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THE MARCHETTI DILATOMETER AND COMPRESSIBILITY

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INTRODUCTION

The dilatometer test (DMT) was initially conceived by Professor Silvano Marchetti as a method to get a lateral modulus response for laterally-loaded steel piles. He started developing an in-situ tool for horizontal modulus in 1974. The DMT was introduced at the ASCE Specialty Conference in Raleigh in 1975 and at the IX ICSMFE, in Tokyo, in 1977.

At the latter conference he was inspired by Burland's statement that "---it can be concluded that testing should be aimed at establishing the simple in-situ parameters. The most important appears to be the one-dimensional compressibility m_v, or the equivalent effective vertical Young's Modulus E_v and the variation with depth." (Burland, 1977). In the same year, Marchetti discovered that there was an apparent correlation between E_D and M, or $1/m_v$.

In 1979 an association between Marchetti and Dr. John Schmertmann resulted in the introduction of DMT equipment to North America, along with continuing research and development of equipment, procedures and interpretation. Major contributions to our understanding of the DMT have been made since then by Schmertmann, Jamiolkowski, Campanella, Robertson and others.

It is important to note that Marchetti provided not only a new device for in-situ testing but also a useful set of correlations that made the DMT immediately useful to practising engineers. In today's parlance the set of correlations amounts to an "expert system". This system takes the raw data from the DMT, computes the basic index parameters and then filters the information through a series of conditional statements to produce an estimate of several useful geotechnical parameters. When we are discussing the DMT it is important to distinguish between the basic data (index properties) which it provides and the interpreted information (conventional geotechnical parameters) which evolves from the "expert system".

THE MARCHETTI DILATOMETER AND COMPRESSIBILITY

In this presentation I will briefly review the DMT equipment and test procedures and show how they provide the basic DMT index values, I_D, K_D, E_D and U_D. I will then focus on one of the geotechnical parameters provided by the "expert system", namely the tangent modulus of compressibility, M_D.

DILATOMETER EQUIPMENT AND TEST PROCEDURES

The essential component of the DMT equipment is the dilatometer blade, the dimensions of which are shown on Figure 1. The blade is made of specially treated and hardened stainless steel. The remaining components, as shown on Figure 2, are a control unit, a calibration unit, pneumatic-electrical cable and ground cable.

The basic dilatometer test is a fairly simple and straightforward procedure. It involves connecting the dilatometer blade to conventional drill rods and feeding a pressure tube through the drill rods from the blade to the control gauge and pressure source. The rods and dilatometer assembly is then pushed (or driven) into the ground to the desired testing level. After completing a test at that level, the dilatometer blade is advanced to the next test level. A test interval of 200 mm is commonly used and provides a nearly-continuous profile.

The procedure at each test interval consists of using gas pressure passing through a control valve to expand the membrane horizontally against the soil while noting the pressures at two membrane positions.

(i) At membrane "lift-off" (A-reading)

(ii) After 1.1mm movement of the membrane (B-reading).

As soon as the 1.1mm expansion has been reached, the gas pressure is released under control until the membrane returns to the lift-off position where a third pressure (C-reading) is noted.

The four steps in a dilatometer test sequence are illustrated in Figure 3.

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The suitability of the DMT in any particular soil profile is determined by whether or not the blade can successfully penetrate the soil (preferably by pushing) without damage. The DMT is particularly useful in low and medium strength soils. Some weak soils (i.e. loose silts and sands) which present both strength and settlement design problems and which are normally difficult to sample or test by other methods can be readily assessed with the DMT. Although the DMT can successfully test some strong soils, it is usually not cost-effective to do so, particularly if the test results will have little influence on the final design. Table 1 provides a guide to the general suitability of the DMT in different types of soil.

ANALYSIS OF FIELD DATA AND DMT INDICES

The A, B and C readings obtained at each test interval are corrected for membrane resistance to obtain the following pressure values:

$$p_0 = A + A \text{ correction}$$
$$p_1 = B - B \text{ correction}$$
$$p_2 = C - A \text{ correction}$$

These measured pressures are used, along with estimated values of vertical effective stress, σ_v' and in-situ pore pressure, U_D to calculate four DMT indices as follows:

$$Material Index; I_D = \frac{p_1 - p_0}{p_0 - u_o}$$

$$Horizontal Stress Index; K_D = \frac{p_0 - u_o}{\sigma'_v}$$

$$Dilatometer Modulus; E_D = 34.7\,(p_1 - p_o)$$

$$Pore Pressure Index; U_D = \frac{p_2 - u_o}{\sigma'_v}$$

TABLE 1 — SUITABILITY OF DMT IN DIFFERENT TYPES OF SOIL

Suitability Ranking:

0 = do not use DMT   2 = good
1 = sometimes suitable   3 = best application

Note: Hammer-driving alters the DMT results and decreases the accuracy of correlations.

SOIL TYPE	SUITABILITY FOR DIFFERENT SOIL CONDITIONS					
	weak, loose * $N_{SPT}<5$, $q_c<15$		medium $N_{SPT}=25$, $q_c=75$		stiff, dense** $N_{SPT}>40$, $q_c>150$	
SOIL TYPE	fills dumped, pumped	natural	fills light cmpxn.	natural	fills heavy cmpxn.	natural
Clays	3	3	2	2	2	2
Silts	2	2	2	2	1	1
Sands	3	3	2	2	1	1
Gravel, lg. shell and concretions	1	1	0	0	0	0
Cobbles	0	0	0	0	0	0
Rock (weathered)	0	1	0	0	0	0
CL+SI+SD	3	3	3	2	2	2
CL+SI+SD+Shell	2	2	2	2	0	0
CL+SI+SD+Rock	1	1	1 **	1 **	0	0
Sand+Gravel	2	2	2 **	1 **	0	0
Organic CL+SD	3	3	2	2	1	1
Residual w/o rock	3	3	2	2	1	1
Residual w/ rock	1	1	0	1 **	0	0
Cemented sand	-	1	-	1 **	-	0
Tallus with rock	-	1	-	1 **	-	0
Glacial Till	0	1	0	0	0	0
Varved Clays	3	2	2	2	1	1
Loess	3	2	2	2	-	-
Peats	3*	2*	2	2	-	-
Slimes, tailings	3*	-	2	-	-	-

* Sensitive testing in very weak soils.
** High risk of damage - use high strength blade & membrane.

Ref— DMT Manual

These index values are basic, unique and repeatable, results from the DMT in the same sense that q_o and R_f are basic to the CPT, P_L is basic to the pressuremeter and N is the basic value from the standard penetration test. The measured index values from the DMT provide a great deal of useful information without any further interpretation.

