Penetration pore pressures in clay by CPTU, DMT, and SBP

Les pressions interstitielles pendant la pénétration dans les essais CPTU, CMT et SBP

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ABSTRACT: Piezocones (CPTU), dilatometer tests (DMT), and self-boring pressuremeters (SBP) all provide similar and apparently consistent data relevant to describing the magnitude of penetration pore pressures generated in intact clays during the installation of displacement-type devices. Piezocones are able to measure pore pressures directly, while it is shown that the DMT contact pressures (po) largely reflect the influence of total penetration pore pressures. The SBP is able to provide an indirect estimate of excess pore pressures via cavity expansion theory. These concepts are supported by databases compiled from 40 sites tested by CPTUs, 29 sites by DMTs, and 42 sites by SBP. A general relationship is shown to exist between the effective preconsolidation stress and the excess pore pressure determined directly or indirectly by in situ tests. Heavily-overconsolidated fissured clays, which have likely undergone passive failure and no longer truly form a continuum, are observed to deviate from the trends exhibited by intact non-fissured clays.

INTRODUCTION

Most in situ testing devices (cones, vanes, dilatometers, push-in spade cells, etc.) cause significant disturbance effects when installed into the ground. Only the self-boring pressuremeter (SBP) has the potential for minimizing these disturbance effects and stress changes during installation. In intact clays, one obvious manifestation of the disturbance is the generation of excess pore water pressures. This response occurs for all displacement-type devices, although pore pressure measurements are often not taken. During the CPTU test, pore pressures are routinely recorded via transducers which are located either on the cone face, immediately behind the tip, or occasionally, at a location on the friction sleeve well above the tip. With specially modified equipment, the measurement of induced pore pressures has been documented for the dilatometer test (Campanella, et al., 1985). Total stress measurements taken by the DMT appear to be controlled by pore pressures generated by insertion of the blade.

PENETRATION PORE PRESSURES

Relative to hydrostatic, the measured penetration pore pressures are due to a combination of changes in octahedral and shear stresses:

$$\Delta u_{meas} = \Delta u_{oct} + \Delta u_{shear} \qquad [1]$$

It is not physically possible to decouple the magnitudes of these components from field measurements. Analytical studies by Baligh (1986) using the strain path method and by Mayne & Bachus (1988) using critical-state theory indicate that the shear component of induced pore pressure at the cone tip during penetration is typically not more than 20% of the total Δu for normally consolidated clays and even less for overconsolidated states. Consequently, the octahedral component dominates at the tip.

For simplicity, this may be approximated by cavity expansion theory:

$$\text{Cyl:} \quad \Delta u_{oct} = C_u \ln(G/C_u) \qquad [2]$$

$$\text{Sph:} \quad \Delta u_{oct} = 4\, C_u \ln(G/C_u)/3 \qquad [3]$$

where C_u = the undrained shear strength and G = shear modulus of the soil. The expression (G/C_u) is termed the rigidity index. Cavity expansion theory suggests that penetration pore pressures are always positive. With specific reference to piezocones, the relative simplicity of cavity expansion theory is supported by available field data reported in the literature.

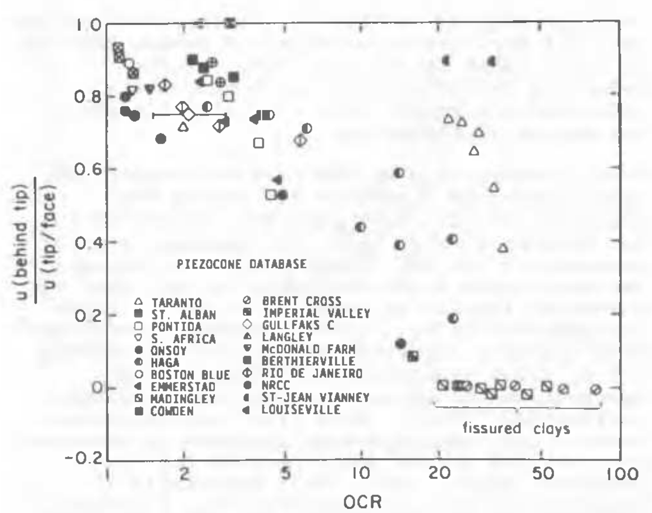

Fig. 1. Effect of Porous Stone Location and OCR on Piezocone Measurement of Pore Pressures.

