Profiling Yield Stresses in Clays by In Situ Tests

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A unified approach for profiling the effective yield stress (σ_p') of natural clays by in situ tests is presented. The empirical methodology is developed from statistical regression analyses of databases involving soft-to-firm normally consolidated clays and stiff-to-hard overconsolidated clay deposits that have been tested using the cone penetration, piezocone, dilatometer, vane shear, pressuremeter, and standard penetration tests. Similar trends are established for field test results in intact clays, whereas deviations occur for fissured materials. The interpreted profiles of σ_p' from in situ tests are quick, economical, and continuous, yet should be verified by companion sets of laboratory oedometer tests on high-quality specimens. The procedures are applied to two case studies involving natural clay deposits near Washington, D.C., where reference consolidation test data were available.

The approximate magnitude of the effective yield stress or preconsolidation pressure ($\sigma_p' = \sigma_{v\max}' = P_c'$) of natural clays can be inferred from the results of in situ tests. This is advantageous because routine tube sampling and one-dimensional consolidation testing on retrieved specimens are often difficult, time-consuming, and expensive and suffer from sampling disturbance effects. However in situ tests are relatively fast and economical, and they test the soil in its natural environment and under its actual anisotropic geostatic stress state. Several theoretical premises for relating σ_p' to in situ test data have been postulated and are reviewed briefly in this paper. From a more practical vantage, first-order statistical relationships are presented for profiling the yield stresses of intact clays from field data obtained from cone, piezocone, vane, pressuremeter, dilatometer, and standard penetration tests. Similar trends are observed for intact clays, whereas fissured clay results are also affected by their macrostructure.

PRECONSOLIDATION STRESS

The maximum past vertical stress or effective preconsolidation pressure (P_c', σ_p', or $\sigma_{v\max}'$) is an important parameter defining the state of stress of clay deposits. Conventionally, this parameter is determined from standard one-dimensional oedometer tests on small specimens trimmed from samples taken from the field. The characteristic e-log σ_v' graphs from consolidation testing show a change in slope at a yield point termed the yield stress, henceforth designated σ_p'. The value of σ_p' separates overconsolidated states (elastic response) from the normally consolidated region (plastic response). Figure 1 shows results from a consolidation test on an overconsolidated sandy clay from Surry, Virginia, and the interpreted yield stress is 900 kN/m^2 at the reported depth of 27 m. It is important to impart sufficiently high stress levels during consolidation loading to define fully the normally consolidated region and magnitude of yield stress. Unfortunately, many commercial laboratories simply run oedometer tests using a standard set of stress increments regardless of the consistency and hardness of the clay, and therefore the tests do not completely reach the virgin compression line. In addition, sampling disturbance effects typically lower the overall e-log σ_v' curve from field conditions. Consequently, the value of σ_p' is often underestimated in routine testing and interpretation (*1*).

If the current state of vertical effective stress (σ_{vo}') is known, then the difference between the yield stress and current stress is referred to as the prestress ($\sigma_p' - \sigma_{vo}'$). Almost all natural soils have been prestressed to some degree because of geologic, environmental, or climatic processes that occur over long periods of time. Erosion, glaciation, desiccation, secondary compression, cyclic loading, groundwater fluctuations, and geochemical changes are typical mechanisms causing preconsolidation effects. In terms of dimensionless parameters, it is common to express the ratio of vertical stresses in normalized form, known as the overconsolidation ratio, $OCR = \sigma_p'/\sigma_{vo}'$. The advantages of this format are that no units are specified and the scaling laws of continuum mechanics can be used (*2*). For the data shown in Figure 1, the current $\sigma_{vo}' = 295$ kN/m^2 and therefore the in situ $OCR \approx 3$ for this marine clay from Virginia.

It should be noted that the stress state of soil is not merely a one-dimensional phenomenon. The use of routine consolidation tests with rigid lateral constraint and incremental application of vertical loads has proliferated because of the simplicity of equipment and test procedures. In reality, the stress history of natural materials is controlled, as a minimum, by a four-dimensional condition involving σ_x', σ_y', σ_z', and time (t). Series of extensive triaxial testing programs have found yield stresses associated with all types of stress paths. Consequently, recent studies in understanding soil behavior have developed the concept of a yield surface. That is, the stress history of natural materials is best characterized by a three-dimensional yield envelope that is rheological and changes as a function of time (age, creep, and strain rate). Figure 2 illustrates the yield surface for the Saint Alban Clay in Quebec (*3*), where typical index properties of the clay are liquid limit (LL) = 45, plasticity index (PI) = 20, water content (W_n) = 75, sensitivity (S_t) = 18, and OCR = 2.2. Here, the yield surface is presented in a Cambridge q-p' diagram, where $q = (\sigma_1 - \sigma_3)$ is the principal stress difference and $p' = \frac{1}{3}(\sigma_1' + \sigma_2' + \sigma_3')$ is the mean effective stress.

