Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-119

A new approach for evaluation of remoulded shear strength in clays using the cone penetration test

Une nouvelle approche pour évaluer la résistance au cisaillement remaniée dans les argiles à l'aide du piézocône

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ABSTRACT: Interpretation of remoulded shear strength in soft clays based on lab and/or in-situ traditional testing can be simple and challenging, depending on the adopted approach. A new approach that uses *CPTU* data in the calculation of the slope parameter $a_q = B_q - 1/Q$, together with laboratory fall cone and field vane shear tests data from 15 sites, demonstrates that when $a_q > 0.5$, the clay under study can be considered as sensitive clay. The proposed relation is intended to be used as a first-order approximation of the remoulded shear strength that can be used as an indication of clay sensitivity. Further data and extended verification of the proposed approach are encouraged in the future for further validation.

RÉSUMÉ: L'interprétation de la résistance au cisaillement à l'état remanié des argiles molles est traditionnellement basée sur des résultats de test au laboratoire ou en chantier. Ce genre d'interprétation peut souvent être difficile dépendamment de la méthode choisie. Une nouvelle approche qui utilise les données *CPTU* dans le calcul du paramètre de pente $a_q = B_q - 1/Q$, ainsi que les données de pénétration au cône et du scissomètre de chantier provenant de 15 sites, démontre que lorsque $a_q >$ 0,5, l'argile étudiée peut être considérée comme argile sensible. La relation proposée est destinée à être utilisée comme approximation du premier ordre de la résistance au cisaillement à l'état remanié pouvant être utilisée comme indication de la sensibilité de l'argile. Des données supplémentaires et une vérification approfondie de l'approche proposée sont encouragées à l'avenir pour une validation plus approfondie.

Keywords: Clay; *CPTU*; remoulded shear strength; vane shear tests; fall cone.

1 INTRODUCTION

General practice and previous studies have shown that the measured sleeve friction resistance (f_s) from cone penetration tests (*CPTU*) can be considered as a remoulded shear strength in non- or low-sensitive clays. However, this approach does not work well when dealing with sensitive and quick clay deposits. Moreover, the sleeve friction in soft (and sensitive) clays is not so reliable (Powell and Lunne, 2005; Lunne, 2010), and the correction of f_s to a total sleeve resistance (f_t) requires a sleeve net ratio from triaxial tests and both measurements of pore pressures at the shoulder (u_2) and behind the sleeve friction (u_3) (Lunne et al. 1997), where the latter one is not typically measured in practice.

Other approaches applying traditional soil behaviour type (*SBT*) charts often fail to identify the material as sensitive (Mayne and Benoit, 2020; Agaiby and Mayne, 2021). Some new approaches propose modified SBT charts using the pore pressure measurements at the tip (u_1) (Gylland et al., 2017) or the added measurement of resistivity, designated *RCPTU* (Sandven et al. 2016; Gylland et al. 2017); however, then require certain additional sensors that are not usually present in traditional *CPTU* testing.

A new approach for calculating the remoulded shear strength (s_{ur}), which can then be applied as an indicator for classifying a soil material as sensitive, is presented in this paper. The approach uses the total cone resistance (q_t) and the u_2 data collected from a standard *CPTU* test for calculating the slope parameter $a_q = B_q - 1/Q$, where B_q = pore pressure ratio and Q = normalized cone tip resistance. Then, based on previous observations stating that when $a_q > 0.5$, the clay under study can be considered sensitive (see Section 2), and using empirical data, a relation for calculating s_{ur} is presented. This relation is a first-order correlation based on data from 15 sites and can be employed to evaluate remoulded shear strength based on *CPTU* data. The paper summarizes and verifies the approach using a global database of *CPTU*, field *VST* (field vane shear test), and laboratory *FC* (fall cone) results compiled from Norway, Finland, Canada, and USA sites.

