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A REVIEW OF UNDRAINED STRENGTH IN DIRECT SIMPLE SHEAR

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ABSTRACT

Normalized undrained shear strengths from direct simple shear (DSS) tests conducted on 50 different clays are compared with strengths determined from triaxial shear tests. The DSS strength is typically observed to be an intermediate strength between triaxial compression and extension. Normally consolidated and overconsolidated data are included in the study. Numerous important factors were not considered including : strain rate, sensitivity, different lab oratories, sampling disturbance, and others. Nevertheless, approximate trends are observed between DSS strengths and data from companion triaxial compression and triaxial extension tests.

Key words : anisotropy, clays, consolidated undrained shear, direct shear test, overconsolidation, shear strength, triaxial compression test (**IGC** : D 6)

INTRODUCTION

Several laboratory devices are available for measuring the undrained strength of clays : standard triaxial, simple shear, plane strain, hollow cylinder, and cubical triaxial. For a given clay, differences in strengths occur among these devices since each method imposes different loading conditions, boundary constraints, initial stress states, and strain rates.

For many clay soils, the undrained shear strength determined from direct simple shear (DSS) tests has been observed to be an intermediate value, generally less than triaxial compression (TC), yet greater than triaxial extension (TE). The DSS strength is important because it represents the average mobilized strength for : embankment stability on soft clays (Trak et al, 1980) ; soft ground beneath spread footings (Kinner and Ladd, 1973) ; and shaft resistance along pile foundations (Randolph and Wroth, 1981). The DSS device has also been used to investigate the behavior of clays under cyclic loading (Andersen et al, 1980).

In this study, DSS strength data from 50 different clays are reviewed in terms of either TC or TE strengths, or both, where available. The triaxial series were either isotropically consolidated (CIUC/CIUE) or anisotropically consolidated (CAUC/CAUE or CK_0UC/CK_0UE). The design of the simple shear apparatus is such that an anisotropic

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(K_0) condition is ensured during the initial consolidation phase.

The undrained strengths were defined by the maximum deviator stress level (q_{max}) for triaxial tests and maximum shear stress (τ_{max}) for simple shear tests. Primarily, triaxial and simple shear tests were strain-controlled tests although a few triaxial series were stress-controlled. Most simple shear tests were performed using the NGI apparatus (Bjerrum and Landva, 1966). Only a few clays were tested in the Cambridge device (Roscoe, 1953).

The strengths are expressed in terms of the normalized shear strength to initial effective vertical stress ratio (C_u/σ_{vc}') in order to allow a comparison of data from different sources. Data have been obtained from normally-consolidated to overconsolidated clays previously reported in the geotechnical literature. In this paper, normally-consolidated strengths (OCR=1) are represented by (C_u/σ_{vnc}'). Overconsolidated strengths are denoted by the general expression (C_u/σ_{vc}') with the approximate OCR shown adjacent to each individual data point. A listing of the symbols, soils, and sources of data is given in Fig. 1. Only three clays were arti-

