$\boxed{\text{Draft}}$ of paper prepared for a 1988 Geotechnical Conference sponsored by the Pennsylvania Dept. of Transportation (PennDOT).

THE COEFFICIENT OF CONSOLIDATION OBTAINED FROM p_2 DISSIPATION IN THE DMT

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March, 1988

1. INTRODUCTION

1.1 The Coefficient of Consolidation

Rate often has equal importance with magnitude in geotechnical engineering problems. For example, when determining the importance of settlement, say the settlement of an embankment, the rate at which the settlement will occur usually determines the seriousness of any problems with settlement. Settlement that continues well after construction may for example mean negative skin friction on piles, a settlement discontinuity at a bridge abutment and the more rapid deterioration of pavement structure and riding quality. Because the coefficient of consolidation represents the key soil property that controls many rate of settlement problems, geotechnical engineers often have a special interest in any test that provides a value for this coefficient. The DMT has now become such a test.

Engineers typically use equation (1) to evaluate rate of consolidation settlement.

$$T = \frac{ct}{H^2} \qquad (1)$$

Where T = a dimensionless time factor associated with a particular degree of consolidation, depending on the geometry of the drainage pattern involved.

c = the appropriate vertical or horizontal coefficient of consolidation, c_v or c_h.

t = the time since the beginning of consolidation.

H = the length of a drainage path representative of a problem, usually the longest path.

When using eqn. (1) to calculate the rate of consolidation settlement one must know the coefficient of consolidation, c.

1.2 The Marchetti Dilatometer Test (DMT)

Schmertmann & Crapps, Inc. first introduced the DMT into the USA in 1979, courtesy of its Italian inventor, Professor Silvano Marchetti. Because of its relative newness some engineers still do not know much about the DMT. Briefly, the test consists of pushing a penetrometer blade with a sharp cutting edge into the soil, stopping and then using gas pressure to expand a circular steel membrane horizontally into the surrounding soil. The operator measures the pressure required to just begin to move the membrane into the soil, referred to as the A-reading, and then the larger pressure required to move the membrane 1 mm into the soil, referred to as the B-reading. After correcting for membrane stiffness these readings become p_0 and p_1, respectively. Marchetti and others have established various correlations to predict the insitu engineering soil properties that existed prior to the disturbance of the soil displacements associated with inserting the DMT blade penetrometer. The interested reader can find many other references describing the DMT in more detail. For example, ASTM (1986) describes in more detail the DMT equipment, the performance of the test, and the data reduction.

1.3 The C-reading and p_2

In the last approximately five years research directed towards evaluating the importance of pore pressures to the DMT results has resulted in giving the DMT user an important new tool of special importance to the subject of this paper. This research has resulted in the discovery that a controlled pressure release or venting of the gas after the B-reading produces another important point in the cycle of membrane inflation-deflation -- namely the gas pressure at which the returning membrane again reaches its initial A-reading liftoff position. We now refer to this as the C-reading and give the symbol p_2 to the C-reading corrected for membrane stiffness. The next section discusses the importance of p_2.

2. p_2 APPROXIMATELY MEASURES PORE PRESSURE

The writer introduced this subject in a previous paper to the 1986 PennDOT Geotechnical Conference in Harrisburg (Schmertmann, 1986). The following constitutes a review and an update.

2.1 In Sands

Campanella and Robertson (1985) first obtained data that indicated p_2 closely measured the total water pressure in high-permeability soils such as sands. They obtained the data reproduced here in Figure 1a. In a specially instrumented research DMT blade they followed the pressure required to produce the full inflation-deflation cycle and simultaneously measured the pore water pressure at the center of the moving membrane. As shown, they found that the load-unload cycle produced essentially no excess hydrostatic pore pressure and the closing p_2 matched the pre-insertion equilibrium water pressure, u_o.

Schmertmann (DMT DIGEST #7A, 1986) explored the lower limit of permeability, in terms of the DMT material index I_D, for which insertion- and test-generated excess pore pressures remained essentially zero. Figure 2 shows his results. This figure appears to show clearly that when I_D equals or exceeds 2.0, then p_2 = approximately u_o (taken as hydrostatic in these data). Others have since confirmed this finding, for example see Figures 3 and 4b. Note that with the I_D-based soil identification system proposed by Marchetti (1980) an I_D of 2.0 represents a silty sand.

Although the writer does not know exactly why p_2 from the DMT appears to successfully measure ambient pore pressure in sands, he and others (Lutenegger, 1988) believe that a small cavity probably forms behind the deflating membrane, which fills with water at the ambient pressure. A very rapid deflation, such as the previously typical sudden release of the gas pressure after the B-reading when performing the DMT without obtaining a C-reading, probably causes very high pore pressures gradients and unstable soil conditions behind the suddenly deflating membrane. Research has also shown that a subsequent A-reading after a sudden release usually gives a second p_o significantly higher than p_2 had the deflation been controlled, perhaps because unstable sand collapses against the membrane and thus adds soil pressure to the second p_o.

2.2 Clays

At the same time as Campanella and Robertson presented Figure 1a, they presented the similar Figure 1b obtained in a clay. This time they found very high excess hydrostatic pressures resulting from performing the DMT. However, their data in clay again shows that the p_2 closure pressure approximately equals the pore pressure on completion of the DMT. The total pore pressure included a large component of excess ambient pore pressure (often referred to as "excess hydrostatic", but this correct only if the ambient pore pressure equals the hydrostatic from a known phreatic surface). Figure 2 also shows that with I_D in the clay range (less than 0.6) the p_2 values can exceed the ambient hydrostatic by large ratios in compressible clays. Figure 3 presents an example log of p_2 illustrating how p_2 tracks hydrostatic in the sand layers but greatly exceeds hydrostatic in the clay layers.

Further research has continued to support the empirical observation that p_2 approximately equals the total DMT-generated pore pressure. For example, included as Figure 4 herein are data from Robertson et. al. (1988) that show the p_2 value approximately equaling test pore pressures in both sand and clays. Figure 5 presents data from another researcher showing how well p_2 matched pore pressures determined by a parallel DMT sounding with a special DMT blade containing a piezometer at the same location as the DMT membrane.

