Use and interpretation of a research dilatometer

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The flat dilatometer (DMT) test was introduced by Marchetti (1980) as a new *in situ* penetration test for soils. The equipment and test procedures are simple, and the test provides repeatable, nearly continuous data that has been empirically correlated to soil type, undrained shear strength (s_u), coefficient of earth pressure at rest (K_0), overconsolidation ratio (OCR), and constrained modulus (M). To better understand the measurements from the DMT, a research flat dilatometer was developed at the University of British Columbia (UBC). The research dilatometer is identical in size, shape, and operation to the Marchetti blade except that instrumentation was added which made passive measurements of pore pressure and deflection at the centre of the membrane, inflation pressure at the membrane, verticality of the blade, and penetration force immediately above the blade. Results from several well-documented sites near Vancouver, British Columbia, using the research DMT are presented and discussed. Results from the research DMT have provided useful insight into the test procedure and interpretation methods of the standard Marchetti DMT. Stress-deflection curves for the DMT are remarkably similar to both self-bored and full displacement pressuremeter test results. Alternate DMT procedures are proposed to estimate ϕ' of sands and coefficient of consolidation in clays. A procedure incorporating the closing pressure (P_2) using a standard Marchetti DMT is proposed and evaluated.

Key words: flat dilatometer test, *in situ*, research, cone penetration test, pore pressures.

Le dilatomètre plat (DMT) a été présenté par Marchetti (1980) comme un nouvel essai de pénétration *in situ* pour les sols. L'équipement et les procédures d'essais sont simples, et l'essai fournit des données quasi continues qui ont une bonne répétitivité et ont été corrélées avec le type de sol, la résistance au cisaillement (s_u), le coefficient de pression des terres au repos (K_0), le rapport de surconsolidation (OCR) et le module confiné (M). Afin de mieux comprendre les mesures obtenues avec le DMT, un dilatomètre plat de recherche a été développé à l'Université de Colombie-Britannique (UBC). Le dilatomètre de recherche est identique en dimension, forme et opération à la lame de Marchetti, sauf que l'on y a ajouté de l'instrumentation pour mesurer en butée la pression interstitielle et la déflexion au centre de la membrane, la pression de gonflement au niveau de la membrane, la verticalité de la lame, et la force de pénétration immédiatement au-dessus de la lame. L'on présente et discute des résultats obtenus avec le DMT de recherche sur plusieurs sites près de Vancouver, Colombie-Britannique, qui sont bien documentés. Les résultats obtenus avec le DMT de recherche ont fourni une perspective utile sur la procédure de l'essai et les méthodes d'interprétation du DMT standard de Marchetti. Les courbes contrainte-déformation du DMT sont remarquablement similaires aux résultats des essais de pressiomètre tant auto-forés que poussés. D'autres procédures sont proposées pour le DMT afin d'évaluer ϕ' des sables et le coefficient de consolidation dans les argiles. Une procédure comportant la pression de fermeture (P_2) obtenue avec le DMT standard de Marchetti est proposée et évaluée.

Mots clés : essai de dilatomètre plat, *in situ*, recherche, essai de pénétration au cône, pressions interstitielles.
[Traduit par la rédaction]

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Introduction

The flat dilatometer (DMT) test was first introduced into North America in 1980 (Marchetti 1980) and has become a simple, *in situ* test. The dilatometer is a flat blade 14 mm thick, 95 mm wide, and 220 mm long. A flexible stainless steel membrane 60 mm in diameter is located on one face of the blade. The membrane is usually inflated using high-pressure nitrogen gas supplied by a tube prethreaded through the pushrods. Beneath the membrane is a sensing device that turns a buzzer off in the control box when the membrane starts to lift off and on again after a deflection of 1 mm at the centre of the membrane. As the membrane is inflated, the pressure required to just lift the membrane off the sensing device (reading A) and to cause 1 mm deflection (reading B) are recorded. Readings are generally made every 200 mm in depth. Readings are made from a pressure gauge in the control box at the surface and entered on a standard data form.

The readings A and B are corrected for membrane stiffness and noted as P_0 and P_1, respectively.

Full details of the standard test procedures are given in ASTM (1986).

The main advantages of the DMT are (*i*) simplicity of operation and maintenance, (*ii*) repeatable test results that are operator independent, and (*iii*) near-continuous data. The main limitations of the test are (*i*) blade and membrane are susceptible to damage, especially when penetrating dense sands or gravelly soils; (*ii*) large pushing force required to penetrate dense soils; (*iii*) no pore-pressure measurements; and (*iv*) limited evaluated experience relative to more well-established *in situ* tests, such as the cone penetration test (CPT).

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Recent changes in the steel used for the blades and membranes have improved the durability of the equipment.

The interpretation of the DMT data is based predominantly on empirical correlations related to three index parameters, namely the material index

$$[1]\quad I_D = \frac{P_1 - P_0}{P_0 - u_0}$$

the horizontal-stress index

$$[2]\quad K_D = \frac{P_0 - u_0}{\sigma'_{vo}}$$

and the dilatometer modulus

$$[3]\quad E_D = 34.7\,(P_1 - P_0)$$

where u_0 = equilibrium pore pressure, often assumed to be hydrostatic, and σ'_{vo} = *in situ* vertical effective stress.

Marchetti (1980) proposed a set of empirical correlations between the above index parameters and soil type, soil unit weight, coefficient of earth pressure at rest (K_0), overconsolidation ratio (OCR), constrained modulus (M), undrained shear strength (s_u), and friction angle (ϕ'). These initial correlations were based on laboratory data from 10 well-documented sites in Italy.

Recently, many studies have been performed to evaluate and improve some of the original correlations (Jamiolkowski *et al.* 1985, 1988; Baldi *et al.* 1986; Schmertmann 1982, 1986; Marchetti 1985; Lacasse and Lunne 1988; Lutenegger 1988). Many of the improvements and new correlations have been related to DMT data in sands, since the original correlations by Marchetti (1980) were based mainly on clay sites.

In general, experience has shown that the DMT correlations often provide a good indication of soil type and reasonable values of s_u, K_0, and OCR for soft to medium, uncemented, insensitive clays (Jamiolkowski *et al.* 1985; Lutenegger 1988). Good experience has also been reported for evaluating ϕ' and K_0 in silica sands when the dilatometer penetration thrust is recorded (Schmertmann 1982; Baldi *et al.* 1986).

Although the flat dilatometer is simple to operate and maintain, the test data are often difficult to conceptually understand. To obtain a more fundamental understanding of the test data and the soil behaviour during penetration and membrane expansion, a research dilatometer was developed. This paper describes the research dilatometer and presents and discusses typical data in clean sands and soft and stiff clays. The DMT data are also compared with CPT data.

Development of research dilatometer

The research dilatometer developed at the University of British Columbia (UBC) was identical in size, shape, and operation to the Marchetti blade except for the following passive measurements: (*i*) pore-water pressure at the centre of moving membrane, (*ii*) deflection at centre of membrane, (*iii*) gas pressure at the blade to activate membrane expansion, (*iv*) verticality of dilatometer blade during penetration, and (*v*) penetration force immedicately above the blade. The penetration force was measured with a load cell located on the pushrods immediately above the flat blade. A separate load cell was also used to measure the total penetration force at the ground surface. The purpose of developing the research dilatometer was not to replace the Marchetti device but to provide additional information to better understand the basic data from the standard device.

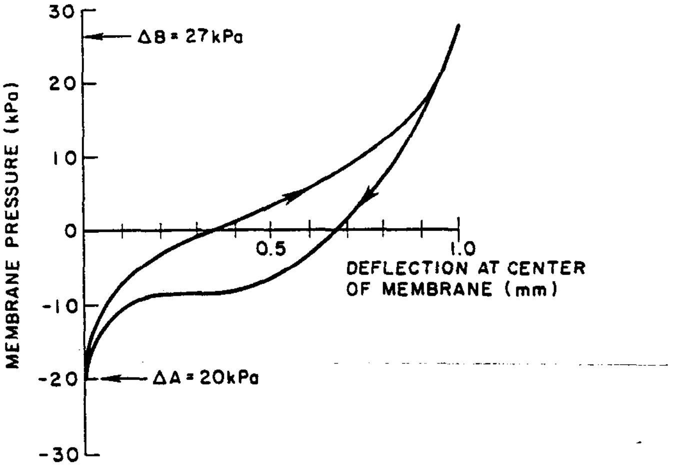

FIG. 1. Typical DMT membrane calibration in air.

In addition to the electronic measuring devices, Marchetti's standard measuring system was retained so that a direct comparison could be made between the research dilatometer data and the standard DMT data.

The research dilatometer was pushed into the ground using the UBC *in situ* testing research vehicle at a standard rate of penetration of 20 mm/s. A complete description of the research vehicle and electronic system is given by Campanella and Robertson (1981).

The testing procedure was identical to that used for Marchetti's standard DMT. In addition, two chart recorders were used to record the data from the electronic sensors. During penetration the blade inclination, pore-water pressure, and penetration force measured behind the blade and at the ground surface were recorded on a strip-chart recorder that was controlled by a depth encoder. The chart recorder could also operate in a time mode to monitor pore-pressure dissipations during a stop in penetration.

The gas pressure inside the blade, pore pressure at the centre of membrane, and deflection at the centre of the membrane were recorded on an X–Y–Y' recorder during each membrane inflation and deflation phase. The Y-axis of the recorder was the membrane deflection.

The gas pressures were corrected for membrane stiffness using a calibration curve recorded for membrane expansion in air.

The membrane was expanded and deflated at least 20 times to produce a consistent calibration curve. Figure 1 shows a typical calibration curve for the research dilatometer membrane which clearly shows that the calibration curve is highly nonlinear and hysteretic.

During penetration in stiff soils or below the water table the membrane is generally pushed to the fully closed position, with the inside membrane pressure vented to the atmosphere.

