Interrelationships of DMT and CPT readings in soft clays

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ABSTRACT: Interrelationships between the flat dilatometer readings (lift-off pressure, p_0, and expansion pressure, p_1) and piezocone readings (cone tip stress, q_t, and penetration porewater pressures, u_2) are explored for three soft clay sites. Within the intact regions, the p_0 and u_2 measurements are quite consistently similar in magnitude, whereas q_t is variably larger than both p_0 and p_1, perhaps somewhat dependent on the effective friction angle of the clay. Companion sets of DMT and CPTU at a given site could be used to better define the extent of the crustal zone, degree of fissuring, intact regions, and related permeability characteristics of these substrata within a clay formation.

1 INTRODUCTION

The combined use of flat dilatometer tests (DMT) together with piezocone penetration tests (CPTU) can be a nice complement in defining sublayer zones and general geostratigraphy within the subsurface environment. While many consider each of these in-situ tests to be self-standing by themselves for detailing a soil layer profile, in some instances, the use of CPT soil behavioral charts (e.g., Robertson, 1990) can, in fact, give misleading or erroneous results and/or miss changes in soil strata and substrata (Zhang & Tumay, 1999).

The standard piezocone test provides three separate readings with depth, including: cone tip stress (q_t), sleeve friction (f_s), and penetration porewater pressure at the shoulder (u_2), whereas the flat dilatometer determines two readings: the lift-off or contact pressure (p_0) and expansion pressure (p_1). For the CPT, soil types are often distinguished by use of 2 of the 3 of the readings, as summarized by Kulhawy & Mayne (1990) and Fellenius & Eslami (2000). The earlier CPT classification methods utilized q_t and f_s, yet some measurement difficulties can be found with the sleeve friction because of roughness, wear, porewater presure corrections, and other factors (Lunne, et al. 1986). On the other hand, soil behavior type (SBT) using q_t and u_2 readings will undoubtably be weak in interpretations for situations involving deep water tables, as porewater readings will be zero or change with capillarity effects. Consequently, SBT methods utilizing all 3 readings have been developed (Campanella & Robertson, 1986; Robertson, 1990). In these systems, conflicts can arise as paired readings or normalized parameters from the q_t-f_s and q_t-u_2 charts can provide different evaluations for the same depths.

For the DMT, the soil type is evaluated from the material index: $I_D = (p_1-p_0)/(p_0-u_0)$ per the recommendations of Marchetti (1980), whereby clays are indicated by $I_D < 0.6$ and sands are identified by $I_D > 1.8$. Further distinctions of silty to sandy subcategorizations are available too. The original relationship appears to solidly produce reasonable evaluations of soil types over two decades later (e.g., Marchetti, et al. 2001). An advantage of the DMT over CPTU profiling is the lack of worry over desaturation of a porous element and ability to detail geostratigraphy at sites having a deep groundwater table.

2 INTRA- AND INTER-RELATIONSHIPS

For each test with multiple measurements, intra-relationships between the individual readings can be sought to ascertain trends in the measurements, particularly within a specific geologic formation or soil type. Within that given geotechnical unit, inter-relationships between different test data (lab or field) can be made to develop correlative and statistical trends. Herein, some interrelationships between the DMT and CPT readings in soft clays have been explored.

Intra-relationships between the two DMT readings in different soils have been explored by Garcia

(1991) based on compiled databases from field tests and calibration chamber test series. The successful evaluation of soil type using I_D would corroborate such findings. For the CPT in clays, intra-relations between tip stress (q_t) and penetration porewater pressures on the cone tip (u_1) and shoulder (u_2) have been produced (Mayne, Kulhawy, & Kay, 1990). The presence of fissures, whether from crustal formation and/or desiccation, or from mechanical overconsolidation effects, was shown significant in the q_t-u_2 link, yet much less so in the q_t-u_1 trends.

Interrelationships between the DMT and CPTU readings have been investigated previously by Mayne & Bachus (1989) who showed that, as a first approximation:

$$p_0 \approx u_{max} \tag{1}$$

where u_{max} = peak penetration porewater pressure given by u_2 in intact clays and by u_1 in fissured clays, as shown by Figure 1.