The **material index** has proved to be a good soil profile indicator, using the classification scheme proposed by Marchetti (1980) and described in Table 3 below:

TABLE 2

Soil Type	Peat/ Sens. Clay	Clay		Silt			Sand	
			Silty	Clayey		Sandy	Silty	
I_D Value	<0.1	0.1-0.35	0.35-0.6	0.6-0.9	0.9-1.2	1.2-1.8	1.8-3.3	>3.3

The DMT I_D accurately indicates changes in the soil profile and can detect relatively thin discontinuities in an otherwise homogeneous soil deposit.

The **pore pressure index**, U_D, evolved from the discovery by Campanella et al (1985) that the corrected closure pressure, p_2 against the membrane at the end of the test closely matched the pore pressure in the soil. Their work at UBC indicated that p_2 in sands (I_D>2) approximately equals the ambient equilibrium water pressure (u_o). In clays (I_D<0.6) it was found that p_2 is an approximate measure of total water pressure against the membrane, the sum of u_o plus the excess pore pressure induced by penetration, u_e. Figure 4 from Robertson et al (1988) is an example of the test results, which illustrate these relationships. The usefulness of the p_2 measurement is also demonstrated on Figure 5 which clearly shows that there is a normal hydrostatic conditions in the lower sand layer.

The **horizontal stress index**, K_D, is also a very important result of the dilatometer test. The K_D profile is highly reproducible in clays; K_D is more variable in sand, probably because of the variability of the sand itself. In normally consolidated clays, K_D is generally constant, in the range of 1.8 - 2.3. K_D is related to the undrained shear strength of clays, lateral earth pressure (K_D), tangent modulus (M), relative density and liquefaction potential in sands.

The **dilatometer modulus**, E_D, provides an indication of modulus of elasticity for the soil. As indicated in Figure 6, the modulus is measured in a zone of soil which is affected by the stress disturbance due to penetration. The line CD in Figure 6 implies that E_D is a form of re-load modulus. E_D is measured under drained conditions in sands and undrained conditions in clays. The drained and undrained pore pressure dissipation effects during the test have been assessed by Campanella et al (1985) and by Boghrat (1982, 1987). Boghrat's results are shown on Figure 7.

Several researchers have found that there appears to be a good relationship between E_D and the equivalent secant Young's modulus at a 25% degree of strength mobilization (E_{25}) in normally consolidated sands. Campanella et al (1985) were the first to suggest this relationship followed by Jamiolkowski et al (1985) and Baldi, et al. (1986).

The main use of the DMT indices, aside from their stand-alone value for understanding soil behaviour, has been to provide estimates of a number of conventional soil parameters. Table 3 is a summary of the connection between various interpreted soil parameters and the DMT indices as outlined by Lutenegger (1988). As with most in-situ penetration tests, it is important to keep in mind that the interpreted parameters are usually approximate estimates. They can be very useful, nevertheless, in providing preliminary information or to indicate the range of actual values.

TABLE 3 — Interrelationships between soil parameters and DMT Indices.

Soil Parameter	DMT Index	Reference
s_u (clays)	I_D, K_D	Marchetti (1980)
ϕ' (sands)	I_D, K_D, thrust or adjacent q_c	Schmertmann (1982) Marchetti (1985)
K_o (clays)	I_D, K_D	Marchetti (1980) Marchetti (1986)
K_o (sands)	K_D, thrust	Schmertmann (1982)
OCR (clays)	I_D, K_D	Marchetti (1980)
OCR (sands)	K_D, thrust	GPE (1983)
M	I_D, E_D, K_D	Marchetti (1980)
E_i	I_D, E_D	Robertson et al. (1988)
E_{25}	E_D	Campanella and Robertson (1983) Baldi et al. (1986)
Cyclic stress ratio to cause liquefaction	K_D	Robertson and Campanella (1986)
k_h (subgrade reaction modulus)	P_o, K_D	Schmertmann and Crapps (1983) Robertson et al. (1988)
CBR	E_D	Borden et al. (1985)

After Lutenegger (1988)

THE DILATOMETER AND COMPRESSIBILITY

As a practising geotechnical engineer, I have come to appreciate the value of the DMT for estimating soil compressibility. I believe that the DMT is the sort of test that Burland probably had in mind in 1977 when he called for a straightforward test to determine in-situ one-dimensional compressibility.

The relationship of DMT results to compressibility of the soils is both theoretical and empirical. The membrane expansion can be modelled as the loading of a circular area on the surface of an elastic half-space. A mathematical relationship between the applied loading and modulus of elasticity is available from the analysis of Gravesen (1960) as follows:

$$\Delta p = \frac{\pi W_r}{4R_0\sqrt{1-\left(\frac{r}{R_0}\right)^2}}\left(\frac{E}{1-\mu^2}\right)$$

where:

Δp = the applied load
W_r = movement normal to the surface of a point at a radius r within the loaded area = 1.1 mm
r = radius to the point of interest = 0
R_0 = radius of loaded area = 30mm
μ = Poisson's ratio

The ratio $E/1-\mu^2$ is known as the dilatometer modulus, E_D. For the DMT dimensions, we have:

$$E_D = 34.7\ \Delta p \qquad (2)$$

There is also a theoretical relationship between the tangent constrained modulus (M), Poisson's ratio (μ) and Young's modulus (E). The constrained modulus (M) is defined, as illustrated in Figure 8, as:

$$M = \frac{\Delta\sigma_v}{\Delta\varepsilon_v}$$

The relationship between M, μ and E at a particular stress level is:

$$M = \frac{E\ (1 - \mu)}{(1 + \mu)(1 - 2\mu)} \tag{4}$$

Using the definition of the dilatometer modulus,

$$E_D = \frac{E}{1 - \mu^2} \tag{5}$$

the relationships for E_D, M and μ are summarized as follows:

(a) For E_D as a drained parameter -

$$M = E_D \frac{(1 - \mu)^2}{(1 - 2\mu)} \tag{6}$$

(b) For E_D as an undrained parameter -

$$M = E_D \frac{(1 - \mu)}{2(1 - 2\mu)} \tag{7}$$

Therefore, as Marchetti deduced, there appears to be some theoretical justification for a relationship between M and E_D which would have the form:

$$M = R_m\ E_D \tag{8}$$

Marchetti (1980) then used high quality oedometer test results to determine emperical correlations between M and E_D . Schmertman (1986) and others have reported good agreement between DMT and odometer M values, for a wide range of soil types, as indicated in Table 4.

TABLE 4
SUMMARY OF COMPARISONS
BETWEEN DMT & OTHER TESTS FOR SOIL COMPRESSIBILITY

Tangent Modulus, M

Item	Clay & Organic	Sand & Silt
No. of Comparisons	22	7
Average	-11%	+1%
Standard Deviation	40%	20%
Range (high)	+55%	+20%
Range (low)	-79%	-29%
Range in average DMT values (bars)	1.5 to 440	10 to 2000

A better test of the applicability of the DMT-based estimates of compressibility to solve real geotechnical problems is to compare predicted with actual settlement values. This has been done by Schmertmann (1986) for at least 14 sites, mainly in North America.