Field testing

A field-testing programme using the research dilatometer was conducted at several sites near Vancouver, British Columbia, during October 1983 to July 1984.

Results from two of the main sites are presented here. Results from other sites are presented by Robertson *et al.* (1988) and Tsang (1987).

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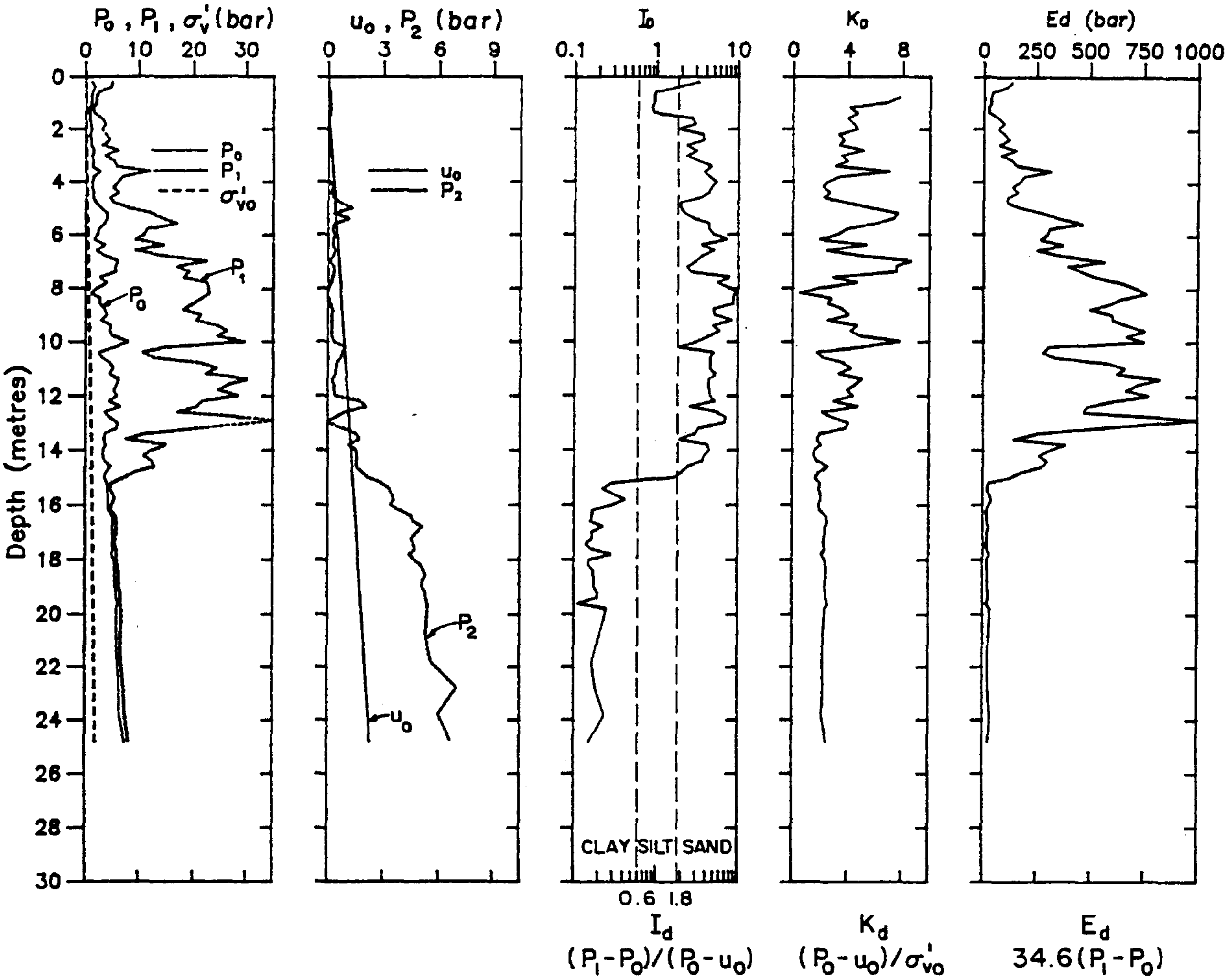

FIG. 2. DMT profile at McDonald's Farm, Vancouver International Airport, B.C. (1 bar = 100 kPa).

McDonald's Farm site

McDonald's Farm is an abandoned farm at the northern edge of Sea Island at the Vancouver International Airport. Sea Island is located between the North Arm and Middle Arm of the Fraser River and is contained by a system of dykes to prevent flooding. The site is approximately level. The mean groundwater level at the site is about 1.5 m below ground surface and varies with the tidal fluctuations of the adjacent Fraser River.

The soil conditions at McDonald's Farm consist of about 2 m of soft organic silty clay underlain by about 13 m of medium to coarse sand. The sand is variable in density, with occasional seams of silt. Underlying the sand is a deep deposit of approximately normally consolidated clayey silt. The clayey silt deposit extends to a depth of about 150 m in this part of Sea Island (Blunden 1975).

A summary of the standard DMT data including the calculated index parameters is presented in Fig. 2. The DMT results clearly identify the basic soil profile. Also shown in Fig. 2 is a profile of the equilibrium water pressure (u_0) and the DMT closing pressure (P_2). More details concerning P_2 are given later in the paper.

232nd Street site

This site is located at the interchange at the Trans-Canada Highway and 232nd Street in Langley, British Columbia. The site consists of an upper and a lower part. The upper site is located at an elevation about 4.8 m above the lower site and is situated on a compacted clay fill that forms part of the approach to the 232nd Street overpass.

The site lies at the western extent of the Fort Langley Formation which consists of interbedded marine, glaciomarine, and glacial sediments. The soil conditions at the lower site consist of a deep deposit of silty clay extending to a depth of at least 20 m. The upper 10 m is overconsolidated due predominantly to desiccation, with the OCR decreasing with depth. Below a depth of about 10 m the deposit is approximately normally consolidated to lightly overconsolidated. The upper 2 m of the deposit is slightly organic. Between a depth of 12.5 and 16 m there are occasional sand lenses. The average plasticity index and natural water contents of the deposit are approximately 19 and 45%, respectively. The sensitivity of the deposit determined with a field vane test varied from 2 to 10 within the upper 5 m and increased to between 10 and 19 below 5 m.

A summary of the standard DMT data at the lower 232nd Street site is presented in Fig. 3. The DMT results clearly indicate a clay deposit to a depth of 20 m.

The soil conditions at the upper site consist of a maxi-

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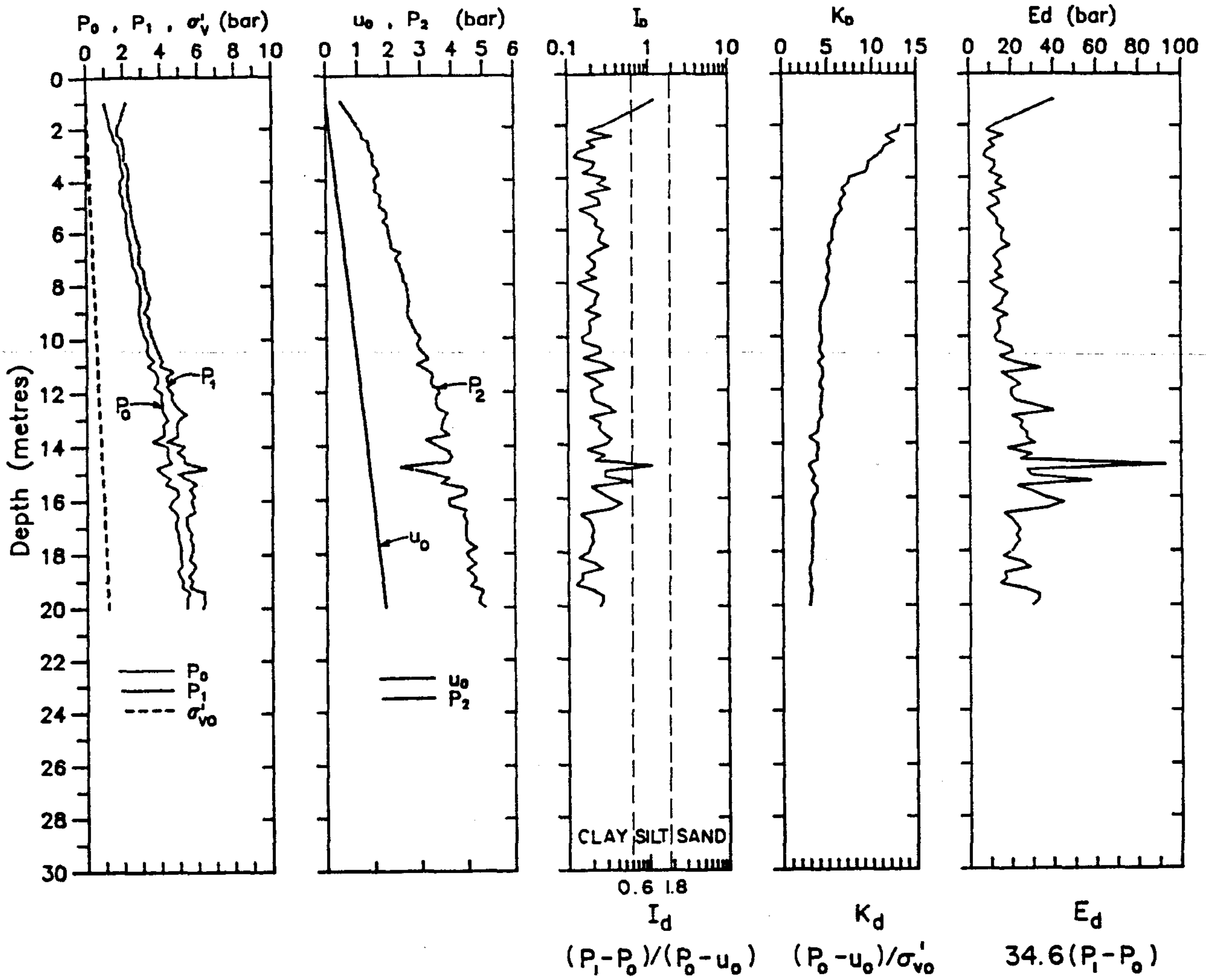

FIG. 3. DMT profile at lower 232nd Street site, Langley, B.C. (1 bar = 100 kPa).

mum of 5 m of a compacted clay fill underlain by the same silty clay deposit existing at the lower site. The OCR of the underlying silty clay deposit decreases with depth in a similar manner to that at the lower site. The apparent OCR in the clay fill is generally greater than about 10. The sensitivity of the clay fill is generally less than 7, whereas the sensitivity of the underlying silty clay increases with depth to about 19.

