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1 author:

Paul W. Mayne
Georgia Institute of Technology

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DETERMINATION OF OCR IN CLAYS BY PIEZOCONE TESTS USING CAVITY EXPANSION AND CRITICAL STATE CONCEPTS

PAUL W. MAYNE[1)]

ABSTRACT

For piezocone penetration in clays, cavity expansion theory describes both the point resistance and induced excess pore water pressure in terms of the undrained shear strength (C_u) and rigidity index ($I_r=G/C_u$). Modified Cam Clay provides a simple effective stress representation of undrained behavior in terms of stress history. Therefore, the two theories may be combined to provide an approximate determination of the in-situ overconsolidation ratio ($\mathrm{OCR}=\sigma_p'/\sigma_{vo}'$) in terms of the effective stress friction angle (ϕ') and normalized piezocone parameter $(q_T-u_m)/\sigma_{vo}'$, in which q_T=corrected cone resistance and u_m=measured pore water pressure. The approach distinguishes between piezocones which measure pore water pressures on the cone tip/face (u_t) and those which measure just behind the tip (u_{bt}). Specific examples are presented to show the general applicability of this simple effective stress model for estimating the in-situ stress history of clay deposits with $1<\mathrm{OCRs}<60$ and $20°<\phi'<40°$.

Key words: cavity expansion, cam clay, clays, cone penetrometers, critical-state, in-situ tests, overconsolidation ratio, penetration tests, piezocone, pore water pressures, preconsolidation, undrained shear strength (**IGC**: C 3/D 3/D 5/D 6)

INTRODUCTION

The relatively recent advent of piezocone probes during the last decade has initiated an extensive search for the most appropriate parameter which correctly profiles the in-situ OCR of clay deposits. The intensity of this ambition is evidenced by the wide range of different piezocone parameters proposed by many researchers and which are summarized in Table 1. Most of these parameters are suggested merely from an empirical standpoint and are based on specific trends observed at a limited number of sites. Only a few of the parameters appear to have been derived from a theoretical standpoint.

The recognition that the cone point resistance (q_c) must be corrected for pore water pressure effects acting on unequal area projections of the cone and which depend on the specific cone has been an important finding of piezocone research. In this regard, any piezocone parameter in Table 1 requiring a measurement of cone resistance must logically

1) Associate Professor, Georgia Institute of Technology, Geotechnical Division, School of Civil Engineering, Atlanta, Georgia, 30332-0355 USA.

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Table 1. List of proposed piezocone parameters for profiling in-situ stress history of clay deposits

	PARAMETER	BASIS	REFERENCE
1.	u_m/q_c	empirical	Baligh et al., 1980
2.	$\Delta u/q_c$	empirical	Campanella & Robertson, 1981
3.	$B_q=\Delta u/(q_c-\sigma_{vo})$	empirical	Senneset, Janbu, & Svanø, 1982
4.	$B_q=\Delta u/(q_T-\sigma_{vo})$	empirical	Wroth, 1984
5.	$\Delta u/(q_c-u_o)$	empirical	Smits, 1982
6.	$\Delta u/\sigma_{vo}'$	empirical	Azzouz et al., 1983
		theory	Mayne & Bachus, 1988
7.	$(q_T-\sigma_{vo}-\Delta u)/\sigma_{vo}'$	theory	Lancellotta, 1985**
8.	$N_u=\Delta u/C_u$	empirical	Tavenas & Leroueil, 1987
9*.	$q_T-\sigma_{vo}$	empirical	Tavenas & Leroueil, 1987
10*.	q_T-u_m	theory	Konrad & Law, 1987
11*.	Δu	empirical	Mayne & Holtz, 1988
12*.	q_T-u_o	theory	Sandven, Senneset & Janbu, 1988
13.	$(q_T-\sigma_{vo})/\sigma_{vo}'$	theory	Wroth, 1988
14.	$(u_t/u_o)-(u_{bt}/u_o)$	empirical	Sully, et al., 1988
15.	q_T, u_m, f_s	empirical	Rad & Lunne, 1988
16.	$(q_T-u_m)/\sigma_{vo}'$	theory	Houlsby, 1988 and This study

Notes: q_T=corrected cone resistance=$q_c+(1-a)u_{bt}$
q_c=measured cone resistance (uncorrected)
u_m=measured penetration pore water pressure
u_t=pore water pressure at cone tip
u_{bt}=pore water pressure behind cone tip
$\Delta u=u_m-u_o$=excess pore water pressure
u_o=hydrostatic pore water pressure
a=net area ratio of cone geometry
σ_{vo}'=effective overburden stress
σ_{vo}=total overburden stress
C_u=undrained shear strength
f_s=sleeve friction (corrected)

* Stress history in terms of preconsolidation stress (σ_p'). All others related to overconsolidation ratio (OCR=σ_p'/σ_{vo}').
** As referenced by Battaglio et al. (1986).

utilize the corrected point resistance (q_T), as described by Campanella and Robertson (1981) and Jamiolkowski et al. (1985). The position of the porous element for measurement of pore water pressures has not yet been standardized (Campanella and Robertson, 1988), but generally, most piezocones can be separated into one of two categories: Type 1, with either the tip/face readings; or Type 2, with readings taken just behind the tip. A comparative test study involving 14 different types of electric cones by Lunne et al. (1986a) showed indistinguishable results between pore water pressure measurements taken on the tip apex or mid–tip of the cone face.