The settlements were calculated using the tangent modulus, M, and the methods suggested by Janbu (1983, 1985). The method can be expressed as follows for determining the settlement of a layer of soil with thickness Δz, at depth z:

$$Settlement, \Delta S = \frac{\Delta\sigma'_v(\Delta z)}{M}$$

Knowing the applied load, P, the vertical stress increase, $\Delta\sigma_v^1$, at depth z, is estimated using appropriate stress distribution charts, tables or algorithms. Using M values derived from the DMT (or from any other appropriate test procedure) the settlement for the layer, illustrated in Figure 10, is determined from the above expression.

Since there is an M_D value determined at 200mm intervals in a typical DMT test, the writer has found it convenient to subdivide the strata below a foundation into 200mm layers. A computer is then used to calculate the compression of each 200mm layer. The total settlement is the sum of the individual layer settlements.

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There are some important precautions which must be taken when using the DMT tangent modulus approach to estimating settlement. The geotechnical practitioner must ensure that M_{DMT} is appropriate for the stress range induced by the foundation loads. If the DMT values were measured in highly over-consolidated (HOC) soils, then M_{DMT} will be appropriate for stresses which do not exceed the preconsolidation pressure (Pc). If the DMT values were measured in normally-consolidated (NC) soils, the M_{DMT} again will be appropriate for stress increases normally encountered in practice. In the case of lightly over-consolidated (LOC) soils, however, the DMT values for M can be misleading, since the increased stress due to loading will probably exceed Pc.

Where significant layers of LOC soils exist below a proposed structure, it is necessary to revise the DMT value of M to reflect the higher compressibility in the stress ranges exceeding Pc. Schmertmann (1986) has developed very useful procedures for estimating revised M-values. This "Special Method" makes use of the modulus number (m) relationship reported by Janbu (1985) and allows reasonable settlement estimates in layers of LOC soils.

A comparison of DMT-calculated with measured settlement is provided on Table 5 and summarized in Figure 10. This comparison indicates that the DMT-based settlement estimates fall well within acceptable geotechnical engineering tolerances.

TABLE 5 - COMPARISONS BETWEEN DMT-CALCULATED AND MEASURED SETTLEMENTS

No.	Location	Structure	Compress. soil	Settlement (mm) DMT	**	Meas.	ratio DMT/Meas.
1	Tampa	bridge pier	HOC Clay	* 25	b,d	15	1.67
2	Jacksonvll.	Power Plant	compacted sand	* 15	b,o	14	1.07 (ave. 3)
3	Lynn Haven	factory	peaty sd.	188	a	185	1.02
4	British Columbia	test embankment	peat org. sd.	2030	a	2850	0.71
5a	Fredricton	surcharge	sand	* 11	a	15	0.73
b	"	3′ plate	sand	* 22	a	28	0.79
c	"	building	quick cl. silt	* 78	a	35	2.23
6a	Ontario	road embankment	peat	*300	a,o	275	1.09
b	"	building	peat	*262	a,o	270	0.97
7	Miami	4′ plate	peat	93	b	71	1.31
8a	Peter-borough	Apt. bldg	sd.& si.	* 58	a,o	48	1.21
b	"	Factory	"	* 20	a,o	17	1.18
9	"	water tank	si. clay	* 30	b,o	31	0.97
10a	Linkoping	2x3 m plate	si. sand	* 9	a,o	6.7	1.34
b	"	1.1x1.3m plate	si. sand	* 4	a,o	3	1.33
11	Sunne	house	silt & sand	* 10	b,o	8	1.25

* Denotes Ordinary M method used

** b denotes settlements calculated before the event
a denotes settlements calculated after the event
o denotes settlement calculations by other than the writer
d denotes dilatometer advanced by driving with SPT hammer.

Schmertmann (1986)

SUMMARY AND CONCLUSIONS

The flat dilatometer (DMT) in-situ testing method, developed by Marchetti, is a useful addition to the geotechnical engineers' procedures for assessing foundation soil characteristics.

Based on our experience, the DMT method is particularly good for estimating compressibility and predicting settlement. The estimated settlements, using both the ordinary method and Schmertmann's "special" method, appear to bracket the actual settlement range with a reasonable degree of accuracy. The method works in a wide variety of material from very dense sands to very soft organic soils.

As with any geotechnical testing method, engineering judgment is required when using the DMT method. In lightly over-consolidated material, for example, the in-situ DMT constrained modulus, M, could be misleading if used without regard to the actual stress level imposed by foundation loads. When used in conjunction with other conventional geotechnical samples and testing procedures, however, these limitations can be overcome.