A summary of the standard DMT data at the upper 232nd Street site to a depth of 8 m is presented in Fig. 4. In this case the DMT results predict that the soil to a depth of 5 m is a compact silt.

Full details of both sites are given by Greig *et al.* (1988).

Results in sand

For penetration fo the research dilatometer through the sand at the McDonald Farm site, from a depth of about 3 to 15 m, no excess pore pressures were recorded and penetration pore pressures were approximately hydrostatic.

Typical research dilatometer membrane expansion and deflation curves corrected for membrane stiffness for dense and loose sand at McDonald's Farm are shown in Fig. 5.

The main points observed from the test results shown in Fig. 5 are as follows: (*i*) no excess pore pressures were generated, indicating drained tests; (*ii*) pressure-deflection curves are similar in shape to self-boring (SBPMT) and full-displacement pressuremeter (FDPMT) curves; (*iii*) slope of expansion from P_0 to P_1 is flatter than slope of small unload-reload loops, suggesting that the DMT curve represents a primary or virgin loading path and not a reloading path; and (*iv*) closing pressure, P_2, after deflation is approximately equal to equilibrium pore pressure, u_0. The fact that no excess pore pressures are recorded shows that the tests are performed under drained conditions and that the recorded total pressures P_0 and P_1 are controlled by the large effective stresses.

Similarities with pressuremeter

To illustrate the similarity of the DMT pressure-deflection curves with those from pressuremeter tests, the DMT results are compared with self-boring and full-displacement pressuremeter curves in Fig. 6. To facilitate the comparison the deflection axis of the DMT's has been converted to an equivalent strain, assuming the following: (*i*) cavity strain = $\Delta R/R_0 \times 100$ (%); (*ii*) for DMT, ΔR = displacement (δ) at centre of membrane and R_0 = 7 mm (half width); and (*iii*) for FDPT and SBPT, ΔR = displacement for average of three strain arms at centre of membrane and R_0 = 33 mm. These assumptions are approximate at

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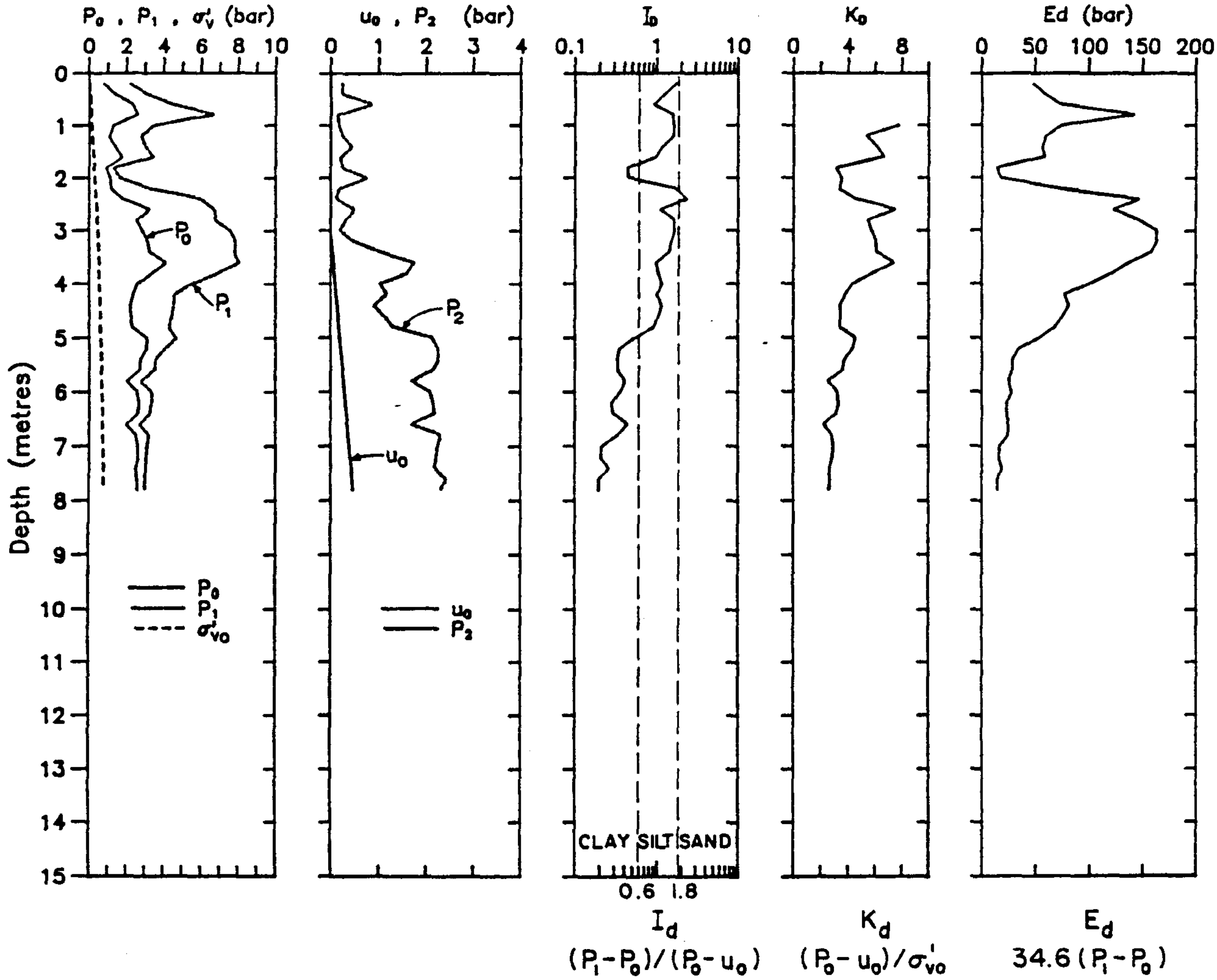

FIG. 4. DMT profile at upper 232nd Street site, Langley, B.C. (1 bar = 100 kPa).

best but do allow a comparison. Figure 6 shows the DMT expansion curves compared with expansion curves from both self-bored and full-displacement pressuremeter curves obtained from nearby soundings at McDonald's Farm. Full details of the pressuremeter testing were given by Robertson (1983) and Hughes and Robertson (1985). The agreement between the shapes of the DMT curves and those from the pressuremeters is remarkably good.

Figure 6 also indicates that the 1 mm total expansion of the dilatometer membrane is quite significant and can represent 14% equivalent cavity strain for pressuremeter expansion. A cavity strain of 10% is a typical maximum expansion for many self-boring pressuremeters.

Recent research with full-displacement pressuremeters (FDPMT) (Hughes and Robertson 1985; Withers *et al.* 1989) has shown that, after penetration in a full-displacement manner, cavity strains greater than about 50% may be needed before the dominant influence of the disturbed sand adjacent to the probe can be overcome. Therefore, although Fig. 6 indicates that strains are quite large around the expanding membrane of a dilatometer, the expansion is probably still dominated by the disturbed sand due to blade penetration.

Figure 6 also shows a remarkable agreement between the slopes of the small unload-reload loops for all three types of tests. Hughes and Robertson (1985) showed that the shear moduli obtained from small unload-reload loops from pressuremeters (G_{UR}) were almost independent of disturbance and that the measured G_{UR} represents the "elastic" response of the sand below the yield surface. The slope of the main pressuremeter expansion curve represents some "elastic-plastic" response of the sand on the current yield locus. Therefore, the slope of the DMT expansion curve from P_0 to P_1 (i.e., E_D) also represents a measure of the "elastic-plastic" response of the sand.

Recent calibration-chamber studies (Jamiolkowski *et al.* 1988) have shown the following relationships for a clean silica (Ticino) sand:

$$[4] \quad \frac{E'}{E_D} = 1.05 + 0.25, \text{ normally consolidated}$$

and

$$[5] \quad \frac{E'}{E_D} = 3.66 + 0.80, \text{ overconsolidated}$$

$$(1.5 < \text{OCR} < 8.5)$$

where E' = Young's Modulus defined at 0.1% axial strain in K_0 consolidated drained compression triaxial tests performed at the same K_0 condition as the calibration chamber. The ratio E'/E_D decreases with increasing density for overconsolidated (OC) sands.

