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Excess pore pressures and the flat dilatometer test

P.K.Robertson, R.G.Campanella & D.Gillespie
University of British Columbia, Civil Engineering Department, Vancouver, Canada
T.By
Norwegian Geotechnical Institute, Oslo

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ABSTRACT: Data is presented comparing pore pressures measured during penetration with UBC's and NGI's specially designed flat dilatometers and a piezocone. Representative data is presented for sands and soft clays and shows that the pore pressures in a DMT during penetration are similar to those measured behind the friction sleeve in a CPTU. Data is also presented to show that the closing pressure using a standard Marchetti DMT is very similar to the penetration pore pressures in sands and soft clays. Dissipation data during a pause in penetration with the DMT and CPTU is presented and discussed. A tentative procedure to estimate c_h using a standard DMT is proposed.

KEY WORDS: Flat dilatometer, pore pressures, CPTU, dissipation.

INTRODUCTION

The flat dilatometer test (DMT) was first introduced in 1980 (Marchetti, 1980) and has become a simple, cost-effective in situ test. The dilatometer is a flat plate 14 mm thick, 95 mm wide by 220 mm in length. A flexible stainless steel membrane 60 mm in diameter is located on one face of the blade. Beneath the membrane is a measuring device which turns a buzzer off in the control box at the surface when the membrane starts to lift off the sensing disc and turns a buzzer on again after a deflection of 1 mm at the centre of the membrane. Readings are made every 20 cm in depth. The membrane is inflated using high pressure nitrogen gas supplied by a tube pre-threaded through the rods. As the membrane is inflated, the pressures required to just lift the membrane off the sensing disc (reading A), and to cause 1 mm deflection at the centre of the membrane (reading B), are recorded. Readings are made from a pressure gauge in the control box and entered on a standard data form. However, one disadvantage with the test was the fact that no pore pressure measurements were made. Several specially designed flat dilatometers have been developed that incorporate pore pressure elements (Davidson and Boghrat, 1982; Campanella et al., 1985; Lunne et al., 1987). However, these devices detract somewhat from the primary advantage of the standard Marchetti device, that is, simplicity.

In 1985 Campanella et al., (1985) presented data from a sophisticated research dilatometer that showed the following main points:

- In soft clays the basic DMT data (P_o, P_1) is dominated by large penetration pore pressures.
- The pressure when the membrane returns to the closed position is the same as the penetration pore pressure.
- In clean sands no excess pore pressures are generated during penetration. Therefore, the closing pressure is approximately equal to the static equilibrium pore pressure (u_o).

Examples of the results are shown in Figure 1.

This paper will present data comparing penetration pore pressures using the University of British Columbia (UBC) research DMT, the Norwegian Geotechnical Institute (NGI) offshore DMT and the piezometer cone penetration test (CPTU). DMT penetration pore pressures will also be compared to the closing pressures using the standard Marchetti DMT.

EQUIPMENT AND FIELD TESTING

Research at UBC and NGI involving the DMT has included the development and use of research flat dilatometers. The UBC research dilatometer is identical in size, shape and operation as the Marchetti design except for the following passive measurements:

1. pore water pressure at the center of the moving membrane,
2. deflection at the center of the membrane,
3. gas pressure activating the membrane,
4. verticality of the dilatometer blade during penetration, and,
5. the penetration force for the blade of the dilatometer.

Typical results from the UBC research dilatometer for tests in a clean sand and soft clay deposit are shown in Figure 1.

In order to fit inside the standard offshore drill string NGI's offshore dilatometer has a slightly different size (width = 77 mm, thickness = 16 mm) and shape compared with the Marchetti design (Lunne et al., 1987). As with the UBC dilatometer, the pore pressure is measured, but the filter is located on the reverse side of the blade, directly opposite the center of the membrane. The operation pressure (oil) is generated by means of a piston pump and the movement of the piston is achieved by a D.C. electric motor. The pressure is recorded continuously in addition to P_0 and P_1. Calibration tests at NGI's research sites in Norway and at UBC's research sites in Canada have shown that the offshore dilatometer gives results very similar to the standard Marchetti device.

The data presented in this paper was obtained at two sites near Vancouver, B.C.. One site is the McDonald Farm site which is located in the Fraser River delta. The site consists of relatively clean sand from a depth of about 2 m to 15 m underlain by an approximately normally consolidated clayey silt deposit.

