

Interpretation of penetration pore pressures to evaluate stress history in clays

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ABSTRACT: The variation of pore pressures around a penetrating cone is used to evaluate the stress history of clay deposits. A theoretical framework is discussed and available data is used to compare various ratios of pore pressures measured on the face, u_1 , and immediately behind the tip, u_2 , of a cone and the OCR (overconsolidation ratio) of the clays. The pore pressure difference, $PPD = (u_1 - u_2)/u_0$, where u_0 is the equilibrium value, appears to give the best global correlation with available data for $OCR < 10$. It is recommended that site specific data be used to develop the correlation whenever possible and especially if the $OCR > 10$.

1 INTRODUCTION

The measurement of pore pressures during cone penetration testing has greatly improved the versatility of the test, and allowed its application to a much broader range of geotechnical problems. One of the main advantages of the simultaneous measurement of tip resistance, local friction and pore pressure, as obtained with the piezocone, is the improved evaluation of geotechnical parameters (Campanella and Robertson, 1988).

Recent research work has been focused on evaluating the pore pressure distribution around a penetrating cone and its dependence on the stress-strain behaviour of soil (Levadoux and Baligh, 1980; Robertson et al, 1986; Tumay et al, 1985). The generated pore pressures have also been shown to depend on soil properties such as sensitivity, stiffness, plasticity index, cementation and overconsolidation ratio.

2 PORE PRESSURE DISTRIBUTION AROUND PENETRATING CONE

Levadoux and Baligh (1980) presented a theoretical basis for predicting the pore pressure distribution around a penetrating cone in slightly overconsolidated Boston Blue Clay ($OCR < 3$). The predicted distribution was verified by field measurements. Based on this work, Baligh et al (1980) suggested that the pore pressure measured

during undrained penetration in clays may be a function of its stress history. Similar results have also been presented by Tumay et al (1985). Subsequently, various pore pressure parameters have been proposed as indicators of stress history. The various correlations equate OCR with one or more of the parameters measured during a piezocone test, namely, the total pore pressure, u , the excess pore pressure, Δu , the equilibrium pore pressure, u_0 , and the tip resistance, q_c , usually corrected to q_t for unequal end area effects (Campanella et al, 1982; Campanella and Robertson, 1988). In some cases the in situ vertical stress, σ_v or σ'_v , is also incorporated. Wroth (1984) pointed out that only the shear induced pore pressure resulting from cone penetration correctly reflects the soil stress history. Based on Critical State Soil Mechanics, Wroth (1984) stated that any pore pressure parameter to be used for OCR correlation should relate a change in pore pressure (Δu) to changes in octahedral and shear stresses around a penetrating cone. Due to problems in evaluating stress changes close to a cone, the most promising pore pressure parameter available was considered to be Bq , as defined by:

$$Bq = \frac{\Delta u}{q_t - \sigma'_v} \quad (1)$$

where:

$$\Delta u = u - u_0 \quad (2)$$

However, this does not allow the octahedral and shear related pore pressures to be separated, since the measuring locations are generally in areas where the soil undergoes complex stress changes. Studies performed by various researchers have shown that no universal correlation exists between B_q and OCR (Battaglio et al, 1986; Campanella et al, 1986; Jamiolkowski et al, 1985; Lunne et al, 1985). Jamiolkowski et al (1985) suggest that while B_q should reflect changes in OCR, further validation of the parameter is necessary in relation to the stress field around a cone. They also suggest that standardization of cone equipment is necessary since the cone and filter geometry may greatly affect the measured pore pressures (Campanella et al, 1986; Robertson et al, 1986).