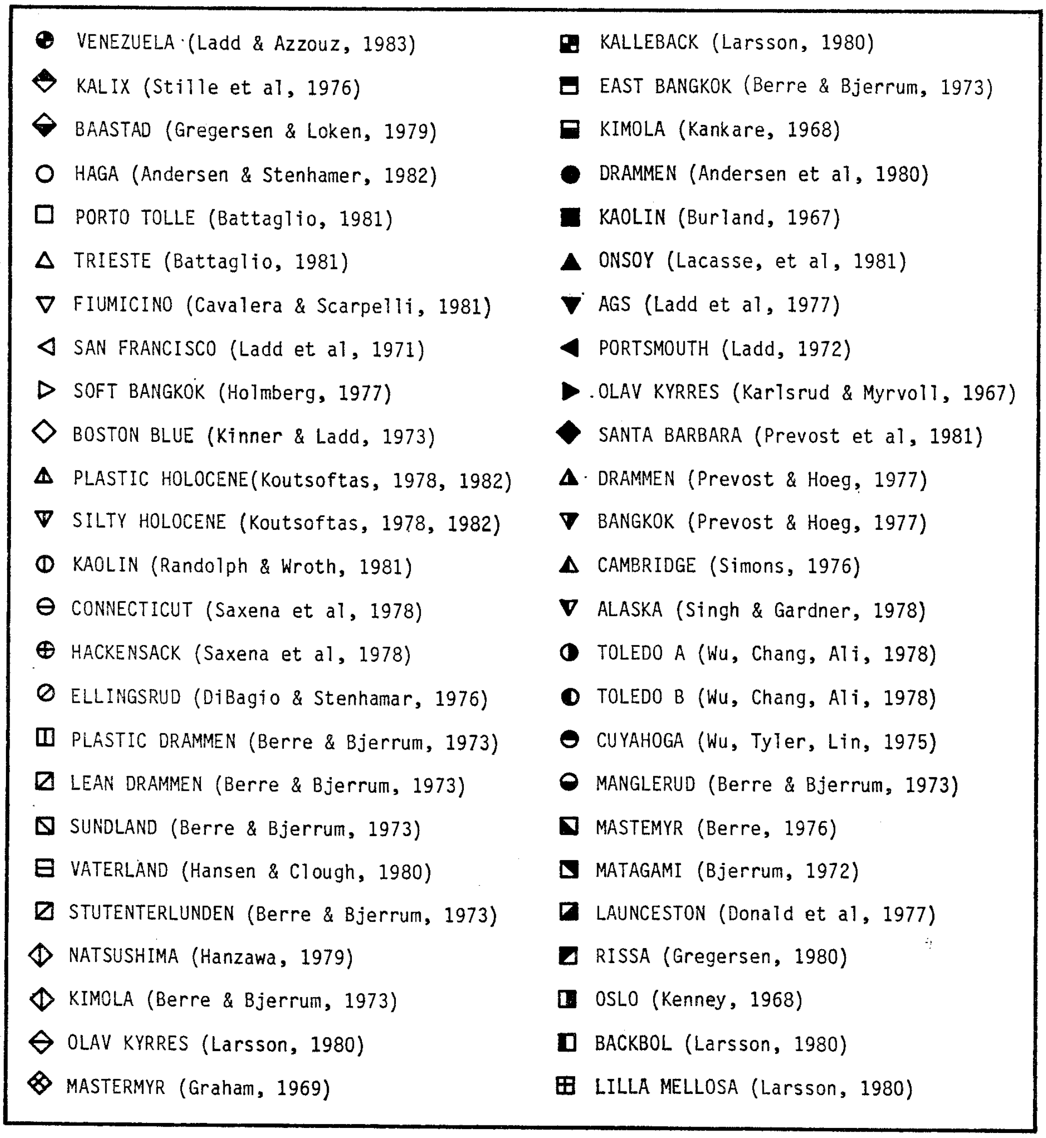

Fig. 1. List of soils, symbols, and sources of data for clays tested under both simple shear and triaxial conditions

ficially prepared soils ; the remainder are natural materials. Plasticity indices for these clays range from 4 to 104.

The use of the simple shear device has been promoted both by the NGI (Berre and Bjerrum, 1973) and by MIT (Ladd and Foott, 1974). However, DSS testing has been severely criticized in recent times (Saada and Townsend, 1981) because of nonuniform and uncertain stress conditions. Nevertheless, many geotechnical studies of soft ground have utilized DSS data, as evidenced by the list of references to this report. In addition, a recent laboratory study by Vucetic and Lacasse (1982) has attempted to address the aforementioned problem of boundary effects within the NGI simple shear apparatus. A study by Duncan and Dunlop (1969) addressed the Cambridge device.

Numerous important factors could not be studied within the scope of this research effort. Significant variables which were not considered include : soil sensitivity, strain rate, effects of aging, soil structure, differences in laboratories, etc. Instead, the intent of this study was to collect a large number of laboratory strength data and observe whether general trends exist between undrained strengths measured under simple shear and triaxial conditions.

NORMALLY-CONSOLIDATED STRENGTH

All soils listed in Fig. 1 were tested under DSS conditions and at least one other strength mode (TC and/or TE). For normally-consolidated clays, Fig. 2 indicates that the undrained strength in simple shear generally falls between 55 and 95% of the undrained strength from anisotropic triaxial compression tests. Fig. 2 includes soils consolidated under both general anisotropic conditions (CAUC) and K_0 conditions (CK_0UC). On the average, the DSS strength is 70% of the CAUC/CK_0UC strength (Mayne, 1982). Separate trends for CAUC and CK_0UC were not observed.

