_{u,DSS} = 20.9$ for the CPTs, $q_{\text{net}}/(\text{OCR}/1.3)^{0.2}/c_{u,DSS} = 20.2$ for the CPTs with correction for OCR, and $c_{u,DSS}/(\sigma'/\text{OCR}^{0.2}) = 0.28$ (assuming $b = 0.8$) for $\sigma'$, assessed from CRSs. In the figures, the dashed dotted lines show these relationships.

As seen in Fig. 3, the confidence intervals are relatively narrow and the dashed dotted lines for CPTs (with and without correction for OCR) and for $\sigma'$, assessed from CRS lie within these intervals, while the dashed dotted lines representing FC and FVT lie, at least in part, outside the confidence intervals. This indicates that the empirical factors given above for the assessment of $c_{u,DSS}$ based on $q_{\text{net}}$ obtained from CPTs and on $\sigma'$, assessed from CRSs (i.e. $N_{kt} = 20.9$, $N_{kr} = 20.2$ and $a = 0.28$) are valid over a large stress interval, whereas the empirical factors for FC and FVT (i.e. $\mu_c = 0.65$, $\mu'_c = 0.65$) show less consistency with stress level indicating that these latter factors may be dependent on the stress level.

Figs. 4 to 8 show the empirical factors, $c_{u,DSS}/\tau_c$ for FC, $c_{u,DSS}/\tau_v$ for FVT, $q_{\text{net}}/c_{u,DSS}$ for CPTs, $q_{\text{net}}/(\text{OCR}/1.3)^{0.2}/c_{u,DSS}$ for CPTs with correction for OCR, and $c_{u,DSS}/(\sigma'/\text{OCR}^{0.2})$ plotted against clay content, $w_L$, organic content, and OCR, in order to investigate whether there are any correlations with these properties. In Figs. 3 to 8 evaluated data reported in Larsson et al. (2007a) from three other sites with sulphide soils (Gideåbacka, Teg and Rödäng) are also included. In the figures, the best fit linear regression lines (black lines) are presented together with the upper and lower 95% confidence intervals for these regression lines (dashed lines, assuming Student's t distributions) and dashed dotted lines representing the empirical factors suggested above. For FC (Fig. 4), no significant correlations were found and the hypothesis of a constant value of $\mu_c = 0.65$ cannot be rejected at the 95% level of confidence. The same holds for FVT (Fig. 5) with the exception of OCR, and the hypothesis of a constant value of $\mu'_c = 0.65$ cannot be rejected at the 95% level of confidence. For CPT without correction for OCR (Fig. 6), there seem to exist (albeit rather vague) correlations with $w_L$, organic content and OCR. However, when CPT has been corrected for OCR (Fig. 7) no significant correlation with any of the studied parameters can be observed, and the hypothesis of a constant value of $N_{kt} = 20.2$ cannot be rejected at the 95% level of confidence. For CPT with correction for OCR (Fig. 6), there seem to exist (albeit rather vague) correlations with $w_L$, organic content and OCR. However, when CPT has been corrected for OCR (Fig. 7) no significant correlation with any of the studied parameters can be observed, and the hypothesis of a constant value of $N_{kt} = 20.2$ cannot be rejected at the 95% level of confidence. For CPT with correction for OCR (Fig. 6), there seem to exist (albeit rather vague) correlations with $w_L$, organic content and OCR. However, when CPT has been corrected for OCR (Fig. 7) no significant correlation with any of the studied parameters can be observed, and the hypothesis of a constant value of $N_{kt} = 20.2$ cannot be rejected at the 95% level of confidence.

The results shown in Fig. 9 have been evaluated both in accordance with Swedish practice for fine-grained soils with a correction for $w_L$ (denoted Corr $w_L$; Table 1) and in accordance with the correction factors,
cone factors and empirical factors proposed for sulphide soil; for FCs 0.65, for FVTs 0.65, for CPTs 20 with a correction for OCR, and for $\sigma'_c$ assessed from CRSs with $a = 0.28$. The results of the FCs, FVTs, CPTs and $\sigma'_c$ assessed from CRSs agree better with the results of the DSSs than the results obtained following Swedish practice for fine-grained soils, Fig. 9a–d. Since there is no correlation with $w_L$ for the empirical factors for FCs, FVTs, CPTs and $\sigma'_c$ assessed from CRSs, Figs. 4–8, it can be expected that the empirical equations for inorganic soils (Table 1) will not be applicable to sulphide soils. For $c_u$-values higher than about 25 kPa, a correction factor of 0.65 for FVTs does not fit the DSS results, suggesting that the correction factor depends on the stress level. There may also be other factors, such as stratification and sample disturbance, which affect the correlations between strength evaluated from DSS and strength from FCs, FVTs, CPTs and $\sigma'_c$ assessed from CRSs. There is thus a need for more detailed experimental data in order to assess and explain possible correlations with other factors in the case of sulphide soils.