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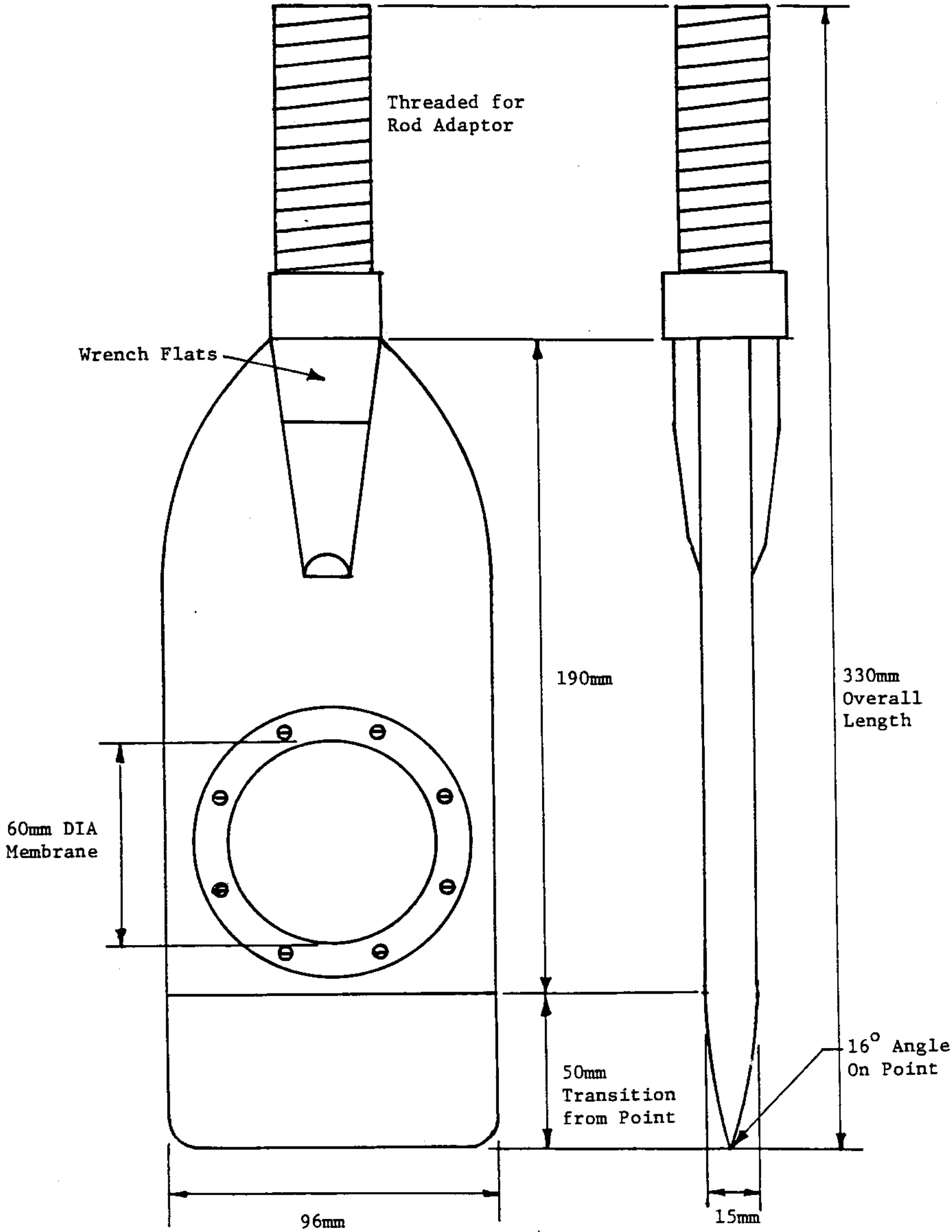
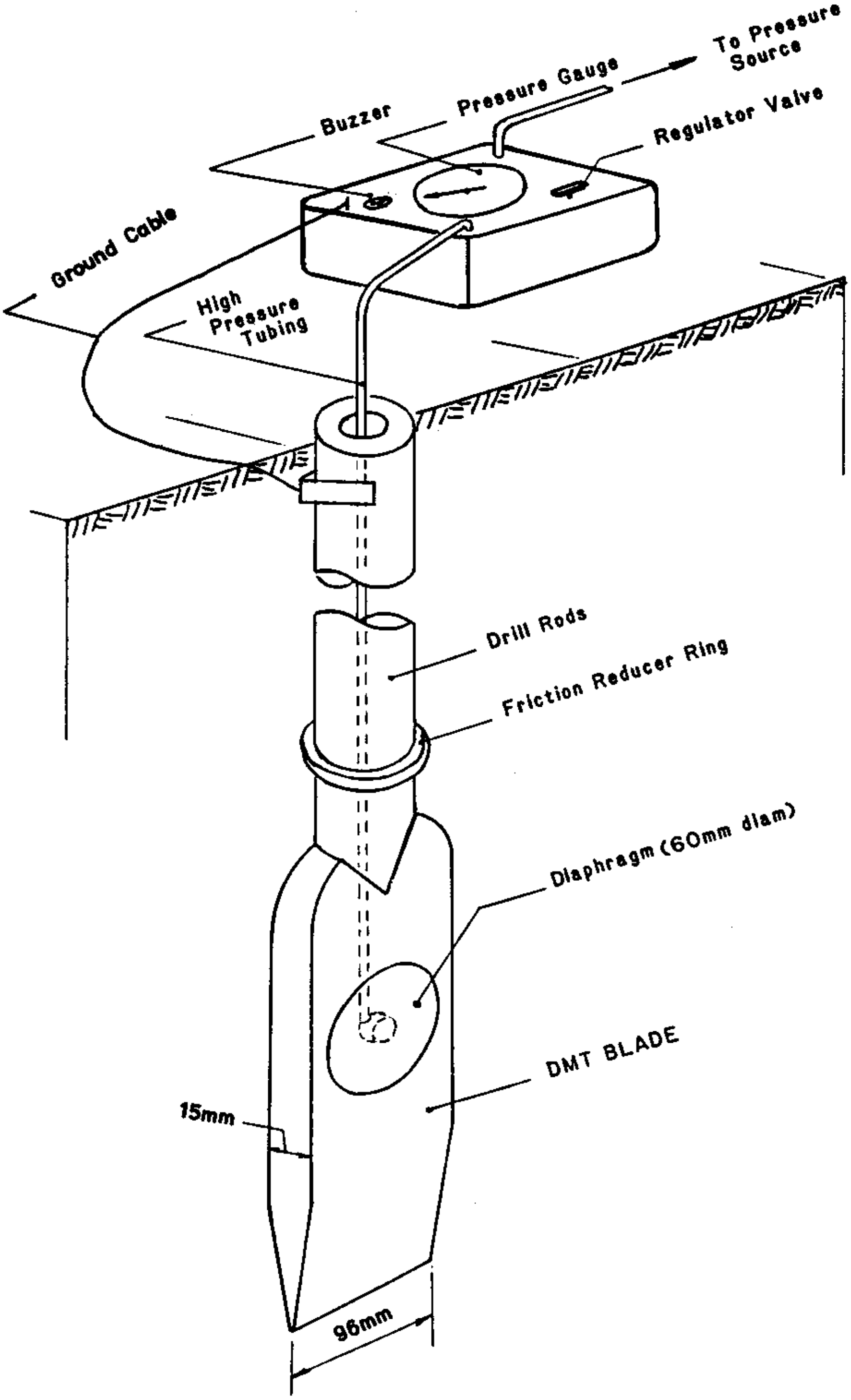