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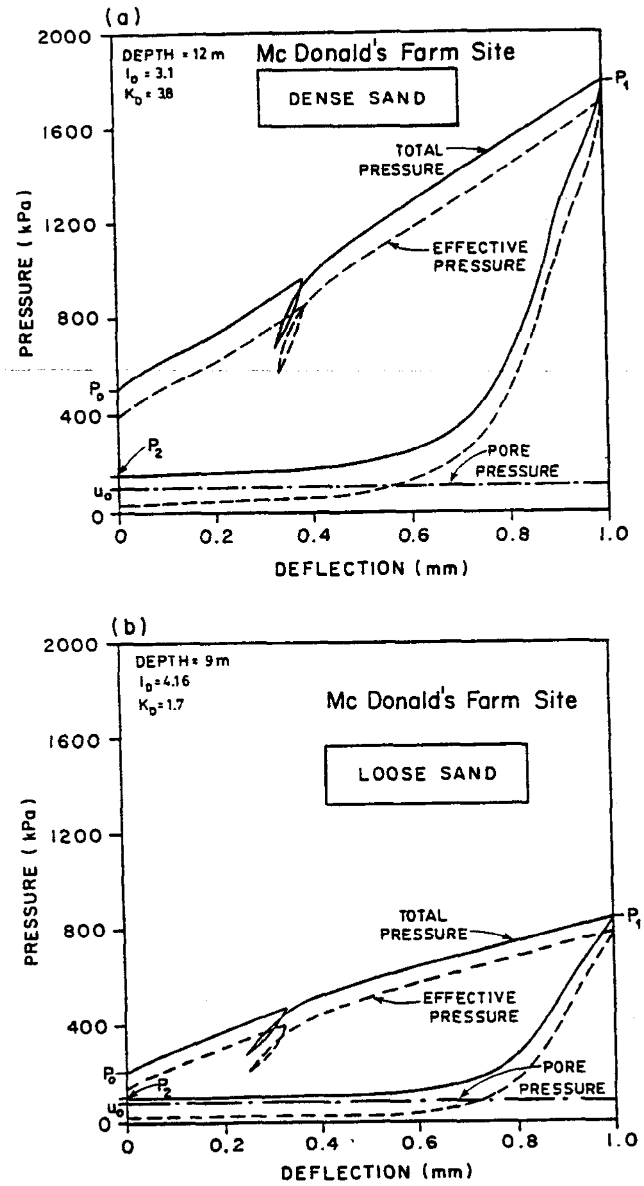

FIG. 5. Typical results from research DMT (*a*) dense and (*b*) loose sand (McDonald's Farm site).

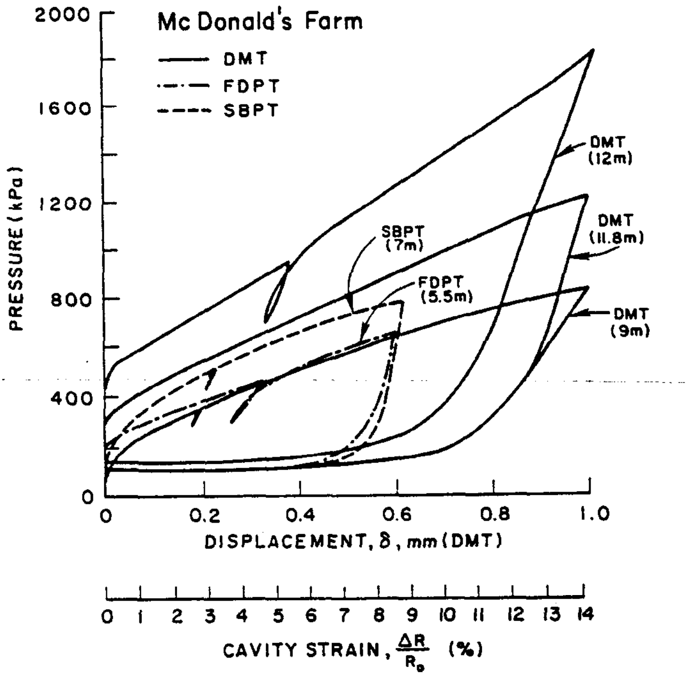

FIG. 6. Comparison of research DMT and pressuremeter test results in sand (McDonald's Farm).

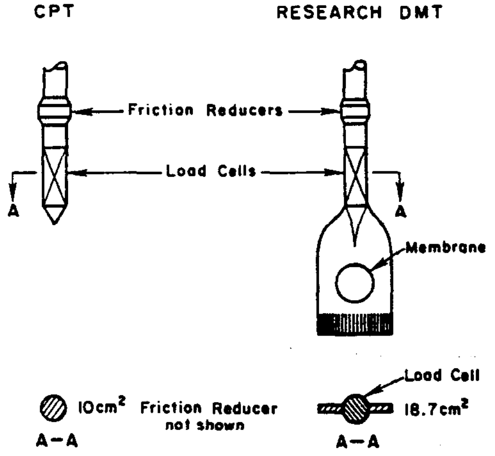

FIG. 7. Schematic of load cell location for CPT and research DMT.

The apparent good agreement between E' and E_D for normally consolidated (NC) Ticino sand may be due to the following: (*i*) E_D is an elastic–plastic response that would be expected to be softer than E'; and (*ii*) E_D is measured at a stress level significantly higher than the mean stress level existing before penetration and membrane expansion which would cause E_D to be much stiffer than E'.

These two factors probably compensate to make E_D approximately equal to E' for normally consolidated sands. However, since the modulus E' at 0.1% strain is generally much larger for overconsolidated sands, the effect of the increased stress level during the DMT may not be sufficient to fully compensate.

It has been recognized for some time that for pressuremeter tests in clean sands the membrane closes back to its original position at approximately the equilibrium water pressure (u_0). Therefore, it is not surprising that the dilatometer membrane also closes at u_0 when testing in clean sands. As the membrane deflates the sand arches and the membrane is closed under the pressure of the water. Clean sands are usually identified from standard DMT data when the material index (I_D) is greater than about 2.0. More discussion about the closing pressure (P_2) is given later in the paper.

Penetration force

The penetration force was measured using a load cell located on the pushrods immediately above the flat blade, as shown schematically in Fig. 7. A friction reducer was located just above the load cell.

Figure 8 compares the penetration force measured at the ground surface with that measured behind the blade for penetration to a depth of 20 m at the McDonald Farm site. The results in Fig. 8 show that, when verticality is maintained, there is little rod friction developed for penetration in sand. If the blade is deflected, the friction developed along

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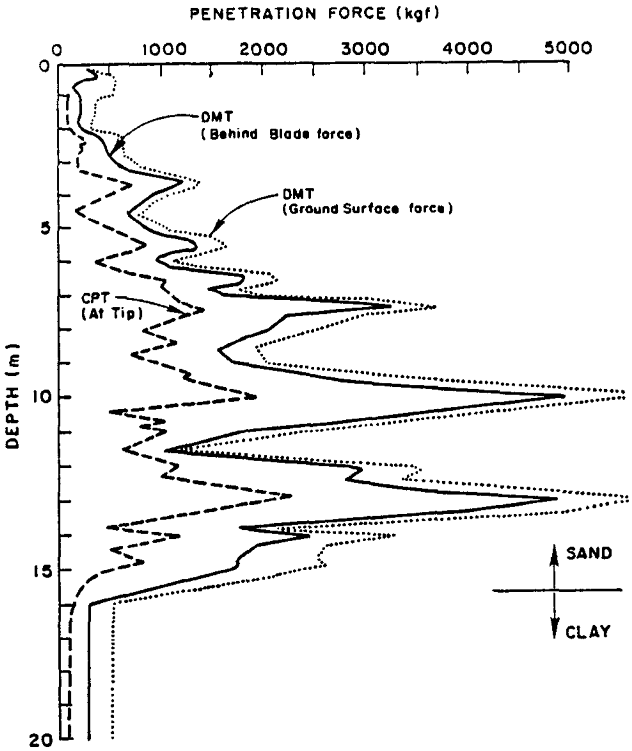

FIG. 8. Comparison of DMT and CPT penetration forces at McDonald's Farm.

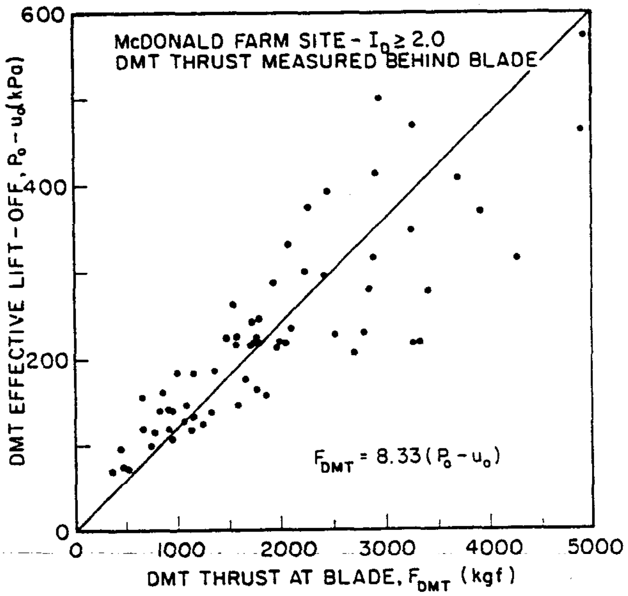

FIG. 9. Relationship between lift-off and penetration thrust at the DMT blade in sand ($I_D > 2$) at McDonald's Farm site.

the deflected pushrods can become very large and can eventually restrict penetration.

Also included in Fig. 8 is the penetration force measured at the tip (see Fig. 7) of a 10 cm^2 cone penetrometer. Figure 8 clearly shows that for penetration in both sand and clay the dilatometer blade requires approximately twice the total surface penetration force of a standard 10 cm^2 cone penetrometer. This can severely limit the penetration capacity for the dilatometer when using light penetration equipment.

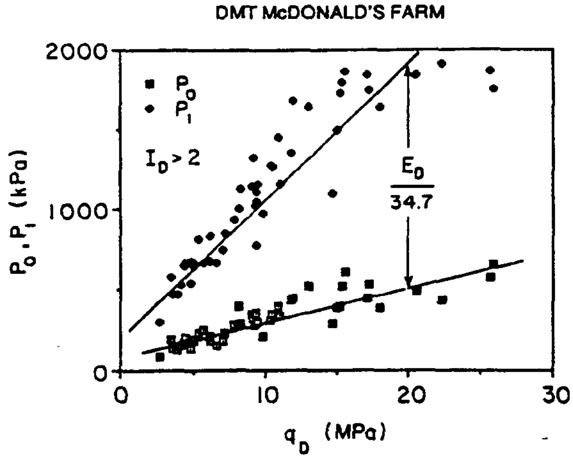

FIG. 10. Comparison between P_0 and P_1 and penetration resistance, q_D, for DMT in sand at McDonald's Farm.