As can be seen from the above, the distribution of induced pore pressure around a cone is very important and related to soil behaviour. It is worthwhile noting that all of the proposed pore pressure parameters use only one value of measured pore pressure, usually that corresponding to a filter located behind the tip. For that reason it is difficult to evaluate the shear induced pore pressures which may provide the basis for an OCR correlation. Robertson et al (1986) recently presented field data on the distribution of normalized pore pressures around a penetrating cone for various cohesive deposits of varying OCR (Fig. 1). The total dynamic pore

pressure, u , is normalized with respect to the hydrostatic pore pressure, u_0 , at the depth of interest. 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.
- 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 above observations, it would appear that the ratio of, or the difference between, the normalized pore pressures measured on the face, $(u/u_0)_p$, and at the base of the cone, $(u/u_0)_b$, may provide a basis for evaluating the stress history of a clay. This relationship can be explained by considering the soil behaviour at each of the measuring locations. On the tip, the high normal stresses appear to dominate the pore pressure response, whereas behind the tip the normal stresses are released and the shear induced pore pressures appear to be dominant. As the overconsolidation ratio of the soil increases, the difference between the pore pressures increases.

For ease of notation and in accordance with the terminology in general use, the pore pressure measured on the tip is designated u_1 , while that behind the tip is designated u_2 . The possible pore pressure parameters are then:

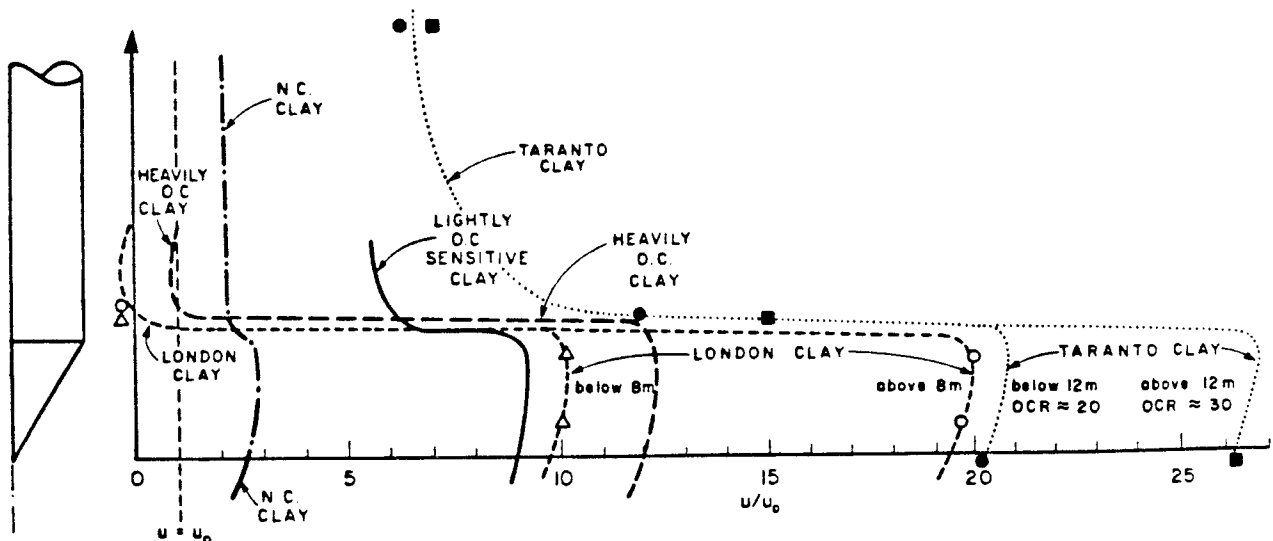


Fig.1 Conceptual pore pressure distribution in saturated clays during CPTU based on field measurements (after Robertson et al, 1986)

(a) the pore pressure ratio, PPR:

$$PPR = (u_1/u_o) / (u_2/u_o) = u_1/u_2 \quad (3)$$

(b) the excess pore pressure ratio, PPR1:

$$PPR1 = (u_1 - u_o/u_o) / (u_1 - u_o/u_o) \quad (4)$$

$$= u_1 - u_o / u_2 - u_o$$

(c) the pore pressure difference, PPD:

$$PPD = (u_1/u_o) - (u_2/u_o) = (u_1 - u_2)/u_o \quad (5)$$

These parameters were evaluated using published data with the aim of establishing a method for predicting OCR in cohesive deposits based on CPTU testing.