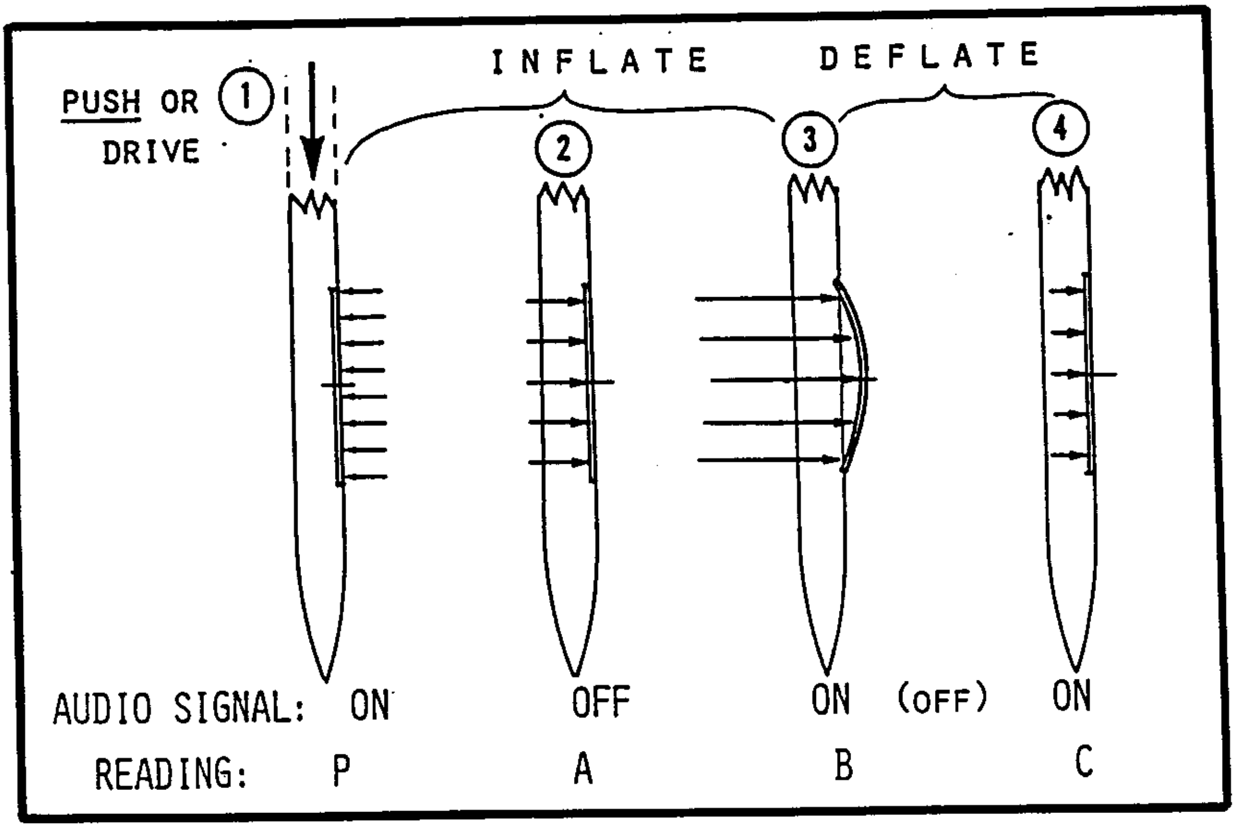
DILATOMETER BLADE DETAILS

DMT | Figure 1

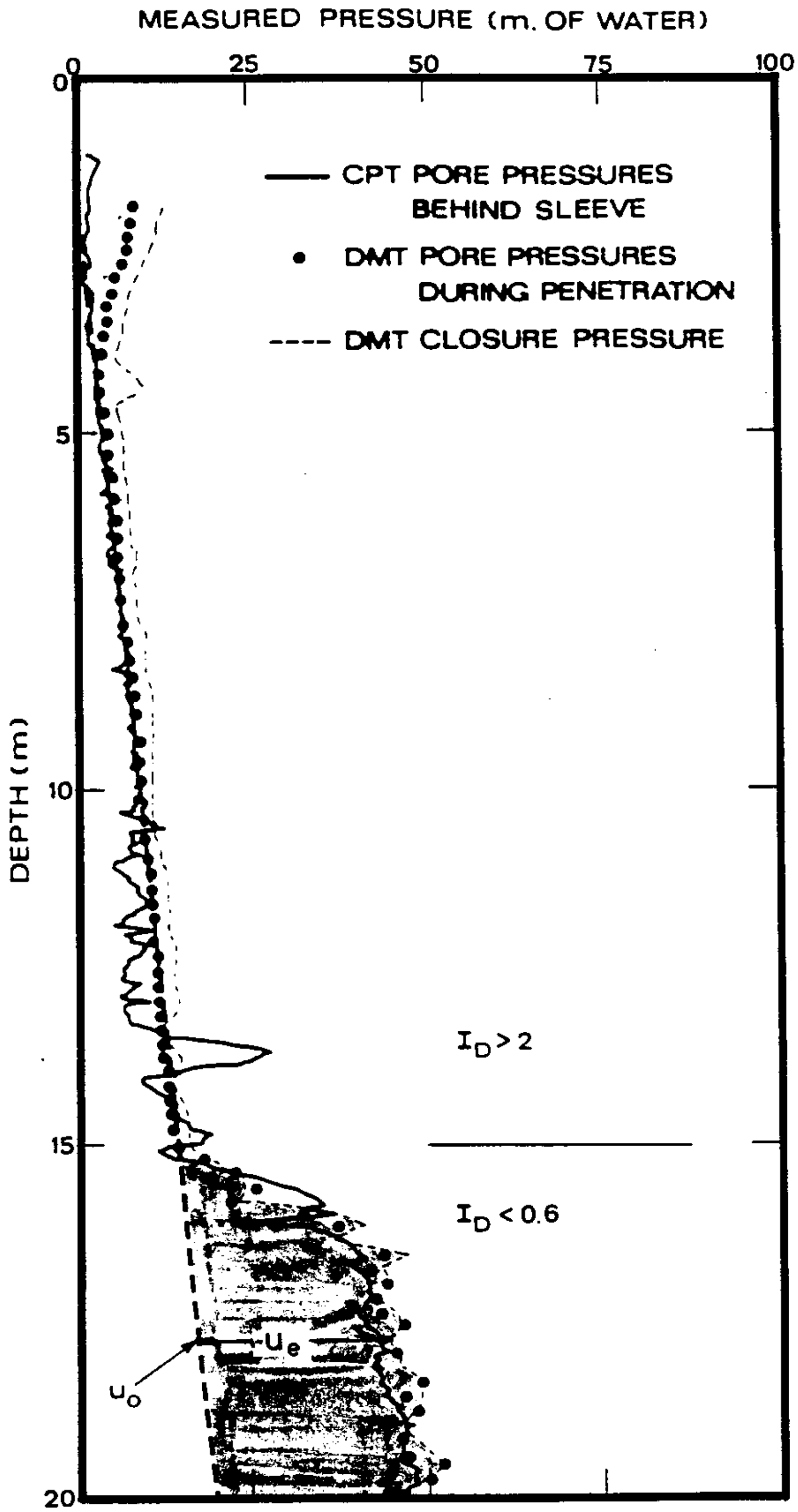


FLAT DILATOMETER EQUIPMENT

DILATOMETER TEST SEQUENCE

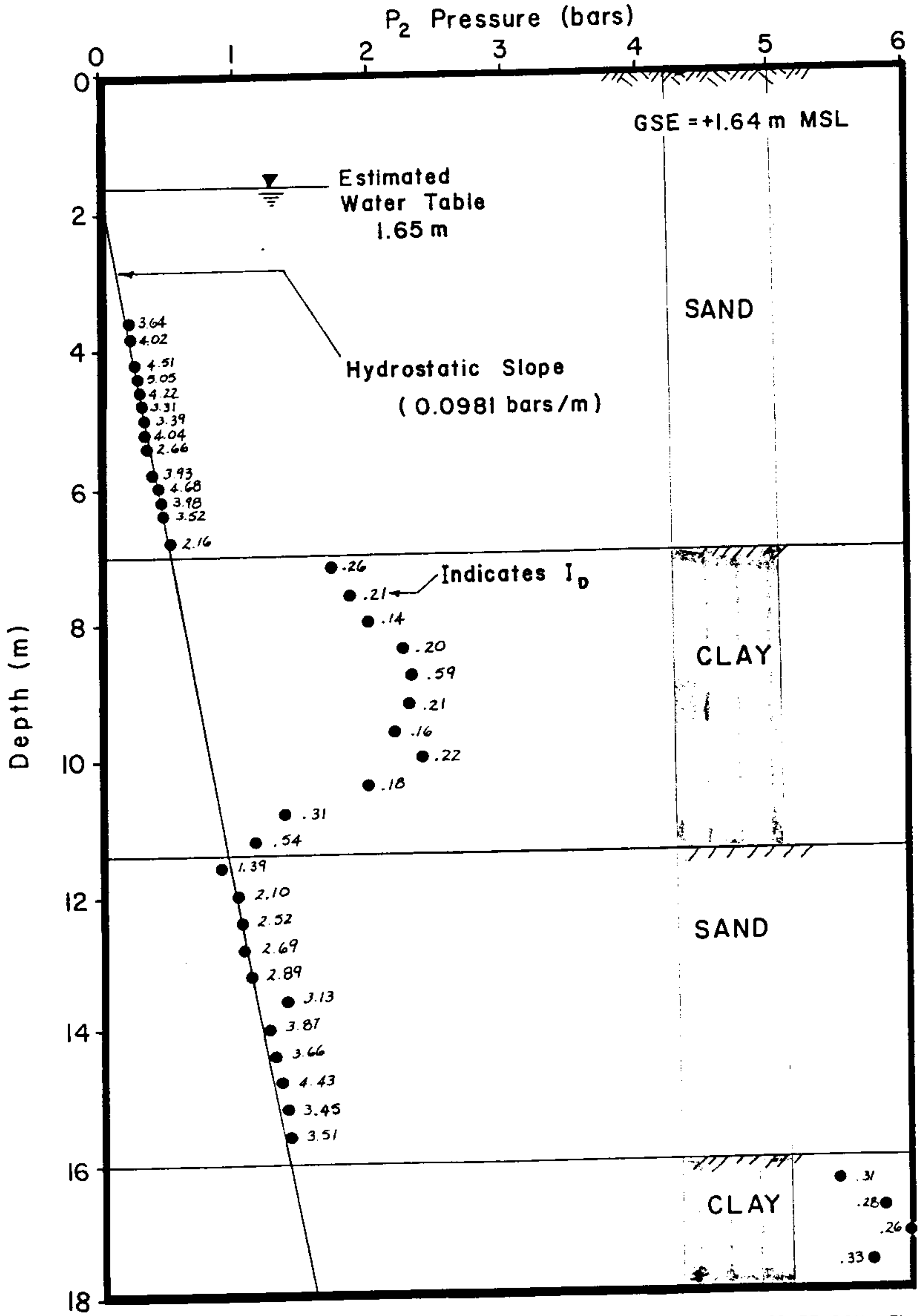


THE 4-STEP DILATOMETER TEST SEQUENCE