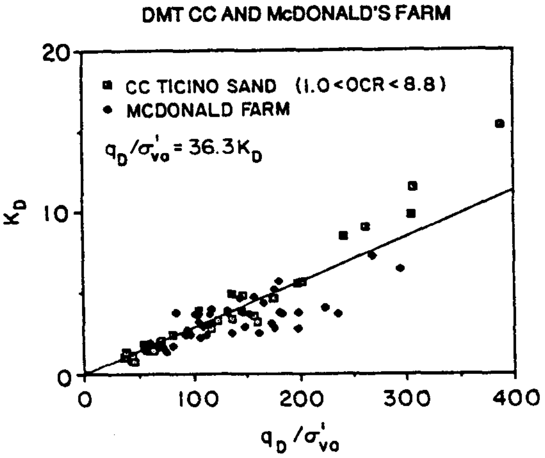

FIG. 11. Relationship between DMT K_D and normalized DMT penetration resistance for calibration chamber (Ticino) and McDonald's Farm sand.

It is interesting to note that the total exposed end area of a flat dilatometer blade penetrating with 10 cm^2 pushrods (see Fig. 7) is about 18.7 cm^2. Therefore, it is not surprising that the total force required for penetration of the dilatometer is approximately twice that required for a 10 cm^2 cone.

Using the penetration force measured just behind the dilatometer blade and an exposed end area of 18.7 cm^2 it is possible to calculate a dilatometer penetration resistance, q_D. This penetration resistance represents a summation of the forces on the base of the blade and on the exposed area of the pushrods at the neck of the blade plus the friction developed along the two faces of the blade.

Based on the DMT and CPT data obtained at McDonald's Farm for penetration in the clean sand ($I_D > 2$), the following approximate relationship between the penetration resistances was observed:

$$[6] \quad q_D = 1.1\, q_c$$

where q_D = DMT penetration stress (DMT thrust / 18.7 cm^2) and q_c = cone penetration stress (cone thrust / 10.0 cm^2). This difference is likely due to the frictional stress on the sides of the DMT in front of the load cell. The cone only measures bearing capacity, whereas the DMT-

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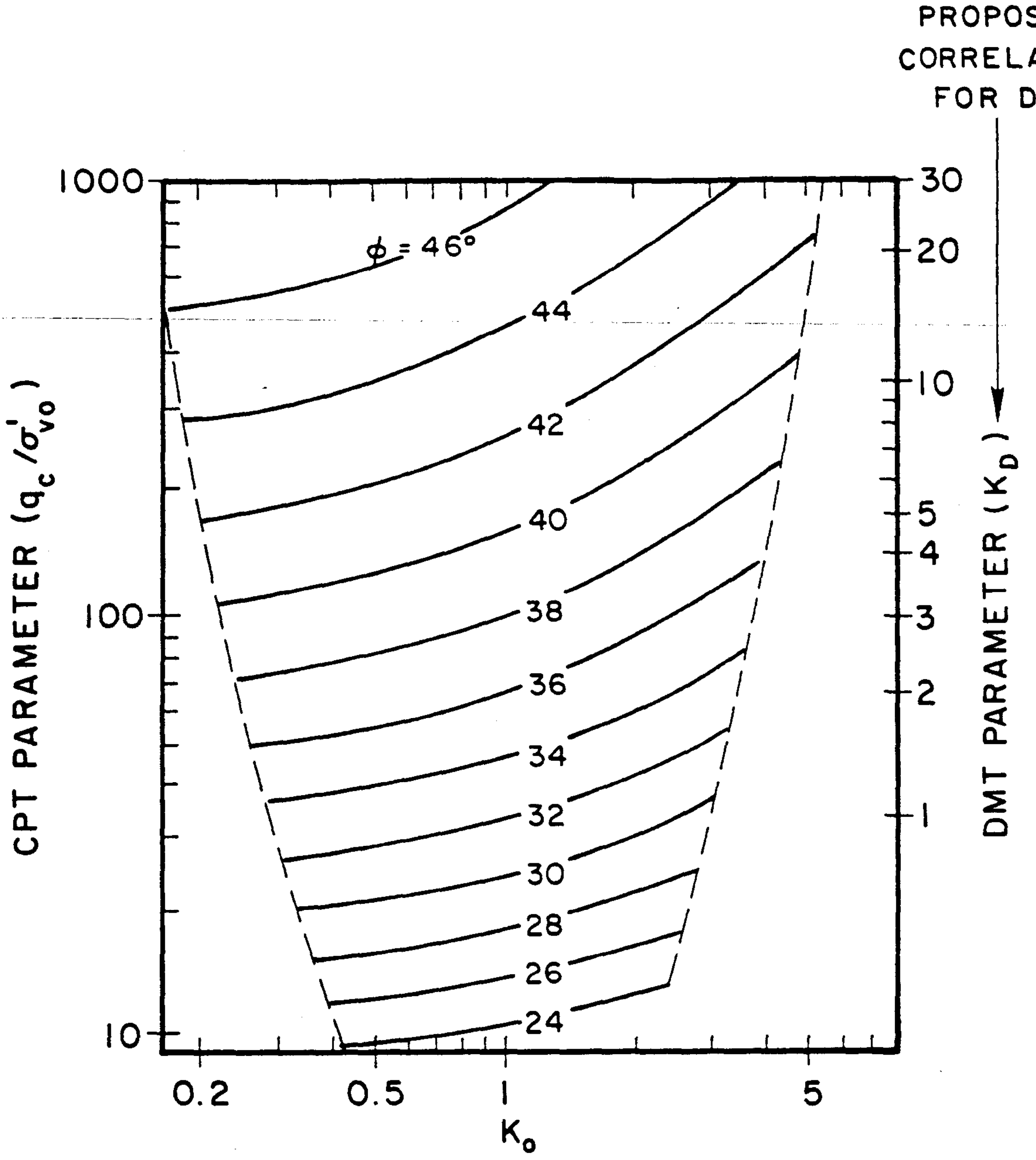

FIG. 12. Proposed chart for predicting peak friction angle, σ', from DMT as well as CPT for uncemented, unaged, silica sand using Durgunoglu and Mitchell (1975) bearing capacity theory (adapted from Marchetti 1985). Assumed cone roughness $\delta/\phi = 0.5$.

measured bearing resistance includes friction and is therefore larger by about 10%.

Schmertmann (1982) suggested a method to evaluate the friction angle of sand (ϕ') using the thrust, usually measured at the ground surface, required to push the flat dilatometer blade. This method is based on the bearing-capacity theory of Durgunoglu and Mitchell (1975). To calculate ϕ', Schmertmann (1982) proposed a series of assumptions to correct the measured thrust at the ground surface to an equivalent bearing stress (q_D) on the tip of the blade. The major assumption is that friction on the pushrods above a small friction reducer could be neglected. Figure 8 shows that this assumption is reasonable for penetration in sand provided verticality is maintained.

Recent research (Wroth 1988; Jamiolkowski and Robertson 1988) using large calibration chambers has shown that there appears to exist a direct relationship between the penetration thrust and the lift-off stress, P_0, for dilatometer testing in clean silica sand. To evaluate this for a natural sand *in situ*, Fig. 9 shows a plot of DMT lift-off stress, $P_0 - u_0$, versus the DMT penetration thrust measured behind the blade in sand at the McDonald's Farm site. It can be seen that in general there is a linear relationship between $P_0 - u_0$ and thrust, suggesting that it is not necessary to measure the force at the surface and subtract the "estimated" rod and blade friction to estimate ϕ' in sands. Instead, the thrust can be directly estimated from P_0 measurements to estimate ϕ'. The *in situ* water pressure, u_0, has been subtracted from P_0 to allow for DMT data obtained over water.

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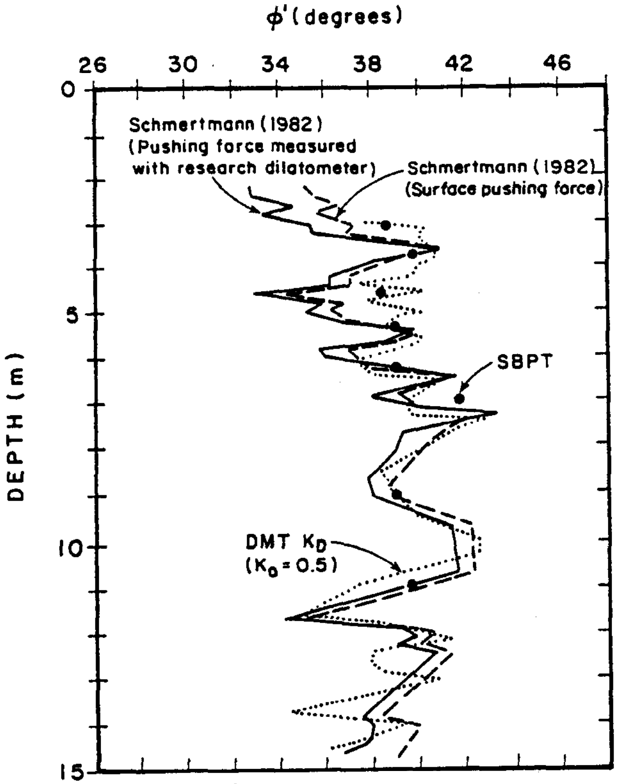

FIG. 13. Comparison of friction angles estimated from DMT results and compared with self-boring pressuremeter (SBPMT).

