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DILATOMETER TO COMPUTE FOUNDATION SETTLEMENT

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ABSTRACT

Sixteen examples demonstrate how the Marchetti dilatometer test (DMT) provides soil compressibility data for the rapid calculation of foundation settlements with an average ratio of predicted to actual settlement equal to 1.18. The examples include sands, silts, clays and organic soils, with settlement magnitudes from 3 to 2850 mm. The settlement prediction method includes the use of the basic, 1-D vertical compression modulus M, with an example calculation using both an Ordinary Method and a Special Method that includes adjusting M for the magnitude of effective stress.

1. INTRODUCTION

Geotechnical engineers have good use for an insitu test that permits a fast and usually adequately accurate calculation of ultimate foundation settlement in most problem soils. The Marchetti flat dilatometer test (DMT) has proven useful for such calculations in sands, silts, clays and even peat. Marchetti invented and developed the DMT in the mid-1970s. A brief description of the DMT follows. The reader can find more information in Jamiolkowski, et. al. (1985), Marchetti (1980, 1981), and Schmertmann (1981, 1983, 1984, 1985).

The basic DMT equipment consists of a stainless steel blade 96 mm wide and 15 mm thick with a sharp edge and a 60 mm diameter stainless steel membrane centered on and flush with one side of the blade. A syringe activated pressure-vacuum system permits the routine field calibration of each membrane. A single, combination gas and electrical line extends through the rods and down to the blade from a surface control and pressure readout box. The operator uses a flow control valve to increase the gas pressure behind the membrane and measures it at two points during its forced horizontal expansion into the soil. The first "A-reading" pressure occurs at membrane "lift-off" and the second "B-reading" pressure after 1.1 mm movement, with both prompted by an audio

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signal. The operator then immediately vents the gas pressure, rapidly at first and then finally more slowly using a second vent control valve to obtain a third "C-reading" pressure when an audio signal indicates the membrane has returned to its original lift-off position. The operator then pushes or drives the DMT blade to the next test depth, usually 0.15 to 0.30 m deeper, and repeats the above approximately 2 minute test cycle.

The A-pressure correlates to the insitu horizontal stress. The difference between the B and the A-pressures correlates to Young's modulus E and the vertical 1-dimensional compression modulus M. Recent, mostly unpublished, research suggests that the C-pressure, obtained after the soil has been pushed aside by the previous 1.1 mm expansion, gives the ambient pore water pressure in sands and includes excess hydrostatic in finer soils. At each test depth the Engineer uses the established theoretical and empirical correlations to reduce the data and interpret for the soil properties used in the settlement analysis. These properties include soil type, E, M, the preconsolidation stress p_c, the vertical effective overburden before the insertion of blade at the time and depth of the DMT, σ_D', and the equivalent overconsolidation ratio (OCR). The Engineer can reduce the data directly in the field using a calculator such as the HP-41, or later in the office using a computer.

After obtaining all the above information for each of the 0.15-0.30 m DMT test depth intervals, the Engineer can plot the results in the form of a near-continuous log and thus obtain a good picture of the soil profile and relevant properties. The I_D parameter calculated from the DMT data provides an index of soil type at each DMT. Boring samples are usually provided as a check on soil descriptions.

Figure 1 presents the log of an actual DMT sounding along the Georgia coastline, with part (a) presenting the complete tabular output and part (b) a computer-printer plot of the strength and compressibility results. The reader can see from Figure 1 that the DMT provides horizontal stress and soil strength data, as well as the properties used for settlement analyses. However, this paper focuses on settlement. The writer will subsequently make use of Figure 1 in an example settlement calculation.

SCHMERTMANN AND CRAPPS, INC. TEST NO. EXAMPLE
FILE NAME: TEST ENGINEERING CO.
FILE NUMBER: 99-999

RECORD OF DILATOMETER TEST NO. EXAMPLE
USING DATA REDUCTION PROCEDURES IN MARCHETTI (ASCE,J-GED,MARCH 80)
KO IN SANDS DETERMINED USING SCHMERTMANN METHOD (1983)
PHI ANGLE CALCULATION BASED ON DURGUNOGLU AND MITCHELL (ASCE,RALEIGH CONF,JUNE 75)
PHI ANGLE NORMALIZED TO 2.72 BARS USING BALIGH'S EXPRESSION (ASCE,J-GED,NOV 76)
MODIFIED MAYNE AND KULHAWY FORMULA USED FOR OCR IN SANDS (ASCE,J-GED,JUNE 82)