(VERTICAL SECTION THROUGH CENTER OF BLADE)



COMPARISON BETWEEN PENETRATION PORE PRESSURES FROM DMT AND CPTU AND CLOSING PRESSURES (C-READING) FROM NGI OFFSHORE DMT AT MCDONALD FARM SITE

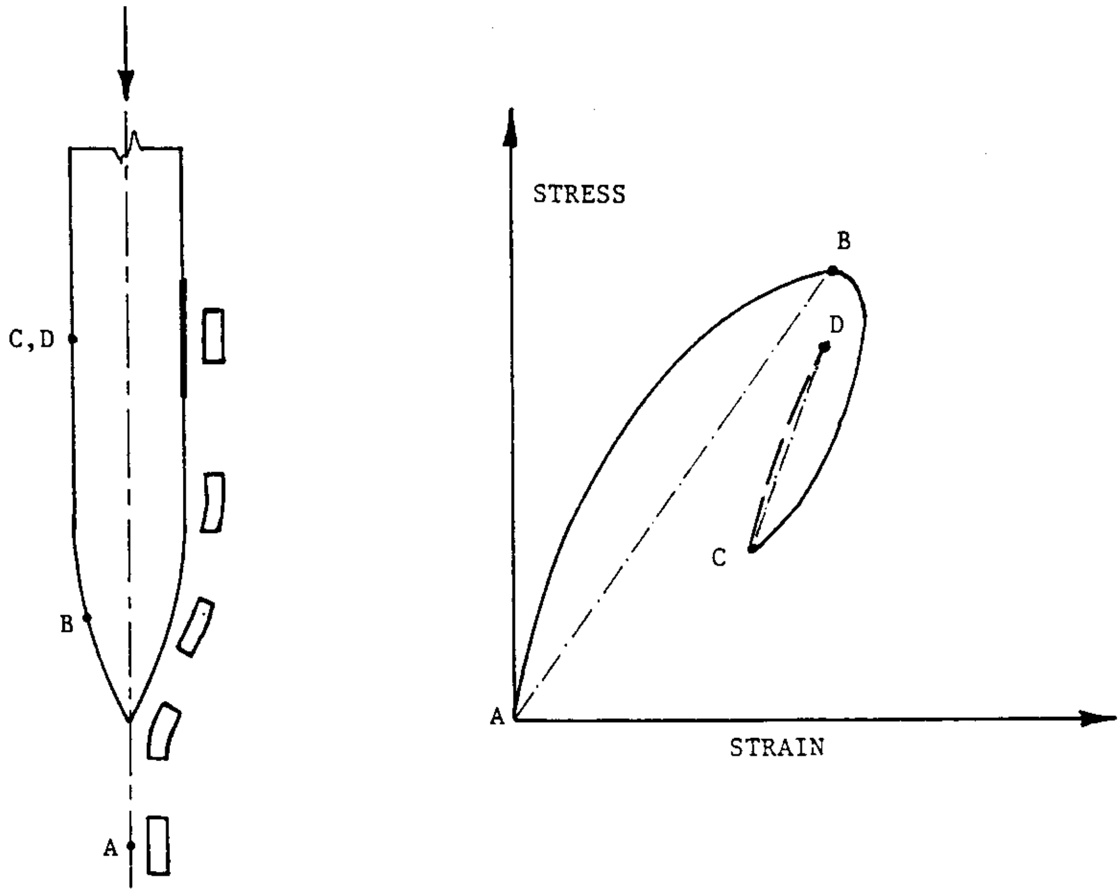
(Robertson, et al., 1988)



