OVERCONSOLIDATION RATIO OF CLAYS FROM PENETRATION PORE PRESSURES

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INTRODUCTION

Evaluation of the stress history, or overconsolidation ratio, from cone penetration tests in clays has become of great interest since the advent of penetrometers capable of measuring in situ pore pressures generated during the penetration process. To this end, various pore pressure parameters have been presented and attempts have been made to correlate variation of such parameters with the stress history of clay deposits. However, it is generally accepted that no unique relationship exists between a specific pore pressure parameter and changes in the overconsolidation ratio (OCR). For a specific deposit, however, it is likely that a pore pressure-OCR relationship can be established.

This technical note evaluates the normalized distribution of dyamic pore pressure measured at two locations on a penetrating cone. The difference between the two values of normalized pore pressure appears to provide a good measure of the overconsolidation ratio in clays.

PORE PRESSURE DISTRIBUTION AROUND A PENETRATING CONE

Levadoux and Baligh (1985) have evaluated the theoretical distribution of excess pore pressure around a penetrating cone for normally consolidated to slightly overconsolidated clays. Good agreement was obtained with field results obtained in Boston blue clay. Similar studies have been presented by Tumay et al. (1985) for very soft cohesive soils. The methods, however, are not suitable for more overconsolidated clays.

Robertson et al. (1986) have recently presented field data on the distribution of normalized pore pressures around a penetrating cone. The total dynamic pore pressure, u, is normalized with respect to the hydrostatic pore pressure, u_0, at the test depth. The variation in the normalized pore pressure, u/u_0, for various soil types is shown in Fig. 1. The following comments regarding the figure can be made:

- The pore pressure measured on the tip or face of the cone is always higher than that measured behind the cone.

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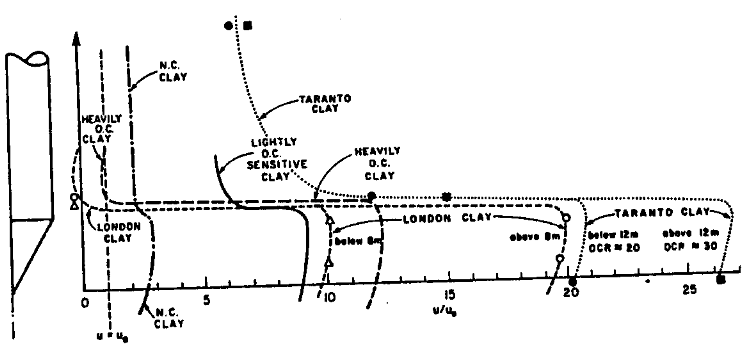

FIG. 1. Conceptual Pore Pressure Distribution in Saturated Clays during CPT with Pore-Pressure Measurements (CPTU) Based on Field Measurements (after Robertson et al. 1986)

- As the overconsolidation ratio increases, the pore pressure measured at the tip or along the face of the cone is positive and increases. However, behind the tip the pore pressure may become negative depending on the level of overconsolidation.
- Based on the preceding observations, it appears that the difference between the normalized pore pressure measured on the face, $(u/u_0)_p$, and at the base of the cone, $(u/u_0)_b$, also increases as the overconsolidation ratio increases.

The latter interdependence forms the basis of the proposed relationship for determining the overconsolidation ratio in clays, i.e.:

$$\left(\frac{u}{u_0}\right)_p - \left(\frac{u}{u_0}\right)_b = f(\mathrm{OCR}) \quad \ldots\ldots \quad (1)$$

PROPOSED RELATIONSHIP FOR ESTIMATING OCR IN CLAYS

In order to evaluate the relationship proposed in Eq. 1, it is necessary to perform piezocone tests using a cone with two filter positions; one located at or on the tip, the other located behind the tip of the cone. Few piezocones exist with this double pore-pressure-measuring facility. However, several studies have been carried out where the influence of filter location on the generated dynamic pore pressure has been evaluated. The data obtained from these studies has been plotted in Fig. 2 against measured or calculated OCR (Battaglio et al. 1986; Campanella et al. 1986; Jamiolkowski et al. 1985; Levadoux and Baligh 1985; Lunne et al. 1986; Powell and Uglow 1986; Robertson et al. 1986; Roy et al. 1982a, 1982b; Sully 1986; Sully and Murria 1987). The data base includes results obtained from various clays in both North and South America and Europe, the details of which are given in Table 1. Information regarding the piezocones used in the various studies is given in Table 2.