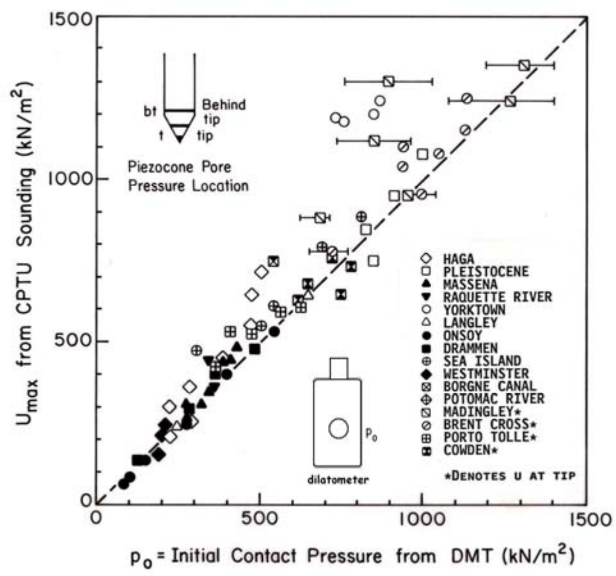

Figure 1. Trend between CPTu porewater pressures and DMT contact pressures in clays (after Mayne & Bachus 1989).

The aforementioned trend was later found applicable for residual silty soils of the Atlantic Piedmont geology by Mayne & Liao (2004).

Direct comparisons of the profiles of the measured cone tip resistance (q_t) with the DMT p_0 and p_1 pressure readings in clays, as well as other readings, have been made at sites in Northwestern Canada (Sully & Campanella, 1990; Sully 1994). Herein, generalized trends are explored between the DMT and CPT measurements at four clays sites tested following the 1989 correlations. These data were obtained from 3 soft clays (two tested by the authors team) and one fissured clay that was overconsolidated by desiccation.

3 CLAY SITES INVESTIGATED

Companion series of DMT and CPTU soundings were obtained in two intact soft clays and one fissured clay by GT field crews, as well data from as one very well-documented intact soft clay site reported in the literature. Table 1 lists the four sites considered for this study.

Table 1. Clay sites with DMT and CPT datafiles.

Site	*Soil Conditions*	*Reference*
Amherst, MA	Soft varved clay	Hegazy (1998)
Bothkennar UK	Soft clay	Nash et al. (1992)
Ford Center, IL	Soft glacial clay	This study
I-10 & 42, LA	Stiff fissured clay	Chen-Mayne (1994)

Recently, tests were performed by the GT field crew in soft clay deposits north of Chicago, Illinois. These in-situ tests were conducted as part of the geotechnical site investigation for the Ford Design Center located on the campus of Northwestern University, in conjunction with an instrumented excavation project. The project is located near the national geotechnical experimentation site (NGES) next to Lake Michigan (Finno, et al. 2000). Subsurface consists of a shallow sandy fill overlying soft silty clays from glacial freshwater lacustrine deposits and a groundwater table located about 3 m deep.

Figure 2 shows the profiles of dilatometer expansion pressure and measured cone tip resistance with depth and Figure 3 presents the dilatometer contact pressure with penetration porewater pressures from two piezocone soundings. The region of intact clay can be interpreted for depths below 9 m, as evidenced by the agreement & similarity of p_0 and u_2 profiles. Above 9 m, less consistency in the readings are observed. For the same depth range, $q_t > p_1$.

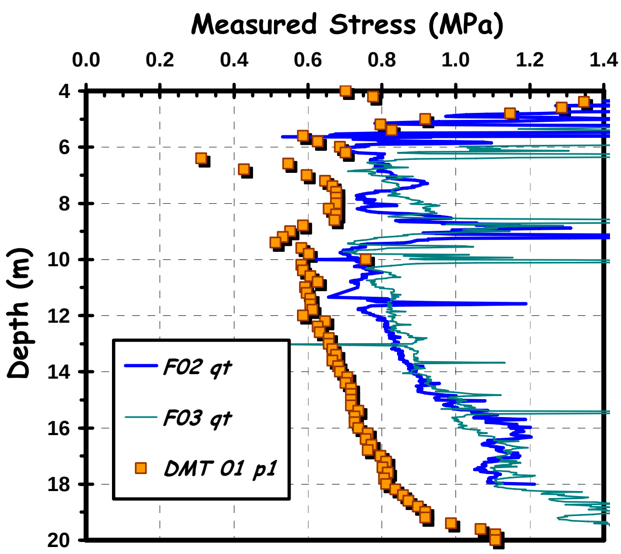

Figure 2. DMT p_1 and CPT q_t at Ford Center Design, IL.