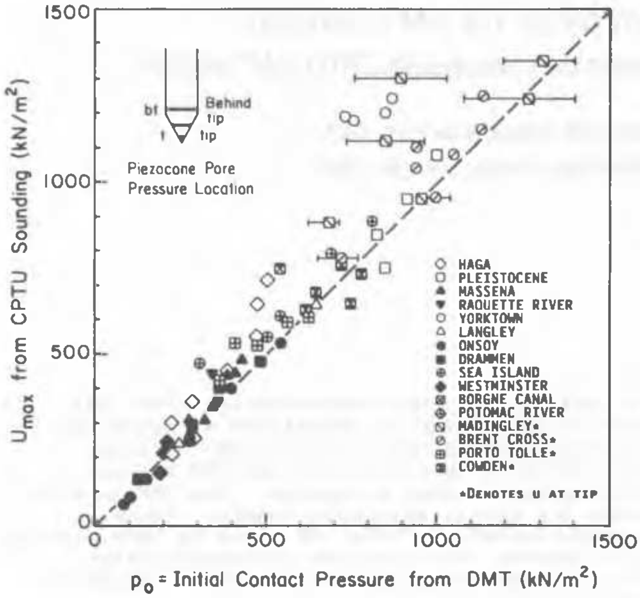

Fig. 2. Comparison of Penetration Pore Pressures Measured by CPTUs and Inferred Values by DMT.

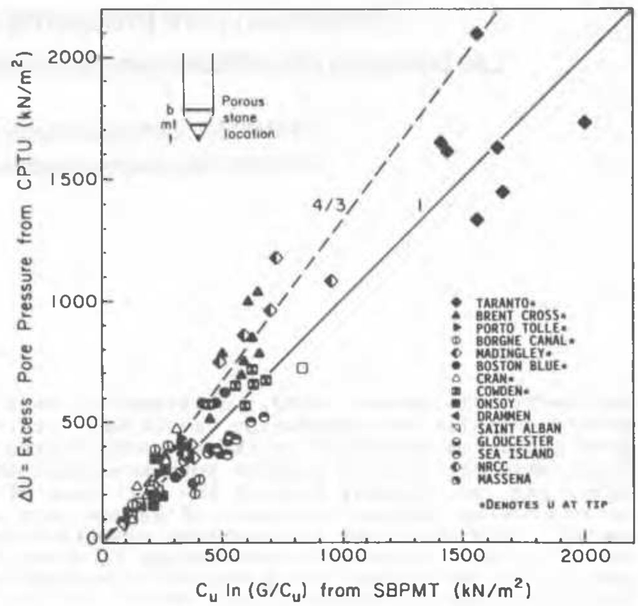

Fig. 3. Comparison of Excess Pore Pressures Measured by CPTUs and Calculated from SBP Data.

For piezocones with porous elements located on the tip/face, positive pore pressures are always observed for intact and fissured clays at all OCRs (Mayne & Holtz, 1988). For piezocones with the porous elements located just behind the tip, positive pore pressures are observed in intact clays but negative pore pressures can occur in very old heavily overconsolidated fissured clays (Lunne, et al., 1986). At this time, it is not clear whether the negative pore pressures measured behind the tip reflect the influence of a greater shear stress versus octahedral stress component at this location or that this is a phenomenon peculiar to fissured clays.

To quantify the effect of transducer position, a review of 20 sites tested by both types of piezocone elements was conducted with the results compiled in Fig. 1. It appears that the ratio of pore pressures measured behind the tip to those taken on the cone face (u_{bt}/u_t) generally decreases with increasing overconsolidation ratio (OCR), yet also depends on the degree of fissuring.