2 THE SLOPE PARAMETER a_q

The slope parameter a_q can be determined as a single value for any clay layer or uniform clay deposit by taking the slope of a plot of the parameter (U-1) versus Q, or alternatively taken as the slope of ($u_2 - \sigma_{vo}$) versus ($q_t - \sigma_{vo}$). Mathematically speaking, it can be calculated as $a_q = (U - 1)/Q = (u_2 - \sigma_{vo})/(q_t - \sigma_{vo}) = B_q - 1/Q$, where $U = \Delta u_2/\sigma_{vo}'$ and $Q = q_{net}/\sigma_{vo}'$. Di Buo et al. (2019) presented the friction angle ratio ϕ'_{peak}/ϕ'_{MO} as a function of the slope parameter a_q for kaolin, natural clays, and sensitive clays. It was observed that sensitive clays are found mainly when $a_q > 0.5$, i.e., the sensitivity of the clays studied increased when the friction angle ratio decreased. This trend was already presented by Bjerrum and Simons (1960) when comparing the ratio of $tan\phi'_{peak}/ tan\phi'_{MO}$ from triaxial tests with sensitivity: $S_t = s_{uc}/s_{ur}$. That is the ratio of $\tan\phi'_{peak}/ \tan\phi'_{MO}$ decreases with an increase in sensitivity. The premise of the present study is that when $a_q > 0.5$, then the material is probably a sensitive clay, and that S_t increases with increasing a_q. However, evaluating S_t can be difficult since that value then depends on the testing method being used to define the reference or benchmark S_t. Specifically, the value of S_t could be assessed using field *VST*, laboratory *FC*, or other approaches like full flow penetrometers, including the T-bar and/or ball (Abuhajar et al. 2010). This paper focuses on the remoulded shear strength as an initial evaluation for clay sensitivity.

3 FIELD AND LAB DATABASE

A database of 15 clay sites has been used to study the relation between the remoulded shear strength from field *VST* and/or lab *FC* tests and the *CPTU* data. Table 1 presents the main characteristics of the sites included. The sites marked with red in the table are sensitive clay sites. The data have been collected from previous publications and technical reports, including *CPTU* and field *VST* data for all the sites except Onsøy, where just lab *FC* data were obtained. The following list presents the reference publications from where data were collected from:

- Bothkennar, UK (Hight et al. 2003)
- Burswood, A.U. (Low et al. 2011)
- Dover, NH (Mayne & Benoît 2020)
- Gloucester, ON (Mayne et al. 2019)
- Gulf of Guinea (Low et al. 2010)
- Kreuzlinger, SW (Springman et al. 1999)
- Louiseville, QC (Leroueil et al. 2003)
- Newbury, MA (DeGroot et al. 2019)
- Northwestern NGES (Finno et al. 2000)
- Perniö, Finland (Di Buo et al. 2019)
- Tiller-Flotten, Norway (L'Heureux, et al. 2019)
- Mink Creek, BC (Geertsema and Torrance 2005)
- Onsøy, Norway (Lunne, Long, & Forsberg 2003)

Table 1. Sites included in the present study.

Site	w_n [%]	*P.I.* [%]	*L.L.* [%]
Bothkennar, UK	56-67	35-44	64-76
Burswood, A.U.	62-88	35-65	64-95
Dover, NH	31-49	9-17	30-42
Gloucester, ON - A	52-56	21-30	36-60
Gloucester, ON - B	51-90	19-35	39-64
Gloucester, ON - C	60-73	20-31	40-57
Gulf of Guinea	104-130	79-122	120-164
Kreuzlinger, SW	29-36	20-25	35-41
Louiseville, QC	70-89	40-47	62-72
Newbury, MA	39-54	19-21	43-49
Northwestern NGES	24-27	15-16	33-34
Pernio, Finland	82-103	21-37	45-66
Tiller-Flotten, Norway	30-44	7-19	25-39
Mink Creek, BC	23-33	4-19	23-40
Onsøy, Norway	55-70	20-50	50-80