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

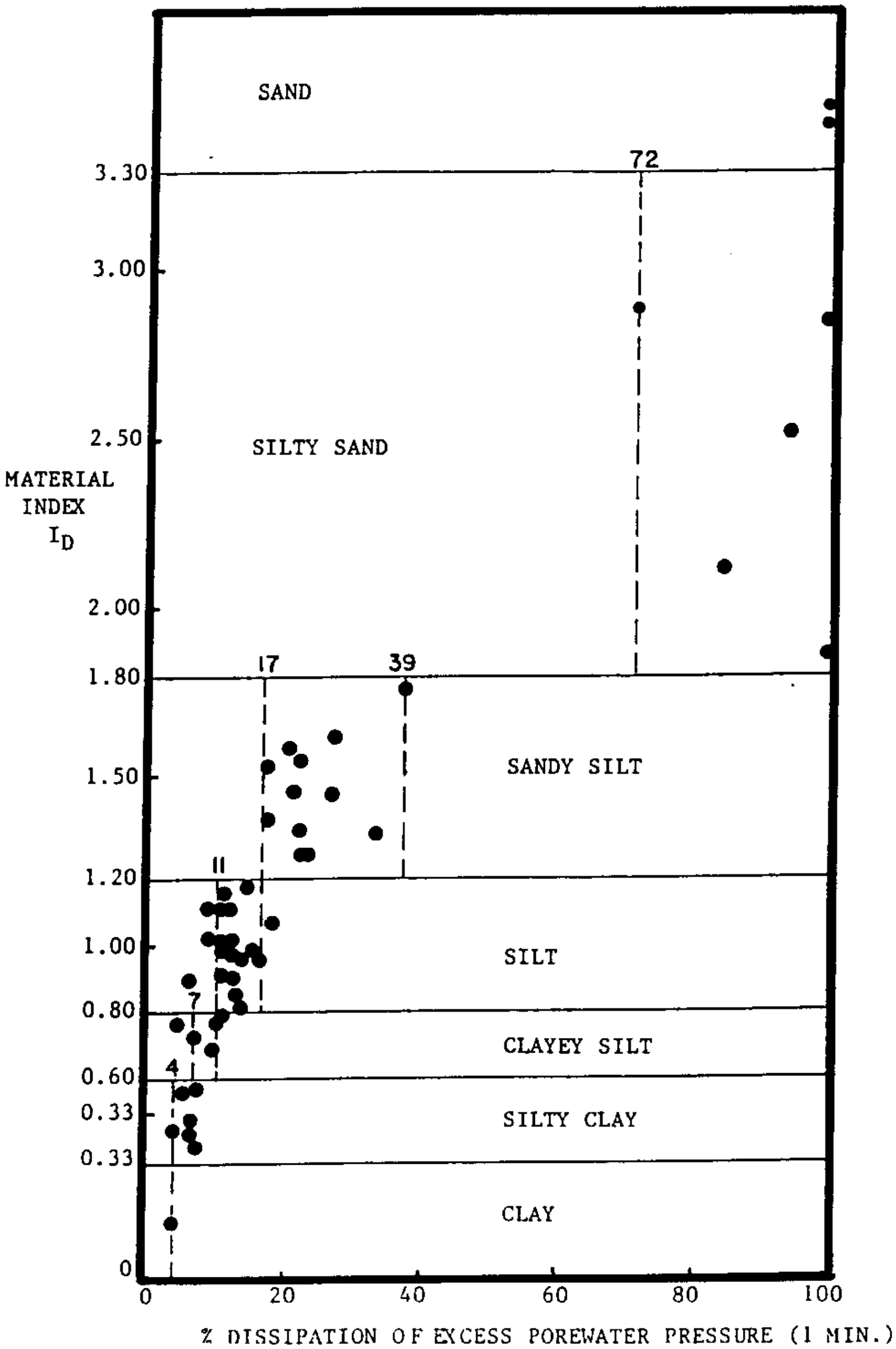
ABC ——— PENETRATION

CD — — — MEMBRANE EXPANSION

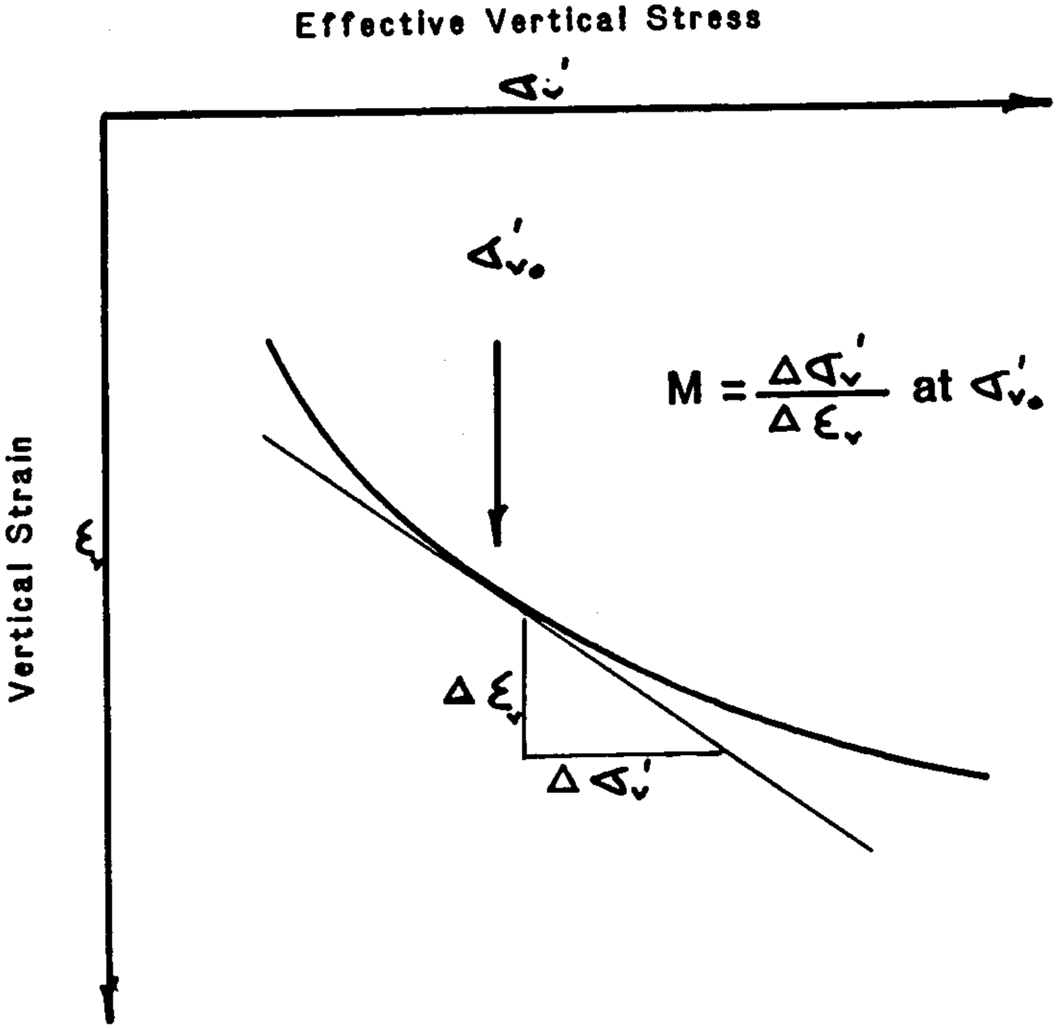


PROPOSED STRESS-STRAIN CURVE FOR AN "AVERAGE" SOIL ELEMENT FACING THE DILATOMETER BLADE AS THE TEST PROCEEDS FROM PENETRATION TO MEMBRANE EXPANSION. (Note the difference between the measured modulus and the modulus during penetration).