The writer does not know the reason p_2 in clays approximately matches pore pressure. This may only happen in soft and medium clays, not highly overconsolidated (probably indicated by a low K_D, as in Figure 4a). Other researchers have noted a similar behavior with the pressuremeter test in soft/weak soils where deflation closure pressures have also approximately matched pore pressures in sands and clays (DMT DIGEST #5A, 1985). Caution: Uglow and Powell (1988) have shown that p_2 did not correctly measure pore pressure in the highly OC, stiff clays they tested and that p_2 in such clays depended on DMT procedures such as testing time and the extent of any overexpansion past the B-reading.

3. p_2 DISSIPATION WITH TIME

3.1 p_2 Dissipation Matches Pore Pressure Dissipation

The initial work by Boghrat (1987) showed that when performing DMTs in clay soils ($I_D < 0.6$) only 10% or less of the excess pore pressure generated had dissipated after 1 minute from stopping the blade penetration. Figure 6(a) shows his results, all involving the dissipation of negative pore pressures in stiff, HOC clays. Lutenegger and Kabir (1988) recently obtained the data in Figure 6(b) that confirms the 10% finding in softer clays that dissipated positive pore pressure. That leaves at least 90% of the excess pore pressure still to dissipate and subject to being measured and analyzed. Initially, researchers merely observed that such dissipation curves, and also the dissipation curves from successive p_o readings, had shapes similar to those already predicted theoretically and measured experimentally in the much more extensive CPT pore pressure dissipation research and literature as noted subsequently.

Figure 7 from Lutenegger (1988) shows a comparison between CPTU-determined pore pressure dissipation, DMT pore pressure dissipation and p_2 dissipation. Note that although the curves have a displacement on the time scale, they all have the same shape. Figure 8 from Robertson et.al. (1988) shows another example of a comparison between DMT pore pressure dissipations and p_2 dissipation. The first example involves parallel tests in a uniform clay, the second comparison comes from different measurements during the same DMT. The above comparisons tend to confirm the reasonable expectation that if p_2 approximately measures total ambient plus excess ambient pore pressures then the dissipation of p_2 with time should approximately track the dissipation of the total pore pressure with time.

One might also reasonably expect that once the first cycle of p_o-p_2 membrane expansion and deflation opens a water-filled small cavity in the soil next the the membrane, and if this cavity remains open with time and therefore does not require periodic reopening, that subsequent p_o readings will track the u dissipation. This would avoid the need for successive p_o-p_2 cycles and make the tracking easier and faster and perhaps also produce smoother data. Professor R. Campanella suggested and has had his students try this method and reports (personal communication) good results at one site.

One might further expect in soils wherein p_o results almost entirely or mostly from pore pressure that the dissipation of the p_o readings only would also track the u dissipation. Marchetti reports (personal communication, Oct. 1987) that such p_o dissipation data produces approximately the same t_{50} as actual pore pressure or p_o-p_2 cycle data. He prefers to use such p_o dissipation curves and the resulting t_{50} values in a qualitative sense to decide relative coeff. of consolidation values as an aid to decisions such as whether or not to use artificial drainage. The writer prefers to at least attempt quantitative determinations despite the uncertainties involved, as discussed subsequently. Then the user can decide how conservatively to use the results in any particular problem situation.

3.2 CPTU Dissipation Theory Applied to DMT

A number of researchers have in the last ten years investigated theoretically the problem of the generation and dissipation of excess pore pressures around a penetrating cone penetrometer, for example Torstensson (1977), Baligh (1980), Gupta (1983) and Baligh and Levadoux (1986). The problem remains complex and each had to make simplifying assumptions. Each presented his results in terms of a dimensionless time factor that includes the square of the radius of the cone penetrometer, the geometrical position of the pore pressure sensing element on the cone tip, and the ratio of modulus to strength of the soil penetrated. We have early indications that the time factor curves presented by Gupta best fit field data (Lutenegger, Saye and Kabir, 1988). However, Baligh and Levadoux (1986) have recently confirmed that the calculated coefficient of consolidation applies primarily to the horizontal direction and to an unloading or a recompression behavior. Thus, estimating field coefficients of consolidation in the vertical direction, and for other than unloading or recompression, requires correction factors as discussed subsequently in Section 3.3.

When applying the CPT theory to the DMT one must use an additional factor to account for the difference in shape between the circular cone penetrometer and the rectangular DMT blade with its length-width ratio of 6.3. A possible simple way to handle this involves using an equivalent radius for the DMT blade instead of the radius of the cone in the definition of time factor for the CPT theory. A 10 square cm cone has a radius of 17.8 mm. A circle with the same cross sectional area as the DMT blade would have a radius of approximately 22 mm. However, both the writer's experience and that of Lutenegger and Kabir (1987) (also Lutenegger, Saye and Kabir (1988)) suggests that an equivalent radius of 24 mm would produce approximately the same results for c_h when using either CPTU-dissipation or DMTC-dissipation tests in the same cohesive soils. The method suggested herein therefore uses $r^2 = 600$ mm^2.

3.3 Example Data and Calculation

Figure 8 presents the data sheet with a worked example for calculating test and field values for c_h. Part (a) lists the field data consisting of a sequence of C-readings taken at successive times after stopping the DMT blade penetration and thus starting the pore pressure dissipation that results primarily from this penetration (Figure 1b shows only small additional pore pressure resulting from the 1 mm membrane expansion after the penetration). Part (b) shows these data plotted on a square root of time scale, which the writer considers most convenient for making the two time extrapolations required — the first for p_2 at zero time and the second for p_2 at equilibrium (theoretically infinite) time. For zero time the writer recommends a linear backward extrapolation, which matches approximately with the aforementioned dissipation theories and which is conservative (produces a greater t_{c50}) vs. the probably more correct continuing flat curvature. The infinite extrapolation reaches the ambient equilibrium pore pressure — which might be known from other data, for example, a hydrostatic condition from a known phreatic surface. If not known, then a curve fitting or mathematical extrapolation to an asymptotic value is required. After making these extrapolations the user can determine the time at 50% C-reading dissipation (or 30% if more convenient) as also shown in the (b) part of Figure 8. He or she then enters this time into the part (c) equation for the test c_h, along with the applicable time factor obtained from the Gupta time factor curves shown. This determines the c_h value applicable to this DMT. It probably does not apply directly to the insitu soil for a loading situation.