LOCATION: 5 FT. SOUTH OF STA 999+00
PERFORMED - DATE: 01 JANUARY 1980
BY: J.DRILLER & CREW -- PUSH BY HYDRAULIC CPT RIG

CALIBRATION INFORMATION:
DA= .22 BARS DB= .43 BARS ZM= .05 BARS ZW= 2.20 METERS
ROD DIA.= 3.60 CM FRICTION RED. DIA.= 4.80 CM ROD WEIGHT= 6.50 KG/M DELTA/PHI= .50

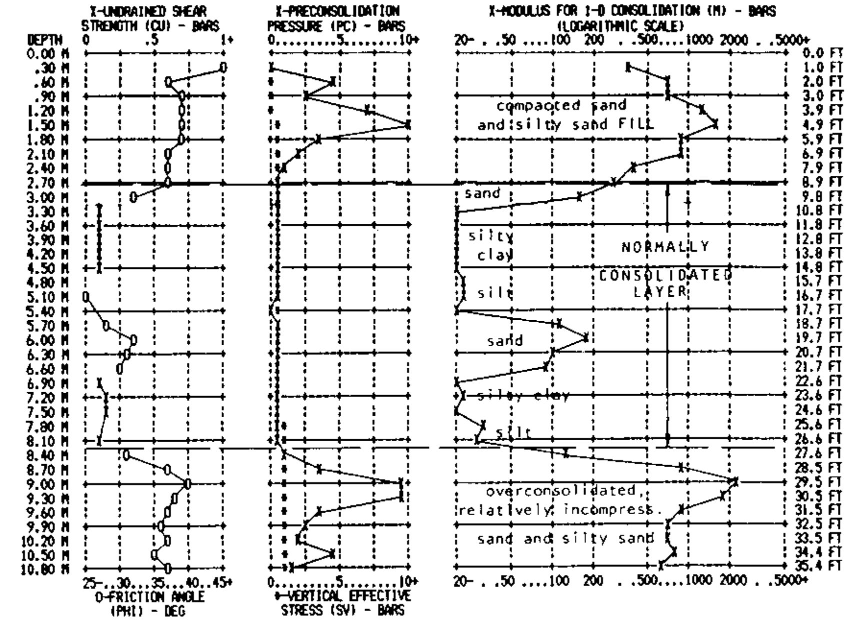
1 BAR = 1.019 KG/CM2 = 1.044 TSF = 14.51 PSI ANALYSIS USES H2O UNIT WEIGHT = 1.000 T/M3