3. PORE PRESSURE RATIOS PPR AND PPR1 VERSUS OCR

The compiled data in terms of PPR and OCR is shown in Fig. 2. For an overconsolidation ratio in the range 1 to 5, the PPR varies from 1 to 2. The initial relation is insensitive to the changes in OCR and would not work well as a predictive tool. At higher overconsolidation ratios, the pore pressure behind the tip, u_2 , becomes very small and may attain negative values. Consequently, the PPR becomes very large, tending to infinity and may become negative. Sully and Murria (1937)

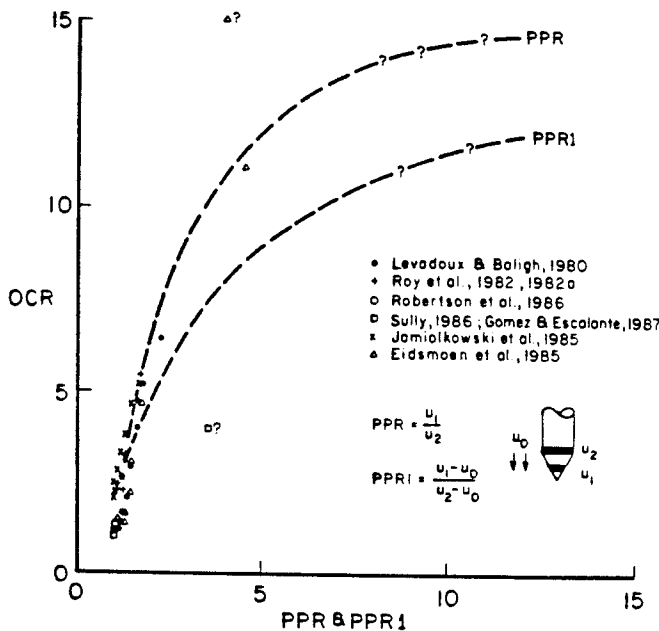


Fig.2 Relationship between PPR (PPR1) and overconsolidation ratio for lightly to moderately overconsolidated clays

obtained a PPR value of around 50 for a moderately overconsolidated clay (OCR = 5.2). Furthermore, when the u_2 value becomes small, the u_1 value is generally large. Small changes in the u_2 can thus cause large changes in the PPR. An example of this is the data obtained by Robertson et al (1986) for the Imperial Valley site. Table 1 shows that for a 0.4 kg/cm² variation in u_2 the PPR changes from 12 to 24 for the same OCR. Similarly, the data also demonstrates the inadequacy of the PPR1 parameter for correlation with OCR.

Table 1. Piezocone data from the Imperial Valley site

u_1	u_2	u_o	PPR	PPR1	PPD	OCR
9.6	0.4	0.76	24	-24.6	12.1	16±8
9.6	0.8	0.8	12	∞	12.0	16±8

Also shown on Fig. 2 is the general correlation for the excess pore pressure ratio, PPR1, and OCR. The PPR1 parameter tends to large values more rapidly than PPR as the pore pressure behind the tip, u_2 , approaches the in situ equilibrium pressure, u_o . No results are shown on the figure for negative PPR or PPR1 values.

