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Ground Property Characterization from In-Situ Tests: Opportunities offered by Measuring Thrust during Flat Plate Dilatometer Testing

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ABSTRACT: This paper describes the advantages of the use of thrust measurements made during a Marchetti Flat Plate Dilatometer test sounding. They provide another method for accurate soil profiling. They may result in more accurate DMT pressure readings because thrust allows use of "advance knowledge" to estimate the change in readings at the subsequent test depth. They also provide data for protection of the equipment. The addition of thrust data provides another variable for estimating the plane strain, drained, soil friction angle using the Durgunoglu and Mitchell bearing capacity theory. Marchetti and others have recently recommended combining CPT and DMT measurements to provide data for liquefaction potential evaluations. The writers present a method to use thrust measurements for evaluations of liquefaction potential using only DMT data. This avoids the unknown, possibly serious, effects of soil variability when combining CPT and DMT data obtained in different soundings.

1 INTRODUCTION

Engineers can take better advantage of the soil properties information potential of Marchetti flat blade dilatometer test soundings (DMTs) by including measurement of the total vertical thrust, P, to advance the blade to each successive test depth. As explained subsequently in more detail, using P has some important benefits that include obtaining a stratigraphic profile, warnings of possible blade damage or loss, more accurate pressure readings, a method for calculating the blade's bearing capacity q_D and then the sand's plane strain friction angle Φ'_{ps}, and using q_D instead of q_c from an adjacent CPT sounding to evaluate a sand's liquefaction potential. Nothing in this paper applies if you advance the blade by driving it with a hammer.

2 WHERE TO MEASURE THE THRUST P

Before using P the engineer needs to decide where to measure it – above ground at the top of the string of rods going to the DMT blade or below ground directly above the blade? The argument for above ground: One can easily install, read, and maintain the load cell. The argument against: One does not measure the parasitic rod/soil side shear above the blade. The argument for directly above the blade: That eliminates the need to know the above parasitic side shear. The argument against: It creates serious equipment design and maintenance problems.

Our DMT research with load cells at both top and bottom of the rods showed bottom cells impractical for routine use and that the parasitic side shear in sands became negligible when machining a "friction reducer" 33% diameter enlargement 'ring' to the rod connector just above the blade, correcting for its additional end bearing, and testing at depths of 15m or less ASTM (2014), Schmertmann, (1982, 1984). Figure 1 shows two examples of similar (P vs z) profiles when using a friction reducer and simultaneously measuring thrust above ground (on rods) and above the blade (on DMT). Discussing Figure 1, Bullock (2015) also wrote *"Separate analyses for friction angle prepared using each thrust measurement provided almost the same values, indicating that the rod friction was not significant for these soundings."*

Figure 1 also shows, after penetrating through a strong into a weak layer, how P drops off sharply to low values and thus also indicates that the parasitic rod shear has a minor effect. However, some experience in Europe suggests that eliminating such a friction ring does not have a significant effect on the thrust required because the prior blade advance has already disturbed the soil around the overhead rods. The writers routinely use a ring but suggest trying a few soundings with and without a ring and compare how it affects the results, particularly the thrust profiling and Φ'_{ps} prediction, and choose which method seems more accurate. Eliminating the ring may reduce the thrust required to advance the blade.

3 USEFULNESS OF MEASURING THRUST

2.1 *Soil Profile of P vs. depth*

During a typical DMT sounding the engineer stops penetration at 100-300 mm depth intervals to obtain the p_0 and p_1 membrane expansion pressure data, and would measure the thrust P during every penetration interval. This provides the P vs. z (depth) points, 100-300 mm apart, for a nearly continuous profile and can detect layers as thin as 100mm. Comparing CPT q_c end bearing profiles with adjacent P profiles shows them similar to 15m depths. This suggests that most, or an important part of P, results from the DMT blade's q_D end bearing.