Pore pressures are seldom measured during DMT installation of the blade nor during the expansion of the steel membrane. However, in the absence of such data, the initial contact pressure of the DMT (denoted p_o or A-reading) has been shown to be dominated by the total pore pressures induced by penetration of the blade (Campanella, et al., 1985). Several researchers have recently suggested the use of a C-reading (or p_2 taken approximately 1 minute after penetration) to be a measure of pore pressure (Lutenegger, 1988). As a first approximation, however, the use of the p_o pressure is advocated as a measure of the total penetration pore pressure (Mayne, 1987). This hypothesis is supported by data presented in Fig. 2 showing data from 16 clay deposits which were tested by both CPTU/DMT. It may be seen that, as a first approximation: $u_{max} = p_o$. Owing to the large pore pressure gradients discussed previously, the CPTU data for heavily overconsolidated clays are biased towards piezocones with porous elements on the tip/face. Note that the Yorktown Formation, which deviates from the trend, is comprised of a very sandy clay having about 50% fines.

Dilatometer data in Fig. 2 were obtained using normally prescribed procedures. Piezocone data were obtained at the standard advance rate of 2 cm/s, except for glacial till at Cowden (0.2 cm/s) since suction (due to the presence of stones in the clay matrix) apparently affected the results. It is noted that although the geometries of the CPTU and DMT are quite different, the magnitudes of induced pore pressures are apt to be comparable since the projected areas of the cone (10 and 15 cm²) and blade (14 cm²) are similar.

As noted previously, the SBP advances with a minimal disturbance to the ground and therefore operates on a philosophical approach directly opposite to that of penetrating cones or blades which cause significant disturbances. The magnitudes of excess pore pressures are quite low during installation of the SBP and, in fact, may be used to evaluate the quality of SBP insertion. The SBP does provide direct measurements of C_u and G, however, which are particularly relevant to the specific boundary conditions associated with the cylindrical expansion of cavities. In this regard, it is interesting to compare Δu as measured directly by CPTU with calculated values derived from cavity expansion theory using SBP data. For 15 sites where both CPTU and SBP were conducted, Fig. 3 shows reasonable agreement between measured and predicted Δu. Again, data for overconsolidated fissured clays are biased towards piezocones with pore pressures obtained at the cone tip. For consistency, Cu and G have been determined from SBP using the definition given by Windle & Wroth (1977), where possible. Based on the previous relationship established in Fig. 2, the DMT inferred equivalent of excess pore water pressure caused by insertion is: $\Delta u = p_o - u_o$. With respect to the DMT, the authors do not know of a cavity expansion theory which specifically addresses the geometry of a flat blade. Nevertheless, a database of 11 clays tested by both DMT/SBP (Fig. 4) shows reasonable agreement between the inferred Δu from DMT and that calculated from SBP data using expressions for cavity expansion of a sphere and cylinder.

PRECONSOLIDATION STRESSES

Using a combination of cavity expansion theory and critical-state concepts, Mayne & Bachus (1988) showed that the overconsolidation ratio ($OCR = \sigma_p'/\sigma_{vo}'$) is related to the ratio of excess pore pressure to effective overburden stress ($\Delta u/\sigma_{vo}'$). Adopting Modified Cam Clay Theory, the undrained shear strength may be expressed in terms of OCR:

$$C_u/\sigma_{vo}' = (M/2)(OCR/2)^{\Lambda} \qquad [4]$$

where $M = 6 \sin\phi'/(3 - \sin\phi')$,
ϕ' = effective friction angle,
$\Lambda = (1 - C_s/C_c)$ = plastic volumetric strain potential. Combining eqns. [2] and [4], the expression for OCR applicable to cylindrical expansion is:

$$OCR = 2\left[\frac{(\Delta u/\sigma_{vo}')}{(M/2)\ \ln(G/C_u)}\right]^{1/\Lambda} \qquad [5]$$

Assuming that $\Lambda = 1$ for simplicity, the effective overburden term may be removed from both sides of eq[4], resulting in an expression for the preconsolidation pressure as a function of excess pore pressure:

$$\sigma_p' = \Delta u/[(M/4)\ \ln(G/C_u)] \qquad [6]$$

For spherical cavity expansion, the (M/4) should be replaced by (M/3). For typical ranges of ϕ' of between 20° and 35° and $50 < G/C_u < 500$, the denominator of eq[6] will vary from 0.8 to 3.1.