A correction needs to be applied to account for whether the field loading will produce virgin compression, recompression or some combination. Tentatively, the writer suggests the following empirical factors by which to divide the test c_h to obtain the applicable insitu c_h: 7 if the applicable field compression is virgin compression, 5 if recompression and then virgin, 3 if recompression and 1 if recompression in a highly overconsolidated cohesive soil.

One may need to apply still another correction to account for a different vertical vs. horizontal coefficient of consolidation. Equation (2) gives the equation for this coefficient in terms of the soil coefficient of permeability, k, and the 1-D compression modulus, M.

$$c = \frac{k\gamma_w}{M} \quad \text{. . . . .} \quad (2)$$

$$c_h = \frac{k_h\gamma_w}{M_h} \quad \text{. . . . .} \quad (2a)$$

$$c_v = \frac{k_v\gamma_w}{M_v} \quad \text{. . . . .} \quad (2b)$$

$$M_h = K\,M_v \quad \text{. . . . .} \quad (3)$$

Permeability usually has the greatest anisotropic variation. Table 1 provides a rough guide for estimating a (k_h/k_v) ratio. Analysis of DMT data includes the routine prediction of the insitu M_v. The writer suggests estimating M_v by assuming it varies proportionally with the anisotropic effective stress condition, namely the K value as shown by eqn. (3) and which the DMT also routinely predicts. Figure 9 also includes the calculations for c_v and k_h and k_v using an assumed anisotropic permeability ratio of 4 in this layered soil and the average DMT- predicted values of K = 1.1 and M_v = 95 bar at this site.

TABLE 1 - Typical Anisotropic Permeability Ratios
(from Baligh and Levadoux, 1986)

Nature of Low-k Soil (clay)	$\frac{k_h}{k_v}$
No evidence of layering	1.2 ± 0.2
Slight layering, e.g., sedimentary clays with occasional silt dustings to random lenses	2.5
Varved clays in northeastern U.S.	10 ± 5

3.4 Field Comparisons

The writer now has found five field cases, including two from PennDOT Research Project 84-24, comparing c_h and c_v values determined from DMT and/or CPTU measurements vs. backfigured values from field settlement or pore pressure dissipation behavior. Table 2 includes these comparisons. The reader can see from the general good agreement between predicted and measured behavior that the DMT and CPT c_h and c_v prediction method looks very promising and appears to predict the coefficient of consolidation with an accuracy perhaps equal to that achieved from laboratory consolidation tests.

The laboratory determination has the advantage of using a good test model and consolidation theory for analysis, but a test takes a long time and uses a very small and always partly disturbed sample. The DMTC and CPTU method performs the test very quickly and relatively economically on a larger volume of insitu soil, but uses a semi-empirical analysis method.

4. CONCLUSIONS

Extensive, but new and therefore preliminary research data indicate that:

4.1 The DMT p_2 reading measures ambient pore water pressures in sands and ambient plus excess ambient pore water pressures in soft-medium cohesive soils with OCR < 3.

4.2 p_2 dissipation curves closely match excess ambient pore pressure dissipation curves in soft-medium cohesive soils with OCR < 3.

4.3 Dissipation curve theories developed for the CPTU and known to be only approximate because of the many theoretical problems involved, also have an approximate applicability to p_2 dissipation data.

4.4 The available comparisons between DMT-p_2 and CPTU dissipation-predicted values of the coefficient of consolidation and field performance indicate a prediction accuracy comparable to that obtained from usually more costly, and always more time consuming, sampling and laboratory consolidation testing.

4.5 The writer believes the theory, documentation and level of practice are now adequate to begin to include these CPTU and DMTC c_v and c_h methods in site investigations for design purposes.

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TABLE 2 - COEFFICIENT OF CONSOLIDATION COMPARISONS:
CPTU & DMTC Method* vs. Backfigured from Field Measurements

Site	Soil	CPT	DMT	c_h	c_v	avg. (ft^2/day)** CPT/DMT	meas.	how	No.	"error" $\left(\frac{\text{DMT-Meas.}}{\text{Meas.}}\right)$	Notes
A	NC Boston blue clay	X			X	0.10			c.10		*** Baligh & Levadoux (86) Research embankment site
							0.11	settlement		-9%	
							0.09	oed. tests	4		
B	NC N.Y. sensitive marine clay		X	X		0.016			4		wick drain research Lutenegger et.al. (88)
							0.016	pore pressures	7	0%	
							0.041	oed. tests	8		
C	Penn. cohesive embankment	X			X	0.17 1.15 0.66			2		S&C Inc. file 586-5
							0.49 1.0 0.75	pore pressures	2 loca.	-12%	entire embankment fill
							1.9	oed. tests	2		
D	Penn. OC, layered, silt-clay	X			X	0.74			6		S&C Inc. file 586-3
			X		X	0.99 x			7 x		
							1.5	settlement	3	-34%	range 0.17 to 2.7 from 29 time curves
							0.97	oed. tests (2 labs)	10 samples		
E	Canada, BC NC, organic clayey silt	X		X		0.5			c.10		wick drain research under test embankment Robertson et.al. (88)
							0.9	settlement		-44%	