A similar trend is observed for isotropic triaxial compression tests (see Fig. 3). The clays presented in Figs. 2 and 3 include both young normally consolidated soils (OCR=1) as well as some aged normally consolidated soils (generally OCR<2) with quasi-preconsolidation due to delayed compression. Generally, it is observed that :

$$(C_u/\sigma_{vnc}')_{DSS}=0.7(C_u/\sigma_{vnc}')_{TC}\pm 0.05 \quad (1)$$

In undrained strength analyses, it is common to assume that the compression mode is an upper bound corresponding to no stress rotation, and extension is a lower bound corresponding to a full stress rotation ($\beta=90°$).

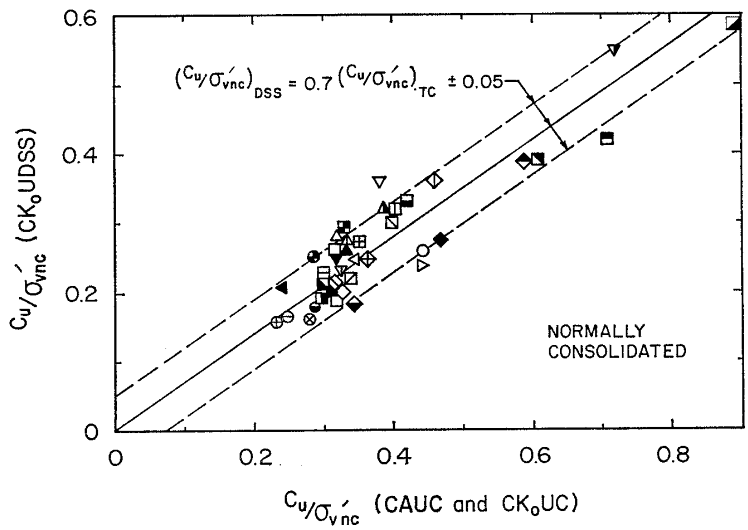

Fig. 2. Comparison of undrained DSS strength and anisotropic TC strength for normally consolidated clays

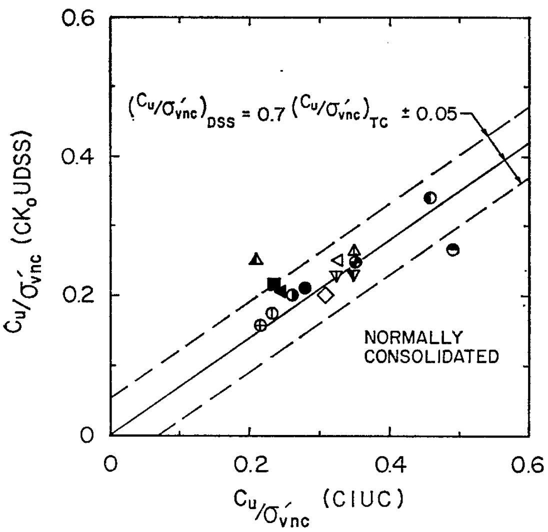

Fig. 3. Comparison of undrained DSS strength and isotropic TC strength for normally consolidated clays

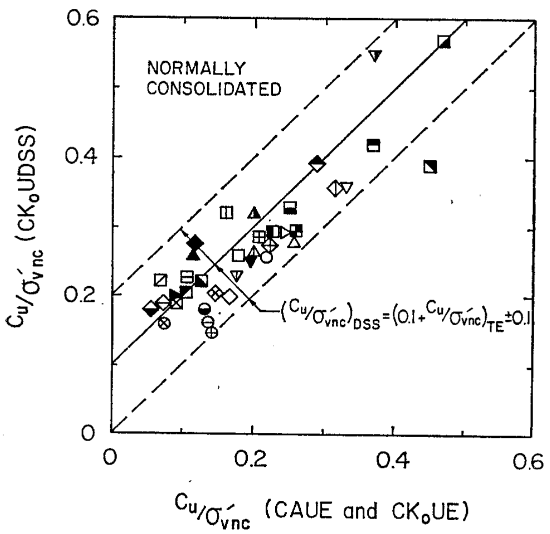

Fig. 4. Comparison of undrained DSS strength and TE strength for normally consolidated clays

The strength in simple shear has often been observed to be intermediate and assumed to represent β between=40° and 50° (Soydemir, 1976; Koutsoftas and Fischer, 1977). Consequently, each of the strengths assumed in TC, DSS, and TE are applicable only to specific loading directions (Larsson, 1980).