A review of yield surfaces from clays worldwide suggests that the effective frictional properties (ϕ') of the clay primarily govern the actual shape of the envelope (*4*). The well-known preconsolidation pressure or yield stress (σ_p') is but one point on the yield surface where the locus crosses the K_{0NC}-line corresponding to normally consolidated conditions. Available stress path and effective

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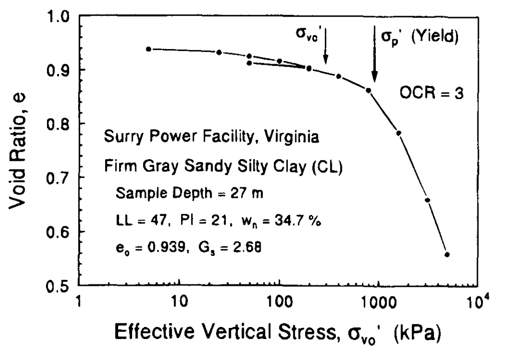

FIGURE 1 Yield stress observed in one-dimensional consolidation test on Surry Clay.

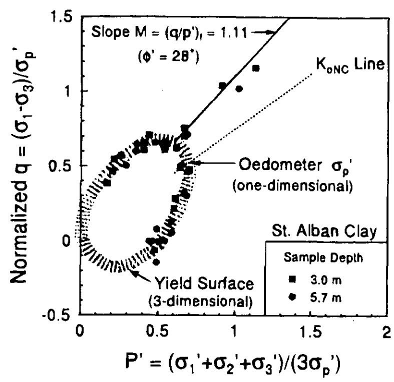

FIGURE 2 Three-dimensional yield surface for St. Alban Clay [after Leroueil et al. (*3*)].

stress strength data suggest that the shape of the yield surface is actually best represented as a rotated ellipse in MIT q-p' space, where the same terms imply different parameters: $q = \frac{1}{2}(\sigma_1' - \sigma_3')$ and $p' = \frac{1}{2}(\sigma_1' + \sigma_3')$. The yield surface concept is particularly useful in explaining the nonuniqueness of obtaining Mohr-Coulomb parameters (c' and ϕ') from limited numbers of strength tests (*5*), as well as the observed degradation of effective cohesion intercept (c') with time (*6*).

IN SITU TESTS

Traditionally, in situ test measurements in clay are used toward evaluating a value of undrained shear strength (s_u) of the deposit. The undrained strength, however, is a nonunique behavioral response of the material that, for a given stress state, depends on strain rate, boundary conditions, and direction of loading. Each particular test method (triaxial, plane strain, simple shear, vane, etc.) must therefore provide a different value of s_u for the same clay (*2*). In past correlative studies, s_u values from various tests often were used interchangeably without due regard to their differences. As a consequence, inconsistent interpretations of s_u have arisen in comparing clays of varied origins and backgrounds. As an alternative to the approach of evaluating s_u, it is suggested that field test data be used to infer the yield stress state of the clay, specifically the uniquely defined σ_p' obtained from one-dimensional oedometer tests.

The detailed profiling of yield stresses from consolidation tests at a particular site is often expensive and can require weeks or months of testing. High-quality samples must be retrieved from the field, carefully transported and stored, and subjected to incremental-load oedometer or constant rate-of-strain consolidation tests at approximately $400/test. Consequently, it is of interest to use in situ tests for this purpose because they are quick and inexpensive and provide nearly continuous and immediate results for analysis. However, the use of in situ tests for this purpose is not without other difficulties. For example, the actual stress path followed during the test is not known, rates of strain are very high, destructuration occurs, and the field measurements are affected by a variety of other soil conditions (fabric, sensitivity, mineralogy, plasticity, etc.) in addition to stress history. Nevertheless, merit in the use of in situ tests for evaluating σ_p' offers an expedient and economical approach that may supplement the results of conventional consolidation testing.

As early as 1957, Hansbo (*7*) suggested the use of field vane measurements for determining σ_p' in the very sensitive clays of Scandinavia. Later in 1979, Tavenas and Leroueil (*6*) indicated that the cone tip resistance (q_c) could be used reasonably to map values of σ_p' with depth in the sensitive clays of Eastern Canada. In 1980 the dilatometer test was introduced for profiling OCRs (*8*). Since that time a number of data bases involving a variety of field tests in clays were compiled where reference profiles of yield stresses were available from companion series of oedometer tests performed on undisturbed samples. The clay sites, sources of data, and specific details on the compilation of information have been presented elsewhere (*9,10*) and include normally consolidated to overconsolidated clays that range from soft to stiff to hard, intact to fissured materials. Many worldwide locations of diverse geologic origins are contained in the collections: marine, glacial, deltaic, lacustrine, alluvial, and diluvial. Differences in origin, plasticity, sensitivity, and age are also likely to be notable factors, but they are not discussed here.