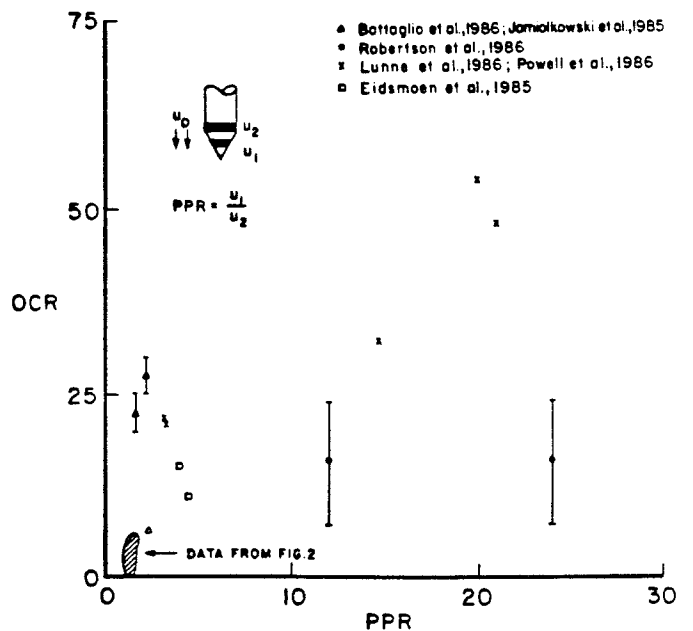


Fig.3 PPR and OCR correlation for all available data

Figure 3 presents the available data for positive PPR values for higher OCR's. The scatter is considerable and a large degree of uncertainty would exist with any proposed correlation; this being true even for some site specific relationships. Since both PPR and PPR1 result from a ratio of measured pore pressures, one usually much larger than the other, errors in measurement become very important. Furthermore, for the same reasons, the cone geometry may account for part of the large variation in the pore pressure parameters at higher overconsolidation ratios. These points will be discussed later.

4. PORE PRESSURE DIFFERENCE, PPD, AND OCR

The idea of using the difference between the normalized pore pressures measured on the face and behind the tip of a penetrating cone had been suggested by Robertson et al (1986). Sully et al (1987), using published data from North and South American clays, obtained the following tentative relationship between the normalized pore pressure difference, PPD, and overconsolidation ratio for $OCR \leq 10$:

$$OCR = 0.66 + 1.43 (PPD) \quad r = 0.98 \quad (6)$$

It was suggested at the time that further validation of the proposed relationship was required but difficult due to lack of data. Figure 4 is an updated version of the earlier work which includes additional information from several European clays (Eidsmoen et al, 1985; Jamiolkowski et al, 1985). Using least squares linear regression, the revised relationship for the PPD-OCR correlation for $OCR \leq 10$ is given by:

$$OCR = 0.49 + 1.50 (PPD) \quad r = 0.96 \quad (7)$$

Considering that the number of data points has been more than doubled compared to the original work (Sully et al, 1987), the agreement is very good for the recommended range of application ($OCR \leq 10$) when comparing equations (6) and (7).

Figure 5 presents data for more heavily overconsolidated clays. As with PPR, considerable scatter also exists for the PPD, and a general relationship for all clays does not appear feasible. Locally, however, a correlation should be possible for specific soil types and equipment characteristics.

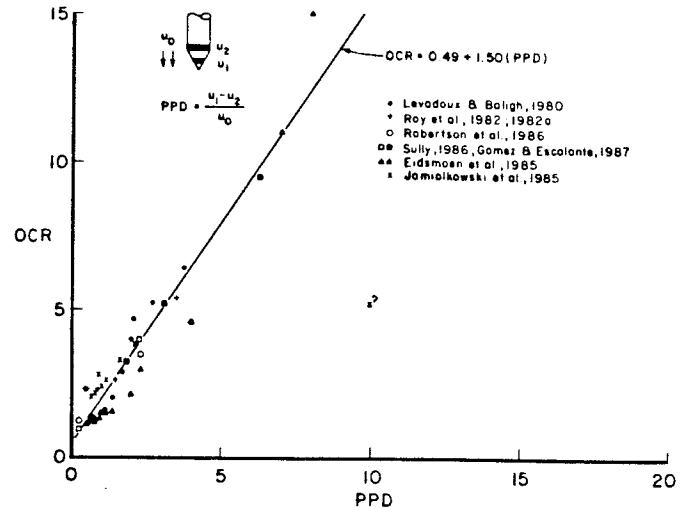


Fig.4 Variation in pore pressure difference, PPD, due to overconsolidation ratio ($OCR < 15$)