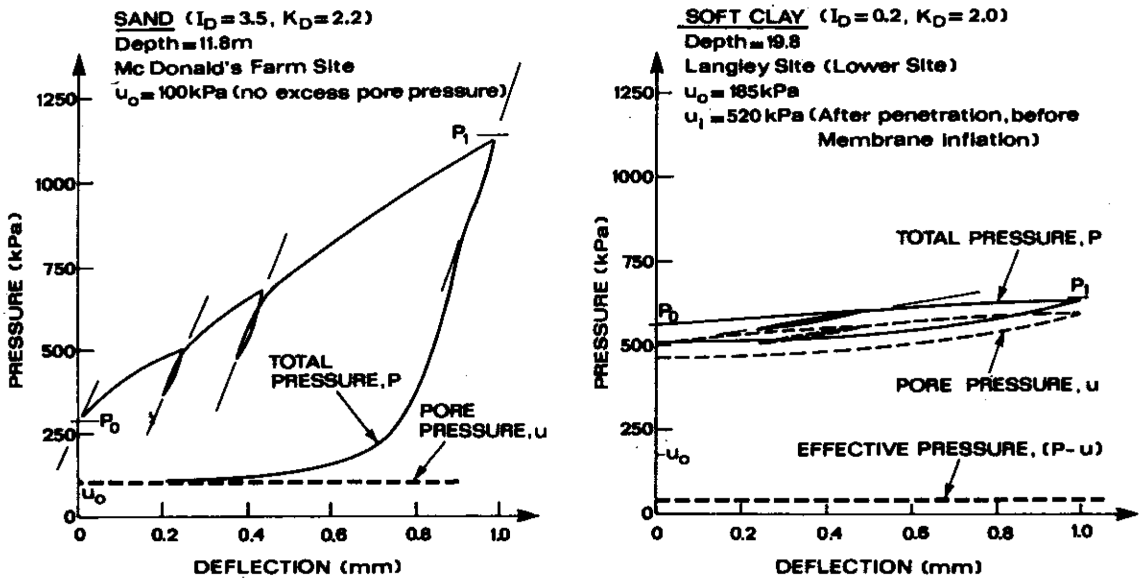


Fig.1 Typical results from UBC research DMT (After Campanella et al., 1985)

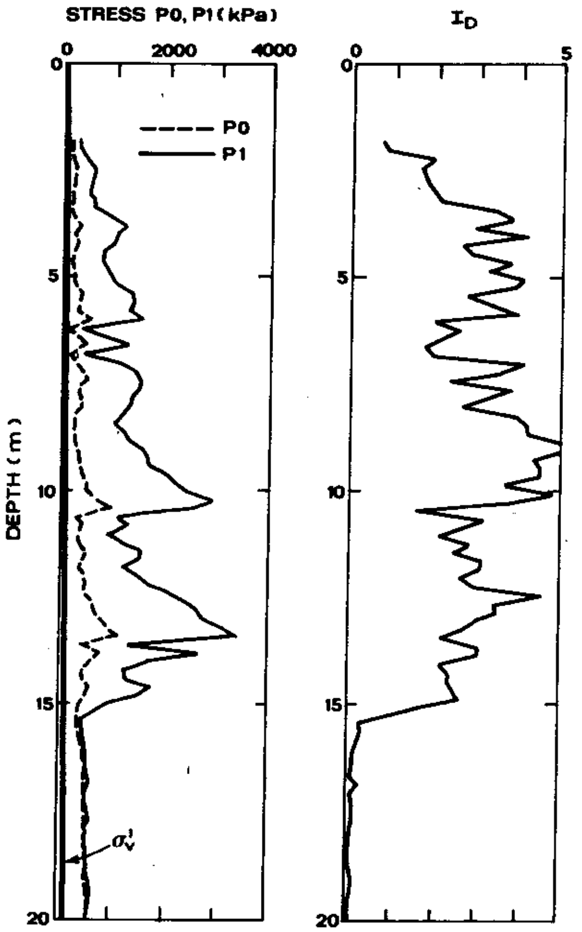


Fig.2 Basic DMT data for McDonald Farm Site obtained with NGI offshore DMT

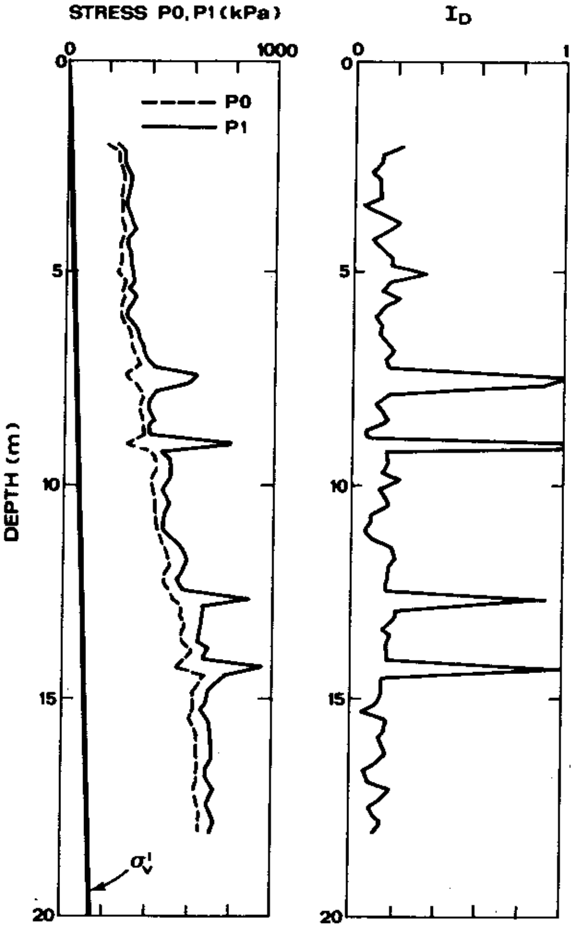


Fig.3 Basic DMT data for Langley Site obtained with NGI offshore DMT

Table 1. Summary of Soil Index Properties for Fine Grained Soils

Site	w %	w_L %	PI %	s_t	OCR
McDonald Farm	23-40	25-42	3-20	2-7	1-2
Langley	27-53	32-59	16-34	7-10	1-3

w - Water Content
w_L - Limit Liquid
PI - Plasticity Index
s_t - Sensitivity
OCR - Overconsolidation Ratio