THEORETICAL BASIS

Simple analytical models, as well as complex numerical simulations, have proved useful in relating σ_p' to the results of in situ measurements. The axisymmetric geometry of the cone penetrometer has permitted analyses interrelating OCR and normalized cone resistance via cavity expansion models (*11*), finite elements (*2*), and strain path methods (*12,13,17*). Piezocone penetration has been evaluated by effective stress analysis (*14*), limit plasticity (*15*), cavity expansion (*16*), and strain path methods (*17*). The dilatometer test (DMT) has also been evaluated by strain path techniques (*17,18*). An approximate approach for interrelating σ_p' and the results of piezocone, dilatometer, and pressuremeter in terms of concepts of cavity expansion versus critical state has been proposed (*19*).

The theoretical relationships for cone, piezocone, pressuremeter, and dilatometer are supported by statistical regression analyses conducted on specific data bases compiled for each in situ test. Similarly, trends for evaluating σ_p' from the vane shear test and standard penetration test are also available, albeit only on an empirical basis. The following section describes the observed average trends for these data bases.

STATISTICAL RELATIONSHIPS

Regression analyses have been conducted on data bases from intact clays only and were performed using two separate procedures. First, an assumed arithmetic-arithmetic pattern between independent and dependent variables was assessed. In these cases, only a small intercept value was determined from linear regressions. Therefore, a best-fit line ($b = 0$; $y = mx$) from least-squares analysis was conducted so that only one variable was obtained in the formulation (Table 1). This facilitates a direct comparison among the various in situ tests because σ_p' is always the dependent variable in this study. The number of data sets (n) and coefficient of determination (r^2) from the regression analysis are reported in each subsequent graph as well as in Table 1. The standard error of the dependent variable (equivalent standard deviation, or SD) for each regression is also given in the figures. Second, an assumed log-log relation was analyzed to give a power function format. That is, if b = intercept and a = slope, then a natural log base regression gives $y = e^b x^a$. In these cases, it was observed that $a \approx 1$ and the results could be adjusted to force the format $y = mx$, where $m = e^b$ and $a = 1$. This best-fit line approach permits a direct comparison between the arithmetic and logarithmic regression models, and an examination of the expressions in Table 1 indicates remarkable similarity between the expressions obtained from both types of regression studies.

In the following figures, log-log axes have been presented to show the vast range of data spanning nearly three orders of magnitude for each variable. If the data were shown arithmetically, several figures would be required to present all of the data. Both the ordinate and abscissa have been made dimensionless by normalization to a reference value equal to atmospheric pressure (p_a = 1 bar $\approx$ 100 kPa $\approx$ 1 tsf $\approx$ 1 kg/cm^2). The dependent variable (dimensionless yield stress or σ_p'/P_a) shown on the ordinate has a significant range that appears to be best represented as log normally distributed ($0.2 \leq \sigma_p'/P_a \leq 50$). Because the arithmetic-arithmetic and log-log relationships generally are similar, the simpler arithmetic statistical expression has been presented in each figure. Statistical results given are for intact clays only.

TABLE 1 Statistical Trends Between σ_p' and In-Situ Tests for Intact Clays

TEST	n	Best Fit Line (b = 0) Arithmetic Relation	r^2	Best Fit Line (m = 1) Log-Log Relation	r^2
VST	205	$\sigma_p' = 3.54\ s_{uv}$	0.832	$\sigma_p' = 4.14\ s_{uv}$	0.759
CPT*	113	$\sigma_p' = 0.287\ q_c$	0.858	$\sigma_p' = 0.240\ q_c$	0.863
ECPT	74	$\sigma_p' = 0.323(q_T - \sigma_{vo})$	0.904	$\sigma_p' = 0.342(q_T - \sigma_{vo})$	0.875
PCPT	77	$\sigma_p' = 0.467\ \Delta u_t$	0.838	$\sigma_p' = 0.461\ \Delta u_t$	0.884
PCPT	68	$\sigma_p' = 0.537\ \Delta u_{bt}$	0.827	$\sigma_p' = 0.474\ \Delta u_{bt}$	0.816
DMT	76	$\sigma_p' = 0.509(p_o - u_o)$	0.896	$\sigma_p' = 0.574(p_o - u_o)$	0.901
SPT	126	$\sigma_p' = 0.468\ N_{60} p_a$	0.699	$\sigma_p' = 0.517\ N_{60} p_a$	0.804
PMT	89	$\sigma_p' = 0.454\ p_L$	0.908	$\sigma_p' = 0.343\ p_L$	0.797
PMT	105	$\sigma_p' = 0.755 s_{up} \ln I_r$	0.895	$\sigma_p' = 0.595 s_{up} \ln I_r$	0.873

NOTES:

VST	= vane shear test	σ_p'	= effective yield stress
CPT	= cone penetration test	s_{uv}	= vane shear strength
ECPT	= electric cone	q_c	= measure cone tip resistance
PCPT	= piezocone test	q_T	= corrected cone tip resistance
DMT	= dilatometer test	σ_{vo}	= total overburden stress
SPT	= standard penetration test	u_t	= pore pressure on cone face
PMT	= pressuremeter test	u_{bt}	= pore pressure behind cone tip
p_a	= atmospheric pressure	p_o	= DMT contact pressure
n	= number of data sets	N_{60}	= energy-corrected N-value
r^2	= coefficient of determination	p_L	= limit pressure
*	= data includes mechanical and electrical cones	s_{up}	= pressuremeter undrained strength
		I_r	= G/s_u = rigidity index
b	= regression intercept	G	= shear modulus
m	= regression slope	Δu	= excess pore water pressure

Cone Penetration Tests

For cone penetration test (CPT), Figure 3 indicates the observed direct trend between σ_p' and net cone tip resistance ($q_T - \sigma_{vo}$). The specific symbols shown refer to the individual sites listed in the compiled data base (*20,21*). All measured cone tip resistances ($q_c \rightarrow q_T$) have been corrected for pore-water pressure effects acting on unequal areas of the cone tip (*20,21*). As noted previously, data are presented in log-log format to show that the relationship covers almost three orders of magnitude in the full range of values both for the ordinate (σ_p'/P_a) and for the independent variable plotted on the abscissa, $1 \leq (q_T - \sigma_{vo})/p_a \leq 60$. It is clear that a well-defined trend occurs between σ_p' and ($q_T - \sigma_{vo}$) for intact clays, but the data for fissured clays fall above this relationship. This is important since a macrofabric of discontinuities exists because of high desiccation effects or passive failure of heavily overconsolidated materials.

Variations are evident in the trend between σ_p' and net cone resistance and, undoubtedly, additional factors play a significant role in the relationship. For an initial first-order estimate, the regression studies for the CPT data indicate the following average trend for intact clays:

$$\sigma_p' = 0.33(q_T - \sigma_{vo}) \quad (1)$$

This is comparable with the originally proposed relationship ($\sigma_p' \approx q_c/3$) observed for structured natural clays in Quebec (*7*) and is consistent with a more recent evaluation of sensitive Swedish clays (*23*) where $\sigma_p' = 0.29$ ($q_T - \sigma_{vo}$). The latter suggests further that clay plasticity also affects the interrelationship for normally consolidated clays. For fissured clays, Equation 1 provides a conservative estimate of preconsolidation, and the appropriate coefficient linking σ_p' and ($q_T - \sigma_{vo}$) may be dictated by other factors, such as degree of fissuring, age, and mechanism of overconsolidation.

Piezocone Tests

The magnitude of pore-water pressures measured by piezocone (PCPT) depends upon the specific position of the porous element on the cone geometry. For simplicity, Type 1 piezocones are classified as having the pore pressures measured on the cone tip/face, whereas the elements on Type 2 piezocones are located just behind the tip (shoulder). The noted trend between σ_p' and measured excess porewater pressures (Δu_t) from Type 1 piezocones is shown in Figure 4 (*a*). The solid dots correspond to clay sites and sources of data cited by Mayne et al. (*20,21*). It is observed repeatedly that intact and fissured clays show distinct behavioral patterns in response. Note that all pore pressures are positive for Type 1 piezocones regardless of whether the clays are soft or hard. The average relationship for intact clays gives

$$\sigma_p' = 0.47\Delta u_t \quad (2)$$

A similar format was investigated by Larsson and Mulabdic (*23*) for Scandinavian clays that indicated an average coefficient term of 0.29 in very sensitive clays of high plasticity and about 0.21 in gyttja (highly organic clays). For Type 2 piezocones, which measure penetration pore-water pressures behind the cone tip (U_{bt}), the trend for evaluating σ_p' is shown in Figure 4(*b*) and indicates for intact clays:

$$\sigma_p' = 0.54\Delta u_{bt} \quad (3)$$

Considering both intact and fissured clays, Type 2 piezocones show a nonunique pattern of excess pore pressure development. At low to moderate OCRs, σ_p' increases with Δu, whereas at higher OCRs in fissured clays, piezocones typically measure zero or negative excess pore pressures during penetration. Thus, although Type 2 PCPTs are necessary for cone tip corrections, they often provide little stratigraphic detail in overconsolidated fissured clays. In this regard, dual- and triple-element piezocones can provide all of the essential information for detailed logging of strata.

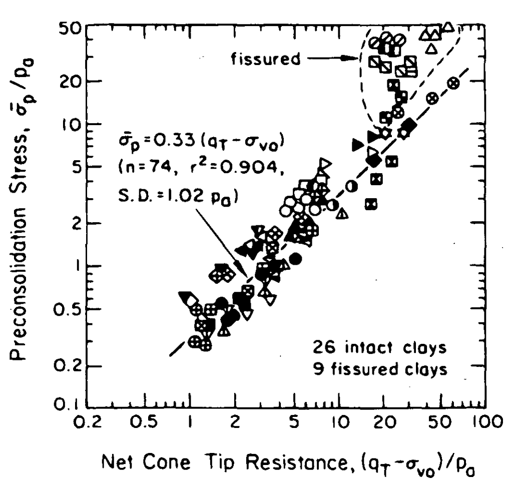

FIGURE 3 Graphical log relationship between σ_p' and ($q_T - \sigma_{vo}$) for cone penetration tests. (Note: arithmetic statistical trend given for intact clays.)