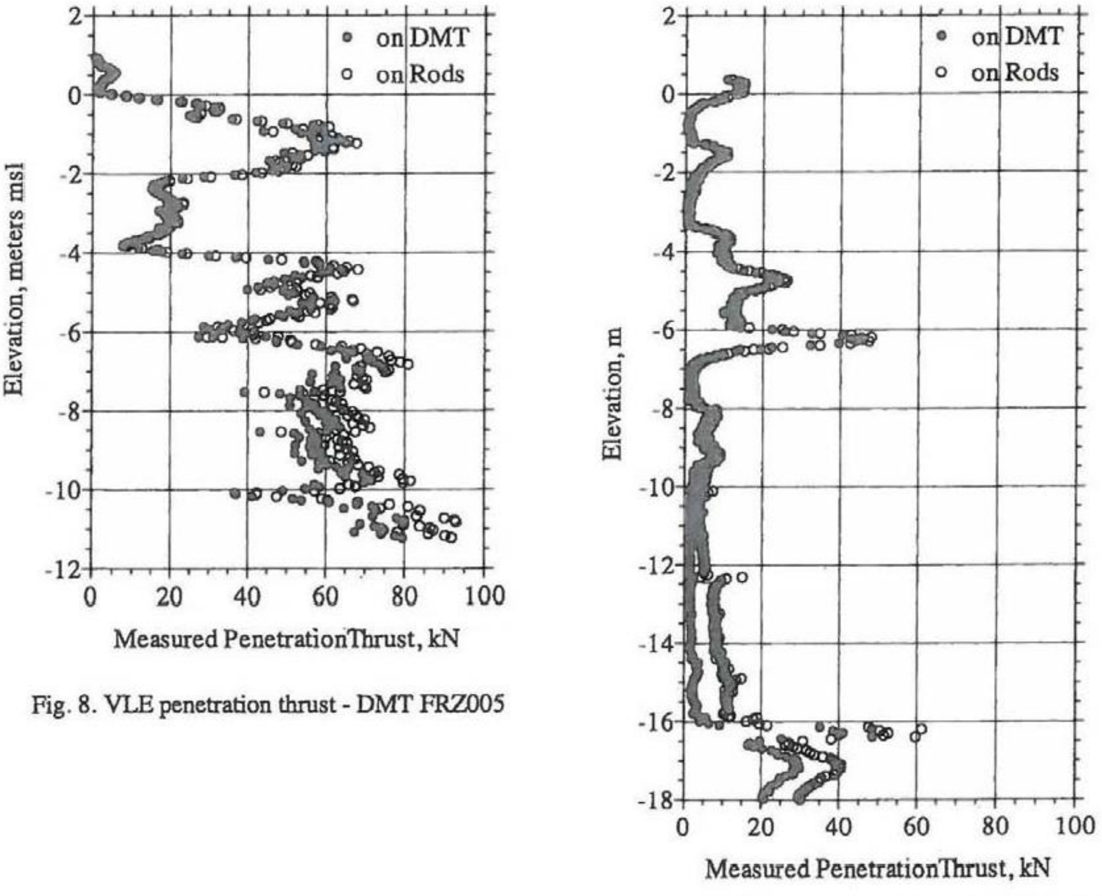

Fig. 8. VLE penetration thrust - DMT FRZ005

Fig. 9. VLW penetration thrust - DMT FRZ007

Figure 1. Examples of Comparative Thrust on Rods and on DMT Blade, from Bullock (2015)

2.2 *Thrust Measurements Help to Prevent Damage or Loss of the DMT Blade*

Engineers often push dilatometer (DMT) blades in the United States and Canada using SPT rigs with a typical range of maximum available thrust from about 31 to 62 kN (7 to 14 kips); and, with CPT rigs with a typical range of about 89 to 267 kN (20 to 60 kips). The potential damage or loss of the DMT blade during penetration increases as the thrust increases. However, soil type and layering can also have a dramatic effect. Most minor damage to the blade relates to pushing into sharp gravel, gravelly and shelly soils, or attempts to push into very strong soils or rock, any of which may cut the membrane or pit the cutting edge of the blade. Minor damage to the DMT blade typically occurs at thrust values less than about 62 kN (14 kips). Increased thrust, especially in sands, result in increased abrasion of the blade and membranes which decreases their useful life, especially when using thrust values over 90 kN (30 kips). A weak layer over a very strong layer may result in loss of the DMT blade when trying to push into the very strong layer when the upper weak layer lacks sufficient lateral support to prevent bucking of the rods above the blade. Loss of the blade usually occurs when the rods break at one of the joints close to the blade. One must make decisions regarding whether or not to continue penetration vs. the risk of damage or loss of the DMT blade during penetration. Previous thrust values provide information to help in these decisions and prevent serious damage to or, in the now rare case, loss of the DMT blade.