* Using combined method shown on example data sheet

** $ft^2/d \times (1.08 \times 10^{-6}) = m^2/s$

*** Part of data used to develop the * combined method

x See Fig. 9 for an example from these data

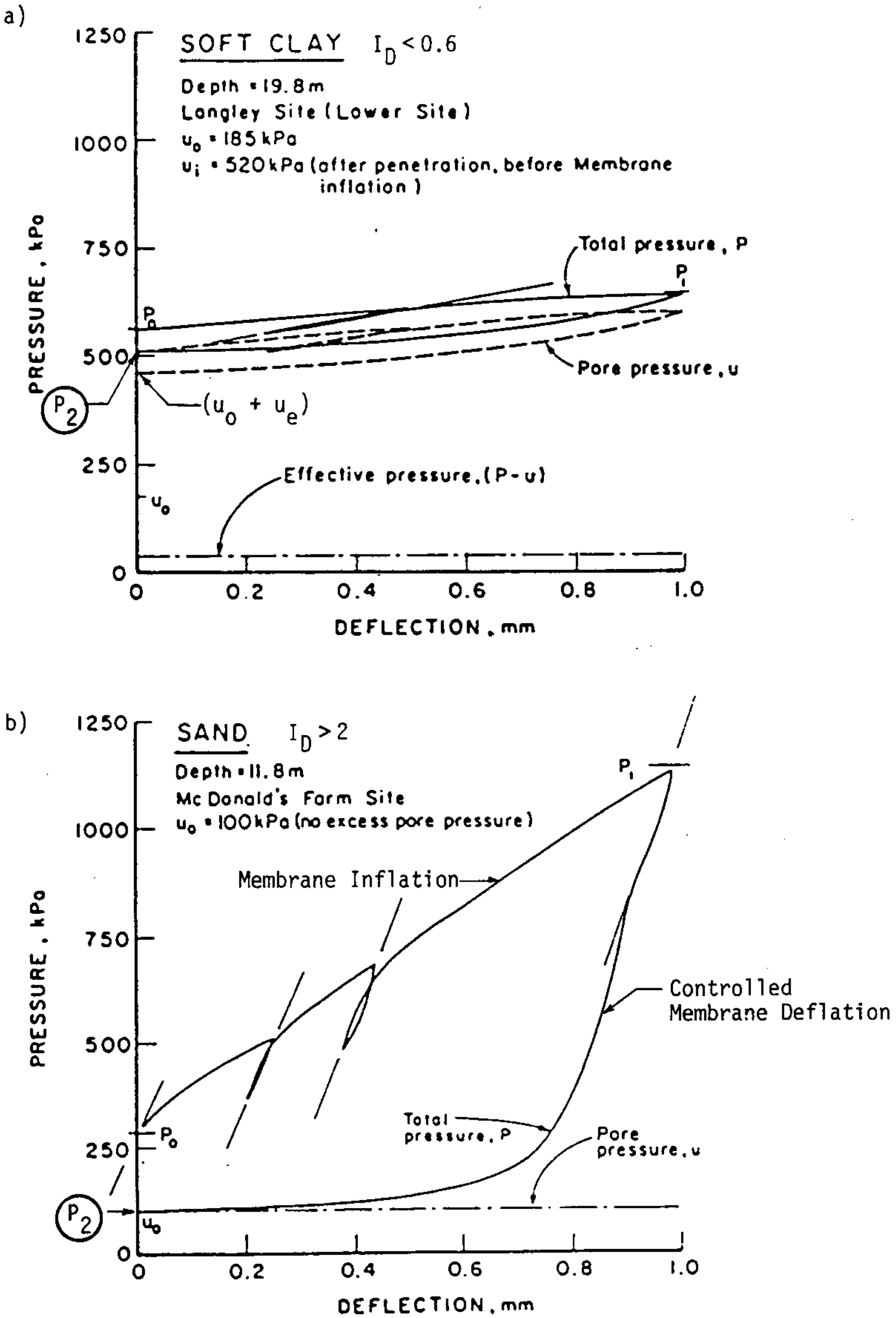


FIGURE 1 TYPICAL RESULTS FROM THE UBC CONTROLLED-DEFLATION DMT RESEARCH USING A SPECIALLY INSTRUMENTED BLADE WITH STRAIN GAGE AND PIEZOMETER MOUNTED ON CENTER OF THE MEMBRANE

(Campanella et al. 85)