The corrected cone resistance q_T necessitates a knowledge of the total measured penetration pore water pressures (u_m) which exist just behind the cone tip (u_{bt}). Consequently, for Type 1 cones with u_m taken at the tip (u_t), some estimate or measurement of u_{bt} behind the tip is needed in order to obtain q_T. For Type 2 cones, u_{bt} is measured directly. This distinction is important since significant differences occur between u_t and u_{bt} (Mayne et al, 1990). In intact clays, the ratio u_{bt}/u_t may be as great as 0.8 to 1.0 (Rad and Lunne, 1988; Sully et al., 1988). However, for fissured clays and crustal layers, the ratio $u_{bt}/u_t \approx 0$. In fact, in heavily–overconsolidated and fissured clays, u_{bt} may actually become negative (Lunne et al, 1986b).

By claiming an analogy with the triaxial pore pressure parameter A_f, Wroth (1984), Keaveny and Mitchell (1986), and Houlsby (1988) postulate that $B_q=\Delta u/(q_T-\sigma_{vo})$ should be a proper profiling parameter for in–situ OCR. However, experimental data reviewed by Mayne and Holtz (1988), Konrad and Law (1987), and Jamiolkowski, et al. (1985) show B_q to be very site specific.

Using a theoretical approach based on the effective stress analysis of a penetrating cone in clay, Konrad and Law (1987a) concluded that the effective preconsolidation pressure (σ_p') is related to the net cone resistance ($q_T - u_m$), the effective friction angle (ϕ') of the deposit, a soil/cone friction factor (δ), and assumed ratio between pore water pressure at the cone tip and behind the tip ($\alpha = u_t/u_{bt}$). For low OCRs, reasonably good agreement was observed between oedometer measured values of σ_p' and piezocone predictions. A correction factor was required at higher OCRs, however, and the model was calibrated using data from only 5 Canadian sites, all with similar mineralogy and geological origins.

Sandven et al. (1988) also developed an effective stress interpretation for calculating σ_p' from CPTU data. This method utilizes the parameter ($q_T - u_o$) and requires an knowledge of ϕ' and the attraction $a' = c' \cot\phi'$, in which c'=effective cohesion intercept. Verification of the approach was supported by data from two Norwegian clay sites.

A cavity expansion/critical state model for profiling OCRs was proposed by Mayne and Bachus (1988) which related OCR to the parameter $\Delta u/\sigma_{vo}'$ and required both ϕ' and the rigidity index ($I_r = G/C_u$). For piezocones with pore water pressures measured at the tip/face of the cone, a piezocone database substantiated direct trends between OCR and $\Delta u/\sigma_{vo}'$, as shown by Fig. 1. For piezocones with elements located just behind the tip, the database showed a similar trend occurs for intact clays, however, a non-unique relationship exists between OCR and $\Delta u/\sigma_{vo}'$ when data from heavily overconsolidated fissured clays are included, as indicated by Fig. 2. While the formulation of Mayne and Bachus (1988) can describe these aspects, a practical difficulty lies in the proper selection of values for the elusive parameter termed the rigidity index (I_r), although it's usage is quite common in theoretical soil mechanics. Of additional concern is the fact that I_r varies with OCR (Wroth

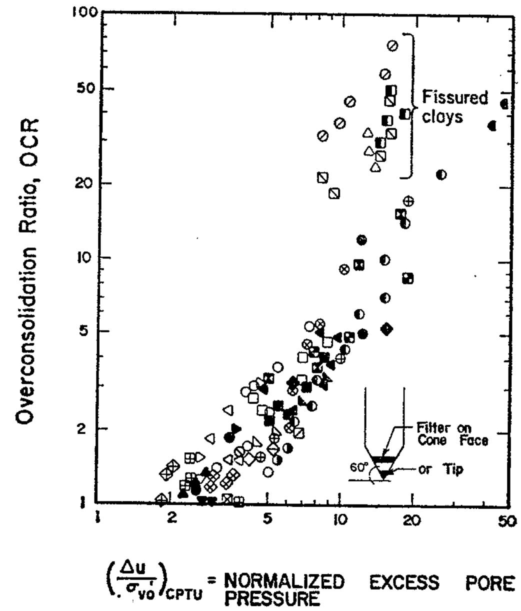

Fig. 1. Observed trend between OCR and $\Delta u/\sigma_{vo}'$ for Type 1 piezocones with porous elements on tip/face

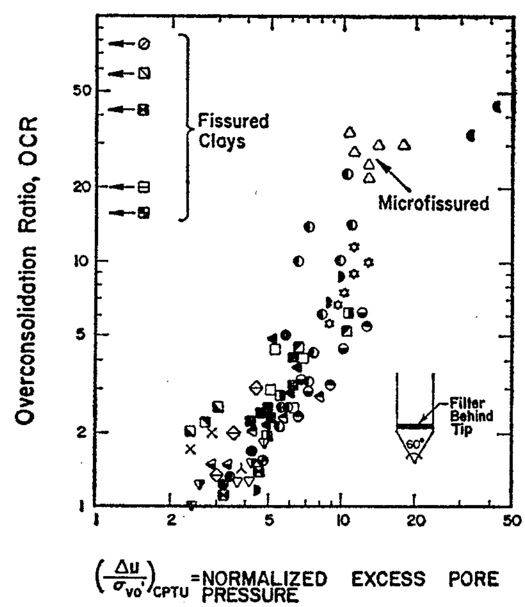

Fig. 2. Observed trend between OCR and $\Delta u/\sigma_{vo}'$ for Type 2 piezocones with porous elements behind cone tip

and Houlsby, 1985).