In Fig. 4, the DSS strength is shown to be typically higher than the corresponding strength in extension. Only one soil (Matagami from Bjerrum, 1972) has C_u/σ_{vnc}' (DSS)

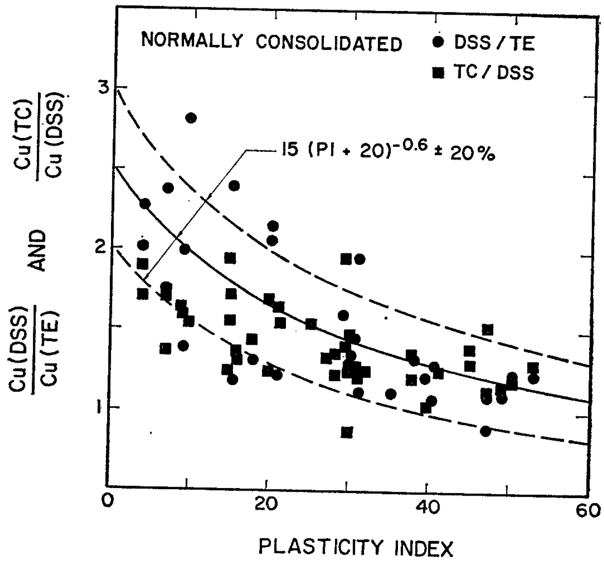

Fig. 5. Undrained strength ratios for DSS/TE and TC/DSS related to plasticity index

less than C_u/σ_{vnc}' (TE). From Fig. 4, the general trend is:

$$(C_u/\sigma_{vnc}')_{DSS} = (0.1 + C_u/\sigma_{vnc}')_{TE} \pm 0.1 \quad (2)$$

The ratios of DSS strength to triaxial strengths show slight trends with plasticity index for PI<60. Fig. 5 indicates that the ratio TC/DSS decreases with PI, as also observed by Sagaseta and Sanchez (1979). The ratio TC/DSS typically ranges from 2 to 1. Five clays with PI>80 are not shown. Similarly, the ratio DSS/TE decreases with PI. The ratio DSS/TE apparently ranges from 3 to 1. These relationships may be approximately expressed as:

$$\frac{C_u(\mathrm{DSS})}{C_u(\mathrm{TE})} = \frac{C_u(\mathrm{TC})}{C_u(\mathrm{DSS})} = 15(\mathrm{PI}+20)^{-0.6} \pm 20\% \quad (3)$$

for PI<60. Eq. (3) can be rearranged to give an expression for the ratio of undrained shear strengths in extension to compression:

$$K_s = \frac{C_u(\mathrm{TE})}{C_u(\mathrm{TC})} = \frac{(\mathrm{PI}+20)^{1.2}}{225} \quad (4)$$

which is consistent with the observed trend for K_s increasing with plasticity index, as noted by Ladd et al (1977) and Mayne (1983).