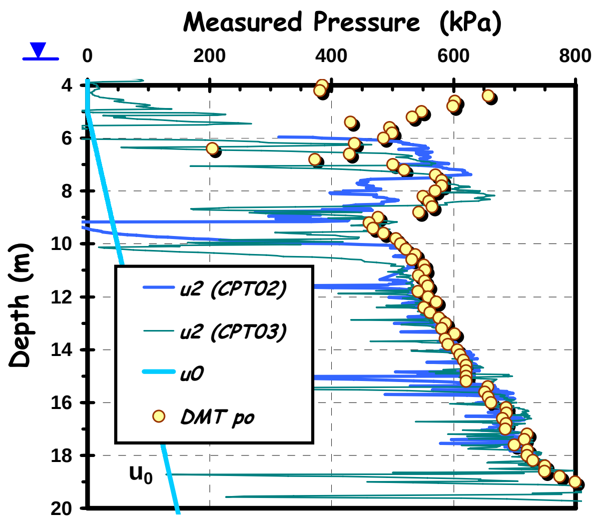

Figure 3. DMT p_0 and CPT u_2 at Ford Design Center, IL.

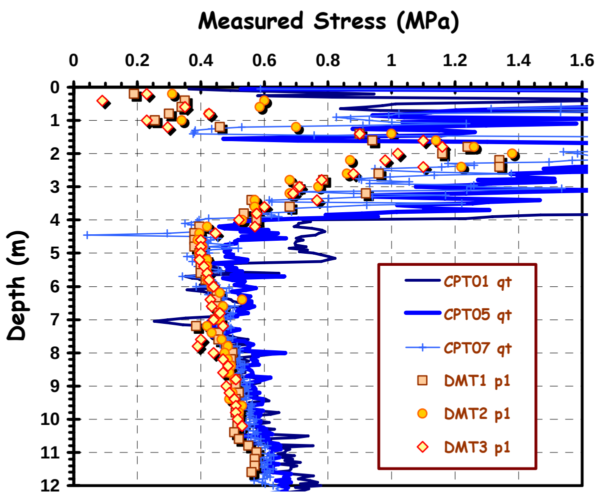

Figure 4. DMT p_1 and CPT q_t at Amherst NGES, MA.

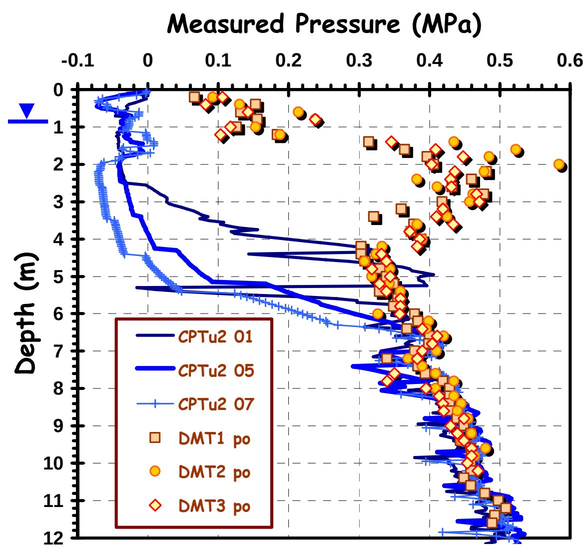

Figure 5. DMT p_0 and CPT u_2 at Amherst NGES, MA.

Series of DMTs and CPTus were conducted by the GT field crew at the Amherst NGES (Martin & Mayne 1997; Hegazy 1998). The soils consist of an upper shallow clay fill and desiccated crust overlying soft varved lacustrine clay. Groundwater lies about 1 m deep. Full details on the testing program and soil properties for the NGES are given by Lutenegger (2000). Figure 4 shows the comparison profiles of three sets of p_1 with three sets of q_t, indicating the intact varved clay below depths of 4 m. Here, the cone tip resistance is just barely greater than the expansion pressures. There is also a parallel profiling of p_1 and q_t in the upper clay fill and desiccated crust, as well.