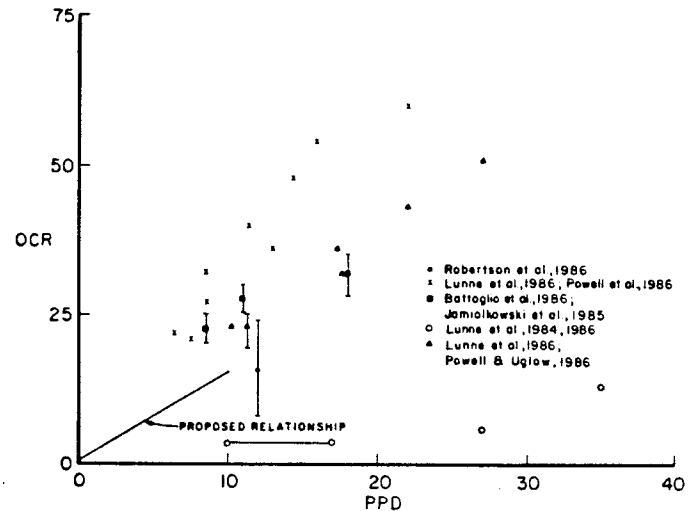


Fig.5 PPD-OCR for all available data ($OCR > 15$)

5. DISCUSSION

Several pore pressure parameters have been defined based on the distribution of total and excess pore water pressure around a penetrating cone. The in situ equilibrium pore pressure is used for normalizing these pressures. These parameters have been evaluated for dependence on the overconsolidation ratio of the soil. Figure 2 suggests that the pore pressure ratios, PPR and PPR1, are not sufficiently sensitive to changes in stress history to be used as indicators of OCR, especially in soft soils. Furthermore, due to large changes in PPR and PPR1 as the u_2 value approaches zero or u_0 , the variations in

the pore pressure parameters at the same OCR are considerable and complicate the use of any correlation. The normalized pore pressure difference, however, appears to provide a good indication of the stress history of cohesive soils. Available data suggests that the proposed relationship is valid for PPD ≤ 10 (Figs. 4 and 5). At higher values considerable scatter in the data is obtained. This is also true for PPR and PPR1. This scatter may be due in part to the microstructure of the clays, e.g, fissuring, sand and silt lenses. In addition, it is likely that unloading of the soil as it passes the base of the tip and the dramatic change of strain rate at this location may also influence the generated pore pressure. In this respect the tolerances between the tip, filter element and friction sleeve may be important factors. Recent research at UBC would suggest this to be the case (Gillespie, 1987; Howie, 1987). Consequently, at higher overconsolidation ratios, cone geometry may contribute appreciably to the measured "soil response" behind the cone tip.

The proposed normalized pore pressure difference (PPD) may not be a conceptually or theoretically "ideal" parameter. For it to be valid, the following conditions should hold for the soil being investigated (Sully et al, 1987):

- 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 behind the tip. Pore pressures measured at the tip can be slightly lower than those measured at the mid-height of the cone face. This may be the source of some of the dispersion evident in Fig. 4.
- filter height or thickness of around 5 mm at both locations. This would ensure more consistent and reproducible measurements where possible plugging of a thin filter is a real hazard. The exact position of the filter is also very important behind the tip because of the very high gradient in that area (Fig. 1).

The ideal parameter for evaluating stress history in clays should relate a change in pore pressure to a change in shear stress (Wroth, 1984). The PPD parameter relates a change in penetration pore pressure to a total stress which varies linearly with the effective stress if the equilibrium pore pressure distribu-

tion is hydrostatic. PPD is obtained using only values measured during a piezocone sounding. Furthermore, the pore pressure transducers generally operate at an adequate percentage of full scale output so as to ensure a good degree of accuracy. Other parameters used to evaluate stress history which incorporate the corrected tip resistance do not function well in soft clays. Measured tip resistances are very low - often around 5% of full scale and subject to considerable errors (Robertson & Campanella, 1984). Dividing small pore pressure by large tip resistances produces a parameter which can vary sufficiently so as to mask any underlying correlation. The use of the equilibrium pore pressure to normalize dynamic pore pressures has the advantage that it suffers from less potential error. The u_0 distribution can be determined from full dissipation tests during the CPTU sounding. Conversely, if the effective or total vertical stress were to be used, a potential error exists in estimating or (even measuring) the density variations which may occur in a soil over small depths in a soil profile.