OVERCONSOLIDATED STRENGTH

Of the 50 clays reviewed, only 3 were ar-

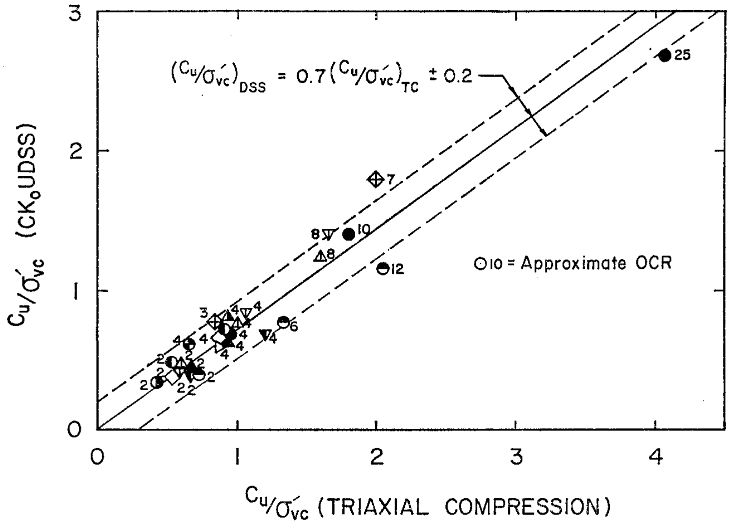

Fig. 6. Observed trend between DSS and TC for overconsolidated states

tificially prepared soils. Many of the clays tested had some natural history of preconsolidation. These clays were often reconsolidated anisotropically (DSS, CAU and CK_0U) or isotropically (CIU) with the effective vertical stresses equal to the estimated in situ overburden stresses. Companion series of oedometer tests were performed to determine the natural or apparent preconsolidation pressures. Approximately one-third of the clays were tested over a range of overconsolidation ratios (OCR), as expressed in terms of effective vertical stress.

Several of the clays were tested at overconsolidated states using the SHANSEP method (Ladd et al, 1971). For these, the specimens were initially consolidated to a young state in the virgin compression range and then rebounded to desired OCRs before shear to failure.

For overconsolidated clays, Fig. 6 presents DSS strengths in terms of triaxial compression data for both natural and induced preconsolidation. No differences have been observed between isotropic triaxial (CIUC) or anisotropic triaxial tests (CAUC and CK_0UC). The observed trend is similar to that for normally-consolidated samples given previously in Figs. 2 and 3. For the database, the ratio of DSS/TC for overconsolidated clays varies with PI in a trend similar to that observed for normally-consolidated clays (Fig. 5) and not with distinct relationships as presented by Sagaseta and Sanchez (1979). On the average, the trend for overconsolidated clays appears to be :

$$(C_u/\sigma_{vc}')_{\mathrm{DSS}} = 0.7(C_u/\sigma_{vc}')_{\mathrm{TC}} \pm 0.2 \quad (5)$$

A similar look at overconsolidated DSS data in terms of triaxial extension is given in Fig. 7. Again, only one soil (Haga clay from Andersen and Stenhamar, 1982) exhibits a DSS strength less than TE, although

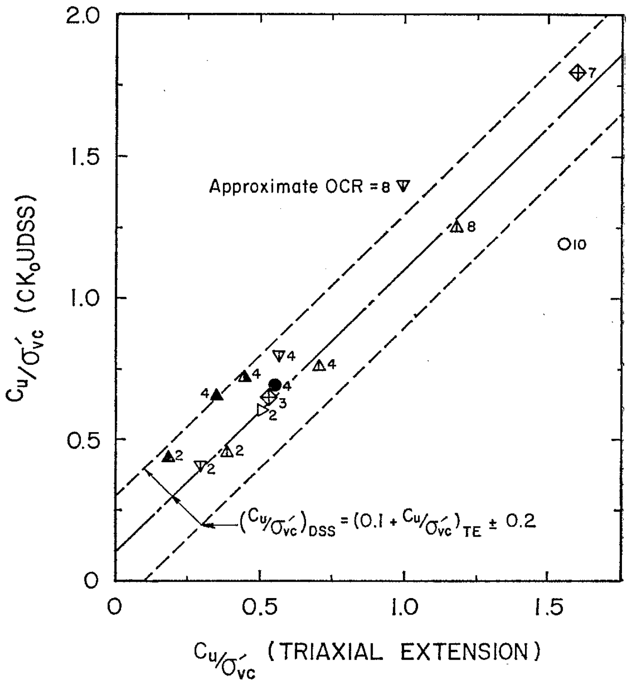

Fig. 7. Observed trend between DSS and TE for overconsolidated states

this may be attributed to the different testing rates used in the two tests. Generally,

$$(C_u/\sigma_{vc}')_{\rm DSS}=(0.1+C_u/\sigma_{vc}')_{\rm TE}\pm 0.2 \quad (6)$$

From another viewpoint, the normalized undrained strength increases with OCR according to the expression :

$$(C_u/\sigma_{vc}')=(C_u/\sigma_{vnc}')\mathrm{OCR}^{\Lambda_0} \quad (7)$$

where Λ_0 is the critical-state parameter (Mayne, 1980 ; Mayne and Swanson, 1981). Koutsoftas (1981) has shown this method applicable for describing the TC, DSS, and TE undrained strengths for an offshore clay.