By adopting a second form of cavity expansion theory to describe the cone point resistance, I_r can be eliminated from the equations, resulting in an expression for OCR in terms of ϕ' and the normalized parameter $(q_T-u_m)/\sigma_{vo}'$. The similarity of this parameter with those independently derived by Konrad and Law (1987a), Battaglio et al. (1986), and Houlsby (1988) is quite interesting.

EFFECTIVE STRESS THEORY

The cone tip resistance (q_T) in clay is often expressed in terms of the undrained shear strength (C_u):

$$q_T=N_{kT}C_u+P_0 \quad (1)$$

where P_0=total overburden stress
and N_{kT}=cone bearing capacity factor

The bearing factor N_{kT} depends upon the specific theory employed and Konrad and Law (1987b) provide a summary of 13 different expressions for N_{kT}. If the spherical cavity expansion theory of Vesić (1977) is invoked, N_{kT} is simply:

$$N_{kT}=(4/3)(\ln I_r+1)+\pi/2+1 \quad (2)$$

where $I_r=G/C_u$=rigidity index
and G=shear modulus

Combining Eqs. (1) and (2), the expression for the net cone tip resistance using cavity expansion theory is given as:

$$q_T-P_0=1.33\,C_u\ln I_r+3.90\,C_u \quad (3)$$

Keaveny and Mitchell (1986) showed that the cavity expansion theory of Vesić (1977) provides a proper representation of cone tip resistance when calculated using a value of C_u as determined from CK_0UC triaxial tests. This is because the stress path directly under the cone tip closely follows that corresponding to a triaxial compression mode.

The Modified Cam Clay (MCC) model is a simple critical-state theory that can be used to determine C_u for triaxial compression loading in terms of effective stresses and stress history effects (Wroth and Houlsby, 1985):

$$C_u=(M/2)(OCR/2)^{\Lambda}P_0' \quad (4)$$

where
$M=6\sin\phi'/(3-\sin\phi')$
ϕ' =effective stress friction angle
Λ =plastic volumetric strain ratio$=1-C_s/C_c$.
P_0'=initial mean effective overburden stress
C_s =isotropic swelling index

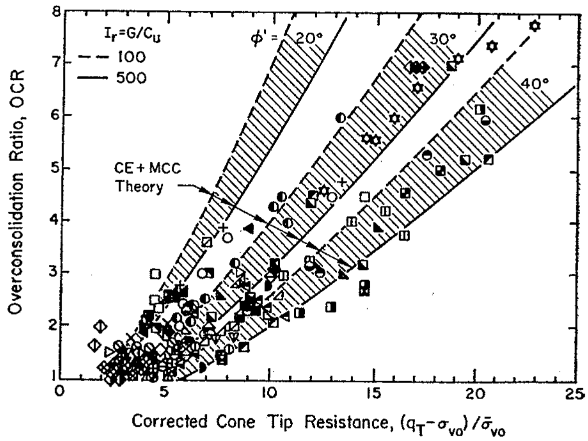

Fig. 3. Observed and CE/MCC predicted relationship between OCR and normalized cone tip resistance

C_c=isotropic compression index

The method is only approximate, however, since it has been developed for isotropically–consolidated clays.

Available laboratory strength data indicates that the parameter Λ is essentially constant for natural clays and averages about 0.75, 0.80, and 0.85 for compression, simple shear, and extension modes, respectively (Mayne, 1988a). A value Λ=0.75 has been adopted herein, corresponding to triaxial compression.

By combining Eqs. (3) and (4), an expression for the in-situ OCR may be derived in terms of the normalized cone tip resistance, $(q_T-P_0)/P_0'$:

$$OCR=2\left[\frac{(2/M)(q_T-P_0)/P_0'}{(4/3)(1+\ln I_r)+\pi/2+1}\right]^{1/\Lambda} \quad (5)$$

Obviously, this method can only be approximate since no attempt has been made to account for initial stress state ($K_0=\sigma_{ho}'/\sigma_{vo}'$), strength anisotropy, stress rotation, or strain rate effects. Available data from 83 piezocone sites (Mayne and Holtz, 1988; Mayne et al, 1990) indicate a reasonable trend exists between OCR and normalized cone tip resistance, as shown by Fig. 3. Since the value of P_0' is not actually known for these sites, σ_{vo}' has been used as the overburden stress. Therefore, the practical version of the normalized piezocone parameter is $(q_T-\sigma_{vo})/\sigma_{vo}'$ which is the form recommended by Wroth (1988) and

Sugawara (1988) for profiling OCR using cone penetration tests. For clarity, only data from OCRs<8 are shown in Fig. 3. It may be seen that Eq. (5) bounds the data for typical ranges of $20° < \phi' < 40°$ and $50 < I_r < 500$.