2.3 *Thrust Measurements Help the Operator to Anticipate the Increase or Decrease in DMT Pressures for Subsequent Readings*

The DMT data are typically considered drained for non-cohesive soils and undrained for cohesive soils. The speed of penetration and the speed of application of the pressures to the DMT membrane may have an effect upon the DMT results. The normal speed of penetration = 20mm/second. D6635-01 in ASTM (2014) standardizes the speed of application of the pressure to the membrane (within limits) to minimize differences in p_o and p_1 values by different operators. The recommended procedure: Apply the pressure quicker in the beginning and slow down when approaching the reading pressure to have a more accurate reading. Thrust measurements provide an advance warning of increasing or decreasing soil strength and the likely increase or a decrease in the next set of pressure readings and thus contribute to obtaining more accurate data.

4 OBTAINING q_D FROM P

Schmertmann (1982, 1984), describes in detail how to extract q_D from P. Figure 2, copied and annotated from Schmertmann (1984), shows the axial forces acting on the sounding rods and the DMT blade. Setting their sum = 0 gives equation (1), which one can solve for q_D. See Notation for another verbal description of each symbol.

$$P + W - F_r - F_q - F_b - q_D(bw) = 0 \qquad (1)$$

3.1 *Comments about F_q and F_b*

F_q results from parasitic end bearing loading on the additional projected bearing area $A_p = ((\pi d^2)/4 - bd)$. With 45 mm diameter AW rods this adds 885 and 1870 mm^2, without and with a ring, respectively, to the blade's end bearing area of 1440 mm^2. The addition occurs where the blade has previously passed, disturbed and then partially unloaded the soil above the top of the blade. The local bearing pressure responsible for F_q will likely fall below q_D at the bottom of the advancing blade. Using q_D when calculating $F_q = (A_p)q_D$ produces a likely too-high F_q and therefore a conservative q_D. The data reduction corrects P to that from a previous lesser depth that most closely corrects for the vertical