In Figure 5, the DMT contact p_0 pressures are comparable to the CPT shoulder u_2 porewater pressures. However, it is also apparent that for two of the CPTs, either the porous elements were insufficiently saturated prior to testing, or else became desaturated during advancement through the crust. Only CPTu sounding 01 appears to have properly delineated the transition into the soft intact region below 4 m. In contrast, the p_0 readings clearly and consistently show the change in strata, as well as a relatively uniformity in the underlying soft clay. Thus, the DMT offers an advantage in that the p_0 measurements are not subject to desaturation effects.

In-situ test data from DMTs and CPTs obtained in the soft clay at the British national experimentation test site at Bothkennar (Nash, et al. 1992) were also reviewed and digitized. These data were utilized to provide a reference benchmark in relative comparisons of the data from the Amherst and Evanston sites.

4 DMT-CPT TRENDS IN INTACT CLAYS

Interrelationships between the dilatometer pressures and cone penetrometer measurements can be approximately formulated in terms of cavity expansion theory (e.g., Mayne & Bachus, 1989; Sully 1994). The relationships can be established in terms of total stress parameters: i.e., the undrained shear strength (s_u) and rigidity index ($I_R = G/s_u$), where G = shear modulus. Alternatively, the relationships may be obtained from more fundamental derivations using critical-state soil mechanics to utilize the effective stress friction angle (ϕ') and stress history in terms of overconsolidation ratio ($OCR = \sigma_p'/\sigma_{vo}'$), where σ_p' = preconsolidation stress and σ_{vo}' = current effective overburden stress (Mayne, 2001). In any event, the expressions can only be approximate since neither the flat dilatometer blade nor the cone penetrometer with 60° apex tip are represented by an infinite cylinder nor by a perfect sphere. Instead, empirical relations can be explored.

For the data corresponding to the intact regions of the three soft clays, Figure 6 shows the direct relationships between p_1 and p_0. Best fit lines from regression analyses with forced intercepts equal to zero are shown for each (y = mx with b = 0). As the groundwater tables are rather shallow for these sites, these regressions correspond directly with the individual material indices for each site, including: the Ford Design Center at Evanston, Illinois (I_D = 0.163 ± 0.069), Amherst NGES in Massachusetts (I_D = 0.166 ± 0.044), and Bothkennar test site in Scotland (I_D = 0.291 ± 0.052). All three sites contain lightly overconsolidated clays with 1 < OCRs < 2 in the soft intact zones. Additional index parameters and properties of these clays are summarized in Table 2, including: natural water content (w_n), liquid limit (LL), plasticity index (PI), and effective stress friction angle (ϕ').

Table 2. Mean values of index parameters for soft clay sites.

Clay Site	*Depth (m)*	w_n *(%)*	*LL (%)*	*PI (%)*	*ϕ' (deg)*
Amherst	6 to 12	62	51	21	22º
Evanston	10 to 18	32	33	17	26º
Bothkennar	2 to 16	65	70	45	37º

The notable trends between p_0 and u_2 at each of the sites are shown in Figure 7, substantiating the original correlation represented by equation (1) based on earlier data. Similarly, forced fit best lines (b = 0) are shown with their associated coefficients of determination (R^2). The interrelationship of p_0 and u_2 appears unique and applies to all three intact clays.

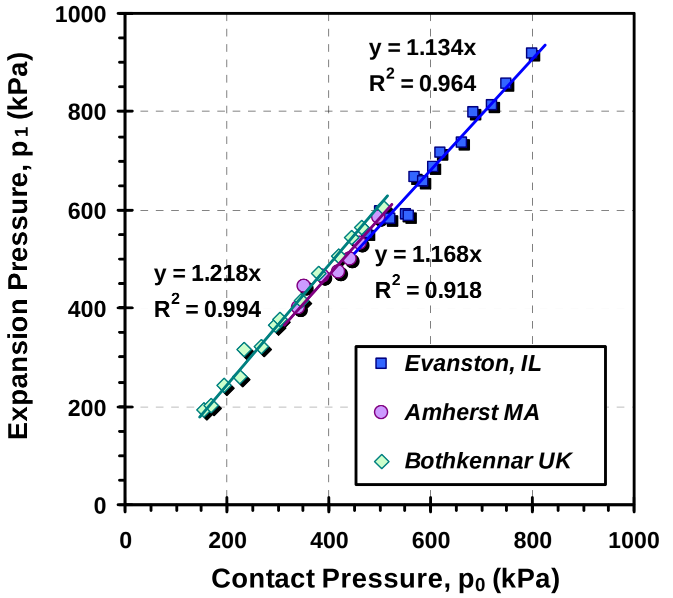

Figure 6. Interrelationships of p_1 with p_0 for intact clays.