Fig. 2 shows that a linear relationship between OCR and the pore-pressure parameter (PPD) is obtained, where:

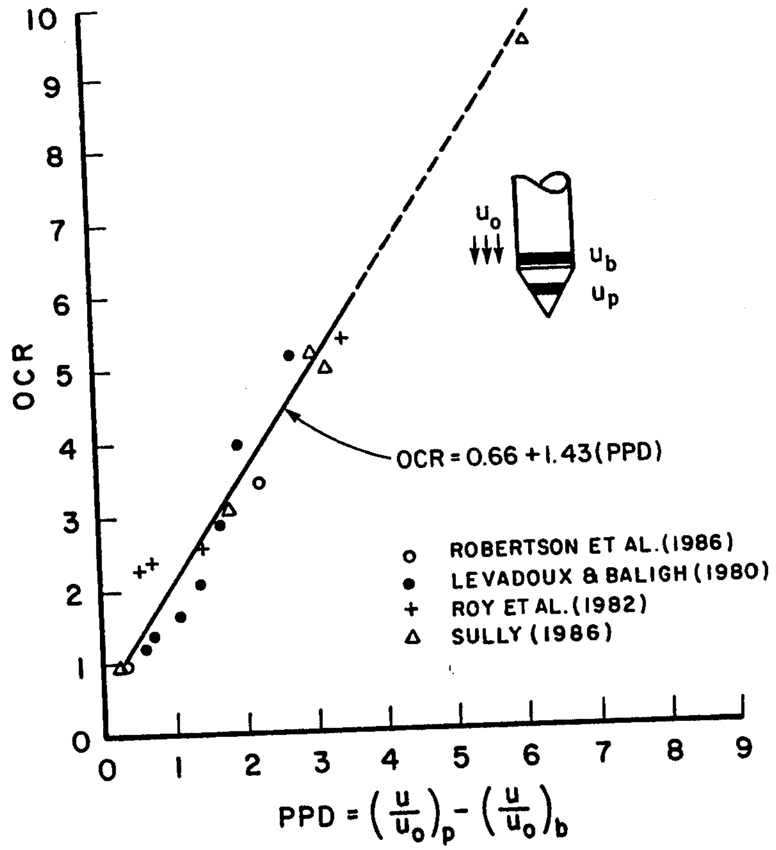

FIG. 2. Effect of Overconsolidation Ratio on Normalized Pore Pressure Difference (PPD)

$$\mathrm{PPD} = \left(\frac{u}{u_0}\right)_p - \left(\frac{u}{u_0}\right)_b \quad \ldots\ldots \quad (2)$$

where $(u/u_0)_p$ = normalized total pore pressure measured at the tip; and $(u/u_0)_b$ = normalized total pore pressure measured at the base of the cone.

Using the minimum least squares method, the following relationship was obtained for OCRs from 1–10:

$$\mathrm{OCR} = 0.66 + 1.43\ (\mathrm{PPD}) \quad \ldots\ldots \quad (3)$$

which has a coefficient of correlation equal to 0.98.

The majority of the results shown in Fig. 2 fall in the range between OCR = 1 and OCR = 5.5, as determined from oedometer tests. Only one result exists for higher OCRs (OCR = 9.5). Consequently, Eq. 3 can be considered to be applicable for OCR's up to a maximum value of 10.

TABLE 1. Data on Soil Types Referenced in Text

Reference (1)	Soil type (2)	$W\%$ (3)	$LL\%$ (4)	$PI\%$ (5)	(Su/P') (6)	OCR (7)	S_t (8)	PPD (9)
Levadoux and Baligh 1985	Boston blue clay	41	45	21	0.25[b]	1.2–5.2	≈6	0.64–2.78
Campanella et al. 1986; Robertson et al. 1986	Haney clay	44	44	18	0.30	1.0–3.5	6–10	0.25–2.3
Roy et al. 1982a, 1982b	Champlain clay	40–100	35–65	15–25	0.5[c]	2.4–5.4	≈16	0.75–3.51
Sully 1986	El Tablazo clay	33–46	33–55	14–28	0.34[c]	1.0–4.0	2–4	0.27–2.15
Sully and Murria 1987	Lagunillas clay	16–30	18–36	5–20	0.24[b]	3.25–9.5	1–2	1.81–6.25
Lunne et al. 1986; Powell and Uglow 1986	London clay	30	70–80	43–55	≥0.7[c]	27.5–>50	—	10.5–20
Battaglio et al. 1986; Jamiolkowski et al. 1985	Taranto clay	25~35	30–36	9~16	≥1.5[c]	20–>30	—	8.0–11.5
Campanella et al. 1986; Robertson et al. 1986	Imperial Valley[a]	—	—	—	—	8–25[d]	—	12

[a] Soil data not available for piezocone test location.
[b] Plane strain compression, PSC.
[c] Triaxial compression, CIU.
[d] OCR estimated from S_u profile.