Dilatometer Tests

The dilatometer test (DMT) provides direct measurements of total lateral stress immediately after insertion of a flat steel blade. The normal procedure for estimating yield stress in clays relies on the original correlation proposed by Marchetti (*8*) between OCR and DMT horizontal stress index, $K_D = (p_o - u_o)/\sigma_{vo}'$, where P_o is the corrected DMT contact pressure or A-reading and u_o is the hydrostatic water pressure. The correlation is based on the results of data from only five clays. The magnitudes of induced total stress and pore pressure at this instant of penetration by a probe are quite similar both theoretically (cavity expansion) and experimentally (*24*). Consequently, a relationship for the DMT is expected to be similar to that from PCPT. The statistical trend for the DMT data base compiled from 24 different intact natural clays is

$$\sigma_p' = 0.51(p_o - u_o) \quad (4)$$

The relationship is presented in Figure 5(*a*) and suggests a generalized form:

$$\sigma_p' = (p_o - u_o)/\delta \quad (5)$$

where $\delta = 2$ corresponds to the mean trend. However, the observed variation noted by Mayne and Bachus (*19*) indicates a typical range

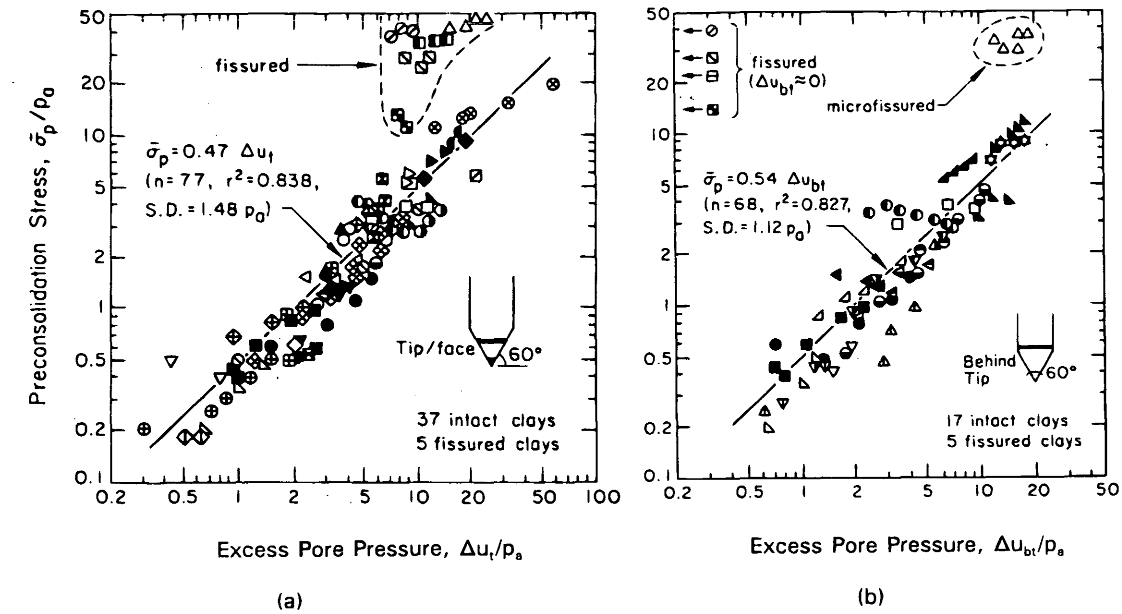

FIGURE 4 **Graphical log relationships between σ_p' and Δu for piezocone penetration tests with (*a*) face and (*b*) shoulder pore pressure measurements. (Note: arithmetic statistics given for intact clays.)**