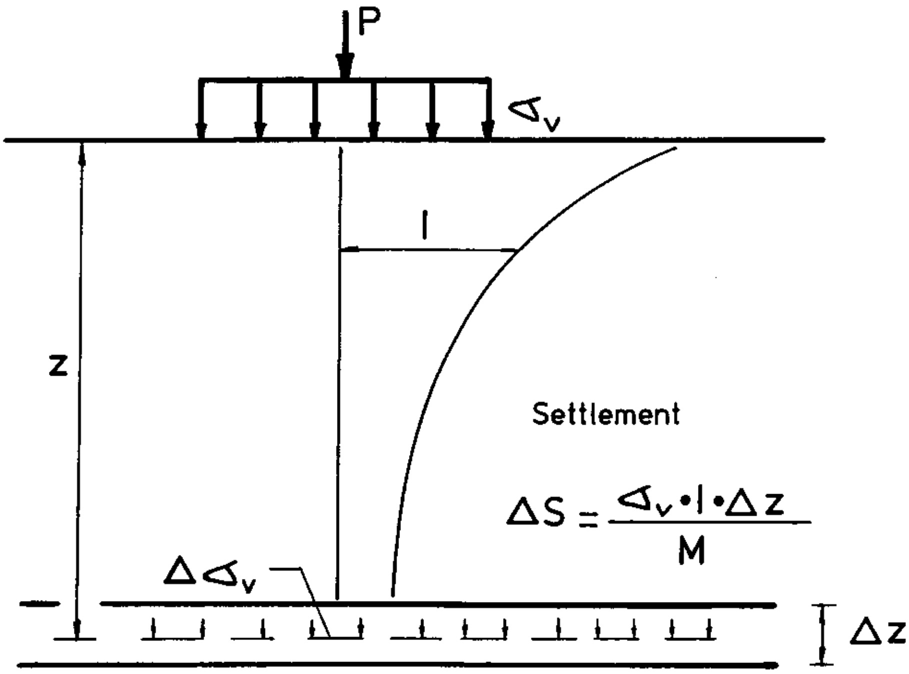
(Marchetti, 1981)



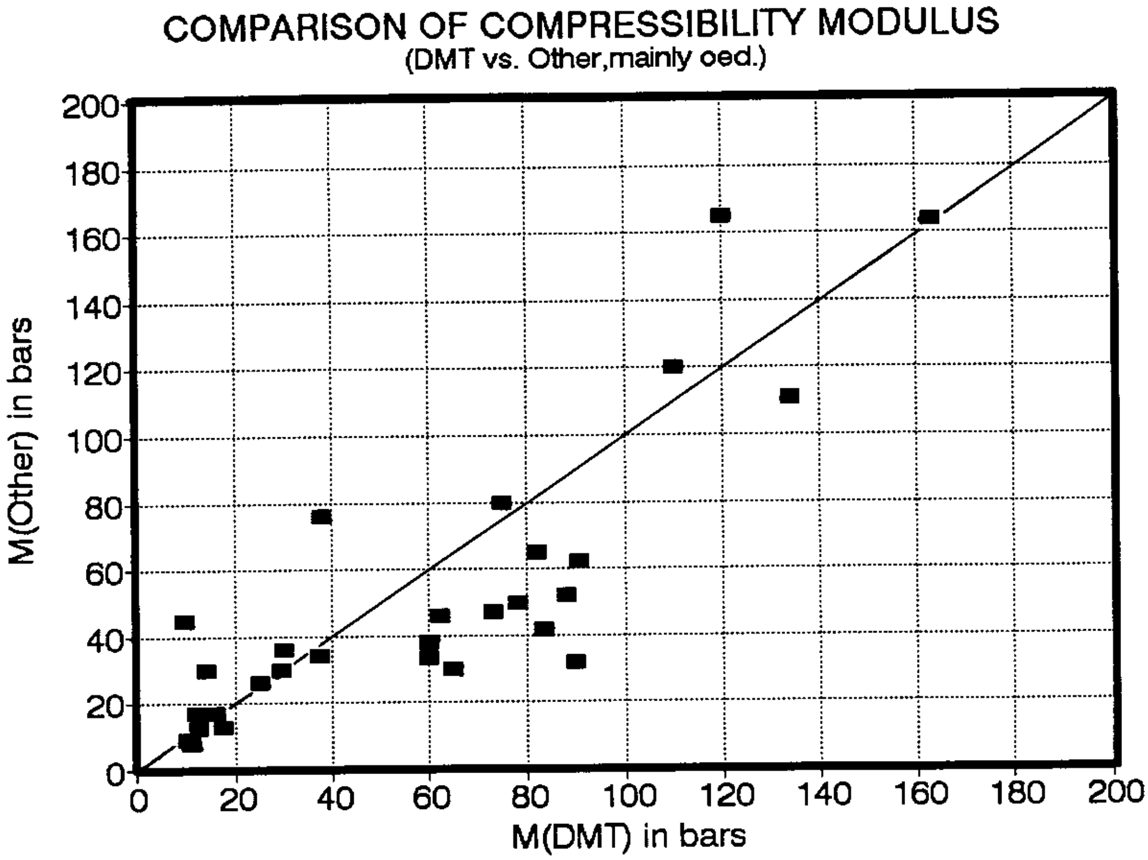
RESULTS OF DRAINAGE STUDIES WITH THE PIEZOBLADE AT THE UNIV. OF FLORIDA (Boghrat, 1987)



DEFINITION OF TANGENT CONSTRAINED MODULUS



CALCULATION OF SINGLE LAYER SETTLEMENT



NOTE: Comparison is for all materials except stiff fissured clays.

COMPARISON of OBSERVED and CALCULATED SETTLEMENT