Z (M)	THRUST (KG)	A (BAR)	B (BAR)	ED (BAR)	ID	KD	UO (BAR)	GAMMA (T/M3)	SV (BAR)	PC (BAR)	OCR	KO	CU (BAR)	PHI (DEG)	M (BAR)	SOIL TYPE
.30	380.	.61	5.25	145.	7.22	10.95	0.000	1.700	.053	.02	.40	.18		47.5	374.9	SAND
.60	760.	2.15	8.95	224.	3.21	18.99	0.000	1.900	.106	4.25	40.13	2.37		36.8	685.0	SILTY SAND
.90	1040.	2.14	9.75	254.	3.72	12.12	0.000	1.900	.162	2.58	15.95	1.50		38.8	676.3	SAND
1.20	1740.	4.15	16.20	415.	3.19	17.21	0.000	1.900	.218	6.98	32.05	2.12		38.9	1234.3	SILTY SAND
1.50	2400.	5.70	20.90	530.	2.97	18.68	0.000	2.000	.275	10.31	37.46	2.30		39.4	1639.0	SILTY SAND
1.80	1800.	3.60	14.70	381.	3.38	9.76	0.000	1.900	.333	3.61	10.85	1.24		39.3	943.9	SAND
2.10	1300.	2.87	14.45	398.	4.60	6.42	0.000	1.900	.389	2.15	5.53	.91		37.4	842.1	SAND
2.40	1060.	1.65	8.75	235.	4.63	3.58	.035	1.800	.408	.86	2.10	.57		37.4	378.1	SAND
2.70	960.	1.31	7.85	215.	5.49	2.58	.060	1.800	.436	.58	1.34	.46		37.0	284.0	SAND
3.00	480.	.91	6.22	170.	6.51	1.66	.095	1.800	.454	.52	1.15	.48		31.8	159.3	SAND
3.30	180.	.79	1.86	15.	.55	1.73	.135	1.600	.464	.37	.80	.47	.085		13.0	SILTY CLAY
3.60	60.	.94	2.06	17.	.53	1.91	.160	1.600	.486	.45	.93	.52	.101		14.6	SILTY CLAY
3.90	60.	1.13	2.24	17.	.44	2.16	.190	1.600	.503	.57	1.13	.59	.122		15.6	SILTY CLAY
4.20	80.	1.16	2.13	12.	.31	2.11	.220	1.500	.519	.56	1.09	.57	.122		10.5	MUD
4.50	140.	1.08	1.95	8.	.23	1.86	.250	1.500	.533	.47	.89	.51	.107		6.8	MUD
4.80	120.	.98	2.37	27.	.93	1.51	.275	1.600	.554	.36	.65	.40			22.9	SILT
5.10	160.	.72	2.10	27.	1.40	.96	.305	1.600	.571	.70	1.23	.63		21.9	22.6	SANDY SILT
5.40	180.	.85	2.18	25.	1.10	1.11	.335	1.600	.588	.23	.40	.27			21.1	SILT
5.70	320.	.88	5.25	136.	7.83	.82	.365	1.700	.607	.55	.90	.48		27.7	115.2	SAND
6.00	620.	1.47	7.92	211.	6.34	1.52	.390	1.800	.633	.68	1.08	.47		32.0	182.1	SAND
6.30	520.	1.17	5.13	121.	4.61	1.15	.420	1.700	.655	.61	.93	.45		30.8	102.5	SAND
6.60	480.	1.02	4.45	101.	4.82	.89	.445	1.700	.680	.55	.81	.43		30.3	86.1	SAND
6.90	320.	1.14	2.39	22.	.78	1.15	.475	1.600	.698	.30	.42	.28	.077		18.6	CLAYEY SILT
7.20	220.	1.71	3.09	27.	.57	1.87	.500	1.600	.720	.65	.90	.51	.145		22.6	SILTY CLAY
7.50	200.	1.78	3.05	23.	.47	1.88	.525	1.600	.742	.67	.91	.51	.151		19.2	SILTY CLAY
7.80	180.	1.42	3.12	38.	1.12	1.29	.550	1.600	.765	.39	.51	.33			32.5	SILT
8.10	240.	1.57	3.16	34.	.89	1.42	.580	1.600	.782	.46	.59	.38	.112		29.1	CLAYEY SILT
8.40	680.	1.73	6.28	142.	3.72	1.36	.605	1.800	.807	.84	1.04	.47		31.4	120.8	SAND
8.70	2200.	5.56	19.10	470.	3.04	5.32	.630	2.000	.838	3.58	4.28	.81		37.3	916.6	SILTY SAND
9.00	4100.	10.05	35.40	900.	3.11	9.53	.655	2.150	.874	9.56	10.95	1.25		39.6	2212.6	SILTY SAND
9.30	3600.	9.85	30.70	736.	2.55	9.13	.680	2.150	.912	9.67	10.60	1.24		38.5	1780.1	SILTY SAND
9.60	2100.	5.60	19.60	486.	3.19	4.64	.705	2.000	.948	3.39	3.58	.76		36.6	891.4	SILTY SAND
9.90	1800.	4.75	17.05	424.	3.39	3.68	.730	1.900	.981	2.56	2.61	.66		35.8	692.5	SAND
10.20	2100.	4.50	18.25	477.	4.22	3.22	.755	1.900	1.011	2.02	1.99	.57		37.3	723.8	SAND
10.50	1900.	6.35	18.90	434.	2.43	4.93	.780	2.000	1.044	4.45	4.26	.84		34.8	806.1	SILTY SAND
10.80	2000.	4.10	17.30	457.	4.64	2.64	.805	1.900	1.076	1.67	1.55	.51		37.0	613.7	SAND

END OF SOUNDING

FIGURE 1a COMPUTER LISTING OF INPUT DATA AND OUTPUT RESULTS FROM AN ACTUAL DMT SOUNDING

Legend: (cols. left to right)
Z, THRUST, A, B = input data from the field
ED, ID, KD = computed dilatometer indices
UO, GAMMA, SV = input for vert. eff. stress SV
PC, OCR, KO, CU, PHI, M, SOIL TYPE = interpreted engineering properties of soil tested



END OF SOUNDING

FIGURE 1b

SHOWING PROFILES OF STRENGTH AND COMPRESSIBILITY PROPERTIES AS DETERMINED FROM THE DMT SOUNDING

2. JANBU SETTLEMENT MODULUS

The settlement analysis procedure when using DMT data has several advantages and disadvantages when compared to other USA practice such as using the semi-log curves from a consolidation test. In addition to speed, economy and possibly less disturbance that are inherent in DMT testing insitu, the advantages include the routine use of a simple settlement modulus concept. Janbu (1963, 1967) long ago developed such a modulus-based settlement analysis procedure, which has now become popular and perhaps dominant in Europe. The 1-D vertical compression modulus, M, gives the tangent value of the slope of the 1-D stress-strain curve. Just as with any other engineering modulus it gives the ratio of cause/effect, in this case stress/strain. The 1-D settlement is calculated by multiplying the stress induced strain by the layer thickness. The DMT settlement analysis procedure described herein is a fundamental procedure that is not linked to any unique analysis method or type of test. The M and p_c values could come from any test providing such information. Of course, this paper uses values obtained from the DMT.