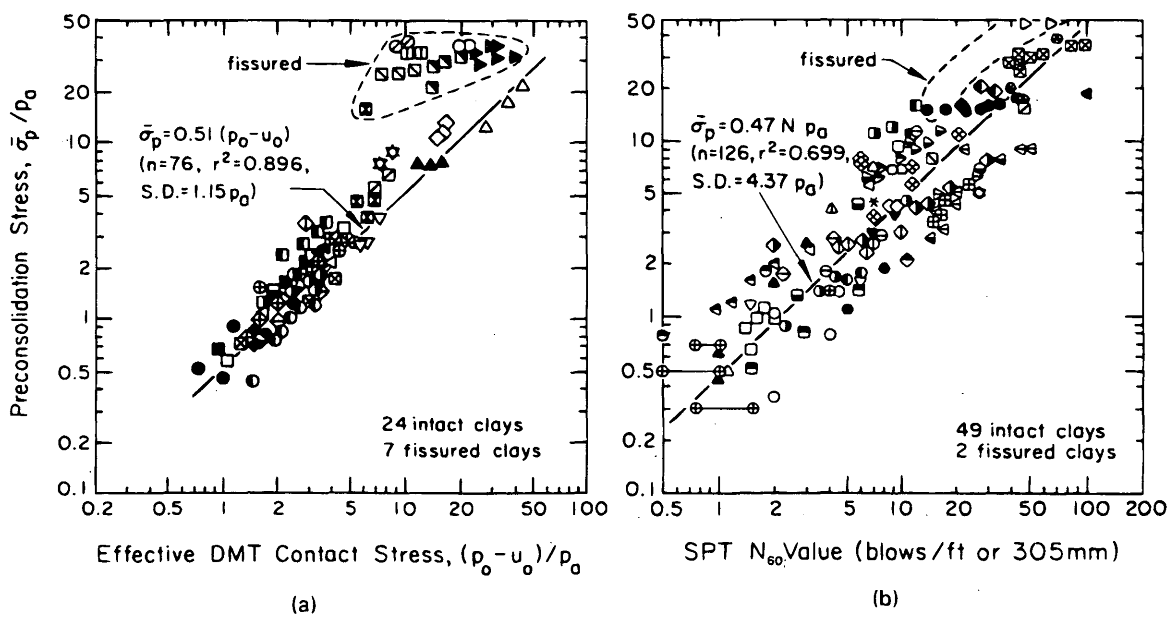

FIGURE 5 **Graphical log relationships between σ_p' and (*a*) effective dilatometer contact stress ($p_o - u_o$) and (*b*) energy-corrected N_{60} from standard penetration test. (Note: arithmetic statistics given for intact clays.)**

of $1.5 \leq \delta \leq 2.5$ for intact clays, whereas the data for heavily OC fissured clays suggest an average $\delta = 0.50 \pm 0.25$. The generalized form appears to be applicable to other in situ tests as well.

Pressuremeter Tests

In routine practice, pressuremeter tests (PMT) are used to better define soil parameters for analysis and to provide reference values for other field tests. Detailed profiling of properties with depth is usually neither cost-effective nor production-oriented. The PMT is useful in overconsolidated clays because it can provide independent evaluations of total horizontal stress ($P_{ho} = \sigma_{ho}$), shear modulus (G), undrained shear strength (s_u), and limit pressure (p_L). The PMT mimics an expanding cylindrical cavity, and the equivalent excess pore pressure calculated from this test can be related to yield stress (*19*). A review of data from self-boring pressuremeter tests in 44 different clays (*10*) indicated

$$\sigma_p' = 0.755 s_u \ln(G/s_u) \qquad (6)$$

Alternatively, the limit pressure (p_L) may be related to the yield stress of the deposit, as noted in Table 1. Associated graphs for these data trends have been presented elsewhere (*9*).

Vane Shear Tests

In Sweden the vane shear test (VST) is routinely used for evaluating profiles of σ_p' in soft sensitive clays (*6*). Using a data base derived from 96 different clay sites (*25*), the average regression relationship between σ_p' and measured s_{uv} from vane tests is

$$\sigma_p' = 3.54 s_{uv} \tag{7}$$

The data trend is in agreement with a recent statistical study of VSTs in four types of sensitive clays in eastern Canada (*26*). The aforementioned relationship is improved if the effects of plasticity are considered in the following empirical format:

$$\sigma_p' = 22 s_{uv} / \mathrm{PI}^{0.48} \tag{8}$$

which is consistent with a state-of-the-art and independent review on the VST by Chandler (*27*). Graphical presentations of the σ_p' versus s_{uv} trends have been made (*9,25*).

Standard Penetration Test

The variation in energy efficiency accounts for much of the observed widespread differences in standard penetration test (SPT) results. Even though the SPT remains a common in situ test in U.S. practice, a majority of testing firms and consulting engineers fail to calibrate the device for energy measurements. The SPT-N value from the test is severely altered by hammer type (pinhead, safety, or donut), drop height, number of rope turns, lifting system (cathead versus automatic trip), age of rope, driller, and other factors. Correlations over the past 40 years have been based on an average energy efficiency of 60 percent, and the energy-corrected SPT resistance is designated N_{60}. Until drillers and engineers adopt a calibration program for each rig, the SPT will remain a relatively uncertain and unreliable test for accurate measurements.

In this study, SPT data from 51 different clays were reviewed (*28*). The trend for σ_p' is shown in Figure 5(*b*) and regression analyses gave the poorest statistics (highest SD and lowest r^2) of any of the in situ test relationships:

$$\sigma_p' = 0.468 N_{60} p_a \tag{9}$$

where N_{60} assumes average U.S. practice. It is noted, unfortunately, that few of the N values were actually corrected for energy efficiency. Recently Decourt (*29*) proposed a similar format between σ_p' and N for Brazilian clays, where the coefficient term equals 0.28. In this manner, each of the aforementioned correlations could be adjusted to site-specific conditions, as calibrated against oedometer results on high-quality tube or block samples.