The applicability of this approach can be investigated by comparing sites with known stress history profiles with either measured or inferred values of excess pore pressure as given by field tests. For example, a study of 40 different clay sites tested by piezocones (Mayne & Holtz, 1988) indicated a trend between σ_p' (as determined from laboratory oedometer tests) and Δu as measured in situ by piezocones. As shown by Fig. 5, the relationship implies an expression of the form:

$$\sigma_p' = \Delta u/\delta \qquad [7]$$

where $1 < \delta < 4$ for intact non-fissured clays. Data for microfissured cemented Taranto Clay (Battaglio, et al., 1986) and the heavily-overconsolidated fissured London and Gault clays (Lunne, et al., 1986) exhibit values of δ on the order of about 0.25 to 0.5. This low range for δ suggests low values of ϕ' and G/C_u, the latter of which are characteristic of overconsolidated clays.

A similar relationship is also observed for dilatometer data compiled from some 29 different clay deposits located worldwide (Fig. 6). The parameter δ is seen to vary typically from 1 to about 3 which is within the aforementioned calculated ranges. Again, fissured clays (Powell & Uglow, 1986) are seen to deviate from the trends established by intact deposits.

Finally, a database listing of 42 clay sites tested by SBP has been summarized by Mayne & Kulhawy (1988). Using the calculated value of Δu derived from SBP data, there exists a remarkable likeness between the trend of σ_p'

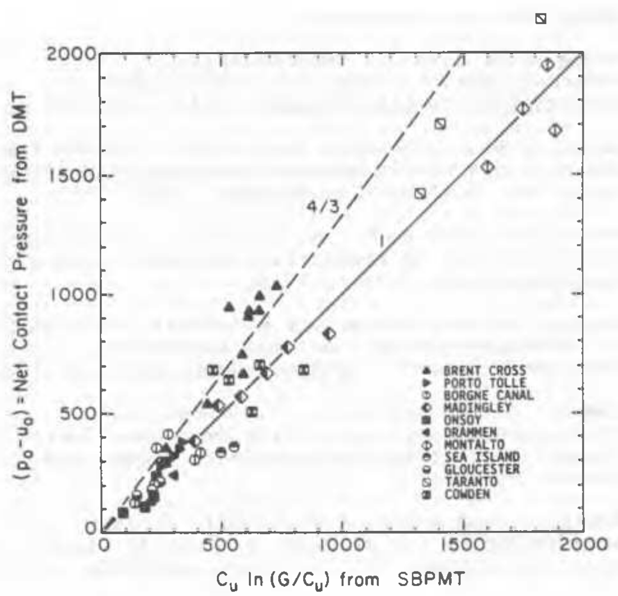

Fig. 4. Comparison of Excess Pore Pressures Inferred by DMTs and Calculated from SBP Data.

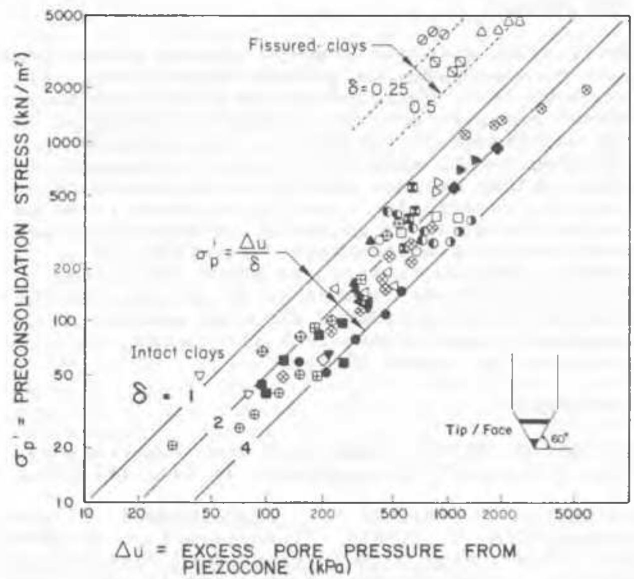

Fig. 5. Relationship Between Preconsolidation Stress and Measured Excess Pore Pressures from Piezocone (Mayne & Holtz, 1988).