From strength data, the parameter Λ_0 is defined as the slope of log (C_u/σ_{vc}) versus log OCR. Typically, Λ_0 ranges between 0.5 and 1.0 for both triaxial compression and extension (Mayne and Holtz, 1985), with $\Lambda_{\rm TE}$ averaging about 12% higher than $\Lambda_{\rm TC}$.

From a review of data on only six clays, Ladd et al (1977) concluded that Λ_0 is generally between 0.75 and 0.85 for DSS tests. As shown by Figs. 8 and 9, the actual range of Λ_0 for DSS is larger, generally between 0.4 and 1.0. Fig. 8 indicates that the normalized undrained strength increases with OCR at approximately the same rate for both DSS and triaxial compression tests. Normalized strengths from triaxial extension tests, however, generally increase with OCR at a rate equal to or faster than DSS. On the average, $\Lambda_{\rm TE}$ is about 12% greater than $\Lambda_{\rm DSS}$. For comparison, a study of data from 100 different clays reported in the geotechnical literature and tested under both compression and extension modes (Mayne and Holtz, 1985) indicates that $\Lambda_{\rm (extension)}$ is between 1.0 to 1.25 times $\Lambda_{\rm (compression)}$.

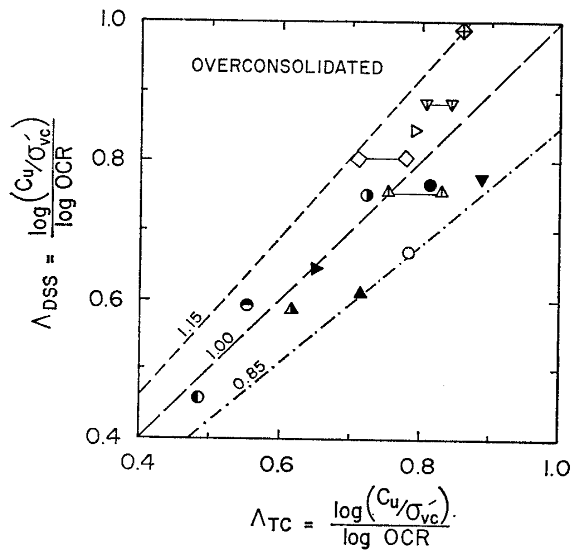

Fig. 8. Strength rebound exponent for simple shear versus triaxial compression

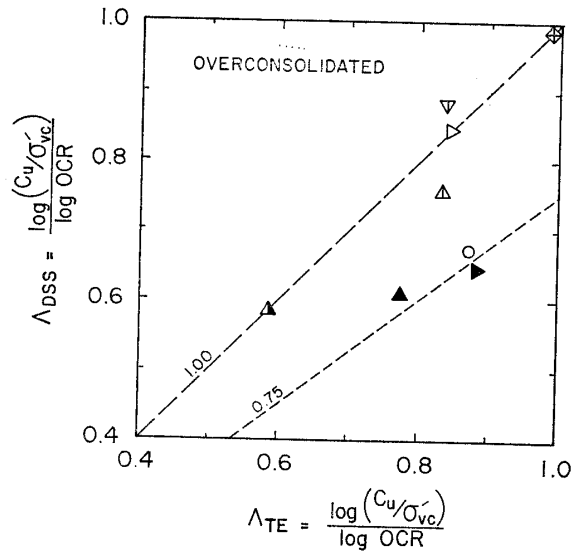

Fig. 9. Strength rebound exponent for simple shear versus triaxial extension

The rate of increase in normalized undrained shear strength with OCR for direct simple shear tests as compared to triaxial conditions may be summarized as :

$$\frac{\Lambda(\mathrm{DSS})}{\Lambda(\mathrm{TC})}=1.00\pm 0.15 \quad (8)$$

$$\frac{\Lambda(\mathrm{DSS})}{\Lambda(\mathrm{TE})}=0.88\pm 0.15 \quad (9)$$

$$\frac{\Lambda(\mathrm{TE})}{\Lambda(\mathrm{TC})}=1.12\pm 0.15 \quad (10)$$

THEORETICAL APPROACH

Expressions for the effects of stress rotation on undrained strength have been presented by Bjerrum (1973), Cavalera and Scarpelli (1981), Prevost (1979), Randolph and Wroth (1981), and others. Using the anisotropic elastoplastic model of Prevost (1979), an approximate relationship for the undrained shear strength under simple shear conditions in terms of triaxial strengths is :

$$(C_u/\sigma_{vc}')_{\rm DSS}=0.5[(C_u/\sigma_{vc}')_{\rm TC}+(C_u/\sigma_{vc}')_{\rm TE}] \quad (11)$$