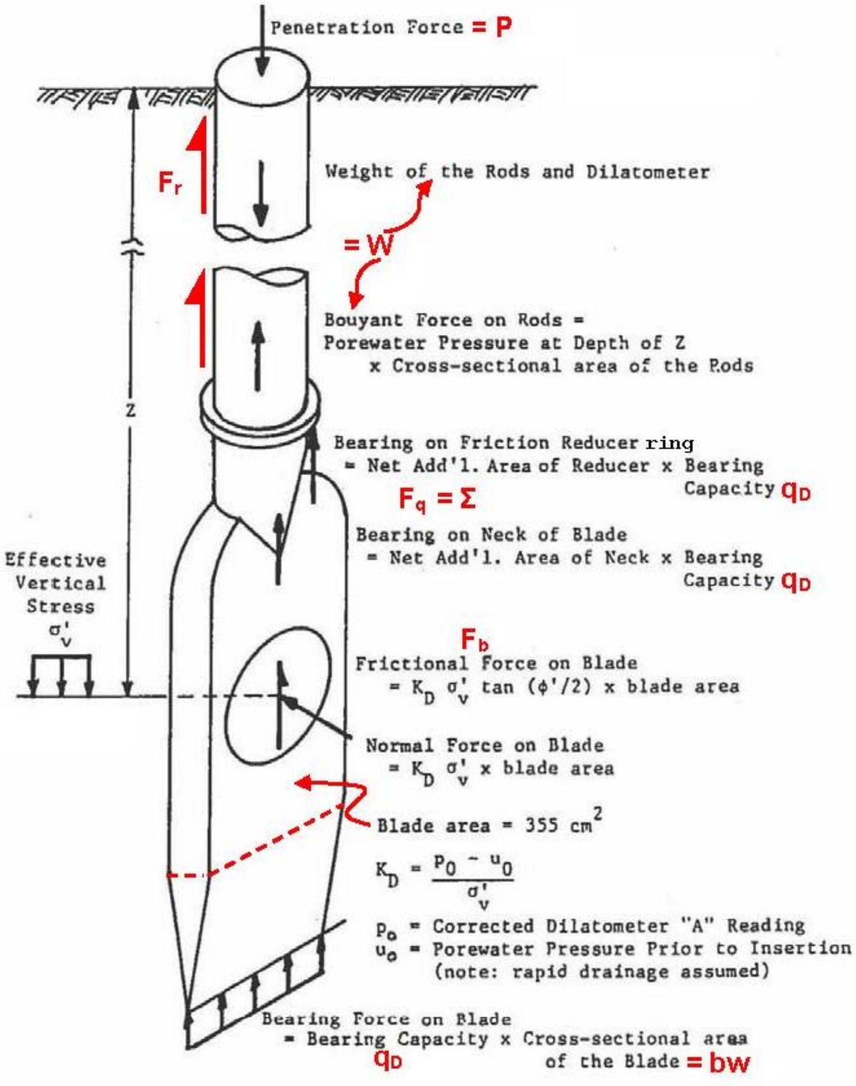

Figure 2. Vertical Forces on DMT Blade and Rods (schematic, annotated)

distance (c. 200 mm) between the ring and center of the blade's membrane.

F_b develops because of the frictional resistance to penetration along the vertical sides and edges of the blade. Because the blade has a (width/thickness) or (w/b) ratio of 7, with a penetration angle $\alpha \approx 16°$ moving the soil outward from its face with passive pressure, we assume negligible friction along the 15 mm blade edges. The two sides of the blade above the 16° bottom cutting edge have a total area, $A_s \approx 355\ \text{cm}^2$. We measure $\overline{\sigma}'_n$ against the blade shortly after the operator stops penetration and reduces the thrust P to zero. The writers use the 60 mm diameter DMT membrane as both a total and effective pressure cell. This works well in rapidly draining frictional soils as described most recently by Bullock (2015). With the membrane located in the area in plane strain, and covering 8% of that area, we assume that the measured p_0, after the corrections for membrane stiffness and water pressure u, provides the average $\overline{\sigma}'_n$ against the entire 355 cm^2. We also assume a frictional soil ($c' = 0$), with an ultimate shear resistance between sand and a smooth steel blade $= \overline{\sigma}'_n \tan \delta'_{ps}$ and $\delta'_{ps} = ½\ \Phi'_{ps}$, based on experimental results by Nottingham and Schmertmann (1975) and the common use of this ½ assumption.

3.2 *Review of Conservatism*

Defining conservative as calculating a too-low q_D, Table 1 lists the writers' estimates of the conservatism of the expressed and tacit assumptions involved with calculating F_q, F_b and F_r to obtain q_D. We believe that the conservative and non-conservative assumptions tend to cancel each other. The subsequent and generally conservative Φ'_{ps} values determined from q_D suggest an overall conservatism in q_D.

Table 1. Estimates of Conservatism

	Assumption	Conservative q_D?	
		Yes	No
F_q	Disturbed soil	✓	
	Using q_D for the unknown q above the blade	✓	
F_b	Negligible edge friction		✓
	p_0 during penetration = p_0 during DMT with penetration stopped and P = 0		✓
	Excess hydrostatic pore pressure = 0 in sands ($I_D \geq 1.8$)	✓	
F_r	Corrected p_0 gives avg. $\overline{\sigma}'_n$ over entire face area of blade	✓	
	$c' = 0$	✓	
	$\delta'_{ps} = ½\ \Phi'_{ps}$	Unknown, but a common assumption	
	$F_r = 0$		✓
Φ'	Schmertmann (1984) (see **4.**)	✓	

5 OBTAINING Φ'_{ps} FROM q_D

Schmertmann (1982, 1984) describes in detail a method to calculate Φ'_{ps} from DMT data in sands. The previous sections herein describe how to extract q_D from the thrust P to advance the DMT blade. This section summarizes the principal concepts used to determine Φ'_{ps} from q_D.