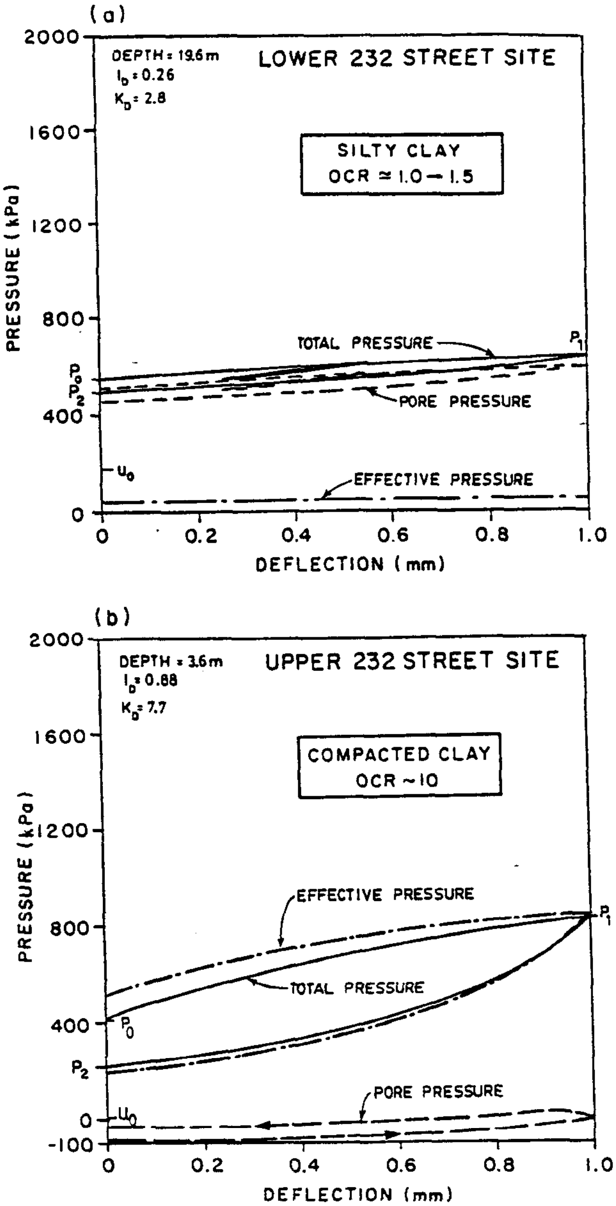

FIG. 14. Typical results from research DMT in (*a*) silty and (*b*) compacted clay (232nd Street site).

Modulus determination

Figure 10 presents the dilatometer data in sand ($I_D > 2$) at McDonald's Farm, where P_0 and P_1 are plotted against the measured DMT penetration resistance, q_D. As shown in Fig. 10, the difference is equal to $E_D/34.7$ ([3]), and according to these results the dilatometer modulus, E_D, can be directly related to DMT penetration resistance as

$$[7] \quad E_D = 2.39\, q_D$$

The average data in Fig. 10 cover a depth from 2 to 15 m, where modulus, E_D, increases linearly with increasing penetration resistance, which also increases approximately linearly with depth.

Converting the DMT penetration resistance to an equivalent CPT penetration resistance from [6] gives

$$[8] \quad E_D = 2.63\, q_c$$

Equation [8] is remarkably similar to that proposed by Schmertmann (1970) for estimating modulus in sand from the CPT. Thus, for the normally consolidated clean sand at McDonald's Farm, drained CPT results give essentially the same indication of modulus as the DMT except that the DMT provides a somewhat more direct measure for a 1 mm expansion, whereas the cone uses an average correlation factor over the soil depth.

Estimating ϕ' in sands

The horizontal-stress index, K_D, is a normalization of P_0 (see [2]) with respect to vertical effective stress. Since $P_0 - u_0$ is directly related to penetration resistance, then K_D is directly proportional to q_D/σ'_{vo}. Figure 11 shows a plot of K_D versus q_D/σ'_{vo} for both the calibration-chamber (cc) Ticino sand data (Baldi *et al.*, in preparation) and the McDonald's Farm sand, which have a similar mineralogy and compressibility. The results in Fig. 11 clearly show an average relationship of

$$[9] \quad q_D/\sigma'_{vo} = 36.3\, K_D$$

which when combined with [6] yields

$$q_c/\sigma'_{vo} = 33\, K_D$$

Experience with the CPT has shown that good estimates of ϕ' can be made for silica sands using the ratio q_c/σ'_{vo}. Hence, it should be possible to estimate ϕ' directly from DMT K_D values.

Figure 12 shows a chart that when first presented by Marchetti (1985) predicted the peak triaxial friction angle (ϕ') for uncemented silica sands from CPT using the method proposed by Durgunoglu and Mitchell (1975). Also included in Fig. 12 is the proposed K_D correlation for DMT given in [10].

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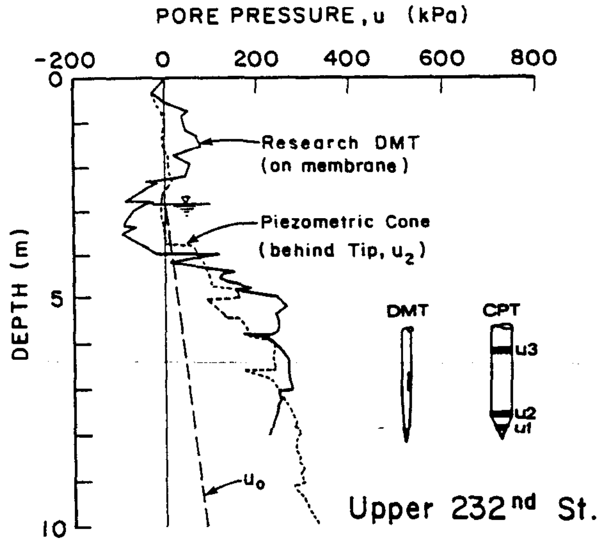

FIG. 15. Penetration pore pressures in overconsolidated clay at upper 232nd Street site.

To evaluate the usefulness of the proposed K_D correlation, a comparison between the calculated friction angles using the method suggested by Schmertmann (1982), with either the surface thrust or the force measured just behind the blade, and using the proposed K_D correlation is shown in Fig. 13. The ϕ' values shown in Fig. 13 using the proposed direct correlation with K_D (Fig. 12) were obtained assuming $K_0 = 0.5$. A review of Fig. 12 shows that it is acceptable to estimate K_0, since there is only a 1° difference in the estimated ϕ' for a variation in K_0 from 0.5 to 1.0.

Figure 13 shows that at the McDonald Farm site the direct correlation using K_D produces ϕ' values similar to those by the Schmertmann (1982) method. Since both are related to penetration stresses, the agreement was to be expected. However, since K_D is directly determined by the DMT, this method is preferred and may be directly coupled to the DMT estimates of K_0, which was not addressed in this study.

Also included in Fig. 13 are friction angle values determined from adjacent self-bored pressuremeter tests (SBPMT), using the method of Robertson and Hughes (1986), which also agree with the other methods. Interpretation of adjacent CPT soundings indicates average ϕ' values varying from about 38 to 40°, which are also in general agreement with the DMT and SBPMT ϕ' values.

Results in clay

Typical DMT pressure–expansion curves were obtained with the research dilatometer for a soft clay (OCR $\approx$ 1.0) and a stiff clay (OCR $\approx$ 10) and are shown in Figs. 14*a* and 14*b*, respectively.

The soft clay example (Fig. 14*a*) is from the lower 232nd Street site where the OCR is approximately 1.0. Test results from the soft clayey silt at the McDonald Farm site were very similar. The research DMT tests in the soft clay deposits ($I_D \le 0.6$; $K_D \le 5.0$) all show the following: (*i*) pore pressures on the membrane during and immediately after penetration are very high; [ii] effective stresses on the membrane are very small and remain almost constant during the expansion and deflation phase of the test; (*iii*) the measured total stresses (P_0 and P_1) are strongly controlled by the high penetration pore pressures; and (*iv*) the measured closing pressure is similar to the *penetration* pore pressure. The high pore pressures generated during penetration are consistent with the high pore pressures recorded during cone penetration (CPTU). This point will be discussed in more detail later.

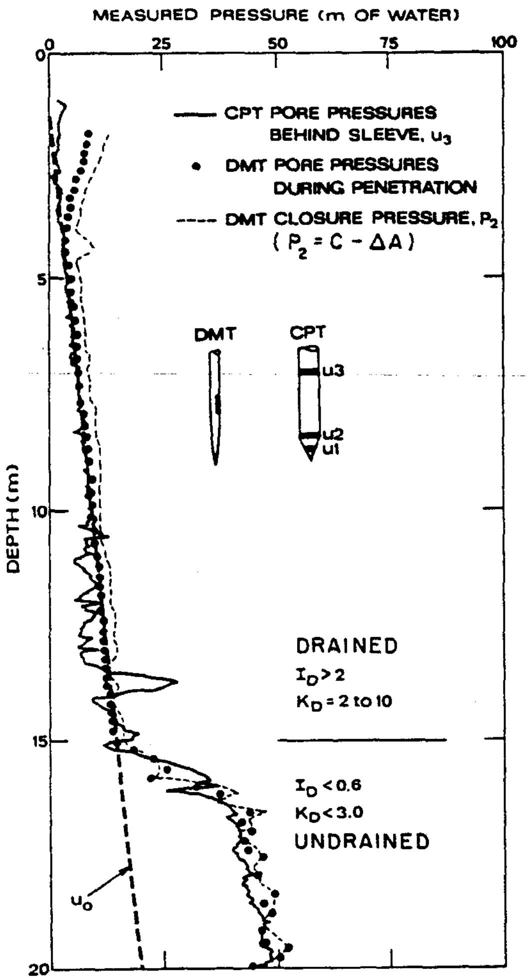

FIG. 16. Comparison between penetration pore pressures and DMT closing pressures (C-reading) at McDonald's Farm (after Robertson *et al.* 1988).