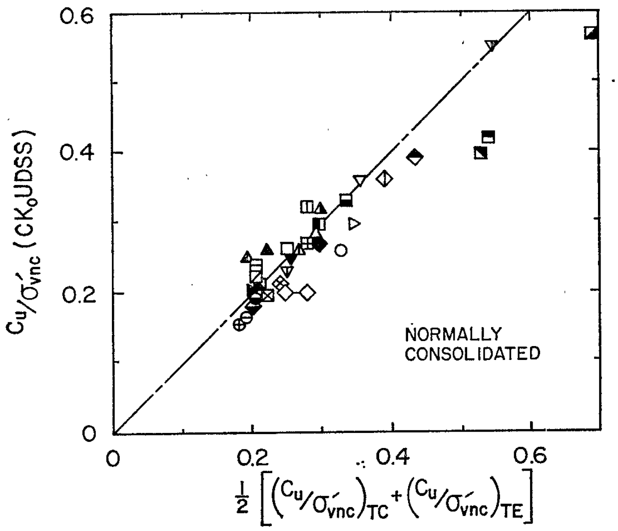

Fig. 10. Comparison of DSS strength and average of triaxial compression and extension for normally consolidated clays

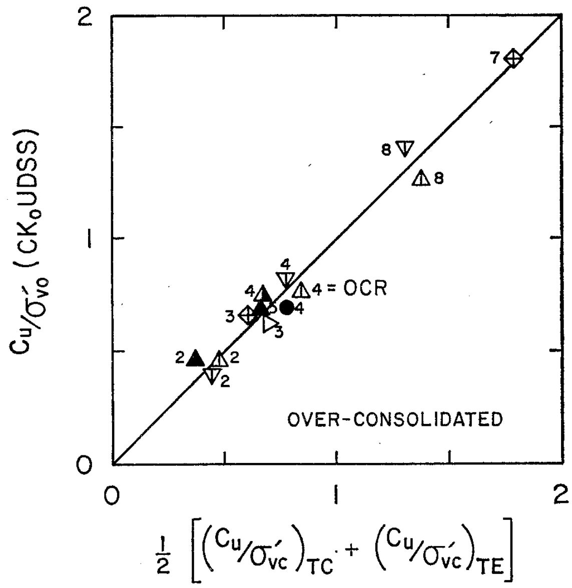

Fig. 11. Comparison of DSS strength and average of triaxial compression and extension for overconsolidated clays

The validity of this expression appears substantiated for the most part by Fig. 10 for normally-consolidated clays and by Fig. 11 for overconsolidated clays. Additional support is provided from the results of model footing tests on clay at different OCRs by Kinner and Ladd (1973). Their study showed that reasonable predictions of ultimate bearing capacity were obtained by using either the DSS strength, the average of TC and TE, or the average of plane strain active and passive tests.

CONCLUSIONS

Based on a review of undrained strength data from 50 clays tested under both direct simple shear and triaxial conditions, the following observations are noted :

(1) For normally-consolidated and overconsolidated states, the normalized undrained shear strength from DSS is on the order of 0.7 ± 0.2 of the strength in triaxial compression.

(2) The normalized strength in DSS for a range of OCRs is generally slightly greater than in triaxial extension and averages about 0.1 to 0.3 higher than the normalized strength in extension.

(3) The normalized strength of clay in direct simple shear increases with OCR at approximately the same rate as in triaxial compression.

(4) The normalized strength of clay in triaxial extension increases with OCR at rate averaging about 12% higher than simple shear.

(5) The ratios of undrained strengths DSS/TE and TC/DSS decrease with plasticity index for PI<60.

(6) The theoretical relationship proposed by Prevost (1979) appears valid and indicates that the undrained DSS strength is approximately equal to the average of the strengths in triaxial compression and extension.

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