# Evaluation of CPTU $N_{kt}$ cone factor for undrained strength of clays

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ABSTRACT: The evaluation of undrained shear strength of clays ($s_u$) is most often sought using the net cone resistance ($q_{net}$ = $q_t$ - $\sigma_{vo}$) and a cone factor ($N_{kt}$) such that $s_u = q_{net}/N_{kt}$. While site-specific calibration of $N_{kt}$ with laboratory reference values (i.e. triaxial compression, simple shear) or field benchmark (i.e. vane) is the best approach, this requires considerable extra time and funding to accomplish. In the approach covered herein, a database involving 407 high-quality triaxial compression tests (CAUC) was used to review strengths from a wide variety of clays ranging from intact soft to firm to stiff to hard and fissured geomaterials. The study considered a total 62 clays, categorized into five groups: soft offshore, soft-firm onshore, sensitive, overconsolidated, and fissured clays. The backfigured $N_{kt}$ factors ranged from 8 to 25 and found to decrease with pore pressure ratio, $B_q = (u_2 - u_0)/q_{net}$.

## 1 INTRODUCTION

### 1.1 *Undrained strength*

The undrained shear strength ($s_u = c_u$) of clays is a predominant geoparameter used to evaluate foundation bearing capacity, including shallow footings, rafts, and pilings, as well as input to short-term stability of excavations, slopes, and embankments. In conceptual terms within the classical understanding on the stress-strain behavior of soils, the undrained strength can be taken as the maximum shear stress ($\tau_{max}$) for a stress path at constant volume. Yet, because of the complex effects of anisotropy, strain rate, direction of loading, and boundary conditions, assigning a single value of $s_u$ to a given clay is not possible. Instead, a family of $s_u$ values must be considered, including shear in compression and extension under various modes.

The various strength modes can be evaluated by laboratory tests on intact, undisturbed soil samples, for instance: anisotropically-consolidated triaxial (CAUC and CAUE), plane strain (PSC and PSE), as well as simple shear (SS), direct simple shear (DSS), torsional shear (TS), and other modes (e.g., CIUC, true triaxial, hollow cylinder, directional shear, etc.).

### 1.2 *Strength modes*

Constitutive soil models help in establishing a general hierarchy of the test modes. For instance, the Wroth-Prevost hybrid model establishes the modal order in terms of normalized undrained shear strength to effective overburden stress for normally-consolidated (NC) clays: $S = s_u/\sigma_{vo}'$, as shown by Figure 1 (Mayne 2008). In this framework, the values of S for all modes are expressed as functions of the effective stress friction angle ($\phi'$) of the clay.

The general hierarchy of the strength modes is borne out by laboratory tests on natural clays, as shown by Kulhawy & Mayne (1990), Ladd & DeGroot (2003), Karlsrud et al. (2005), and others.

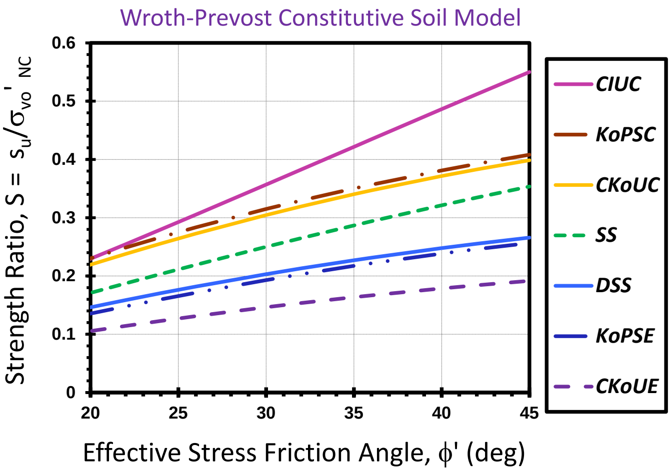


Figure 1. Normalized strength ratios for various shearing modes for Wroth-Prevost hybrid constitutive soil model (after Mayne 2008).