In addition to q_T, piezocones provide a measure of penetration pore water pressures (u_m). The excess pore water pressures ($\Delta u = u_m - u_o$) generated during cone penetration may also be expressed in terms of cavity expansion and critical-state concepts (Mayne and Bachus, 1988). While it is not possible to decouple field measurements of Δu into these components, a theoretical separation is possible. The excess pore water pressures induced by a advancing probe are due to a combination of changes in octahedral and shear stresses:

$$\Delta u_{\text{meas}} = \Delta u_{\text{oct}} + \Delta u_{\text{shear}} \qquad (6)$$

Using the strain path method, Baligh (1986) has shown that u_m measured on the tip is dominated by octahedral stresses with Δu_{shear} generally less than 20 percent of the total measured Δu. For spherical cavity expansion, Vesić (1972) determined that the octahedral component of excess pore water pressure could be expressed simply by:

$$\Delta u_{\text{oct}} = (4/3) C_u \ln(I_r) \qquad (7)$$

Eq. (7) may be considered as an approximate first order expression for $\Delta u_t \approx \Delta u_{\text{oct}}$ for Type 1 piezocones in stiff clays. Therefore, for Type 1 piezocones, Eqs. (3) and (7) may be combined to give an expression for the net cone resistance:

$$q_T - P_0 = \Delta u_t + 3.90\, C_u \qquad (8)$$

Substituting the expression for C_u from Eq. (4) results in:

$$q_T - P_0 = \Delta u_t + 1.95M(\text{OCR}/2)^{\Lambda} \qquad (9)$$

This may be rearranged to provide an expression for OCR:

$$\text{OCR} = 2\left[\frac{1}{1.95M}\left(\frac{q_T - u_t}{P_0'} - 1\right)\right]^{1/\Lambda} \qquad (10)$$

By adopting a value of $\Lambda = 0.75$ and for simplicity, taking $P_0' = \sigma_{vo}'$, the predictive form for practical use becomes:

$$\text{OCR} = 2\left[\frac{1}{1.95M}\left(\frac{q_T - u_t}{\sigma_{vo}'} - 1\right)\right]^{1.33} \qquad (11)$$

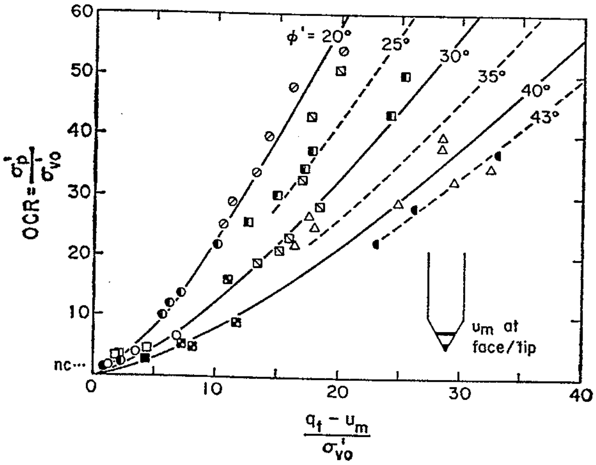

Fig. 4. Measured and approximate predicted relationships between OCR and normalized parameter $(q_T - u_t)/\sigma_{vo}'$ for Type 1 piezocones

Fig. 4 indicates that reasonable values of OCR are predicted for Type 1 piezocones advanced into stiff clays using this approximate approach. The individual symbols shown in Fig. 4 correspond to the individual sites listed in Mayne and Holtz (1988) and Mayne et al. (1990). However, for Type 1 piezocones, there exists some uncertainty in the q_T resistances since only u_t measurements are obtained and u_{bt} values are required for the correction of cone point resistances. This is especially true in soft to medium clays, since the difference between point resistance and pore water pressure $(q_T - u_t)$ is small and not particularly reliable. It is not possible to properly correct cone tip resistances unless Type 2 piezocone soundings are also conducted to obtain u_{bt} or unless special piezocones with both porous elements are utilized.

Behind the cone tip, a higher proportion of shear-induced pore water pressures are generated. In addition, the relevant stress path likely does not correspond to a triaxial compression mode (Keaveny and Mitchell, 1986). The magnitude of induced pore water pressures depends on the relative distance between the total and effective stress paths, which are not truly known. If a constant P stress path is assumed (Mayne and Bachus, 1988), then the shear-induced component of the excess pore pressure becomes:

$$\Delta u_{\text{shear}} = P_0'(1-(\text{OCR}/2)^{\Lambda}) \quad (12)$$

Alternatively, a CIUC triaxial stress path may be assumed and the shear-induced component of Δu would be expressed simply as:

$$\Delta u_{\text{shear}} = P_0'[1+(M/3-1)(\text{OCR}/2)^{\Lambda}] \quad (13)$$

However, as noted previously, only an approximate expression is obtained in either case since the MCC model applies specifically to isotropically-consolidated materials. A similar, yet not identical, formulation was used by Randolph, Carter, and Wroth (1979) for describing the behavior of driven piles in clay using cylindrical cavity expansion and plane strain boundary conditions.