Basic DMT data for the McDonald Farm site is shown in Figure 2. Full details of the site are given by Campanella et al., (1983).

The second site is near Langley, B.C. and consists of lightly overconsolidated glaciomarine silty clay interbedded with thin lenses of silt and sand. Basic DMT data for the Langley site is shown in Figure 3. A summary of the index properties of the fine grained soils is given in Table 1.

The dilatometers were pushed into the ground at a constant rate of penetration of 2 cm/sec. Before and after each sounding the dilatometers were calibrated for membrane stiffness.

The basic dilatometer data (readings A and B) are corrected for offset in the measuring gauge and for membrane stiffness (P_o, P_1).

Using P_o and P_1 the following three index parameters were proposed by Marchetti:

$$I_d = \frac{(P_1 - P_o)}{P_o - u_o} \quad \text{- Material Index}$$

$$K_d = \frac{P_o - u_o}{\sigma'_{vo}} \quad \text{- Horizontal Stress Index}$$

$E_d = 34.6 (P_1 - P_o)$ - Dilatometer Modulus

where u_o is the assumed in-situ hydrostatic water pressure and σ'_{vo} is the in-situ vertical effective stress.

The basic DMT data in Figures 2 and 3 also includes the Material Index parameter (I_D). For the clean sand at the McDonald Farm site $I_D > 2$. For the underlying clayey silt at the McDonald farm site and the silty clay at the Langley site $I_D < 0.6$ and generally approximately equal to 0.2.

DMT AND CPTU PENETRATION PORE PRESSURES

Figures 4 and 5 present the measured pore pressures during penetration from the DMT and CPTU, for the McDonald Farm and Langley sites, respectively. Pore pressures from the CPTU were measured at three locations; on the face of the tip, immediately behind the tip and behind the friction sleeve. The pore pressures from the DMT were measured on the center of the membrane for the UBC blade and on the reverse side of the blade for the NGI blade.

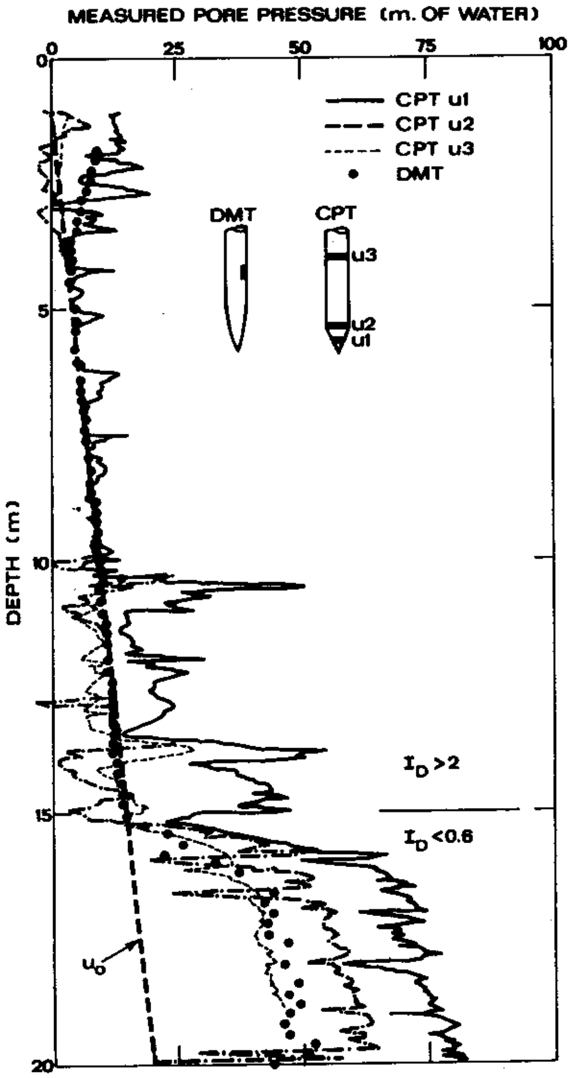


Fig.4 Penetration pore pressures from NGI offshore DMT and CPTU at McDonald Farm Site