### 1.3 *Strength evaluation by piezocone tests*

Field testing by piezocone penetration testing (CPTU) in clays is standardised by e.g. ASTM

(2012), ISO (2012) and ISO (2014). For marine environments, including rivers and lakes, consideration can also be given to a free fall tool equipped with a cone penetrometer (e.g. Dayal 1980; Peuchen et al. 2017).

While several expressions are available for interpreting the in-situ undrained shear strength in clays from CPTU results, the most common and reliable is given by:

$$s_u = \frac{q_t - \sigma_{vo}}{N_{kt}} = \frac{q_{net}}{N_{kt}} \tag{1}$$

where $\sigma_{vo}$ = total overburden stress, $q_{net}$ = net cone resistance and $N_{kt}$ = cone factor.

The appropriate choice of $N_{kt}$ can be made on the basis of theoretical, experimental, and/or statistics relationships. Site-specific calibration of the CPTU with either selective laboratory strength testing performed on high-quality samples and/or selective field vane shear testing (VST) is the best approach, albeit requires considerable time and financial expense because of the more involved testing program, specifically added costs of drilling, sampling, transport, and testing. Moreover, the effects of sample disturbance on laboratory results are essentially inevitable and unavoidable in most instances (e.g. ISO 2006; ISO, 2014).

Guidance on the empirical selection of $N_{kt}$ factors have been given for various clays. For CPTUs in soft to firm clays, Lunne et al. (2005) recommend a value $N_{kt}$ = 12 for the CAUC undrained shear strength, $s_{uc}$. A study of piezocone data on 3 onshore and 11 offshore clays by Low et al. (2010) found the range: $8.6 \leq N_{kt} \leq 15.3$, with a mean value of $N_{kt}$ = 11.9 for the triaxial compression mode. Similarly, a study of 17 soft to firm intact clays found a mean value of $N_{kt}$ = 11.8 for $s_{uc}$ corresponding to the CAUC triaxial mode (Mayne et al. 2015).

For differing shearing modes, other operational values of $N_{kt}$ must be used. For instance, Low et al. (2010) found a mean $N_{kt}$ = 13.6 for the laboratory average strength ($s_{uAVE}$) from triaxial compression, direct simple shear, and triaxial extension (range: $10.6 \leq N_{kt} \leq 17.4$), which is close to the direct simple shear mode ($s_{uDSS}$). For calibration with the field vane ($s_{uv}$), they determined $N_{kt}$ averages 13.3 with a range $10.8 \leq N_{kt} \leq 19.9$.

For several sensitive Norwegian clays tested in CAUC mode, Karlsrud et al. (2005) show the cone factor is lower and within the ranges: $7.5 \leq N_{kt} \leq 11.5$. Similarly, for a soft sensitive clay in Québec, Wang et al. (2015) reported that an $N_{kt}$ = 10.5 was needed to match VST results.

In contrast, for overconsolidated and fissured clays, Powell & Quarterman (1988) showed that a much higher $N_{kt}$ factor ($20 < N_{kt} < 30$) was necessary to match reference values of $s_u$ obtained from laboratory triaxial compression tests and field plate load test results.

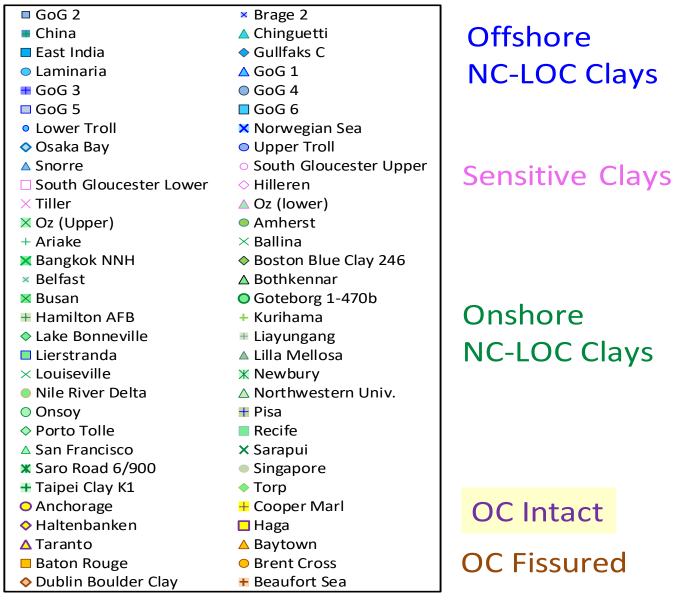


Figure 2. List of 62 clays with CAUC-CPTU data.