CASE STUDY APPLICATIONS

The aforementioned methodology has been used to profile σ_p' at two sites where in situ testing was conducted for site characterization of clay deposits in the Washington, D.C., area.

Suitland, Maryland

The Smithsonian Support Center in Suitland, Maryland, required detailed analysis of the yield stress profile of the subsurface soils for supporting several large warehouses, offices, and showrooms on shallow foundations (*30*). The site is underlain by an interesting geology of layered and varied sedimentary strata formed during different epochs. Figure 6(*a*) illustrates the sequence of strata and typical index properties of the clays. The uppermost 6 m of very dense sands and gravels required preboring. Below these terrace deposits, soft sandy clays of Miocene and Eocene age were encountered that were underlain by very stiff overconsolidated clays of Cretaceous age. Groundwater is approximately 6 m deep at the site. Typical SPT resistances were 4 to 6 blows/300 mm in the Calvert and Aquia

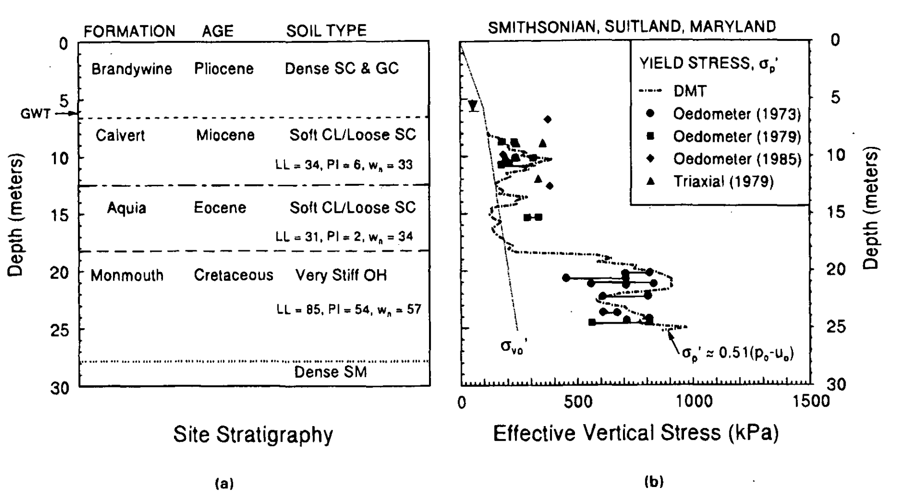

FIGURE 6 Field data at Smithsonian Center, Suitland, Md.: (*a*) general stratigraphy; and (*b*) yield stresses from oedometer and dilatometer tests.

formations and about 12 to 16 blows/300 mm in the underlying Monmouth formation. The reference preconsolidation stresses of the clays were reconstructed using several series of oedometer tests made on recovered specimens taken during different exploration programs at the site. These were supplemented by interpretations of σ_p' using CIUC triaxial test data (*31*). Figure 6(*b*) illustrates the use of DMT data via Equation 4 for estimating the yield stresses at the site. The DMT clearly indicates the dramatic changes in σ_p' between different strata. It is also noted that the original correlation (*8*) gives estimated σ_p' that are twice that of Equation 4 in the lower Cretaceous unit. In the original expression, OCR was correlated with the dilatometer index $K_D = (p_o - u_o)/\sigma_{vo}'$, based on data from only eight clays. The direct expression for σ_p' in terms of net contact stress $(p_o - u_o)$ given herein is based on data from 31 sites, which is statistically specific to intact clays.

Anacostia, Washington, D.C.

The construction of a new helicopter hangar and communications facility at the Anacostia Naval Air Station in Washington, D.C., required additional characterization of the lightly overconsolidated alluvial organic clayey silts (LL = 83; PI = 37, $w_n = 68$) that extend up to 30 m in depth. The site is located at the confluence of the Potomac and Anacostia rivers, and the results of in situ dilatometer tests and laboratory consolidation tests were reported previously (*24*). Cone tip resistances and penetration pore pressures from Type 2 piezocone soundings with a 15-cm² tip are presented in Figure 7. These readings can be used via Equations 1 and 3 to provide estimated profiles of σ_p' with depth, as shown in Figure 8, and the clayey silts have corresponding overconsolidation ratios in the range of 1.5 to about 4 (*32*). An examination of the data in Figure 8 shows that the tip resistance slightly overpredicted σ_p', and the pore pressure data slightly underpredicted σ_p'. A partial explanation is the uncertainty associated with the relatively large correction (*22*) based on the net area ratio for this cone ($a = 0.60$); thus, q_T may be a bit high. Also, saturation was accomplished with water (although glycerine has proven better) and may have been less complete because of the larger diameter cone, thus yielding a lower registration with the Δu readings. In any event the estimates from the two independent piezocone readings are in relative agreement with the reference oedometer results.