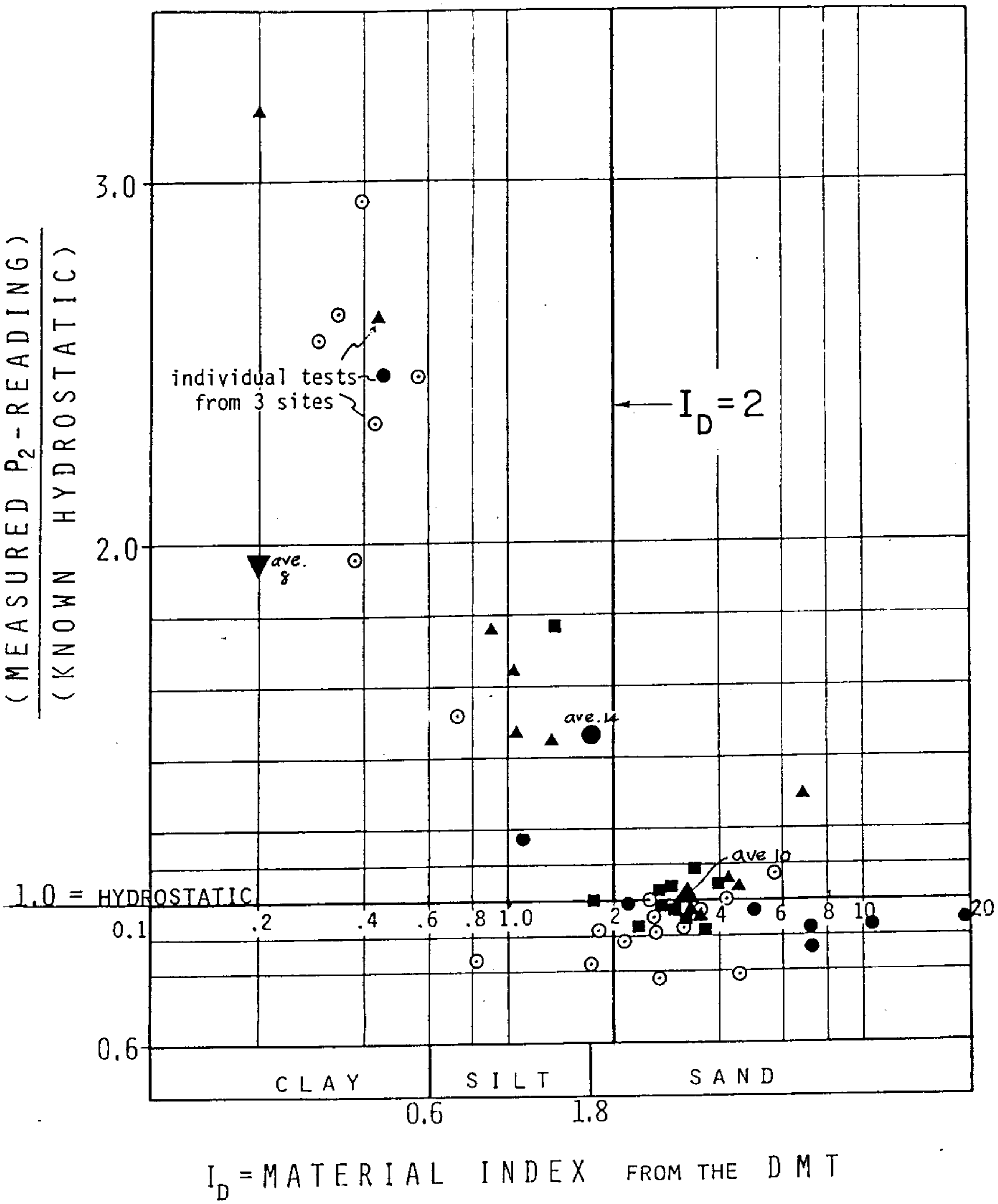


FIGURE 2 P_2 — HYDROSTATIC RATIO COMPARED WITH MATERIAL INDEX

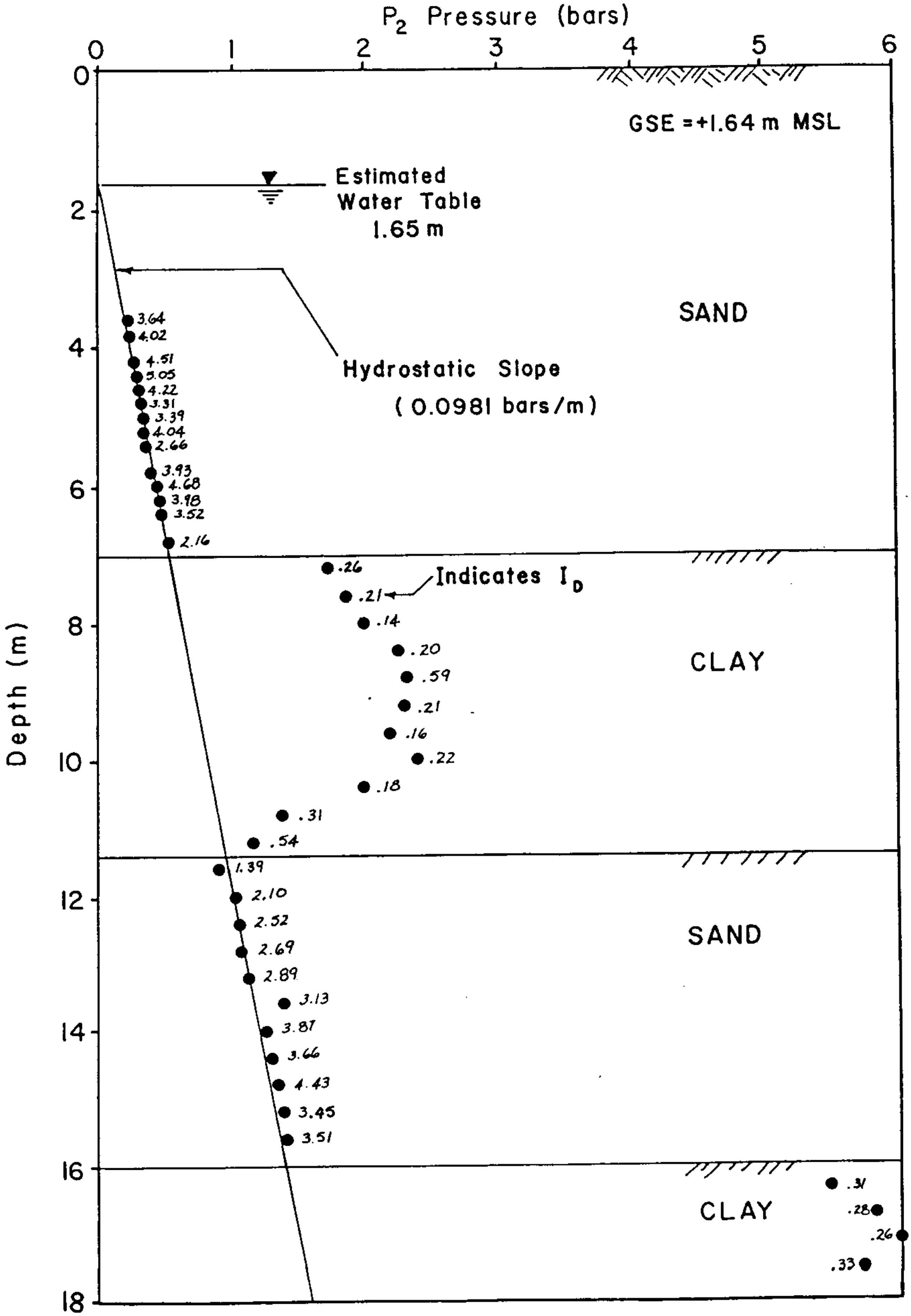


FIGURE 3 P_2 vs. DEPTH RESULTS FROM CAUSEWAY AT CHOCTAWHATCHEE BAY, FL
(GPE Inc. Demonstration Sounding, 1987)