w_n: natural water content, *P.I.*: plasticity index, *L.L.*: liquid limit

Figure 1 and Figure 2 present the observed relationships between the parameter a_q and the ratio $s_{ur}/\Delta u_2$. Figure 1 includes the s_{ur} data measured by field *VST*, while Figure 2 includes the s_{ur} data measured by lab *FC*. All data in the database are presented in both figures, and a large scatter is observed; however, a clear distinction between sensitive and non-sensitive clays is distinguished at the threshold: $a_q = 0.5$, as expected. When taking the average values for each site (Figure 3 and Figure 4), a relationship between the ratio $s_{ur}/\Delta u_2$ and a_q is proposed.

4 VERIFICATION WITH KLETT CLAY

Long et al. (2019) summarized the characteristics of Klett clay, Norway. The Klett site comprises non-sensitive clay to about 6 m to 8 m and quick clay with significant silt lenses below this down to at least 30 m depths. The materials encountered are typical of the marine clays found in Scandinavia and North America. The *CPTU* data at Klett showed that above 7.5 m, the values of f_s are close to 4 kPa, and these fit well with the s_{ur} data reported using the lab *FC* tests. The clay is a quick-clay below 7.5 m depth, and $s_{ur} < 0.5$ kPa based on lab *FC* were reported. Some limited field *VST*s were available but higher than those obtained from the lab *FC*. The authors mentioned that this finding is consistent with that observed for other Norwegian clays, especially quick clays, and is attributed to uncertainties in rod friction at depth and torque measurements taken from the surface.

Figure 5 presents the estimated s_{ur} when applying the approach presented in this paper (i.e. equation in Figure 4). A sufficient match is obtained with the data from lab *FC* tests. The observed differences might be attributed to the intrinsic variability in the data from the database (i.e., data coming from different sources where different approaches for interpretation may differ depending on the applicable standard for interpretation of the lab *FC* tests). Still, the estimated values are in the same range of the ones measured.

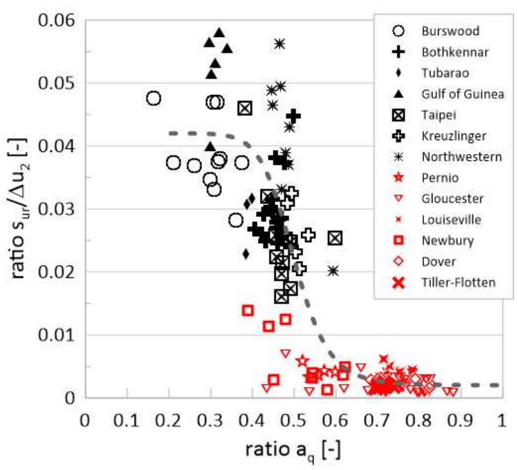

Figure 1. All data sets containing s_{ur} from field VST.

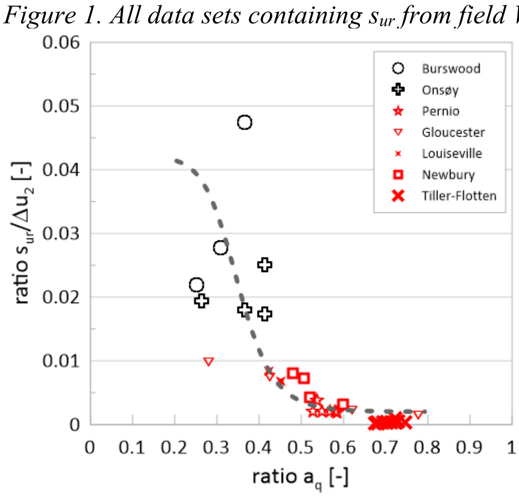

Figure 2. All data sets containing s_{ur} from lab FC.

The approach presented in this paper may be applied as a first-order approximation of the s_{ur} to indicate clay sensitivity.