It is interesting to note that the effective stresses are very small and are essentially unchanged during the membrane expansion. The applied total stress increment ($P_1 - P_0$) during membrane expansion is equally matched by a rise in pore pressure. This response is consistent with a cavity expansion in an elastic perfectly plastic material when the material adjacent to the expanding membrane is at failure; any increase in cavity pressure causes an equal increase in pore pressure on the membrane, and the effective stress remains essentially unchanged. This implies that the clay adjacent to the flat dilatometer membrane is at failure due to the penetration process and that subsequent membrane expansion causes only an increase in pore pressure equal to the applied membrane-pressure increment ($P_1 - P_0$).

It is also interesting to note that when the membrane closes the total stress is approximately equal to the penetration pore pressure existing before membrane expansion. Therefore, it is possible to estimate the penetration pore pressure in soft clay from a standard dilatometer by recording the closing

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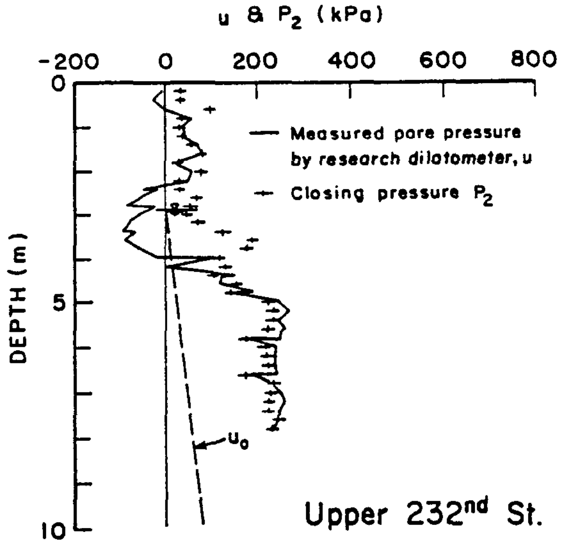

FIG. 17. Comparison of closing pressure and penetration pore pressure of DMT in overconsolidated clay at upper 232nd Street site.

pressure. Schmertmann (1988) has suggested that the closure pressure from a standard dilatometer test be called P_2. Also, the difference between the lift-off and closure stresses ($P_0 - P_2$) represents an estimate of the effective stress on the membrane, at least for tests in soft clay ($I_D \leq 0.6$; $K_D \leq 5.0$).

The stiff clay data shown in Fig. 14*b* were obtained from the compacted clay fill at the upper 232nd Street site. The research DMT data in the stiff, compacted, high-OCR clay deposit ($K_D > 5.0$; $I_D < 2.0$) show the following: (*i*) pore pressure on the membrane during and immediately after penetration are very small and mostly negative; (*ii*) effective stresses on the membrane are large and change in a similar manner to, but usually larger than, the applied total stresses; (*iii*) the closure pressure (P_2) appears to be unrelated to either the penetration or the equilibrium pore pressures; and (*iv*) the pressure-expansion curve from P_0 to P_1 is nonlinear. Comparing the two plots in Fig. 14 shows that for a DMT in fine-grained soils the pore pressures generated during penetration have a significant influence on the subsequent membrane expansion.

Pore pressures

Robertson *et al.* (1988) compared the penetration pore pressures from the research DMT with those recorded at three locations on a 10 cm^2 cone and showed that (*i*) DMT penetration pore pressures are very similar to penetration pore pressures measured behind the friction sleeve in the CPTU; (*i*) in clean sand no excess pore pressures are generated during DMT and CPTU penetration; and (*iii*) in soft clay large excess pore pressures are generated during penetration for both the DMT and CPTU. A similar comparison between DMT and CPTU penetration pore pressures in soft clays has been reported by Lutenegger (1988).

Figure 15 shows the penetration pore pressures measured from the research DMT and a CPTU at the upper 232nd Street site. Figure 15 shows the following: (*i*) in the saturated, stiff, compacted clay fill ($K_D > 5.0$) from 2.5 to 4.0 m, both DMT and CPTU penetration pore pressures are negative; and (*ii*) for both the DMT and CPTU, penetration pore pressures rapidly jump to large positive values when penetrating the underlying softer clay, where $K_D < 5.0$. Figure 15 clearly shows that in stiff saturated clays, where $K_D \geq 5.0$, the DMT and CPTU penetration pore pressures have a similar trend and can be negative. This indicates that a stress reduction occurs as the soil elements pass behind the tip of the dilatometer blade in a similar manner to that postulated for cone penetration (Robertson *et al.* 1986).

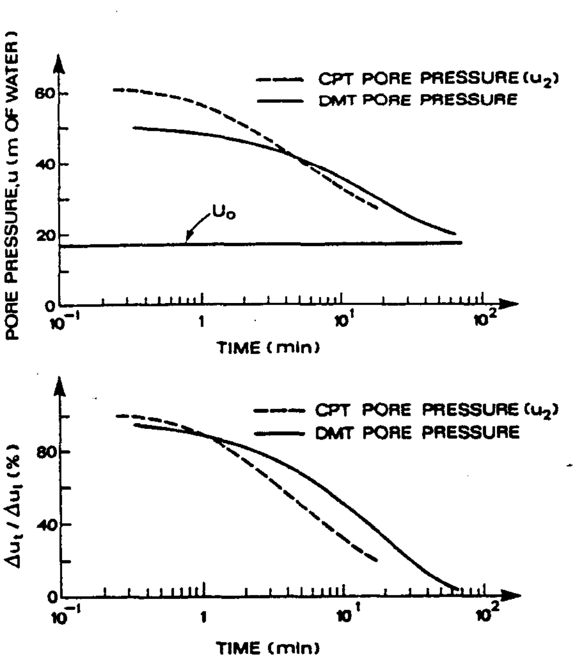

FIG. 18. Pore-pressure dissipations using research DMT and CPTU (immediately behind tip) in clayey silt at McDonald's Farm (20 m depth) (after Robertson *et al.* 1988).

Campanella *et al.* (1985), Robertson *et al.* (1988), and Lutenegger (1988) showed that the DMT closure pressure (P_2) is approximately equal to the DMT penetration pore pressure for penetration in soft clay ($I_D < 0.6$; $K_D \leq 5.0$) and for clean sands ($I_D > 2.0$). Since no excess pore pressures are generated during CPT and DMT penetration in clean sands, the closure pressure (P_2) is approximately equal to the equilibrium pore pressure (u_0). A summary of the results presented by Robertson *et al.* (1988) is shown in Fig. 16. Schmertmann (1988) has recommended that the recording of the closure pressure (P_2) be included in the suggested DMT procedure.

Figure 17 compares the measured DMT penetration pore pressures with the closing pressures (P_2) for the upper 232nd Street site. Although the closing pressures (P_2) shown in Fig. 17 were obtained using the research dilatometer, similar (P_2) values have also been obtained using the standard Marchetti dilatometer.

Figure 17 shows that in stiff clay deposits, where $I_D < 2.0$ and $K_D > 5.0$ (2.0–4.0 m), the DMT closing pressures appear to be unrelated to the negative penetration pore pressures. This is consistent with data presented by Lutenegger (1988) for clays with OCR > 2.5.

Dissipation rates

Figure 18 presents an example of the dissipation of excess pore pressures during a stop in penetration in a soft clay

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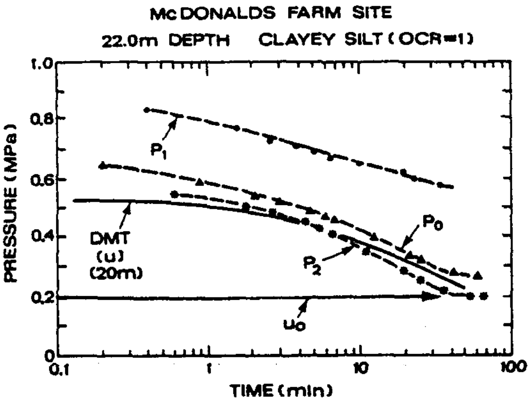

FIG. 19. Comparing pore-pressure dissipations from repeated A(P_0), B(P_1), and C(P_2) DMT readings (corrected) and those measured by research DMT.

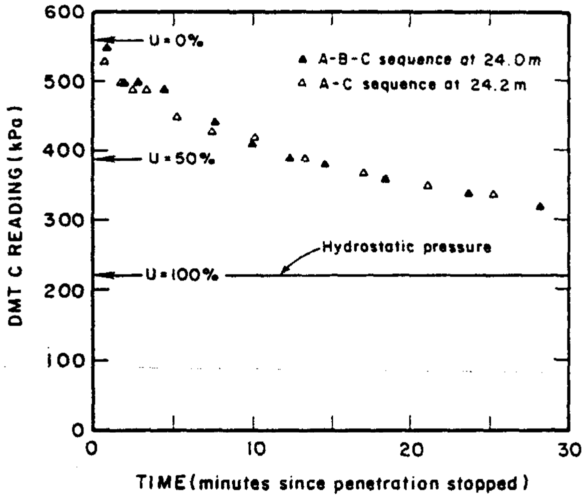

FIG. 20. Excess pore-pressure dissipation using repeated A-B-C and A-C sequences in DMT at adjacent 0.2 m depths.

for the research DMT and CPTU. The example shown is from the McDonald Farm site at a depth of 20 m, where $I_D < 0.6$ and $K_D = 2.0$. The CPTU dissipation data are for the pore-pressure element located 5 mm behind the shoulder of the tip (u_2).

Figure 18 also shows that when the dissipation data are normalized with respect to the equilibrium pore pressure (u_0), the rate of dissipation for the pore pressures around the DMT is slower than that around the 10 cm^2 cone.

At the McDonald Farm site at a depth of 20 m the time for 50% dissipation is approximately twice as fast for the 10 cm^2 CPT as it is for the DMT. The slower dissipation is probably related to the approximate two-dimensional shape of the flat dilatometer blade.