For Type 2 piezocones, the measured excess pore pressures can be considered to be the sum combination of Eqs. (7) and (12), resulting in:

$$\Delta u_{bt} = (4/3)C_u \ln I_r + P_0'[1-(\text{OCR}/2)^{\Lambda}] \quad (14)$$

Subtracting Eq. (14) from (3) and substituting the expression for C_u from Eq. (4) results in:

$$q_T - P_0 - \Delta u_{bt} = 1.95M(\text{OCR}/2)^{\Lambda}P_0' - [1-(\text{OCR}/2)^{\Lambda}]P_0' \quad (15)$$

or,

$$q_T - P_0 - u_{bt} + u_0 = P_0'[(1.95M+1)(\text{OCR}/2)^{\Lambda} - 1] \quad (16)$$

When rearranged, this provides a direct expression for OCR for Type 2 piezocones that measure pore water pressures behind the tip (u_{bt}):

$$\text{OCR} = 2\left[\frac{1}{1.95M+1}\left(\frac{q_T - u_{bt}}{P_0'}\right)\right]^{1/\Lambda} \quad (17)$$

By again adopting a value of $\Lambda = 0.75$ and taking $P_0' = \sigma_{vo}'$, the form for practical use becomes:

$$\text{OCR} = 2\left[\frac{1}{1.95M+1}\left(\frac{q_T - u_{bt}}{\sigma_{vo}'}\right)\right]^{1.33} \quad (18)$$

It is of interest to note that, if the alternative shear-induced pore pressures given by Eq. (13) were used in the derivation in lieu of the simplified form given by Eq. (12), the resulting expressions for OCR in Eqs. (17) and (18) would differ only by the value 1.62($=[4/3+\pi/2+1]/2-1/3$) replacing the 1.95 term. Considering the overall approximate nature of the method, however, a more precise derivation is unwarranted unless a more complex formulation were developed to include the effects of K_0, stress rotation, anisotropy, strain rate, as well as other factors.

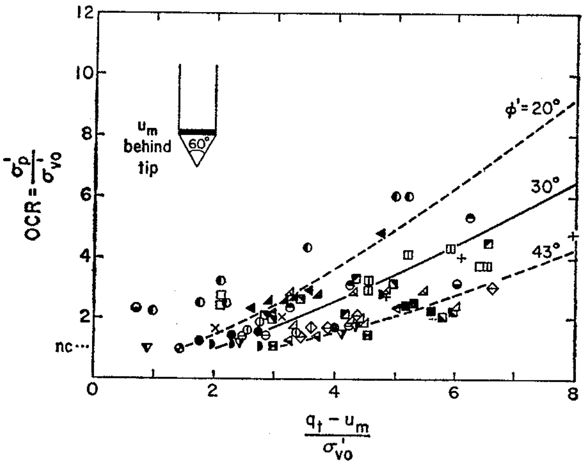

Fig. 5. Measured and predicted relationships for OCRs in terms of normalized parameter $(q_T - u_{bt})/\sigma_{vo}'$ for Type 2 piezocones in clays with 1<OCRs<6

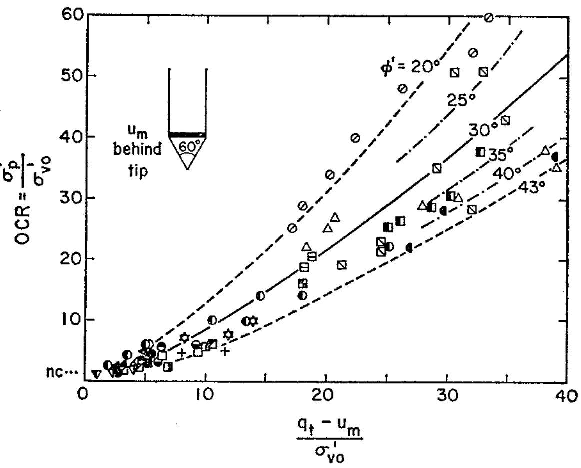

Fig. 6. Measured and predicted relationships for OCRs in terms of normalized parameter $(q_T - u_{bt})/\sigma_{vo}'$ for Type 2 piezocones in clays with 6<OCRs<60

The trend of OCR versus the piezocone parameter $(q_T - u_{bt})/\sigma_{vo}'$ is illustrated in Fig. 5 with data from Type 2 piezocones advanced into low to moderately overconsolidated clays with OCRs<10. For these type of cones, q_T resistances are properly corrected for pore water pressures acting on unequal areas. Predicted values for $\phi' = 20°$, 30°, and 43° using