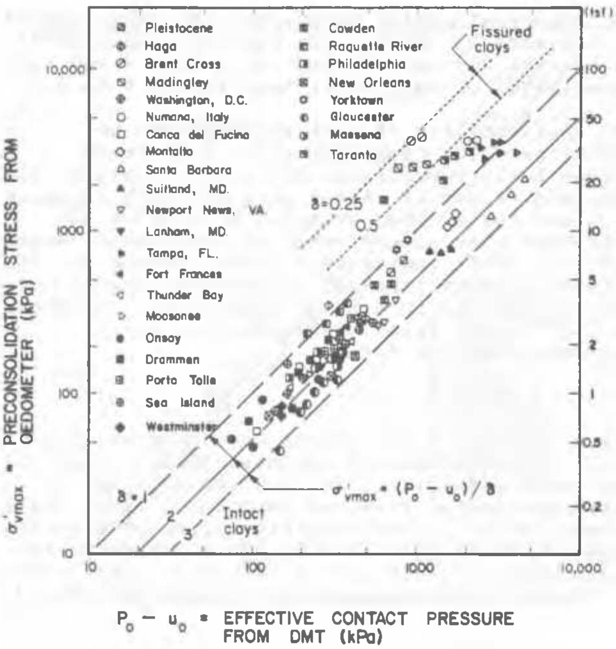

Fig. 6. Relationship Between Preconsolidation Stress and Inferred Δu From Dilatometer.

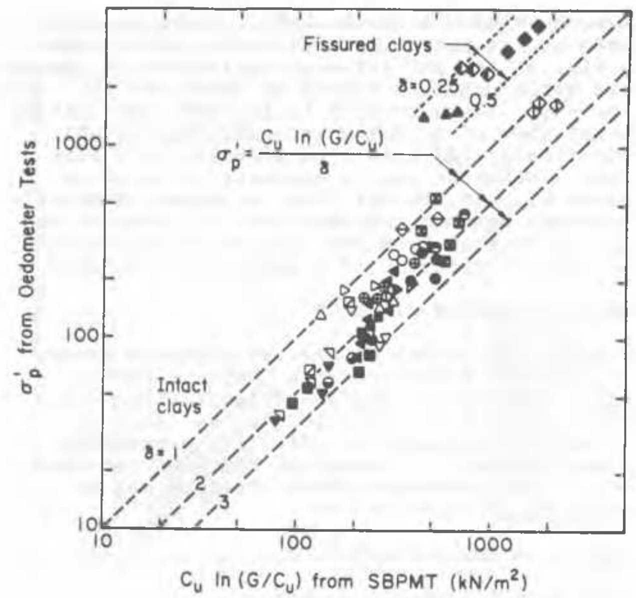

Fig. 7. Relationship Between Preconsolidation Stress and Calculated Δu From SBP.

with [$C_u \ln(G/C_u)$] shown in Fig. 7 and the trends cited previously for CPTU and DMT. Data from Camkometer probes are represented by solid or partially darkened symbols while the open symbols primarily denote the French Pafsor probe or the Japanese monocell device. Also note that for the SBP, eq[6] reduces to the more simplified form: $\sigma_p' = 4\ C_u/M$.

CONCLUSIONS

While CPTUs directly measure induced penetration pore pressures during advancement in clays, it is shown that DMT-p_o pressures give comparable values and SBPs provide reasonable estimates of the magnitudes of penetration pore pressures assuming cavity expansion theory. A direct relationship between the effective preconsolidation pressure (σ_p') and excess pore pressure (either measured or inferred) is shown to exist with similar trends observed for CPTU (40 sites), DMT (29 sites), and SBPMT (42 sites). For each of these databases, it is observed that heavily-overconsolidated fissured and/or cemented clays deviate from the trends exhibited by intact clays.

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