Theoretical solutions for $N_{kt}$ are readily available, including expressions based on limit plasticity (e.g. Konrad & Law 1987), cavity expansion theory (e.g. Mayne 2016), and strain path method (Teh & Houlsby 1991), as well as algorithms that approximate the results from numerical finite element simulations (Lu et al. 2004). Yet, these approaches require additional input geoparameters that must be assessed beforehand, such as rigidity index ($I_R = G/s_u$), cone roughness ($\alpha_c$), lateral stress state ($K_0 = \sigma_{ho}'/\sigma_{vo}'$), friction angle ($\phi'$), and/or other variables.

As a consequence of the aforementioned uncertainties and lack of guidance towards an available and reliable means for selecting $N_{kt}$, a detailed database approach was devised, with the results reported by Mayne (2014).

Table 1. Summary of CAUC $s_{uc}$ versus CPTU $q_{net}$ for clays

| Clay Group | No. sites | No. data | Statistical Regressions | | Factor = 1/m | Mean |
|---|---|---|---|---|---|---|
| | N | n | Slope m | Coef.[a] $r^2$ | $N_{kt}$ | $B_q$ |
| Offshore NC-LOC | 17 | 115 | 0.0812 | 0.980 | 12.32 | 0.51 |
| Onshore NC-LOC | 30 | 191 | 0.0833 | 0.867 | 12.00 | 0.53 |
| Sensitive NC-LOC[b] | 5 | 43 | 0.0968 | 0.507 | 10.33 | 0.84 |
| OC Intact | 5 | 36 | 0.0737 | 0.862 | 13.57 | 0.49 |
| OC Fissured[c] | 5 | 22 | 0.0445 | 0.393 | 22.47 | -0.01 |
| All Clays | 62 | 407 | 0.0750 | 0.923 | 13.33 | 0.55 |

[a]Note: $r^2$ = coefficient of determination (for $N_{kt}$ only)
[b]Note: confidence level for sensitive clays is low
[c]Note: uncertainty level for OC fissured clays is high

## 2 CPTU-CAUC DATABASE

### 2.1 *Clay data*

The database focused on a total of 62 clays that were categorized into five main groupings: (a) 17 offshore soft-firm clays that are normally-consolidated (NC) to lightly-overconsolidated (LOC); (b) 30 onshore clays that are NC-LOC, (c) 5 sensitive clays that are NC-LOC, (d) 5 overconsolidated (OC) intact clays, and (e) 5 OC fissured clays.

A listing of these individual clays is given in Figure 2, including assignment of a separate symbol for each site. For tracking purposes, the clay symbols are also grouped by color according to each category: offshore (blue), onshore (green), sensitive (pink), intact OC clays (purple dot with yellow infilling), and fissured OC clays (brown symbol with orange infilling). The results and findings herein are based on a review of high-quality laboratory and field data obtained from the open literature and private unpublished technical reports.

The strength data for these sites were obtained from high-end laboratory tests, including consolidated triaxial tests, and in selected cases, also direct simple shear mode. In addition to the strength results, index parameter values and other information were also collected about each of these sites, including: water content ($w_n$), liquid limit (LL), plasticity index (PI), unit weight ($\gamma_t$), preconsolidation stress ($\sigma_p'$) and overconsolidation ratio ($OCR = \sigma_p'/\sigma_{vo}'$), as well as other available data (i.e. groundwater table, calcium carbonate content, etc.), where reported.

For both the NC-LOC offshore and onshore series, the in-situ OCRs generally ranged between 1 and 2.5. These 47 soft-firm clays represent the bulk of the dataset with $n$ = 306 paired sets of data and are characterized by an average $B_q$ = 0.52.

### 2.2 *Laboratory test procedures*

For each of the 62 clays considered, a reference value of $s_{uc}$ was evaluated from a CAUC or $CK_0UC$ test, or test series program, performed on an individual specimen obtained from undisturbed sampling. Corresponding CPTu data were acquired at the same site at elevations consistent with the sampling depths.