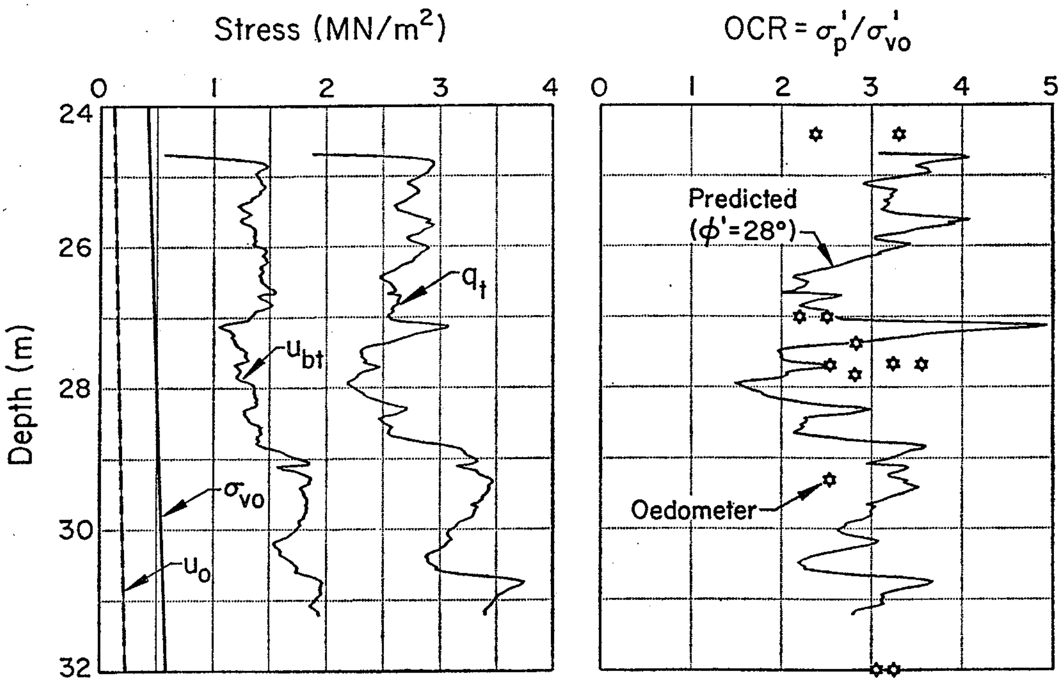

Fig. 7. Piezocone profiling of OCR in Miocene clay at power plant site south of Jamestown, Virginia

Eq. (18) are superimposed on the graph and are seen to bound the data. For data corresponding to heavily-overconsolidated clay deposits with OCRs<60, a similar relationship is observed, as shown by Fig. 6. Also, it is interesting to note that Fig. 6 includes data from intact and fissured clays, as well as cemented soils.

According to the cavity expansion/critical-state theory, the effect of ϕ' on the predicted value of OCR is rather important. Most of the piezocone data in Figs. 5 and 6 fall within the ranges given for $20° < \phi' < 43°$. While some may argue that effective stress friction angles as high as 43° are unusual for clay, a survey of laboratory strength data on various clays indicate a considerable number of clays have friction angles as high or higher than these values (Mayne and Holtz, 1985). For example, recent data on 12 Japanese clays reported by Nakase and Kamei (1988) indicate ϕ' between 39° and 42° for triaxial compression tests. Furthermore, since the suggested model is a simple effective stress approach that assumes $c'=0$ and utilizes only a single value of ϕ', it is appropriate to think of the operational ϕ' as a secant value and not as a best fit value. As an example, the results of triaxial compression tests on Saint-Jean Vianney clay reported by Vaid et al. (1979) indicate the material to have an ultimate ϕ' of 40°.

On a final note, the effective stress MCC theory can be collapsed using Eq. (4) to provide a total stress expression for calculating OCR from Type 2 piezocones:

$$\mathrm{OCR}=2\left[\frac{1}{6.56\,C_u/\sigma_{vnc}'+1}\left(\frac{q_T-u_{bt}}{\sigma_{vo}'}\right)\right]^{1.33} \tag{19}$$

in which C_u/σ_{vnc}' = normally consolidated undrained strength ratio for OCR=1. The analogous expression for Type 1 piezocones, in which Δu due to shear has been omitted, is given by:

$$\mathrm{OCR}=2\left[\frac{1}{6.56\,C_u/\sigma_{vnc}'}\left(\frac{q_T-u_{bt}}{\sigma_{vo}'}-1\right)\right]^{1.33} \tag{20}$$

ILLUSTRATIVE EXAMPLES

The proposed method is illustrated by application to two sites underlain by marine clays

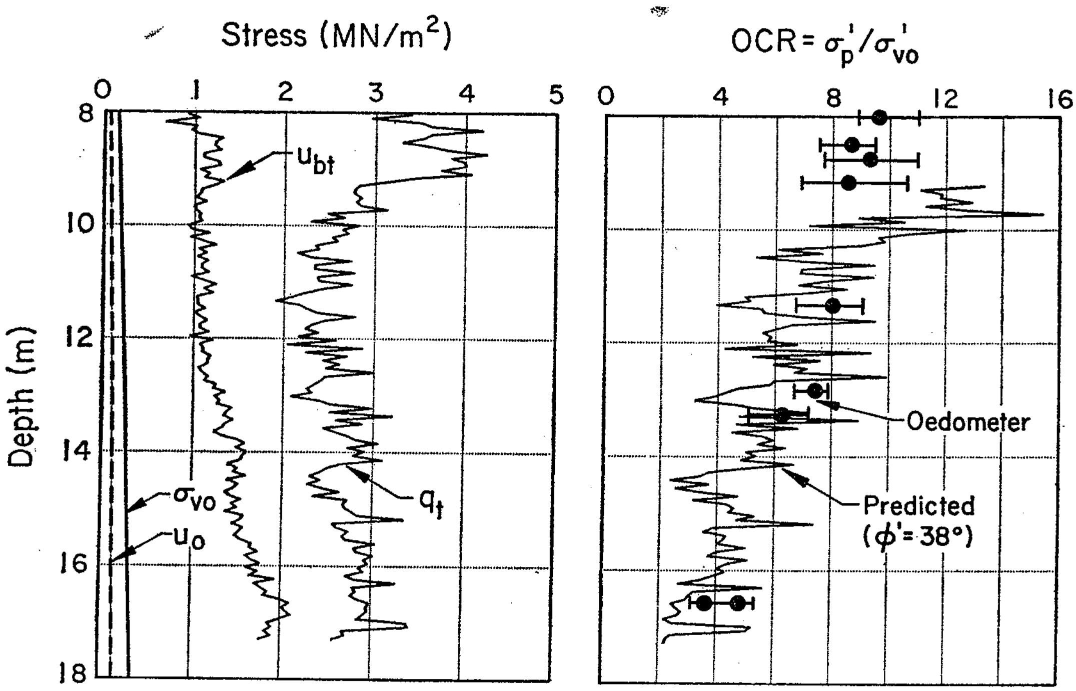

Fig. 8. Piezocone profiling of OCR in Yorktown Formation at accelerator facility in Newport News, Virginia