6. CONCLUSIONS

The idea of using the pore pressure distribution around a penetrating cone has been shown to give a good indication of stress history in clays. The proposed relationship uses pore pressures measured at or on the tip, u_1 , and behind the tip, u_2 . It is also possible with present day equipment to measure pore pressures behind the friction sleeve, u_3 (Battaglio et al, 1986; Jamiolkowski et al, 1985; Robertson et al, 1986). Conceptually, this would appear to give a better indication of the pore pressure generated in shear (Wroth, 1984). Measuring the pore pressure behind the friction sleeve also has the advantage that both pore pressure readings (on the face and behind the friction sleeve) can be taken simultaneously and only one sounding is required.

As stated previously, as the soil passes the base of the tip, it is subject to very complex stress changes. On the tip the high normal stress appears to dominate the generated pore pressures. Behind the friction sleeve the shear stress response probably controls the generated pore pressure. The PPD relationship presented uses pore pressures u_1 and u_2 , since these are more readily reported in the literature. It is likely,

however, that the pore pressures u_1 and u_3 will provide a better indicator parameter, especially in more heavily overconsolidated cohesive soils. This is particularly true since the very large pore pressure gradient that exists just behind the tip (Fig. 1) is very much reduced behind the friction sleeve, giving more reliable measurements. Figure 6 presents data from piezocone tests carried out in the Taranto Clay (Battaglio et al, 1986) where three pore pressure locations were used. As would be expected, the PPD is larger using the u_3 value. From the plots shown, it would appear that a better relationship resulting in less scatter is obtained by using u_3 rather than u_2 in the PPD expression.

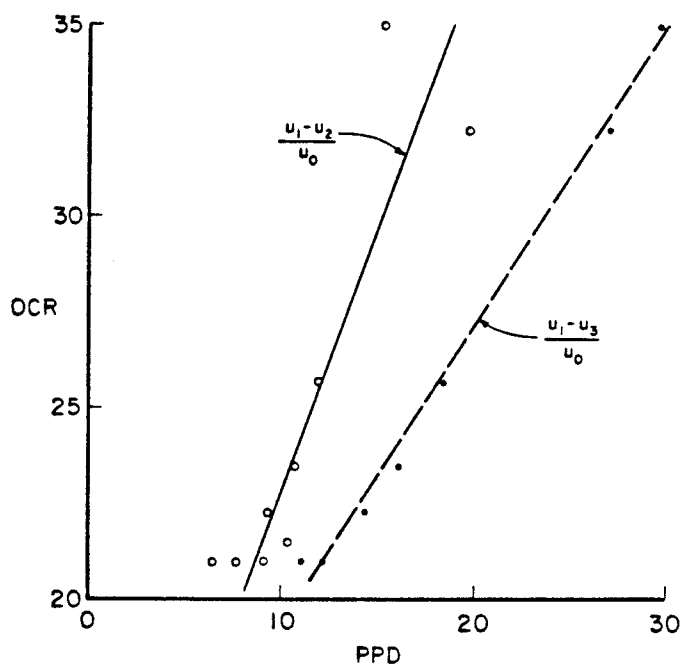


Fig.6 Comparison of PPD parameters using u_1 and u_2 or u_3 for heavily overconsolidated Taranto clay

The proposed PPD parameter, $(u_1-u_2)/u_0$, serves as a good general indicator of OCR in lightly to moderately overconsolidated clays. However, each deposit under consideration should be evaluated separately, so that specific soil and equipment characteristics can be considered. This will permit site specific correlations to be produced which may or may not be in agreement with the general equation presented here, $OCR = 0.5 + 1.5(PPD)$. For highly overconsolidated soils ($OCR > 10$), a global relationship does not appear to exist and it is recommended that site specific correlations be used.

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