One important issue is that the testing laboratories used different reconsolidation techniques to restore in-situ stress states on the specimens, including: direct recompression to $\sigma_{vo}'$ and $\sigma_{ho}'$, true $K_0$ conditions versus general anisotropic states ($K_c$), unloading-type SHANSEP, and recompression-type SHANSEP methods, as well as other variants (Lunne et al. 2006). In some cases, the differences in $s_{uc}$ obtained from different laboratory procedures may be small (say CAUC versus $CK_0UC$). For some clays, the use of classical SHANSEP testing destructures the specimens by consolidating past the in-situ yield stress or preconsolidation stress ($\sigma_p'$), giving quite a different strength in comparison to recompression-type series of tests that do not exceed $\sigma_p'$ (Le et al. 2008). Also, both types of SHANSEP approaches rely on laboratory one-dimensional consolidation testing and approximate interpretation models for estimating the OCR at each elevation, which in turn is utilized to provide the undrained shear strength via normalized strength ratio power law trends established by the testing program (Ladd & DeGroot 2003).

These $s_u/\sigma_{vc}'$ versus OCR trends somewhat assume that vertical and lateral variability of the soil deposit is negligible, where in fact there may be significant or subtle changes across the site. In some instances, the traditional normalized strength plots have shown to vary with water content (Finno & Chung 1992).

Note, in the cases involving the few fissured clays, the CAUC types of tests have rarely been performed. Hence, the majority of $s_u$ reference data for fissured clays were procured from the results of isotropically-consolidated triaxial tests (CIUC) which are believed still valid since $K_0$ > 1 for these geomaterials. Regardless, the characterization of fissured clays represents a major challenge in practice, e.g. Vitone and Cotecchia (2011). The work presented here is less reliable in fissured clays and therefore should be used with care.

### 2.3 *Piezocone data*

For the offshore series, most CPTu data were obtained using Fugro equipment, thus comparable results in high quality and reliable measurements. For the onshore series, the published results came from a variety of different commercial systems and it was not possible to scrutinize these for their design, maintenance & wear, analog-digital resolution, compliance with ASTM/ISO standards, preparation of filter elements, saturation, and other factors.

In all but one case (Osaka Bay), all three CPTu readings ($q_c$, $f_s$, $u_2$) were obtained for each site.

The test depths ranged from 1.4 m to 245.6 m below ground surface, with a mean test depth of $z$ = 17.1 m. Cone resistances ranged from 112 kPa to 10.7 MPa, with a mean $q_{net}$ = 1082 kPa. Sleeve friction values ranged from 0.5 kPa to 167 kPa with a mean $f_s$ = 19 kPa. Penetration pore pressures varied from -22 kPa to 7.2 MPa, with a mean $u_2$ = 567 kPa. Using the CPTU soil behavior type (SBT) charts established by Robertson (2009), the range of soil behavior type index was determined as $2.3 \leq I_c \leq 3.7$, with a mean $I_c$ = 3.12 and S.D. = 0.24. The corresponding soil zone was 3 (clay).

Note that the table excludes cemented clays, carbonate geomaterials, and weak rock showing $I_c$ values on the order of 3. These geomaterials provide specific challenges for CPTU interpretation. It is also noted that CPTU $u_2$ measurements can be problematic for high OC and fissured clays. In such cases, acquisition of $u_1$ measurements should be considered (Robertson et al. 1986; Peuchen & Terwindt 2014), with approximate conversion to $u_2$ (e.g. Peuchen et al. 2010).

## 3 UNDRAINED STRENGTH FROM CPTU

### 3.1 *Database results*

The total collection of 407 paired sets of undrained shear strengths obtained from triaxial compression mode tests ($s_{uc}$) versus the net cone resistance ($q_{net}$) are presented in Table 1 and sorted according to clay category as shown. The table also shows mean values for pore pressure ratio $B_q = (u_2 - u_0)/q_{net}$. Figure 3 provides the summary graphical results for each of the groups.