and located in southeastern Virginia. For both sites, CPTU data were acquired using a 15-cm² area cone with 60° apex and porous stone element located behind the tip. The net area ratio for correction of q_c to q_T for this cone was $a=0.65$. In-situ OCRs were determined from one-dimensional consolidation tests conducted on samples obtained from adjacent soil borings made at the site. The applied stresses in the consolidation tests were taken as high as 5 MN/m² in order to help better define the yield point corresponding to σ_p'.

Miocene Clay

A site located south of the James River near Jamestown, Virginia is underlain by approximately 24 m of Pleistocene terrace deposits overlying Miocene clay extending to depths well over 80 meters. The Miocene clay is lightly overconsolidated yet rather stiff due to its relatively great depth. A portion of the logging record of one of 5 similar piezocone soundings in this clay is presented in Fig. 7 (Mayne, 1988b). Typical index properties include: $W_L=63$, $I_p=37$, $W_n=39$, and $CF=$ 10%. Results of CID triaxial compression tests indicated $\phi'=28°$ for this material. As illustrated by Fig. 7, reasonable agreement is seen between the predicted OCR profile using Eq. (18) and the actual measured values determined from oedometer tests. The in-situ OCR is seen to be constant at about 3 ± 0.5 within the depth of interest from 24 to 32 meters.

Yorktown Formation

The site for a new electron beam accelerator facility for study of high-energy nuclear physics is located off Jefferson Avenue in Newport News, Virginia. The Yorktown Formation at this location lies below depths of about 8 to 10 meters and consists of a very sandy clay with barely 50% fines and the following index properties: $W_L=31$, $I_p=4$, $W_n=31$, and $CF=7\%$. A series of CIU and CID triaxial compression tests indicated $\phi'=38°$ (Mayne, 1988a). Fig. 8 shows q_T and u_{bt} from one of 18 similar piezocone soundings, such as presented by Mayne and Holtz (1988). The predicted and measured OCRs are also shown in Fig. 8 with OCRs decreasing with depth

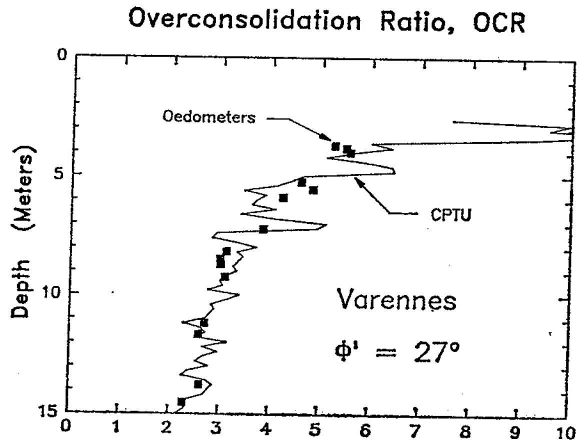

Fig. 9. Profile of OCR by piezocone in lightly overconsolidated sensitive clay at Varennes site (data from Konrad and Law, 1987a)

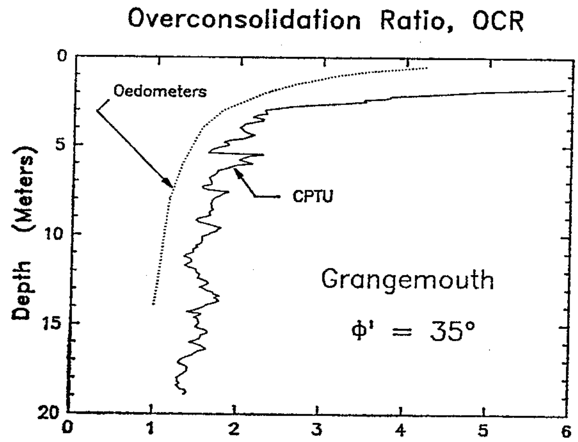

Fig. 11. Profile of OCR by piezocone in normally consolidated alluvial clay at Grangemouth site (data from Powell, et al., 1988)

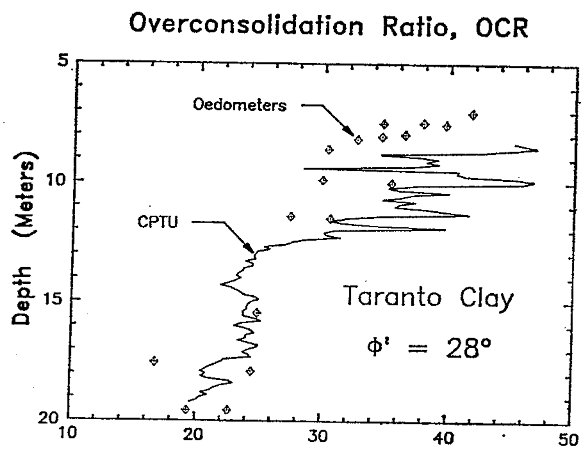

Fig. 10. Profile of OCR by piezocone in heavily overconsolidated cemented Taranto clay (data from Battaglio, et al., 1986)

from about 10 to 4 within the range of study.