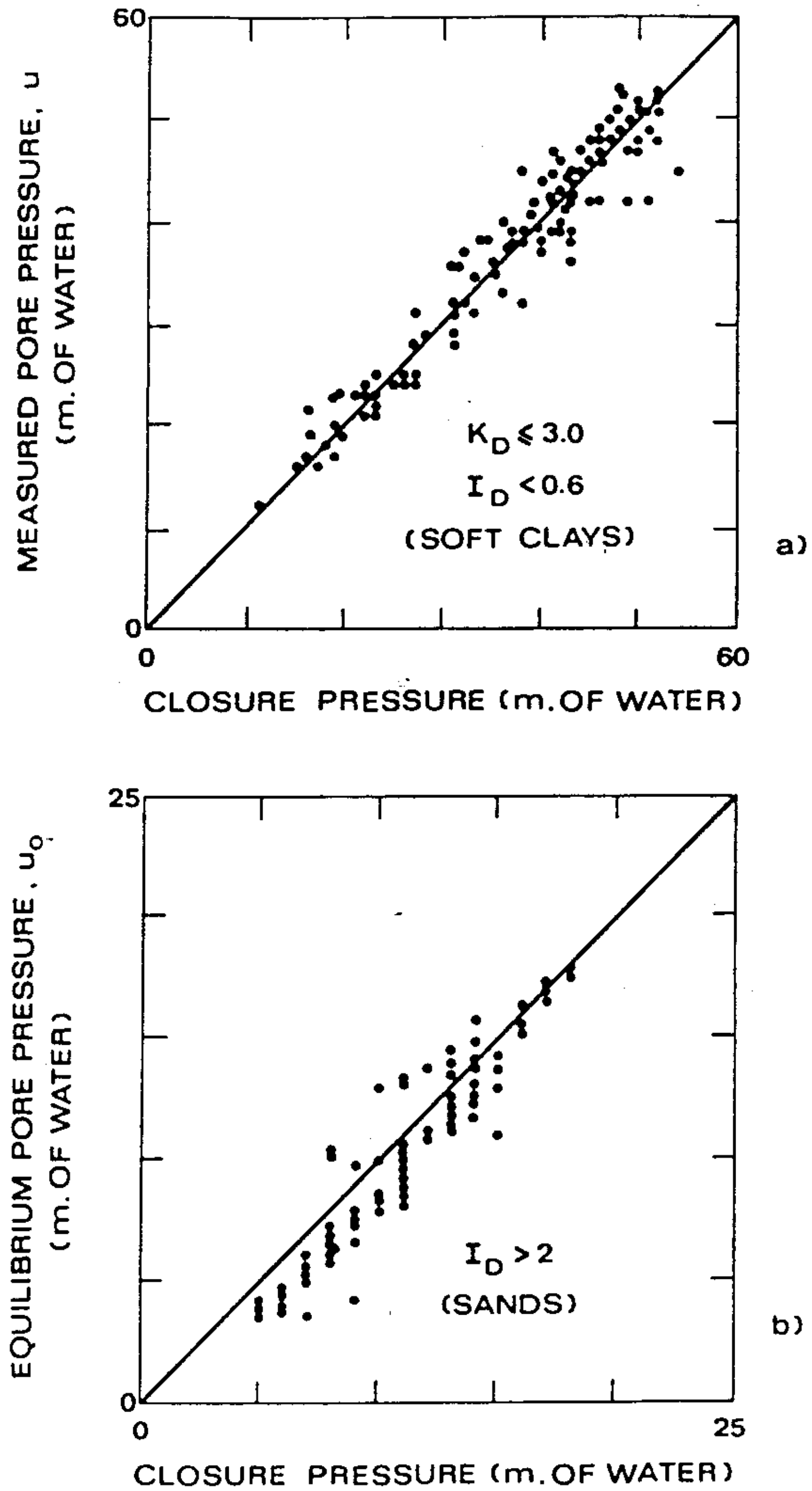
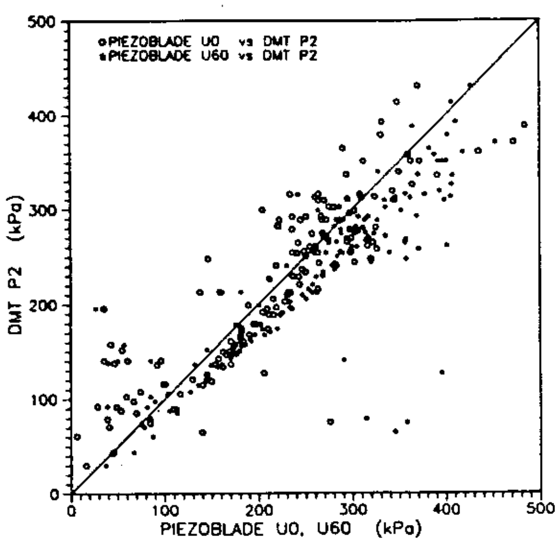
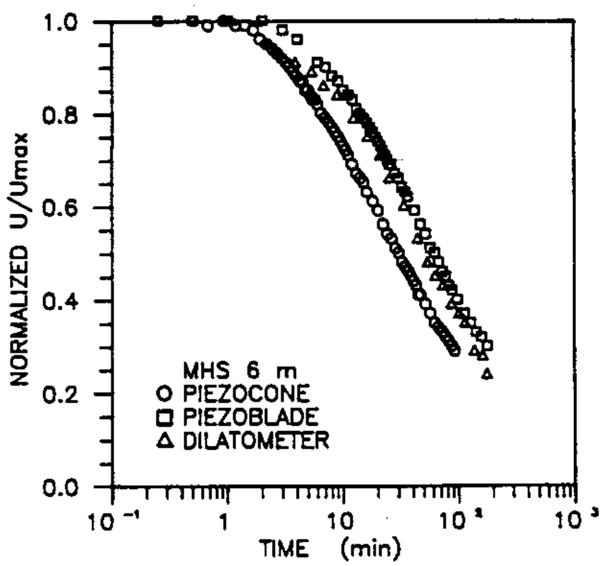


FIGURE 4 COMPARISON OF: (a) CLOSING PRESSURES AND MEASURED PORE PRESSURES IN SOFT CLAY, AND, (b) CLOSING PRESSURES AND EQUILIBRIUM STATIC PORE PRESSURES IN SAND

(Robertson, et al., 1988)