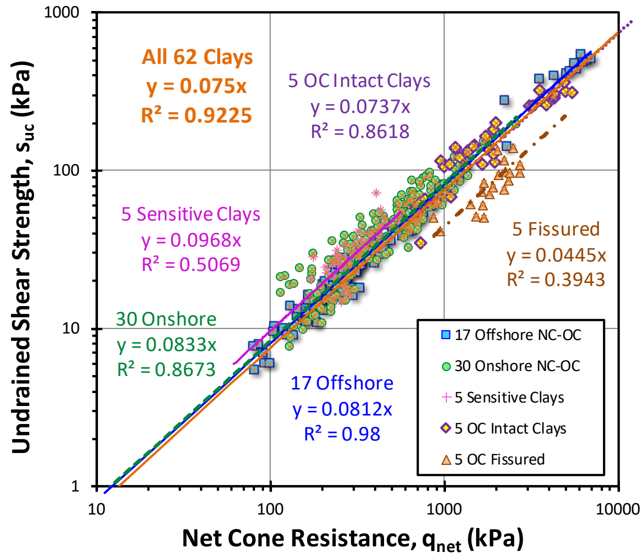


Figure 3. CAUC undrained shear strength versus net cone resistance for the five clay groups.

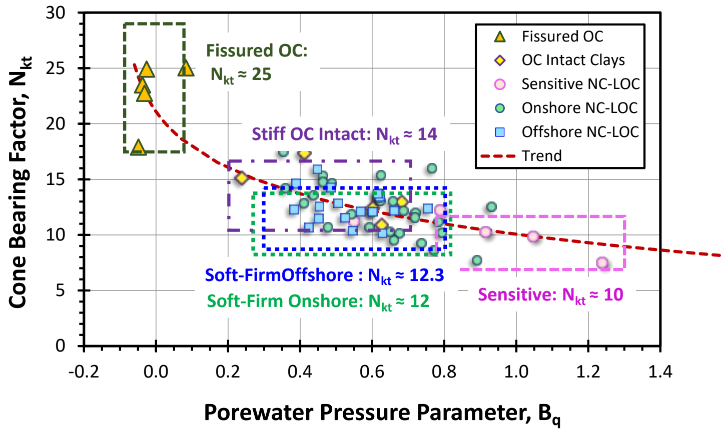


Figure 4. Trend of $N_{kt}$ with $B_q$ for the five clay groups.

Figure 4 presents the $N_{kt}$ - $B_q$ relationship for $s_{uc}$ for the five clay groups. Following the approach used by Low et al. (2010) whereby a single $N_{kt}$ is recommended for preliminary studies, each clay group could be assigned a typical value such as listed in Table 1, or by guidance in Figure 4: $N_{kt}$ = 10 (sensitive clays); $N_{kt}$ = 12 (NC-LOC soft-firm onshore clays); $N_{kt}$ = 12.3 (NC-LOC offshore clays); $N_{kt}$ = 14 (OC intact clays); and $N_{kt}$ = 25 (OC fissured clays).

Within each group, however, there is considerable range and variance for the specified $N_{kt}$ that could be associated with sample disturbance, clay mineralogy, fabric, organic content, and other variables.

### 3.2 *$N_{kt}$ trend with $B_q$*

One well-known relationship indicates that $N_{kt}$ decreases with $B_q$ (Lunne et al. 1985; Skomedal & Bayne, 1988; Lunne et al. 1997; Hong et al. 2010; Knappett & Craig 2012; Mayne et al. 2015). Figure 5 presents this direct trend for the database of Table 1. In this case, each of the 62 clays is given weighting by a single point, so as to not bias the relationship obtained by regression analyses. Adopting a continuous function between the clay groups, then $s_{uc}$ is obtained from:

$$N_{kt} = 10.5 - 4.6 \cdot \ln(B_q + 0.1) \quad (2)$$

which only applies when $B_q > -0.1$.

For the NC-LOC offshore group, the derived $N_{kt}$ factor = 12.3 is close to the value $N_{kt}$ = 12 recommended by Low et al. (2010). Similarly, the NC-LOC onshore group gave $N_{kt}$ = 12.0. For other clay groups, the $N_{kt}$ can be smaller (sensitive clays, where $B_q$ > 0.75) or higher (fissured OC clays, where $B_q < 0.5$).