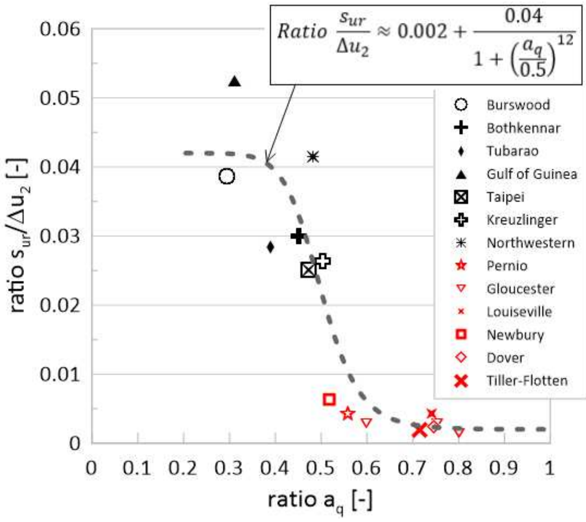

Figure 3. a_q vs. $s_{ur}/\Delta u_2$, average values & s_{ur} from field VST.

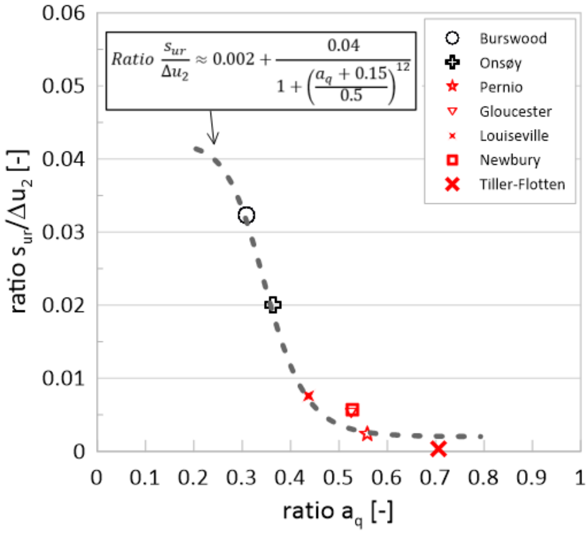

Figure 4. a_q vs. $s_{ur}/\Delta u_2$, average values & s_{ur} from lab FC.

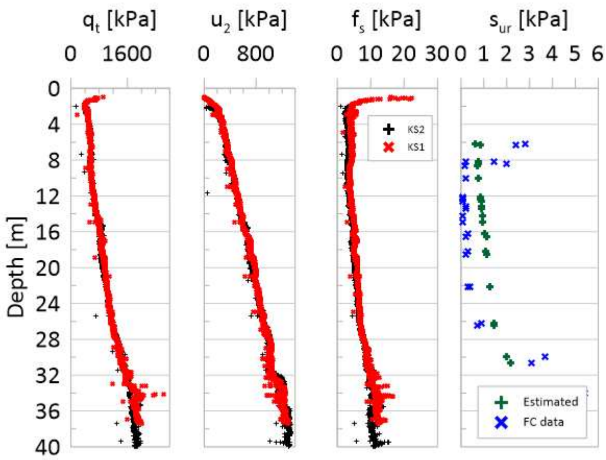

Figure 5. Verification of proposed approach at Klett site.

5 CONCLUSIONS

A discussion of remoulded shear strength of clays based on cone penetration test data has been presented. A novel approach relates the slope parameter a_q and the remoulded shear strength evaluated by either the field vane shear test or the laboratory fall cone test. The approach is verified at an independent testing site having layers of sensitive and non-sensitive clay. The proposed relation is intended to be used as a first-order approximation of the remoulded shear strength that can be used as an indication of clay sensitivity. Further data and extended verification of the proposed approach are encouraged in the future for further validation. Finally, the empirical data used in the present study confirms previous observations stating that when $a_q > 0.5$, the clay under study can be considered sensitive.

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