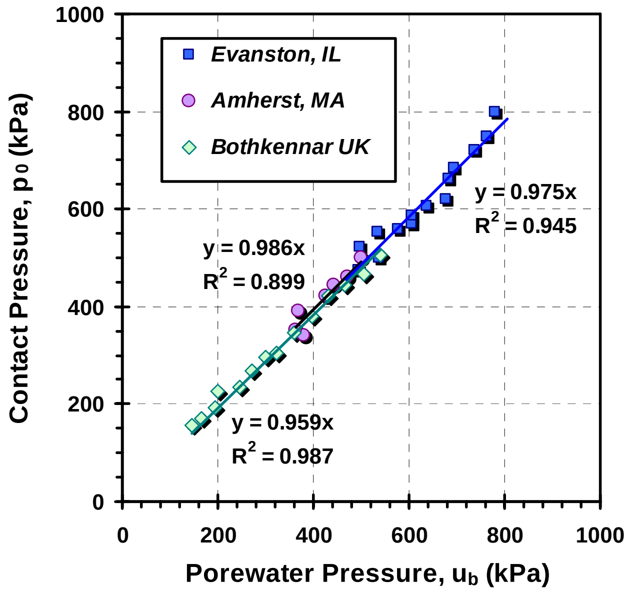

Figure 7. One-to-one relationship between DMT p_0 and CPT u_2 readings in soft intact clays.

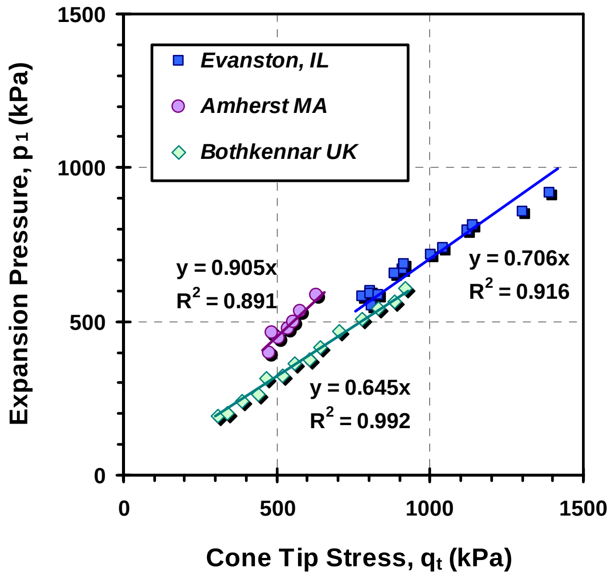

Figure 8. Observed relationship between DMT p_1 and CPT q_t readings in soft intact clays.

For the p_1 trends with q_t, Figure 8 shows that each of the clays shows a distinct and unique interrelationship. In this case, the ratios p_1/q_t appear to decrease with the effective stress friction angle of the clay.

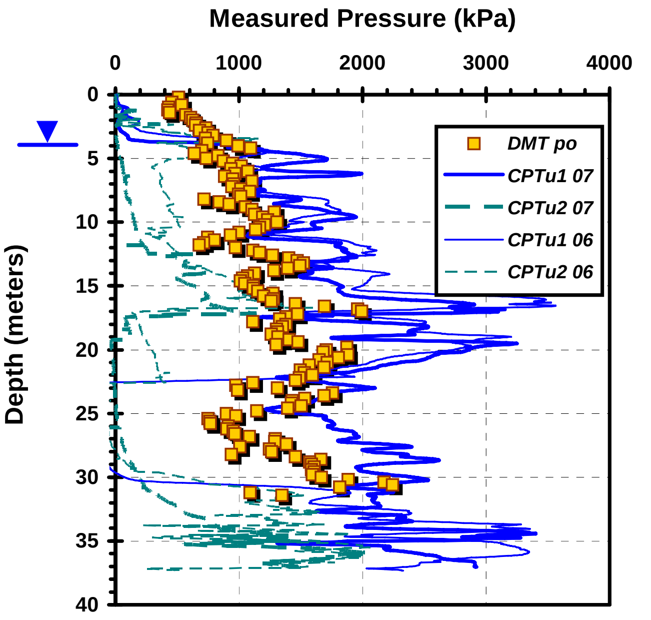

Figure 9. Comparision of p_0 with u_1 and u_2 readings in overconsolidated clay at I-10 and Route 42 near Baton Rouge, LA