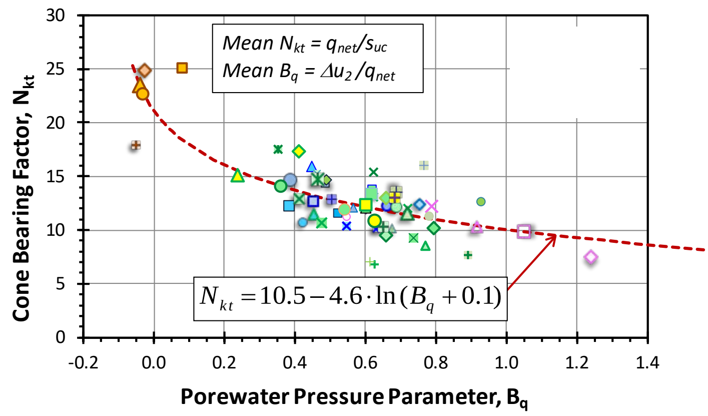


Figure 5. Overall trend of $N_{kt}$ with $B_q$ for 62 individual clays.

Negative or low $B_q$ values are often characteristic in fissured OC clays. Negative $B_q$ values for onshore clays are limited by cavitation but considerable negative $B_q$ values are possible in an offshore setting. Therefore, the limiting value of $B_q > -0.1$ is forced by the logarithmic algorithm. Also, no paired TC-CPTU tests were available to extend into that range.

Fugro software includes automated profiling of $N_{kt}$ values according to the above equation. The algorithm allows manual selection of a range of $I_c$ values. It also allows profiling for a bandwidth of $N_{kt}$ values, by applying range factors such as 0.8 $N_{kt}$ and 1.15 $N_{kt}$. The range factors can be selected to match regional knowledge, expected data variability and site-specific laboratory test values.

Using the database, reverse statistics can be conducted to evaluate the reliability of the methodology. The laboratory-derived $s_{uc}$ versus the CPTU data for the entire dataset of 406 triaxial compression tests are shown in Figure 6. Two sets of statistical measures have been performed, as listed in Table 2: (a) arithmetic; and (b) regressions using both least squares and best fit lines. Statistics are done for three groupings: (1) soft-firm onshore & offshore clays (plus 5 sensitive clays); (2) NC and OC intact clays; and (3) all clays.

Table 2. Statistics on $N_{kt}$ from $B_q$ methodology

| Parameter | Soft-Firm NC-LOC clays | Intact NC-OC clays | All clays: NC, OC, and fissured[a] |
|---|---|---|---|
| No. of data, n | 356 | 386 | 406 |
| μ = ratio of measured/estimated | 1.093 | 1.091 | 1.087 |
| S.D. | 0.279 | 0.272 | 0.279 |
| COV = S.D./μ | 0.255 | 0.250 | 0.256 |
| Regression slope m | 0.947 | 0.964 | 0.996 |
| Coefficient $r^2$ | 0.965 | 0.963 | 0.935 |
| S.E.Y. | 13.21 | 14.68 | 16.05 |

[a]Note: Caution should be applied when using these results in fissured clays

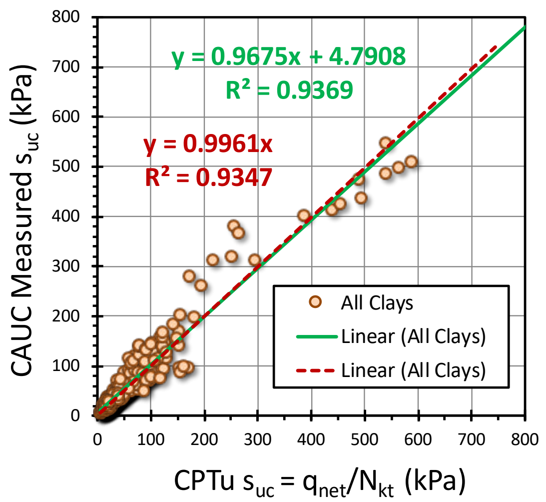


Figure 6. Measured CAUC strength versus CPTU-evaluated strength with $N_{kt}$ = fctn ($B_q$) for all 62 clays.