Experience from Swedish inorganic clays says that for OCR corrections should be made for strength values obtained from CPTs and FVTs but not for values from FCs, and that the correction is larger for CPTs (Larsson and Åhnberg, 2003, 2005). The results of the present study for sulphide soils also indicate that there are dependence on OCR for strength values from CPTs and from FVTs. A possible explanation of the correlation between empirical factors obtained from CPTs and from FVTs and OCR could be the different modes of deformation and effective stress paths developed during the shearing in the tests. For the CPT, the penetration of the cone causes the soil to be displaced (predominantly) horizontally (Larsson et al., 2010; Löfroth, 2008), and the mass displacement is large. This leads to increases in the total horizontal stress and in the excess pore pressure. The pore pressure increase is at first lower than the increase in total horizontal stress, and this leads to an increase in the effective horizontal stress. With increasing deformation, the effective horizontal stress finally reaches the horizontal preconsolidation pressure. From this stage on, the increase in pore pressure corresponds to the increase in total horizontal stress, since the effective yield stress cannot be exceeded in undrained conditions, and the effective horizontal stress remains equal to the horizontal preconsolidation pressure (Larsson, 1977; Larsson et al., 2010). The vertical stresses below the cone also increase, but the horizontal preconsolidation pressures govern the behaviour of the soil at cone penetration. In CPTs, the effective horizontal stresses thus correspond to those in a normally consolidated state and the total cone resistance depends on this. The strength evaluated from cone resistance measured in a normally consolidated state should therefore be corrected for the change in strength that occurs when the soil is unloaded and becomes overconsolidated. The evaluated $c_u$ value should thus be adapted to correspond to the prevailing stress state in situ.

In the FVT, the mass displacement is less than in the CPT when the vane is inserted. In inorganic clays, the $c_u$ values also have to be corrected for OCR. In organic soils such as sulphide soils, the soil is less rigid and this leads to a relatively smaller increase in horizontal stress during installation of the vane than with inorganic clay. The test is therefore performed at the natural state of consolidation and the need for correction is less significant. For the FC, there is so far no research showing that a correction should be made for OCR in any type of soil. For the studied sulphide soils, none of the three constituent parts (i.e. the soil particles consisting of clay minerals, organic matter and iron sulphides) seem to significantly affect the empirical factors needed for the assessment of $c_u$ from the results of the methods investigated. Nor is there any obvious relation to $w_L$ or the organic content. However,
both the organic content and the clay content probably influence the empirical factors, and the sulphide soil can be expected to behave like a soil intermediate between a mineral (inorganic) soil and an organic soil, which is supported by the following comparisons: The calibrated $N_{kt}$ of 20.2 for CPTs when correcting for OCR, is approximately the average of the typical values of around 16 for inorganic clays and around 24 for gyttja (Larsson, 2007). The resulting

$$
\mu_{C} = \mu_{V} = 0.65 \text{ for } F C \text{ and } F V T \text{ with } 
$$

also approximately the average of the typical values of about 0.8 for inorganic clays and 0.5 for soils with a high organic content (Larsson et al., 2007b; Larsson, 1990). The factor

$$
cu_{DSS} = 0.28
$$

is approximately the average of the typical values of about 0.22 for inorganic clays and 0.4 for organic soils (Larsson, 1990). The deformation at failure for the DSSs on sulphide soils was larger than that normally obtained for inorganic clays, which is a typical undrained behaviour for soils containing organic material and a higher silt content (Yu, 1993).

6. Conclusions

For Swedish fine-grained soils classified as sulphide soils, the measured strength values from FCs and FVTs should be corrected by a factor $\mu = 0.65$ according to

$$
c_{u} = 0.65r_{c,V}
$$

where $c_{u}$ is the undrained shear strength corresponding to a direct shear mode, and $r_{c,v}$ is the strength value obtained from FCs ($r_{c}$) or FVTs ($r_{v}$). However, care should be taken when using this relationship for FVTs for higher stresses since the appropriate correction factor can be dependent on the stress level.

For CPTs, $c_{u}$ (corresponding to a direct shear mode) should be evaluated using a cone factor of $N_{kt} = 20.2 \approx 20$ and a correction for the overconsolidation ratio OCR according to

$$
c_{u} = q_{t} - \sigma_{vo} = \frac{(OCR-0.2)}{20} c_{u,DSS}
$$

where $q_{t}$ is the total cone resistance and $\sigma_{vo}$ is the total overburden pressure.

For a vertical preconsolidation pressure, $\sigma_{vo} = \sigma_{c}$, assessed from CRSs, $c_{u}$ (corresponding to a direct shear mode) should be evaluated as

$$
c_{u} = 0.28\sigma_{c}OCR^{-0.2}
$$

The results of the FCs, FVTs, CPTs and $\sigma_{c}$, assessed from CRSs, evaluated in accordance with the factors proposed for sulphide soils, agree better with the results of the DSSs than the results obtained following Swedish practice for fine-grained soils with a correction for $w_{L}$.

No correlations were found between the empirical factors for FCs, FVTs, CPTs and $\sigma_{c}$ assessed from CRSs, and the clay content, $w_{L}$, or organic content, but there was a relation to the OCR for the CPTs and the FVTs.

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Fig. 8. Evaluated $c_{usds}/(\sigma'_{c} \cdot OCR^{-0.2})$ as functions of a) clay content, b) $w_{l}$, c) organic content, and d) OCR.

References


Fig. 9. Plots of the corrected strength $c_{u,corr}$ in accordance with $w_0$ for inorganic clays (Table 1) and in accordance with empirical factors proposed for sulphide soil versus $c_{u,DSS}$ for a) FCs 0.65, b) FVTs 0.65, c) CPTs (with correction for OCR), and d) $\sigma_v$ assessed from CRSs with $a = 0.28$.

SGF, 1966. Recommended correction of shear strength values from FCs and FVTs. Minutes From a Meeting Held by the Swedish Geotechnical Society at the Swedish Geotechnical Institute, Stockholm.