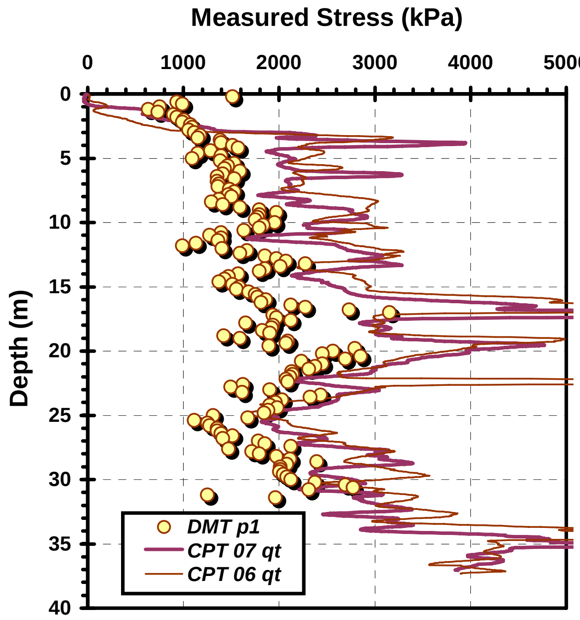

Figure 10. Comparision of p_1 with q_t profiles in OC clay at Baton Rouge, LA.

5 DISCUSSION FOR FISSURED CLAYS

In the case of fissured overconsolidated clays, the piezocone shoulder porewater pressures tend towards zero and even negative values (Mayne, et al. 1990). Thus, since face porewater pressures at the tip or midface (u_1 readings) will remain as positive values, these will better correlate with DMT p_0 readings. Yet, it is likely that $u_1 > p_0$, as shown previously in Figure 1 by fissured London clay at Brent Cross and fissured Gault clay at Madingley (Lunne, et al. 1997).

This facet is illustrated by DMT and CPTU data collected at the I-10 and state route 42 site near Baton Rouge, Louisiana (Chen & Mayne, 1994), as shown in Figure 9. Index parameters for the stiff clay are given in Table 3. At this site, a multi-element piezocone was used and perhaps the water-saturated porous elements were not as responsive as those should glycerine or silicon oils have been used for the saturation process. In any event, the p_0 more closely parallels a profile with the measured face u_1 porewater pressures than with the u_2 readings that are normally used in practice because of the need for porewater corrections on the measured cone tip resistance (Campanella & Robertson, 1988; Lunne et al., 1997).

Table 3. Index parameters of stiff fissured clay from Louisiana

Clay Site	*Depth (m)*	*w_n (%)*	*LL (%)*	*PI (%)*	*ϕ' (deg)*
Baton Rouge	5 to 30	34	61	33	27°

Interestingly, the relative profiles of DMT expansion pressure and CPT tip resistance with depth appear to behave similarly to that noted for the intact clays and the p_1 interrelationship with q_t is not apparently affected by the presence of fissuring.

In the case of fissured crusts overlying soft clays, the DMT can be used to help delineate the extent of the desiccation zone, without fear of desaturation of porous elements or poor element saturation practices associated with piezocone deployment. In companion sets of DMT and CPTU soundings, the results can be used together to better define the zone of intact clays where permeability characteristics are likely to be low. In the upper crustal regions with fissuring, the permeability will be higher and will also reduce the operational undrained shear strength.

6 CONCLUSIONS

Interrelationships between DMT pressures and CPT readings are explored to discern general trends in soft clays. Data from three soft intact clays show that the DMT contact pressure (p_0) is about equal to the CPT shoulder (u_2) penetration porewater pressure and the CPT tip stress (q_t) exceeds the expansion pressure (p_1) by 10 to 50 percent. Companion sets of DMT and CPT can help better define the extent of crustal & desiccated zones. In fissured clays, the profiles of q_t and p_1 appear similar, but p_0 more closely follows the CPT face (u_1) porewater pressures because u_2 readings go negative.

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