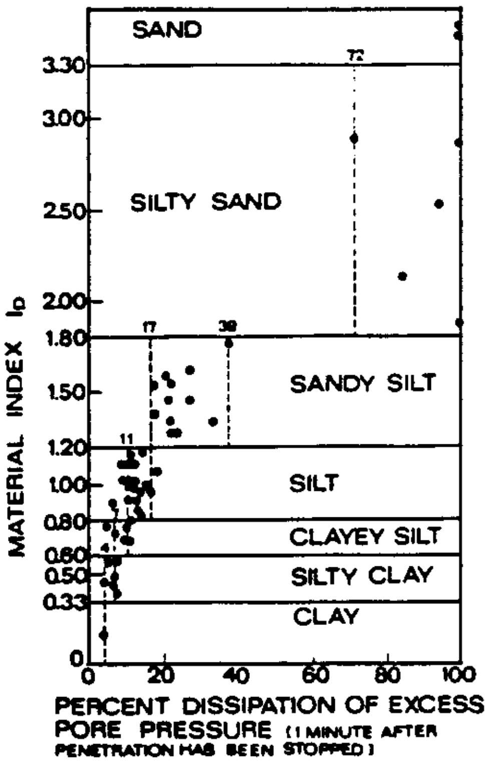


Comparison between Piezoblade U_{excess} and DMT p_2



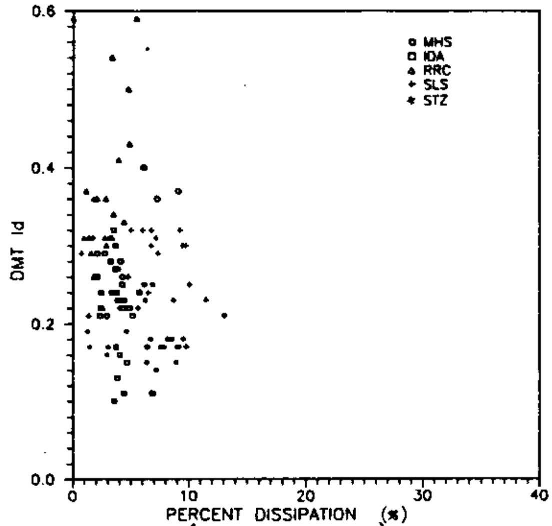
Comparison of Piezocone and Piezoblade dissipation tests with p_2 dissipation

Figure 5 (from Lutenegger & Kabir, ISOPT-1, 1988) Figure 7



(a) Degree of Dissipation of Excess Pore Water Pressure 1 min. After Penetration as a Function of I_D (Davidson and Boghrat, 1983)

(dissipation of - pore pressures)



(in 1 minute)

(b) Percent dissipation of Piezoblade pore pressure vs. DMT I_D.

(dissipation of + pore pressures)

FIGURE 6

(from Lutenegger, ISOPT-1, 1988)

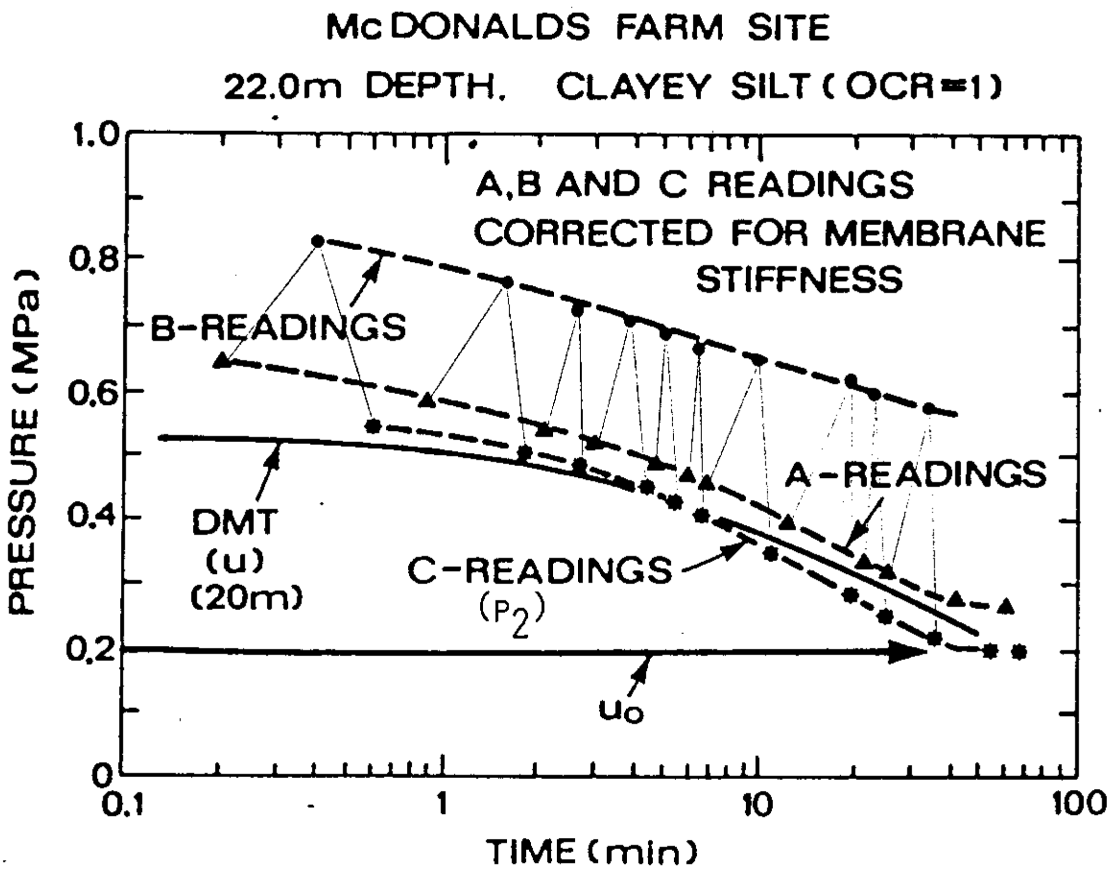


FIGURE 8 REPEATED A, B AND C-READINGS (CORRECTED FOR MEMBRANE STIFFNESS) USING STANDARD DMT COMPARED WITH DMT PORE PRESSURE DISSIPATION (MCDONALD FARM SITE) (Robertson, et al., 1988)