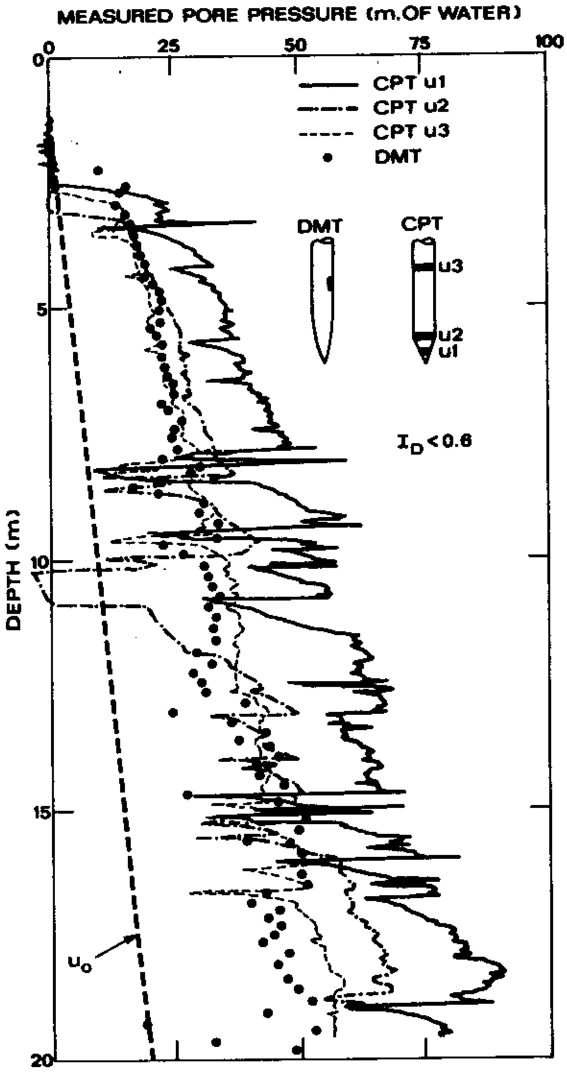


Fig.5 Penetration pore pressures from UBC research DMT and CPTU at Langley site

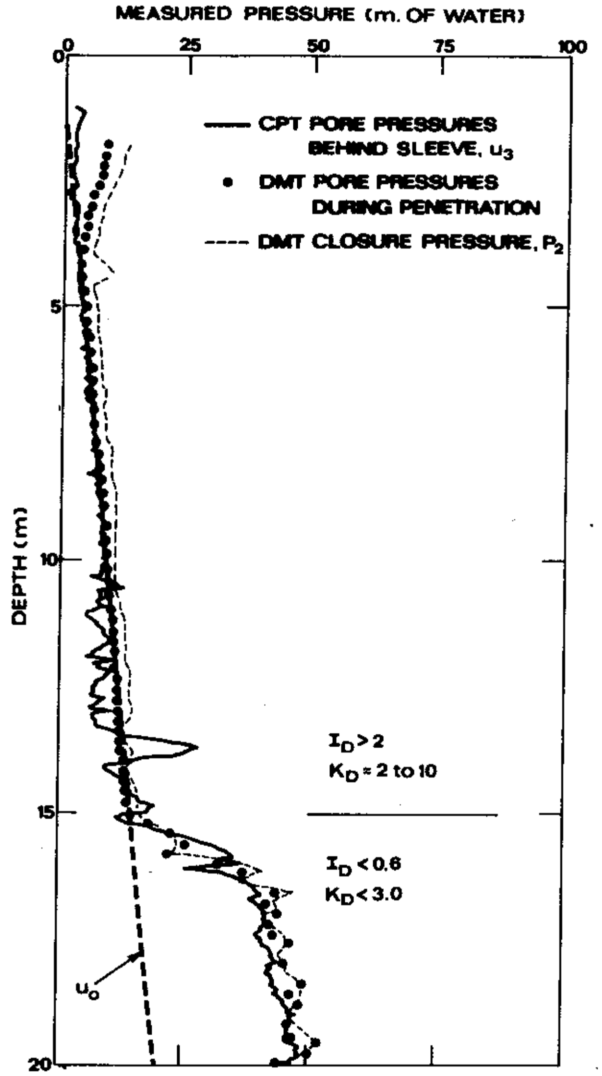


Fig.6 Comparison between penetration pore pressures from DMT and CPTU and closing pressures P_2 from NGI offshore DMT at McDonald Farm Site