Further verification is required before Eq. 3 can be used beyond a PPD of about 6 (see Fig. 2).

Three results for OCR values higher than 15 have been included in Fig. 3 for comparison with the proposed correlation. For the Imperial Valley site the OCR values were obtained indirectly using the undrained shear strengths (S_u) and the Schmertmann method (1978) and the possible range of variation is indicated. Eq. 3 predicts an OCR of around 18 for the Imperial Valley site which is within the range of 16 ± 8 obtained by the method proposed by Schmertmann. It may well be that direct determination of the overconsolidation ratio will provide a better agreement with the value obtained with Eq. 3.

The OCR values for Taranto and London clays (Brent Cross) were determined from oedometer tests (Lunne et al. 1986; Jamiolkowski et al. 1985).

The results shown in Fig. 3 for London clay and Taranto clay do not agree with the proposed relationship. Both clays are heavily overconsolidated. The London clay is highly fissured. Under these conditions, the penetration process may not be completely undrained with the result that the true maximum dynamic pore pressure may not be recorded. In addition, for the London clay the fissures are usually covered with a dusting of silt, possibly giving rise to an increased bulk permeability. The effect of fissuring appears to constitute an upper limit for the applicability of Eq. 3 in the region of OCR = 20.

The Taranto clay is microfissured and highly cemented (Jamiolkowski et al. 1985).

For the proposed pore pressure parameter (PPD) to be valid, the following conditions must apply:

- Phreatic level close to the ground surface. For results obtained at greater depths, this condition is less important.
- Approximately hydrostatic pore-pressure distribution.
- Pore-pressure filters located at or on the tip and at the base of the tip. Pore pressures measured at the tip can be slightly lower than those measured at the midheight of the cone face. This may be the source of some of the dispersion evident in Fig. 2. However, errors in the estimated OCR due to this difference are not significant.
- Filter height of 5 mm at both measuring locations.

TABLE 2. Details on Piezocones Considered in This Study

Site-soil (1)	Reference (2)	Piezocone type (3)	Filter position (4)	Filter material (5)	Filter thickness (mm) (6)
Boston Blue Clay	Levadoux and Baligh 1985	Wissa	T & B[a]	Steel/Stone	12.8/7.0
Haney clay	Campanella et al 1986; Robertson et al. 1986	UBC	T & B	Polypropylene	5
Champlain clay	Roy et al. 1982a, 1982b	Laval	T, B[b]	Steel, aerolith	Variable
El Tablazo clay	Sully 1986	Hogentogler	T, B	Polypropylene	5
Lagunillas clay	Sully and Murria 1987	Hogentogler	T, B	Polypropylene	5
London clay	Lunne et al. 1986; Powell and Uglow 1986	Delft SML	B	Sintered stainless	3
		van den Berg	B	Stainless steel	3
		McClelland (15 cm²)	T	Sintered stainless	6
Taranto clay	Battaglio et al. 1986; Jamiolkowski et al. 1985	ISMES	T, B	Sintered stainless	3
Imperial Valley	Campanella et al. 1986; Robertson et al. 1986	UBC, Hogentogler	T & B, T, B	Polypropylene	Variable

[a] Simultaneous measurements with filters at tip/face and behind tip.
[b] Separate soundings with filters at tip/face or behind tip.
Note: All tests carried out at penetration rate of 2 cm/s.
Cone apex angle for all tests equal to 60°.

CONCLUSION

Based on critical state soil mechanics, Wroth (1984) proposed that the pore pressure parameter, Bq, should give a good correlation with OCR in clays, where:

$$Bq = \frac{u - u_0}{q_t - \sigma_v} \quad (4)$$

where u = dynamic pore pressure measured at the base of the cone; u_0 = hydrostatic pore pressure; q_t = tip resistance corrected for unequal end area effects (Campanella et al. 1986); and σ_v = total vertical stress. Studies carried out have shown, however, that no universal relationship exists between Bq and OCR (Battaglio et al. 1986; Jamiolkowski et al. 1985; Robertson et al. 1986; Wroth 1984).