Durgunoglu and Mitchell (1973, 1975) developed a theory for calculating the bearing capacity for the near-surface penetrometers used on the moon. This theory improved on existing theories by explicitly taking into account the variables of horizontal stress, penetrometer shape, axisymmetric and plane strain penetrations, point angle, soil-friction angle and friction coefficient along the penetrometer point material surface. It seemed to produce good bearing capacity predictions in its lab verifications over $z/w \leq 30$, and reasonable results on the moon. Subsequent papers Mitchell and Lune (1978), Villet and Mitchell (1981) showed that the D&M theory also gave reasonable bearing capacity predictions for much deeper CPT and DMT soundings. Schmertmann (1982) also found that this theory produced reasonable results when compared with such soundings in soil with $I_D \geq 1.8$ (sands and silty sands). Marchetti (2015) still continues to support the validity of using the D&M theory with q_D but also notes alternate methods for obtaining Φ'_{ps} from the DMT and Φ'_{ax} from the CPT.

The D&M theory uses the Mohr-Coulomb model for soil shear strength. Therefore q_D (and q_c) also depend on plane strain (and axisymmetric) c' and Φ'. Still assuming $c' = 0$ in sands, then $q_D = f(\Phi'_{ps}$ and $K_0)$ and in principle one can calculate Φ'_{ps} from q_D. This requires an iteration procedure with K_0. Computers can now easily solve this problem during routine data reduction. Experience and research, as described in Schmertmann (1982, 1983-91, 1984) have shown that using the above D&M method produces reasonable and usually conservative values of Φ'_{ps}. It has the advantage of a partly theoretical basis vs. mostly empirical alternatives and incorporates the insitu horizontal stress in the form of K_0. The writers use a K_0 value in sands ($I_D \geq 1.8$) determined from equation (2), developed from the results from 16 DMT and CPT tests in large triaxial chambers. The unaged, uniform sands varied from fine to coarse, with OCR = 1 (mostly) to 5.6 and K_0 from 0.33 to 0.96.

$$K_0 = \frac{40+23\,K_D-86\,K_D(1-\sin\Phi'_{ax})+152(1-\sin\Phi'_{ax})-717(1-\sin\Phi'_{ax})^2}{192-717(1-\sin\Phi'_{ax})} \tag{2}$$

The writers use equation (1) with the D&M theory and the measured K_D and thrust P as follows:

1. Use P to get q_D

2. Use the D&M theory, a ‘known’ q_D and K_D, plus a trial value of K_0 to calculate a Φ'_{ps}.
3. Convert to the equivalent Φ'_{ax}.
4. Put Φ'_{ax} in equation (2) and calculate a K_0.
5. Substitute this K_0 in step 2 and repeat steps 3.,4. etc. until getting an acceptable match between the trial K_0 and calculated K_0 that gives the final set of K_0 and Φ'_{ax} values.

6 CONVERTING q_D TO q_C AND Φ'_{ps} TO Φ'_{ax}

Mitchell and Lune (1978) used the D&M theory, among others, to calculate Φ'_{ax} in sands from CPT tests in lab chambers and field sites. They concluded “For the sites and chamber tests included in this paper the values of $\Phi'_{(ax)}$ found by this method agree very well with the laboratory measured values.” Schmertmann (1982, 1983) found from a similar comparison that the D&M theory underpredicted Φ'_{ax} by 1° to 3.2° over the dry sand depth (z) range of 4 to 46m, and a relative density (D_r) range of 45 to 90%. Using the same theory Schmertmann (1982) calculated the ratios of (q_D/q_c) and found the ratio insensitive to depth and horizontal stress. Only Φ' mattered over a range of 25° to 45°. Actual research comparisons in large chamber tests and in the field give (q_D/q_c) ratios of about 1.1 ± 0.1.

Many researchers have clearly shown that $\Phi'_{ps} > \Phi'_{ax}$ because plane strain prevents particle movements in one dimension and axisymmetric strain does not. For example, see Terzaghi, Peck and Mesri (1996). This effect becomes negligible in loose sands with $\Phi'_{ps} \leq 32°$. The writers use and recommend equation (3) as an empirical method for converting between Φ'_{ps} and Φ'_{ax}. Use $\Phi'_{ax} = \Phi'_{ps}$ when $\Phi'_{ps} \leq 32°$. It fits conservatively with the more detailed data in Terzaghi et.al. (1996).