ADDITIONAL APPLICATIONS

The aforementioned approach may be further evaluated by application to several well-documented sites reported in the geotechnical literature. All of the subsequent examples are taken from sites tested by Type 2 piezocones in order that proper q_T values have been obtained. Groundwater levels at these sites were relatively shallow and generally less than 1 meter.

Varennes

The site of Varennes is located near Montreal, Canada and has been described by Konrad and Law (1987a). The lightly-overconsolidated deposit consists of a sensitive Leda-type clay with a sensitivity of about 20. Konrad and Law (1987b) indicate $\phi'=27°$ for this material. Fig. 9 illustrates reasonably good agreement between measured and predicted OCRs which decrease from about 5 to 2 in the depth interval from 3 to 15 meters.

Taranto

The Taranto clay is a heavily-overconsolidated cemented clay in southern Italy and is reported to be micro-fissured (Jamiolkowski et al, 1985). Data from Type 2 piezocones have been reported by Battaglio, et al. (1986). A series of CK_0UC triaxial tests indicated a strength envelope described by $\phi'=28°$ and $c'=70$ kN/m^2. Fig. 10 presents the OCRs determined by both standard oedometers and constant rate of strain consolidometers, indicating a stress history profile with OCR$\approx$40 at a depth of 7 meters decreasing to OCR$\approx$20 at a depth of 20 meters. Results predicted using Eq. (18) are seen to be in good agreement with the laboratory data.

Grangemouth

The alluvial clay at Grangemouth, Scotland

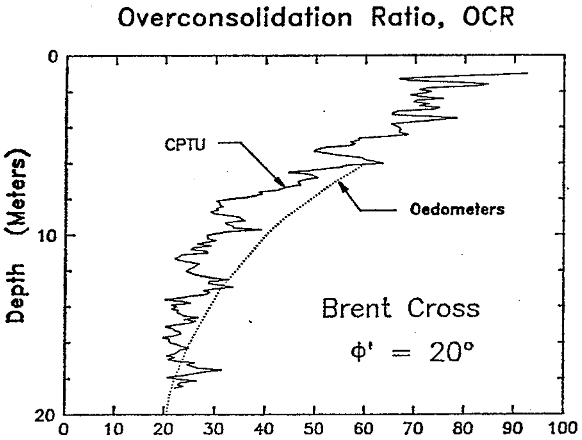

Fig. 12. Profile of OCR by piezocone in heavily overconsolidated fissured London clay at Brent Cross (data from Lunne, et al., 1986)

serves as a national test site for the British Research Establishment. Stress history profiles from oedometer tests have been reported by Powell and Uglow (1988), indicating a lightly overconsolidated state that reaches a normally consolidated condition at depths below 15 meters. Piezocone soundings are presented by Powell, et al. (1988), who also show that CAUC triaxial tests give $31° < \phi' < 36°$. Fig. 11 indicates a slight overprediction of the OCR profile at this site using the CE/MCC approach.

Brent Cross

The site of Brent Cross is underlain by heavily-overconsolidated fissured London clay. Piezocone data for the site has been reported by Lunne, et al. (1986), Powell et al. (1988), and Rad and Lunne (1988). Stress history profiles presented by Powell and Uglow (1986) show OCRs decreasing from 60 to 20 in the depth interval from 6 to 20 meters. Powell et al. (1988) characterize the effective stress friction angle in the range $18° < \phi' < 21°$. Adopting an average value $\phi' = 20°$, measured and predicted profiles of OCR are observed to agree quite well, as shown in Fig. 12.

CONCLUSIONS

1. A coupling of cavity expansion (CE) theory and Modified Cam Clay (MCC) concepts allows for the derivation of the in-situ OCR in terms of the piezocone parameter $(q_T - u_m)/(\sigma_{vo}')$ and effective stress friction angle (ϕ'). CE theory is used for representing octahedral penetration pore water pressures and cone tip resistances. MCC describes shear-induced pore water pressures, stress history effects, and undrained strength from an effective stress approach.

2. The *CE/MCC* method is best applied to Type 2 piezocones with transducer readings of pore water pressure taken behind the tip (u_{bt}). The approximate closed-form expression for Type 2 piezocones is given by Eq. (18):

$$\mathrm{OCR} = 2\left[\frac{1}{1.95M+1}\left(\frac{q_T - u_{bt}}{\sigma_{vo}'}\right)\right]^{1.33}$$

in which $M = 6\sin\phi'/(3 - \sin\phi')$.

3. An approximate application of the method to Type 1 piezocones with u_t measured at the cone tip/face is given by Eq. (11) and should be restricted to stiff clays. For soft clays, the difference $(q_T - u_t)$ is often small and unreliable.

$$\mathrm{OCR} = 2\left[\frac{1}{1.95M}\left(\frac{q_T - u_t}{\sigma_{vo}'} - 1\right)\right]^{1.33}$$

4. Although the model does not include the effects of initial stress state, anisotropy, stress rotation, or strain rate, it does provide reasonable first-order estimates of in-situ OCR for a variety of clay deposits, as illustrated by several examples with OCRs ranging from 1 to over 60 and ϕ' from 20° to 38°.

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