Since the DMT closing pressure (P_2) closely resembles the pore pressure on the DMT membrane in soft clays ($I_D \leq 0.6$; $K_D \leq 5.0$), it should be possible to record the closing pressures with time and obtain a dissipation curve from a standard Marchetti DMT. Figure 19 shows the results of a repeated expansion–deflation test (P_0, P_1, P_2) obtained using a standard Marchetti dilatometer at a depth of 22 m at the McDonald Farm site. For comparison the pore-pressure dissipation recorded using the research dilatometer at a depth of 20 m is also shown in Fig. 19. For the research dilatometer pore-pressure dissipation, the pore-pressure sensor on the membrane was used and no membrane expansion was performed. Figure 19 shows that the P_2 readings follow a very similar dissipation curve to that of the actual DMT pore pressures. Also it is interesting to note that the P_2 readings tend towards the *in situ* equilibrium pore pressure (u_0) after complete dissipation of the excess pore pressures.

Based on the observations shown in Fig. 19, several methods have been recently suggested to estimate the coefficient of consolidation (c_h) which include repeated A–B–C readings (Robertson *et al.* 1988; Schmertmann 1988) and repeated A-readings only (Marchetti and Totani 1989) to approximate pore-pressure dissipation. Figure 20 shows an example of recent comparisons of DMT closure dissipation curves at the Laing Bridge site on Sea Island (about 3 km from McDonald's Farm) in the soft clay silt. Figure 20 compares C-readings determined by repeated A–B–C sequences with repeated A–C sequences at alternate depths. These recent results show that repeated A–C readings do give similar results but are considerably easier to perform than the repeated A–B–C readings and are therefore a preferred method.

The addition of the P_2 reading during the standard DMT can provide valuable additional data, such as verification of drained consitions in sands and undrained conditions in cohesive soils. P_2 dissipation can also yield data to estimate the coefficient of consolidation in soft clays ($I_D < 0.6$; $K_D \geq 5.0$).

Verticality

To evaluate the influence of nonverticality on the DMT data, two soundings were performed at the McDonald Farm site with the research dilatometer blade given an initial inclination. The research DMT contained a calibrated slope sensor located just above the blade.

Two soundings were carried out with the membrane first on the underside and then on the upper side of the blade, which was initially at an inclination (pushed sideways) of about 3°. Results are summarized in Fig. 21. The two soundings were performed approximately 3 m apart and extend to a depth of about 10 and 13 m, respectively. Penetration was stopped in the dense sand due to excessive rod friction developed along the inclined rods.

The results in Fig. 21 show that there is little difference between the DMT data P_0 and P_1 and the horizontal stress index, K_D, for blade inclinations of less than about 15°. The natural variability of the McDonald Farm sand makes it difficult to clearly identify a difference in the data down to a depth of about 8 m. Experience with cone penetrometers containing slope sensors suggests that inclinations are not likely to exceed 12° for penetration into homogeneous deposits to a depth of less than 20 m.

Summary

A research dilatometer has been developed and used in the field in an effort to better understand the measurements made using a standard Marchetti dilatometer. The research dilatometer is identical in size, shape, and operation to the Marchetti blade except that passive electronic measurements were made of pore pressure and deflection at the centre of

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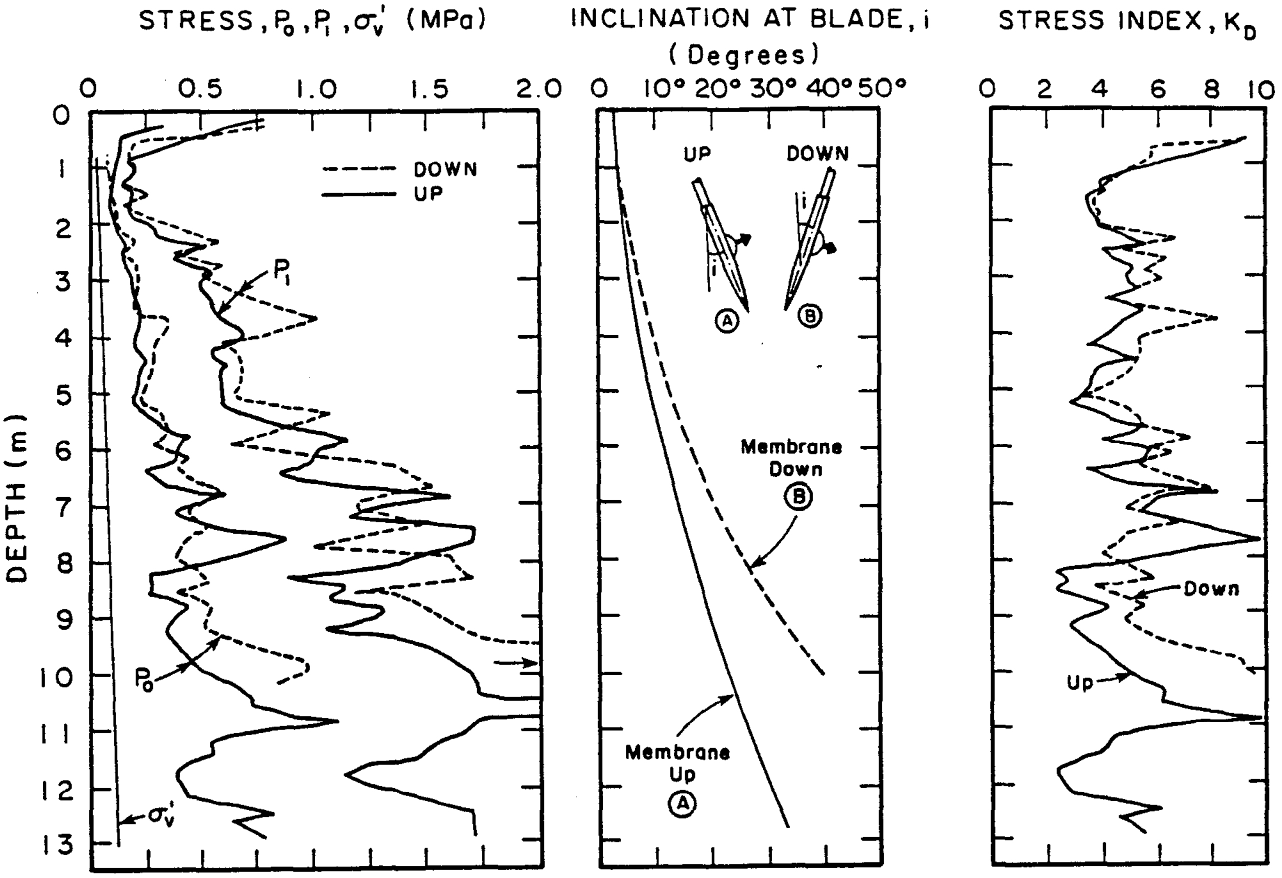

FIG. 21. Effect of nonverticality of DMT results during penetration at McDonald's Farm.

the membrane, gas pressure to inflate the membrane, verticality of the blade, and penetration force immediately above the blade.

Results from several research sites near Vancouver, British Columbia, using the research dilatometer have shown the following general points.

(1) The calibration curve of the circular membrane is highly nonlinear and hysteretic.

(2) The pushing force for the dilatometer is approximately twice that of a 10 cm^2 cone penetrometer.

(3) Little rod friction is developed along the push rods for testing in clean sand deposits when verticality is maintained. For blade inclinations greater than about 15°, rod friction in sand can become excessive.

(4) For testing in sand, there appears to be little error in the measured DMT data for blade inclinations less than 15°.

(5) The pressure–deflection curves for expansion and deflation of the dilatometer membrane show remarkable similarities with the expansion and deflation curves for self-bored or full-displacement pressuremeters.

In clean sands ($I_D \geq 2.0$) the following points have been observed.

(1) No excess pore pressures are generated during penetration and dilatometer membrane expansion.

(2) The closing pressure (P_2) is approximately equal to the equilibrium pore pressure (u_0).

(3) The slope of the expansion curve, i.e., E_D, represents some elastic-plastic response of the sand.

(4) P_0 and P_1 appear to be related to penetration resistance, thus providing a basis to relate penetration resistance to modulus.

(5) Correlation of P_0 to penetration resistance removes the need to measure thrust to calculate ϕ' in sands.

(6) Based on the relationship between P_0 and penetration resistance, a preliminary direct correlation between the DMT index K_D and friction angle ϕ' has been proposed.

In soft clays ($I_D \leq 0.6$; $K_D \leq 5.0$) the following points were observed.

(1) Large excess pore pressures, similar to those recorded behind the tip of a cone penetrometer, are generated on the centre of the membrane during penetration.

(2) Effective stresses on the membrane are small and remain almost constant during the standard expansion and deflation phase of a DMT.

(3) The measured total stresses (P_0 and P_1) are strongly controlled by the large penetration pore pressures.

(4) The measured closing pressure (P_2) is approximately equal to the penetration pore pressure.

In stiff clays ($I < 2$; $K_D > 5.0$) the following points were observed.

(1) Penetration pore pressures on the centre of the membrane can be very small and in some cases negative, similar to those recorded behind the tip of a penetrating cone.

(2) The measured total stresses (P_0 and P_1) are strongly controlled by the high effective stresses.

(3) The measured closing pressure (P_2) appears to be unrelated to either the penetration or the equilibrium pore pressure.

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There also may be some benefit in exploring the use of the interpretation concepts developed for the pressuremeter for interpretation of the DMT. This may provide a useful framework to better understand and improve some of the existing empirical DMT correlations.

The results from the research dilatometer illustrate the complexity in the interpretation of DMT data and suggest that additional factors such as mineralogy, stress history, sensitivity, soil stiffness, and macrofabric probably influence the basic DMT data.

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