The pore-pressure parameter, PPD, has been shown to give a good relationship with OCR for the five clay soils presented (OCR < 10). The PPD parameter appears to include the effects of plasticity, sensitivity, and cementation. However, as shown in Table 1, the sensitivity of the soils considered is somewhat limited. The soil sensitivity may influence the

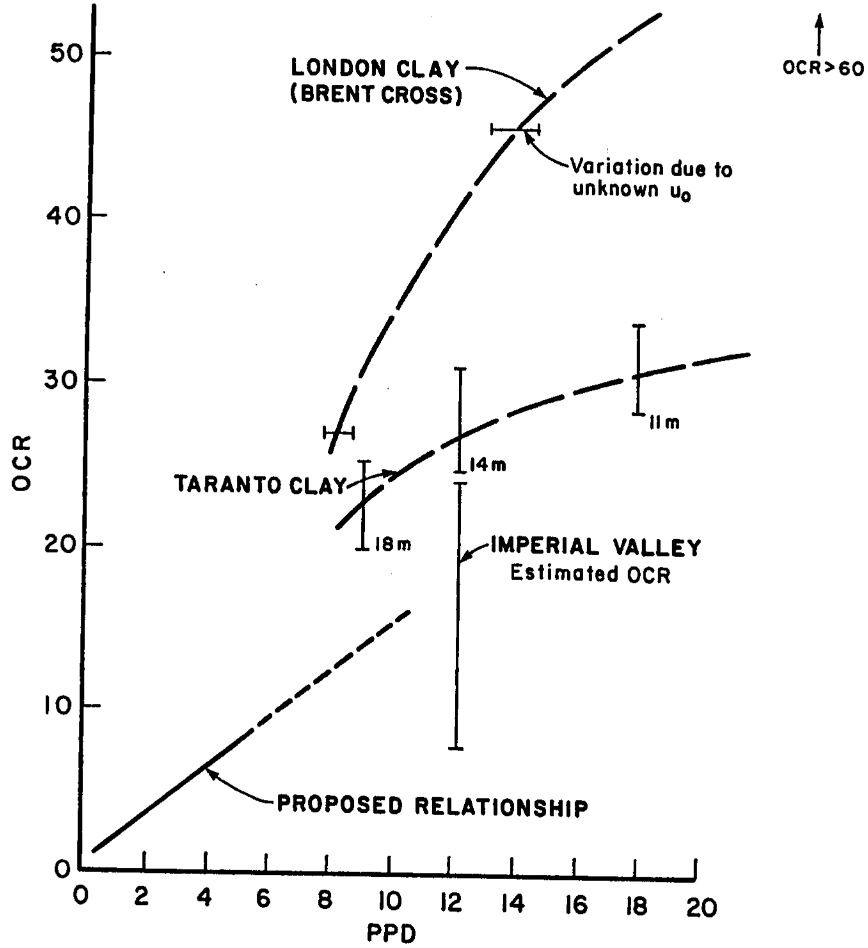

FIG. 3. Variation of PPD for Highly Consolidated Soils: London Clay (Brent Cross), from Lunne et al. (1986) and Powell and Uglow (1986); Taranto Clay, from Battaglio et al. (1986) and Jamiolkowski et al. (1985); and Imperial Valley (Estimated OCR) from Campanella et al. (1986) and Robertson et al. (1986).

applicability of the proposed relationship since this property greatly affects the shear generated pore pressures. For the three highly overconsolidated soils, the PPD-OCR relationship does not agree with field data. This may be due, in part, to partial drainage of excess pore pressures during penetration caused by the soil microstructure.

The proposed relationship (Eq. 3) can be explained in terms of dominant soil behavior at each of the measuring points. On the tip, the high normal stresses appear to dominate the soil response, whereas behind the tip the pore pressures appear to be principally dependent on the level of shear stress. As the overconsolidation of the soil increases, the difference between the two pore pressures increases. Dividing the dynamic pore pressure, u, by the hydrostatic pore pressure, u_0, in effect gives a ratio of the excess pore pressure to a total in situ stress, similar to that obtained with the *Bq* definition.

The proposed pore pressure ratio may not be a conceptually ideal parameter since it requires a phreatic surface close to the ground surface and an approximately hydrostatic pore pressure distribution. The former requirement makes the use of PPD difficult for offshore applications. However, offshore cone-penetration-test (CPT) work is often performed by zeroing the data channels at the mudline, therefore, the overlying water pressure is removed from the pore pressure profile. This may enable the use of the PPD ratio for certain offshore applications.

Due to the limited data available it is not possible to evaluate a confidence interval for the OCR predicted from the PPD parameter. Preliminary results indicate that a better correlation exists than that presently obtained using the *Bq* parameter (Battaglio et al. 1986; Jamiolkowski et al. 1985; Robertson et al. 1986; Wroth 1984).

Finally, it is recommended that the proposed relationship be verified for any new soils under study prior to general application. Additional data will provide further evaluation for a wider range of clay soils. At present few piezocones are available that incorporate dual pore pressure measurements. For the time being, the proposed PPD parameter can be evaluated by conducting two soundings at a locality with different filter locations. This, however, is only reasonable for onshore studies.

North Sea offshore site investigation practice now requires the use of cones with two pore pressure elements. Further research on the distribution of excess pore pressures around penetrating cones may prove this to be desirable as an international standard.

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