$$\Phi'_{ax} = \Phi'_{ps} - \frac{(\Phi'_{ps} - 32°)}{3} \tag{3}$$

7 USING q_D TO ESTIMATE LIQUEFACTION POTENTIAL (LP)

As detailed by Marchetti (2015), the writers consider it well established that LP depends importantly on the existing horizontal stress and stress history of silts and sands, and that the DMT K_D parameter increases with K_0 and aging. The risk of liquefaction decreases with increasing K_D, but not uniquely. Introducing another measurable parameter directly related to LP and sand structure, such as the local bearing capacity q_c (or potentially q_D) from insitu penetration tests, seems to improve LP predictions. The writers counted at least four papers in the DMT-2015 Conference Proceedings that proposed LP prediction methods that combine K_D and q_c, with q_c obtained from an adjacent CPT sounding at the same elevation as K_D in the DMT sounding.

Using an adjacent CPT sounding creates at least two problems, namely the cost of a possible additional CPT sounding and the uncertainty that inherently variable sand deposits may result in K_D and q_c obtained in sands with significantly different structure and LP. It seems obvious that using q_D from the same sounding, at or above and below the elevation of determining K_D greatly reduces the risk of testing significantly different sands. Furthermore, the thrust measurements from the DMT sounding itself should provide adequate profiling at its location.

The writers understand that liquefaction rarely occurs at depths of more than 15m. That means, based on the previously described experience in Section **1.**, that sounding rod side shear, F_r, has a negligible effect at most potentially liquefiable sites. Current LP correlations include q_c vs. q_D because the much more extensive use of the CPT vs. DMT sounding method has given engineers the opportunity to include q_c in LP correlations. The writers believe q_D may do equally well with an expanded correlation data base, perhaps better with the above better assurance of testing the same sand. Does an accurate q_c of adjacent sand trump a less accurate calculation of q_D on the same sand or visa-versa? More research and experience should resolve this question.

8 CONCLUSIONS

a) Profiling thrust provides a useful, real-time, measure of stratigraphy. It permits anticipating the next set of DMT p-readings and guarding against equipment damage.
b) Using a “friction ring” with a 33% increase in rod diameter above the DMT blade will reduce parasitic rod side shear to negligible values in sands at depths of less than 15m.
c) Summing thrust and the other vertical forces calculated using the ordinary DMT data permits calculating a generally conservative q_D.
d) The Durgunoglu and Mitchell bearing theory permits detaining Φ'_{ps} from q_D and Φ'_{ax} from q_c.
e) Using q_D directly with K_D from the same DMT sounding can potentially avoid using a possibly erroneous q_c from an adjacent sounding in combined (K_D-q_C) liquefaction potential correlations.
f) We find the many benefits of routinely measuring the penetration thrust P during a DMT sounding well worth the extra time and expense.

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10 LIST of SYMBOLS

A_p	parasitic end bearing area above blade
A_S	area of blade exposed to side shear
b	blade thickness
CPT	= static cone penetration test
c′	effective cohesion strength
D_r =	Relative density (%)
DMT	Marchetti dilatometer test
d	ring, or rod diameter if no ring
F_r	side shear force along DMT rods
F_q	parasitic bearing force on ring and/or rod connector
F_b	side shear force on blade
I_D	material index = $[(p_1-p_0)/(p_0-u_0)]$
K_0	(horiz/vertical) effective stress ratio before DMT (or CPT)
K_D	horizontal stress index = $[(p_0-u_0)/(\sigma'_{vt} - u_0)$
LP	Liquefaction Potential (various definitions)
OCR	overconsolidation ratio
P	thrust force
P_z	P at depth z
p_0	corrected DMT membrane lift off pressure, movement = 0.05 mm
p_1	corrected pressure at 1.1 mm movement
q_C	CPT cone bearing capacity
q_D	DMT blade bearing capacity
SPT	Standard penetration test (dynamic)
u_0, u	total water pressure on membrane
W	buoyant weight of DMT rods and blade
w	blade width
z	depth of center of membrane below ground surface
α	angle of cutting edge of blade, 50 mm transition from edge to b
δ'_{ps}	effective blade/sand friction angle
Φ′	effective friction angle
Φ'_{ax}	axial-symmetry Φ′
Φ'_{ps}	plane strain Φ′
Σ =	sum of
$\overline{\sigma}'_n$ =	effective avg. normal stress on blade
σ'_v =	estimated effective vertical stress at depth z