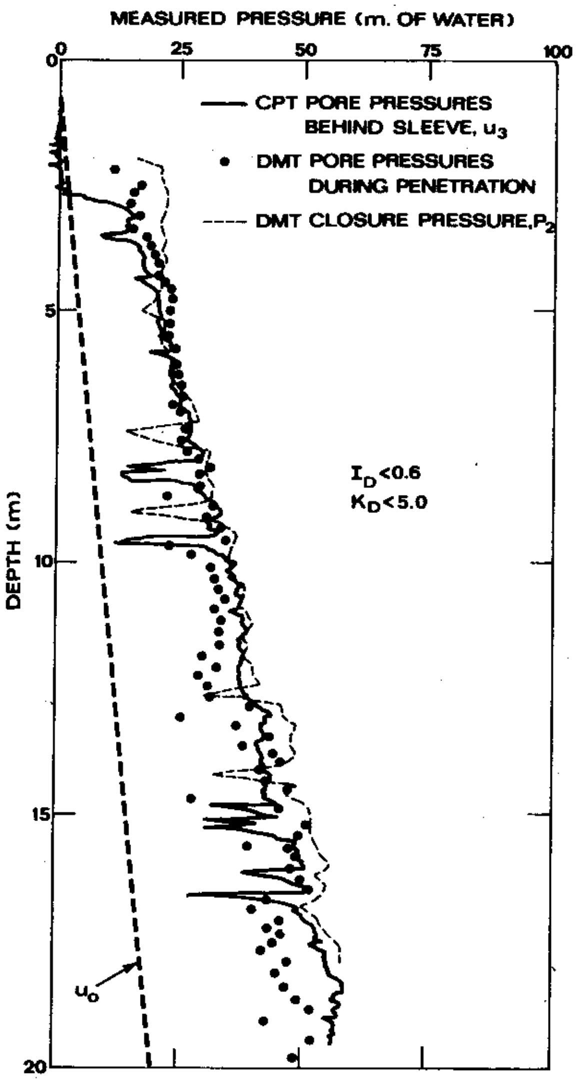


Fig.7 Comparison between penetration pore pressures from DMT and CPTU and closing pressures P_2 from UBC research and NGI offshore DMT at Langley site

Figures 4 and 5 clearly show that the DMT penetration pore pressures are very similar to the pore pressures measured behind the friction sleeve in the CPTU.

In the clean sand deposit (2 m to 15 m) at the McDonald Farm site no excess pore pressures were generated during the DMT penetration. In the clayey silt and silty clay deposits large excess pore pressures were generated during penetration in both the DMT and CPTU. The difference in pore pressures measured at different locations on the cone is consistent with results recorded elsewhere (Campanella et al., 1985; Jamiolkowski et al., 1985; Lunne et al., 1986). The results from the Langley site are complicated by the interlayering of the silt and sand lenses.

These results confirm the previous findings (Campanella et al., 1985) that in soft clays ($I_D \leq 0.6$; $K_D \leq 5.0$), the basic DMT data (P_0, P_1) is dominated by large penetration pore pressures. These pore pressures are influenced by the soils undrained shear strength, stress history and stiffness and macrofabric. Therefore, it is not surprising that the basic DMT data can be related to undrained shear strength and stress history for some soils. But that any correlation relating them will not be unique for all soils.

CLOSING PRESSURE FROM DMT

The closing pressure is a new measurement proposed by the authors and is obtained by slowly deflating (15 to 30 sec) the dilatometer membrane (after the P_1 reading) until contact is reestablished. When the closing pressure is corrected for membrane stiffness it is referred to as P_2.

Figures 6 and 7 compare the measured penetration pore pressures using UBC's research DMT, NGI's offshore DMT and CPTU with the closing pressure for the Mc Donald and Langley sites. More details are given by T. By et al. (1987). For clarity only the CPTU data measured behind the friction sleeve is presented.

Although the closing pressures shown in Figures 6 and 7 were obtained using UBC's research or NGI's offshore DMT, similar results have been obtained at both sites using the standard Marchetti DMT.

Figures 6 and 7 clearly show that, for the clean sand and soft clay deposits tested, the DMT closing pressures are very similar to the penetration pore pressures from the DMT and those recorded behind the friction sleeve from the CPTU (u_3).

In clean sands, because no excess pore pressures are generated during penetration, the DMT closing pressure is very close to the static equilibrium pore pressure (u_o).

It is interesting to note from Figure 7 that the DMT closing pressure also records low values within the silt or sand lenses. There is clearly the potential to reinforce or possibly improve soil classification with the standard DMT if the additional closing pressures are also recorded.

Figure 8a presents a summary of DMT penetration pore pressures and closing pressures for soils where $I_D \leq 0.6$.

Since the soils tested where generally soft, the relationship shown in Figure 8a may apply only to soils where the DMT horizontal stress index $K_D \leq 5.0$.

Figure 8b presents a summary of the hydrostatic pore pressures and DMT closing pressure for soils where $I_D > 2$, (i.e. sands).

The relationships shown in Figure 8 are remarkably consistent and indicate the potential usefulness of recording the closing pressure (P_2) in standard DMT.