FIGURE 9 EXAMPLE C-DISSIPATION, WILKES-BARRE, PA

SCHMERTMANN & CRAPPS, INC. Job No. 699

Coeff. Consol. c_h from DMT C vs. time, using a combined Baligh/Gupta/Robertson/Lutenegger method

data by: PJB date: 14 Jul 87

analysis by: JHS (21') date: Dec 87

FIELD DISSIPATION DATA

@ DMT # DCPT-5 Depth 6.33 m Elev

ΔA = 0.17 bar

ΔB = 1.69 bar

SOIL: clayey silt, layered, inorg., LOC, PI ≈ 10 %

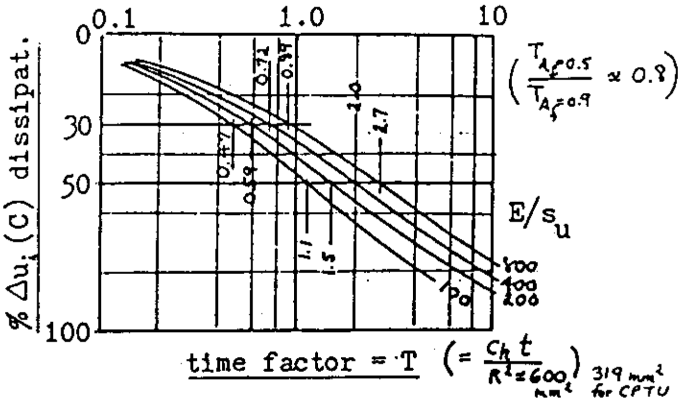
(from R.C. Gupta dissertation, 1983) with piez. element 4R above point

$t_o = 0$ stop watch

a

A readings (b)	B readings (b)	C (15-30 s from B)	time t h	time t m	time t s	$(t-t_o)$ min
3.92	7.20	1.90		1	05	1.08
2.86	6.75	1.33		2	17	2.28
2.41	6.55	1.01		3	28	3.47
2.18	6.40	0.78		4	39	4.65
1.94	6.35	0.55		8	03	8.05
1.73	6.25	0.19		14	58	14.97

(note $\frac{T_{4R}}{T_{base\,cone}} \approx 1.15$) $A_f = 0.9$



$\left(\frac{T_{A_f=0.5}}{T_{A_f=0.9}} \approx 0.8\right)$

time factor = T $\left(= \frac{c_h t}{R^2 = 600\,mm^2}\right)$ 319 mm² for CPTU

estimate E/s_u = ~~400~~ $T_{\cancel{30}\,50}$ = 2.0

c

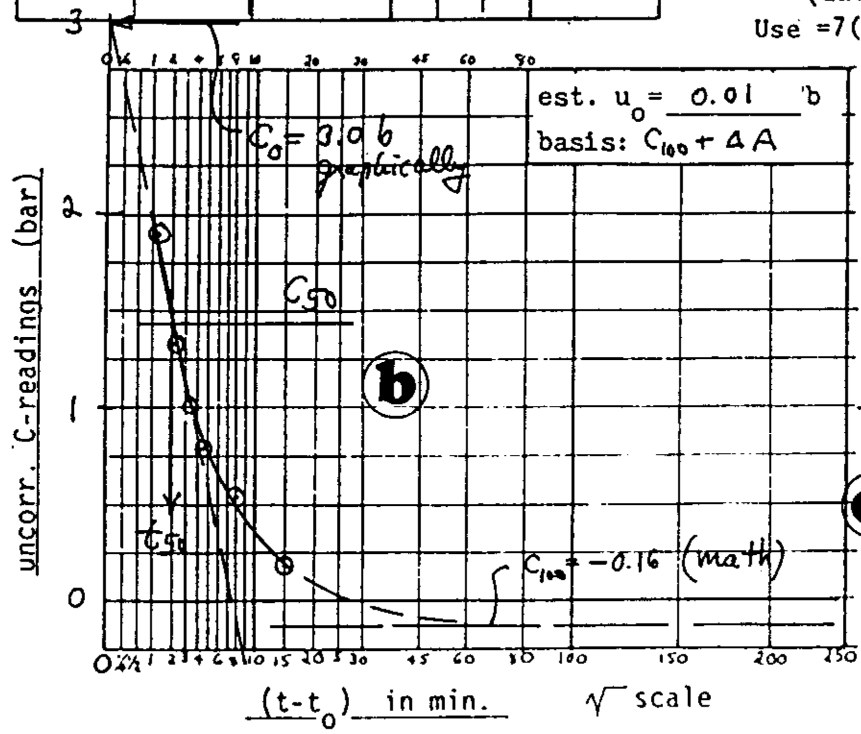
$$C_{h_{DMT}} = 600 \left(\frac{T_{50}}{t_{50}}\right) = 600 \ \frac{mm^2}{min}$$

$$\times 1.56 \times 10^{-2} = 9.4 \ ft^2/day$$

est. c_{hDMT}/c_{hField} = 3.0

(due to DMT load/unload behavior)

Use =7(NC), =5(NC-OC), =3(LOC), =1(HOC)



$(t-t_o)$ in min. $\sqrt{\ }$ scale

GRAPH OF FIELD DATA TO GET $(t-t_o)$ AT C_{50}

$C_{(t-t_o)=0} = \Delta u_i + u_o - \Delta A$

= 3.0 b (by graphic extrapol.)

$C_{100} = u_o - \Delta A \quad (t \to \infty)$

= -.16 b

$C_{\cancel{30}\,50} = \frac{3.0 - .16}{2}$ = 1.42 b

t_{50}(graph) = 2.0 min

d

$$\text{field } k_h\left(\frac{ft}{min}\right) = \frac{\text{field } c_h (ft^2/d)(\gamma_w = 2.1 \times 10^{-5})}{(K_o\ M_D = M_h \text{ in bar})}$$

$$= \frac{9.4\ (.000021)}{3 \times (1.1 \times 95)} = 6.3 \times 10^{-7}\ ft/min$$

est. k_v/k_h = 1/4 $\times K_o = c_v/c_h$ = 0.28

then field $\boxed{k_v \approx 1.6 \times 10^{-7}\ ft/min \quad c_v \approx 0.87\ ft^2/d}$