DISCUSSION OF RESULTS

Statistical relationships have been presented between σ_p' and each of the measured in situ test parameters. Variance in the trends is evident for these relationships, as noted in the original database sources (10, 11, 19–21, 24, 25, 28). One intent of this study was to acknowledge that a simple unified approach exists that is common to several types of in situ tests. Care should be taken in the use of any empirical relationships, however, and site-specific calibration of in situ tests with oedometer test results is warranted and recommended. In this regard, a more generalized format may be more useful and prudent for interrelating σ_p' to in situ parameters:

PCPT1 PCPT2 DMT PMT

$$\sigma_p' \approx \frac{\Delta u_t}{\delta} \approx \frac{1.2\Delta u_{bt}}{\delta} \approx \frac{1.1(p_o - u_o)}{\delta} \approx \frac{1.6 s_u \ln I_r}{\delta}$$

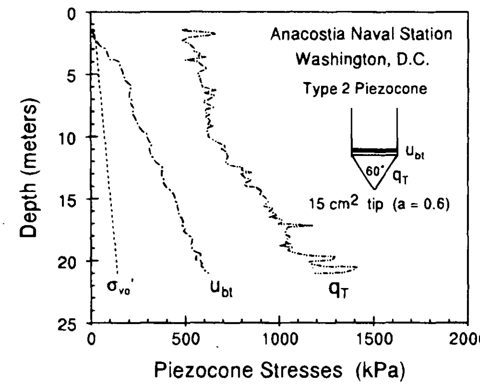

FIGURE 7 Piezocone data in alluvial clay at Anacostia Naval Air Station, Washington, D.C.

CPT VST SPT

$$\approx \frac{0.7(q_T - \sigma_{vo})}{\delta} \approx \frac{7.6 s_{uv}}{\delta} \approx \frac{N_{60} p_a}{\delta} \quad (10)$$

where experimentally observed values are typically in the range $1.5 < \delta < 2.5$ for intact clays, whereas for fissured materials the range is generally $0.4 \leq \delta \leq 0.8$. From a theoretical consideration of cavity expansion and critical state concepts (*19*), the value of δ for intact soils can be approximately obtained as

$$\delta = (4/3)(\phi'/100)\ln(I_r) \quad (11)$$

where ϕ' = effective stress friction angle and $I_r = G/s_u$ = rigidity index of the clay. However, the relevant values of these parameters often are not known a priori during in situ testing, and therefore the mean statistical trends presented may be useful. More rigorous and fundamental relationships have been developed for certain tests, such as the piezocone (*17,32,33*) and dilatometer (*10,18*), and these

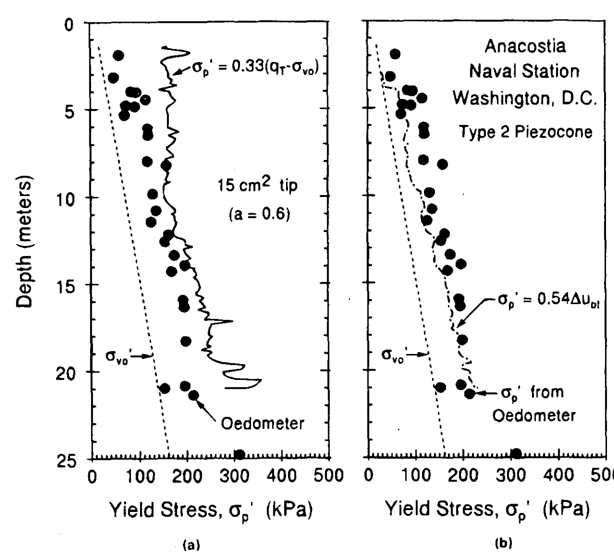

FIGURE 8 Comparison of measured and interpreted yield stresses from (*a*) cone tip resistance and (*b*) penetration pore pressures.

use the normalized parameter OCR for more proper representation of stress history effects (2).

CONCLUSIONS

In situ tests may be used to profile the approximate value of effective yield stresses (σ_p') in natural clay deposits. Statistical relationships are presented for evaluating σ_p' from cone, piezocone, dilatometer, pressuremeter, vane, and standard penetration test data in intact clays. The trends illustrate the existence of a unified approach common to all tests. Conservative estimates are obtained in fissured deposits because the discontinuities affect the in situ measurements. Advantages of the approach include the immediate, continuous, and economical evaluation of the stress state of cohesive materials, in contrast to difficulties associated with sampling, disturbance, handling, and long testing times for laboratory testing. However, reference values of σ_p' should always be obtained from conventional consolidation tests to verify that the empirical procedures are valid. A generalized format is outlined to permit site-specific calibration with in situ test data.

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