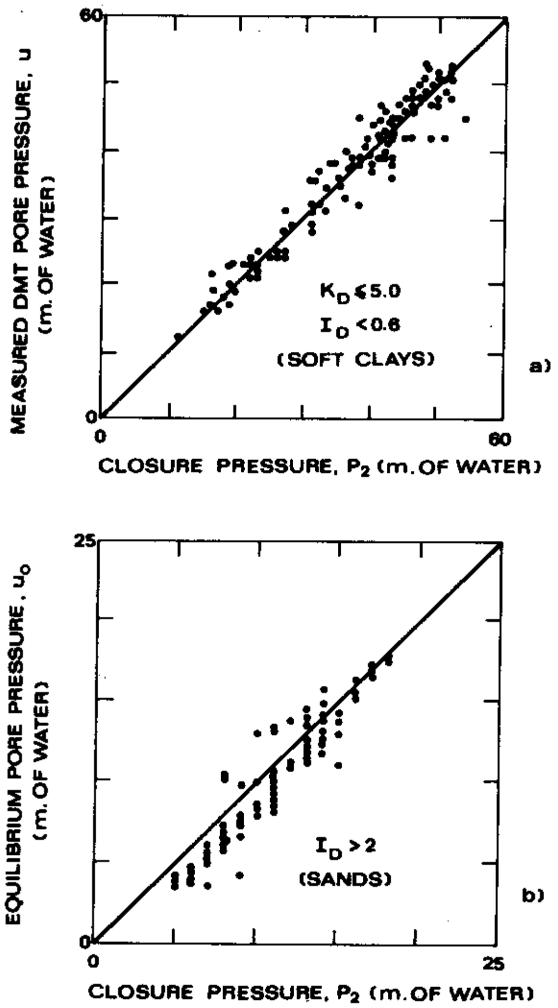


Fig.8 Comparison of: (a) closing pressures and measured pore pressures in soft clay, and, (b) closing pressures and equilibrium static pore pressures in sand

DISSIPATION RATES

Figure 9 presents a typical example of the dissipation of excess pore pressures during a stop in penetration for the research DMT and CPTU. The example shown is from the McDonald Farm site at a depth of 20 m. The CPTU dissipation data is for the pore pressure element located immediately behind the tip.

Figure 9 shows that, when the dissipation data is normalized with respect to the equilibrium static pore pressure (u_o), the rate of dissipation for pore pressures around the DMT is slower than that around a 10 cm^2 cone.

At the McDonald Farm site at a depth of 20 m the times for 50% dissipation are:

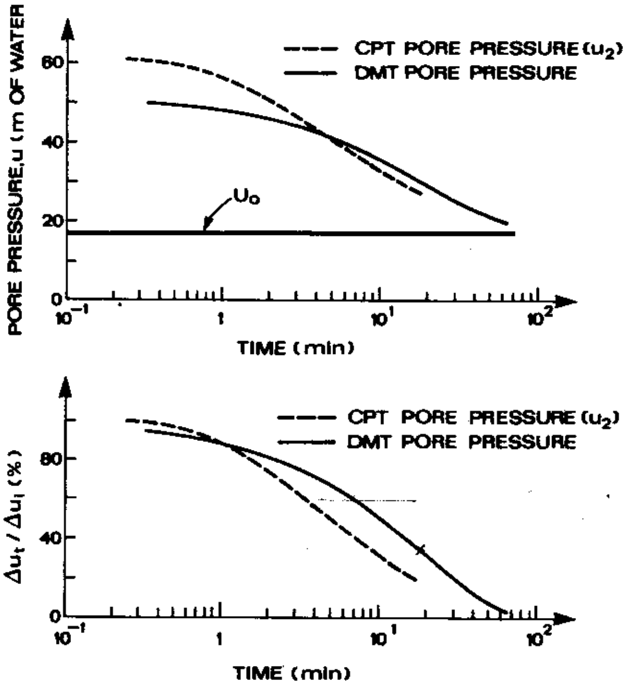


Fig.9 Comparison of pore pressure dissipations using UBC research DMT and 10 cm^2 CPTU at McDonald Farm site, Depth=20 m

DMT $t_{50} = 9.5$ mins
CPTU (10 cm^2) $t_{50} = 4.5$ mins

The time for 50% dissipation is therefore approximately twice as fast for the CPTU (10 cm^2) as it is for the DMT.

The slower rate of dissipation is probably related to the approximate 2-D shape of the flat dilatometer blade.

Marchetti et al. (1986) suggest the possibility of recording the DMT A-reading with time during a stop in penetration, and plotting the A-reading versus log time similar to a dissipation test. This type of test was performed using a standard DMT at a depth of about 20 m at the McDonald Farm Site, and the results are shown in Figure 10.

The contact pressure, A-reading, when corrected for membrane stiffness is the lift-off stress, P_o. The difference between the P_o and the penetration pore pressure (u) is the effective stress acting on the membrane, as shown in Figure 10. In soft clays the effective stress immediately after penetration ($\bar{\sigma}_{hi}$) is very low. As the excess pore pressures dissipate the effective stresses increase. Therefore, immediately after the stop in penetration the A-reading is slightly higher than the pore pressure (DMT-u). At the end of dissipation when all the excess pore pressures have dissipated the effective stress has increased ($\bar{\sigma}_{hc}$) and the difference between the A-reading and u_o is larger than at the beginning of dissipation.

Marchetti et al. (1986) suggested using this technique to estimate the effective stress acting on a driven displacement pile after consolidation ($\bar{\sigma}_{hc}$).

Since the closing pressure (P_2) closely represents the pore pressure on the DMT membrane (see Figures 6 and 7) it should be possible to record the C-reading with time and obtain a dissipation curve from a standard Marchetti DMT.