For the arithmetic statistics (dashed red line of Fig. 6), the ratio of measured-to-estimated values gives a mean value μ, with desired best results at 1.00. Also, the standard deviation (S.D.) and coefficient of variation (COV = S.D./μ) are given. A COV as close to 0.0 is ideal. For the regressions (solid green line of Fig. 6), the best fit line provides a slope, while the least squares equation provides a slope and intercept. In all 3 groupings, a small intercept of around 6 kPa or less was obtained and slopes of both best fit line and least squares linear equation were within 3% of each other. Also given are the values of coefficient of determination with $r^2$ averaging about 0.95 and the standard errors of the y-estimator (S.E.Y.) ranging from 13.2 to 16.1.

## 3.3 *Strength anisotropy*

As noted in Section 1.2, clays exhibit strength anisotropy, often with the hierarchy: $s_{uc} > s_{uDSS} > s_{ue}$. For a given deposit, a reasonable means to quantify its strength anisotropy is to run parallel sets of compression, direct simple shear, and extension tests on undisturbed samples taken at various depths. In review of lab data collected herein, Fig. 7 shows trends for 157 sets of data where all three modes were available.

Using the compression mode ($s_{uc}$) as the reference, the ratios $K_{45} = s_{uDSS}/s_{uc}$ and $K_s = s_{ue}/s_{uc}$ can be used to represent loading at 45° and 90° (horizontal), respectively. Despite prior studies showing that $K_s$ increases with PI (Kulhawy & Mayne 1990) and $K_s$ increases with natural water content (Karlsrud et al. 2005), no such trends were observed with this database. Won (2013) presented similar findings.

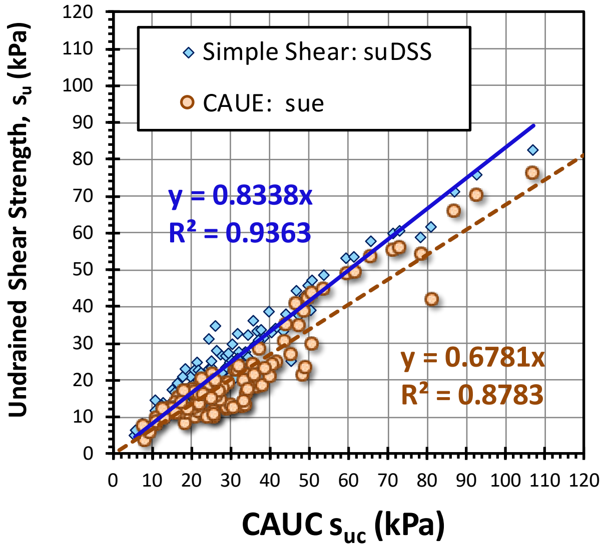


Figure 7. Strength anisotropy results from clay database.

The strength anisotropy data from this study indicate the average relationships:

$$s_{uDSS} = 0.834\ s_{uc} \quad (r^2 = 0.936) \tag{3}$$

$$s_{ue} = 0.678\ s_{uc} \quad (r^2 = 0.878) \tag{4}$$

Also, the following average trends were observed:

$$s_{uAVE} = 0.999\ s_{uDSS} \quad (r^2 = 0.976) \tag{5}$$

$$s_{uAVE} = 0.839\ s_{uc} \quad (r^2 = 0.977) \tag{6}$$

# 4 CONCLUSIONS

A high-quality database consisting of 407 laboratory triaxial compression tests paired with field piezocone data from 62 clays was grouped into five categories: offshore, onshore, sensitive, overconsolidated, and fissured geomaterials. A general trend to handle soft to firm to stiff to hard intact clays and fissured clays was observed indicating $N_{kt}$ decreasing with pore pressure parameter, $B_q$.

The results are considered highly valuable for use as a reference database for assessing $N_{kt}$. However, caution should be applied when using the database at new sites containing limited high-quality laboratory data, particularly when sensitive clays or overconsolidated fissured soils exist.

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