Figure 11 shows the results of repeated A, B and C-readings (P_o, P_1, P_2) obtained using a standard DMT at a depth of 22 m at the McDonald Farm site. For comparison the pore pressures recorded using the research DMT at a depth of 20 m are also shown in Figure 11. For the research DMT pore pressure dissipation no membrane expansion was performed. Figure 11 shows that the P_2 readings follow a very similar dissipation curve to that of the actual DMT pore pressures. Also interesting is the fact that the P_o value (A-reading) decreases in a different manner if the membrane is

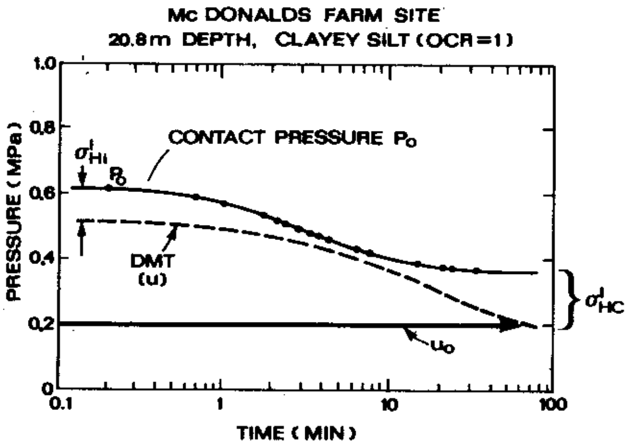


Fig.10 Repeated A-readings (corrected for membrane stiffness, P_o) using standard DMT compared with DMT pore pressure dissipation (McDonald Farm Site)

expanded to the full 1 mm deflection (i.e. B-reading). Whereas, in Figure 10, the P_o reading was performed with no expansion. This difference in response is probably related to the changes in effective and total stress around the membrane during dissipation. The increases in effective stresses are reflected in the progressive increase between P_o and P_1 as dissipation occurs (i.e. an apparent increase in I_D).

Because of the similarity between the dissipation curves of the DMT pore pressures and the C-readings, it should be possible to estimate the coefficient of consolidation, c_h, using a standard DMT and repeating the A, B and C-readings (P_o, P_1, P_2) with time. The resulting plot of P_2 versus log time should be similar to the dissipation of excess pore pressures around the dilatometer membrane. The final P_2 value after complete dissipation also represents a measure of the equilibrium pore pressure, u_o.

By comparing the shape of the DMT pore pressure dissipation curve, shown in Figure 9, with the theoretical curves for CPTU (Torstensson, 1977, cylindrical solution) it is possible to produce empirical dissipation curves for DMT data, as shown on Figure 12. The time factor, T, in Figure 12 is taken to be:

$$T = \frac{c_h \cdot t}{R^2} \qquad \ldots (1)$$

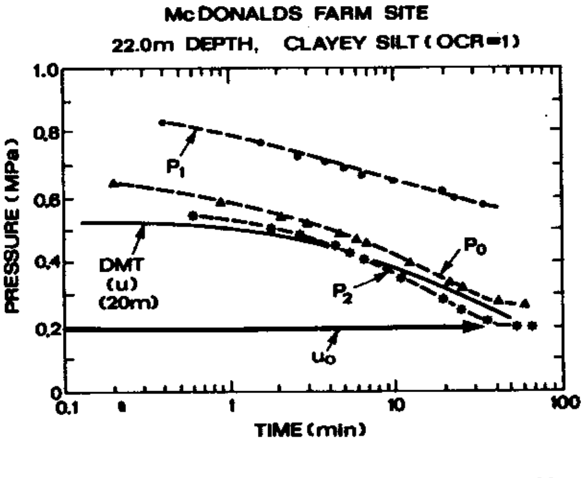


Fig.11 Repeated A, B and C-readings (corrected for membrane stiffness P_o, P_1, P_2) using standard DMT compared with DMT pore pressure dissipation (McDonald Farm site)

where:

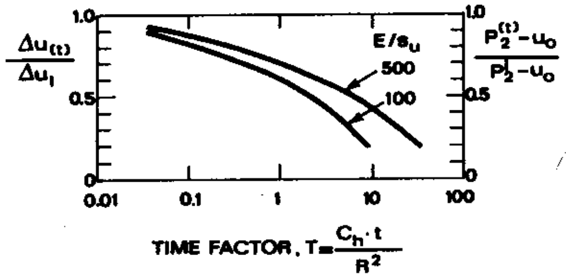
T - DMT time factor

t - time for percentage dissipation

R - equivalent radius of DMT blade. The equivalent radius for a standard DMT blade (14 mm by 95 mm) is 20.57 mm.

To estimate c_h using a standard DMT the procedure recommended would be as follows;

1. Stop penetration
2. Inflate and slowly deflate DMT membrane and record A, B,, and C-readings (P_o, P_1, P_2)
3. Repeat step 2. and monitor the time elapsed since the stop in penetration.
4. Plot P_2 (C-readings) versus log time
5. Check that the final P_2 values are approximately equal to u_o
6. Check that shape of dissipation plot (P_2 versus log time) is similar to that given in Figure 12.
7. Record the time for 50% dissipation (t_{50}).
8. Use equation (1) above to estimate c_h, use $T_{50} \approx 4$, and R - 20.57 mm.



u_o = EQUILIBRIUM PORE PRESSURE

$\Delta u_{(t)}$ = EXCESS PORE PRESSURE AT TIME t

Δu_i = INITIAL EXCESS PORE PRESSURE

R = EQUIVALENT RADIUS (20.57mm)

C_h = COEFFICIENT OF CONSOLIDATION

E = YOUNG'S MODULUS

s_u = UNDRAINED SHEAR STRENGTH

$P_2^{(t)}$ = P_2 VALUE AT TIME t

$P_2^{(i)}$ = INITIAL P_2 VALUE (t=0)

Fig.12 Tentative empirical Time Factors for Dissipation test using DMT

The proposed method given above is preliminary and requires further field verification. It is probable that the above approach is only valid for soft normally to lightly overconsolidated clays (i.e. $I_D \leq 0.6$ and $K_D \leq 5.0$).

The major advantages in using the DMT C-reading (P_2) approach to obtain dissipation data are:

- no problems related to saturation of porous elements, as in CPTU,
- P_2 values closely resemble pore pressure values, when $I_D \leq 0.6$ and $K_D \leq 5.0$.,
- P_2 values tend towards equilibrium pore pressure (u_o), therefore, providing important additional hydro-geologic data.

The observation that P_2 values tend towards the equilibrium pore pressure (u_o) as dissipation proceeds can be useful for dissipation tests in low permeability clays. Dissipation can be stopped when the P_2 values have decreased by 50% based on an estimate of u_o.

This can significantly improve the time required for DMT dissipation tests.

SUMMARY

Data has been presented comparing penetration pore pressures using the UBC research DMT, the NGI offshore DMT and CPTU.

Results show that in clean sands and soft clays the DMT penetration pore pressure is very similar to the pore pressures measured behind the friction sleeve of the CPTU.

The closing pressure (P_2) from a standard Marchetti DMT is very similar to the DMT penetration pore pressure for clean sands and soft clays. In clean sands no excess pore pressures are generated and the closing pressure represents a good approximation of the equilibrium piezometric pressure (u_o).

The dissipation of excess pore pressures during a stop in penetration is slower for the DMT than for the CPTU. Time for 50% dissipation for the DMT is approximately twice that of a 10 cm^2 cone.

If the DMT inflation is repeated at one depth in a soft clay the plot of P_2 versus log time is almost the same as the dissipation of the DMT pore pressures. A tentative procedure to estimate c_h from the repeated C-readings using a standard Marchetti DMT is proposed. However, this procedure is tentative and requires further field verification. The procedure, at present, is only recommended for tests in soft clays, where $I_D \leq 0.6$ and $K_D \leq 5.0$.

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REFERENCES

By, T., D. Gillespie, T. Lunne and R.G. Campanella (1987). "Comparison of UBC's Research Dilatometer, NGI's Offshore Dilatometer and Marchetti's Standard Dilatometer". The University of British Columbia and Norwegian Geotechnical Institute NGI, Report 52157.

Campanella, R.G., Robertson P.K., Gillespie D. and Greig J. (1985). "Recent Developments In-Situ Testing in Soils", Proceedings of XI ICSMFE San Francisco.

Campanella, R.G., Robertson P.K. and Gillespie D. (1983). "Cone Penetration Testing in Deltaic Soils", Canadian Geotechnical Journal, Vol.20, No.1.

Davidson, J.H. and Boghrat A.G. (1983). "Flat Dilatometer Testing in Florida", Proceedings of the International Symposium on Soil and Rock Investigation by In-Situ Testing, Paris, Vol.II.

Jamiolkowski, M., Ladd C.C, Germaine J.T. and Lancellotta R. (1985). "New Developments in Field and Laboratory Testing of Soils", State-of-the-Art Paper at 11th International Conference SMFE (ICSMFE), San Francisco.

Lunne, T., Eidsmoen T., Gillespie D. and Howland J.D. (1986). "Laboratory and Field Evaluation of Cone Penetrometers", Proceedings of In-Situ 86, Specialty Conference, ASCE, Blacksburg, Virginia.

Lunne, T., R. Johnsond, T. Eidsmoen and S. Lacasse (1987). "The Offshore Dilatometer". Paper submitted to the International Symposium on Offshore Engineering, Brazil Offshore 87. 24-28 August 1987, Rio de Janeiro.

Marchetti, S. (1980). "In-Situ Tests by Flat Dilatometer", ASCE Journal of Geotechnical Eng. Div., No.106, GT3.

Marchetti, S., Totani G., Campanella R.G., Robertson P.K. and Taddei B. (1986). "The DMT-σ_{hc} Method for Piles Driven in Clay", Proceedings on In-Situ 86, Specialty Conference, ASCE, Blacksburg, Virginia.

Torstensson, B.A., (1977). "The Pore Pressure Probe", Nordiske Geotekniske Møte, Oslo, Paper No.34.1-34.15.