The DMT determines the properties of the soil insitu at the time of the test and therefore at only one point on the M-σ_v' curve. With only normally consolidated (NC) soil insitu the DMT will provide no direct information about unloading or reloading moduli. With only overconsolidated (OC) soil insitu, the DMT will provide no direct information about virgin compression moduli. If needed, one must estimate the missing moduli using the best data and principles available, as discussed subsequently in Section 4.

Janbu expressed the value of M in terms of a dimensionless modulus number, m, multiplied by a function of the vertical effective stress which depends on the soil type and its state of consolidation. Equations (2a, b, c and d) present his approach, which the writer recommends and expands on in Section 4.

For NC clay (and organic soils), $M = m\,\sigma_v'$ . . . . (2a)

(where $m = [(1+e)/C_c] \ln 10$, e = void ratio and C_c = compression index) . . . . (2b)

For NC silts and sands, $M = m(\sigma_a' \sigma_v')^{0.5}$ . . . . . (2c)

(where σ_a' = a reference stress of magnitude = 1)

For OC soils and rocks, $M = m$ . . . . (2d)

Figure 2a illustrates Janbu's (1963) unifying concept of relating modulus number to porosity in all soil materials. He recently presented similar, updated graphs in his Rankine Lecture, Janbu (1985), as shown in Figures 2b and 2c. Figure 2 presents typical m value ranges that apply to normally consolidated (NC) soils. It provides a useful framework in which to evaluate the reasonableness of the M values determined by the DMT, or to estimate the values of M needed in Sections 4.3 and 4.4. Note that overconsolidated (OC) soils have higher m and M values.

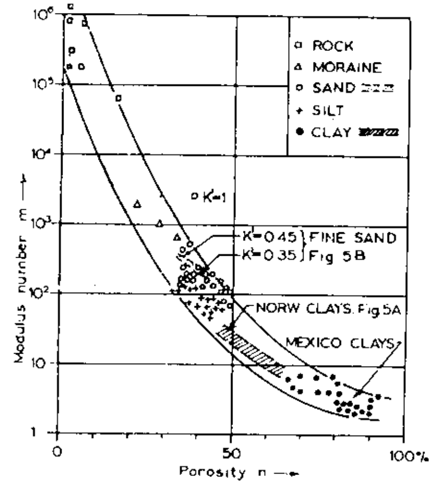
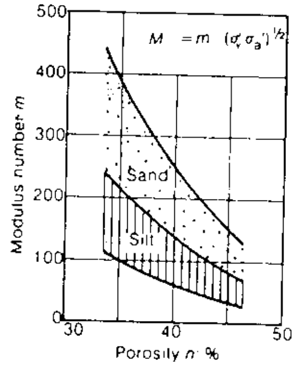
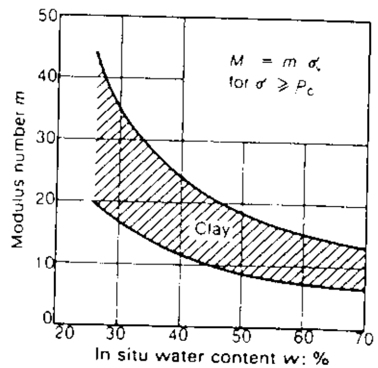


FIGURE 2

REFERENCE VALUES OF 1-D MODULUS NUMBERS, m, VS. POROSITY AND WATER CONTENT IN GEOTECHNICAL MATERIALS

(a) General relationship between m and porosity for all geotech materials (from Janbu, 1963)





Typical modulus numbers for normally consolidated sand, silt and clay

(b) For Sand and Silt (from Janbu, 1985)

(c) For Clay (from Janbu, 1985)

3. EXAMPLE SETTLEMENT CALCULATIONS

Table 1 presents a step by step procedure for calculating settlement using DMT data for the relevant soil properties. The first part of the table lists 7 steps for the Ordinary Method of analysis wherein M does not vary with stress level and is taken equal to M as found from the DMTs. The second part of Table 1 lists 5 additional steps needed in the Special Method to include varying M with varying stress level. Relatively few problems require using the Special Method. The listing in subsequent Table 5 shows only 3 out of 16 cases, all involving weak soils near the surface. A little experience with comparing the results from using both methods on the same problem will soon show the user when the additional work involved to use the Special method seems justified. The following example can start that experience with a case wherein the Ordinary Method seems adequate.

Consider the following example settlement calculation problem. Assume the soil conditions given by the data in Figure 1 and consider placing a 6 m (20 ft) equivalent flexible, circular footing at a depth of 0.9 m (3 ft) and loading it to provide a net pressure increase of 191 kPa (2 tsf). How much ultimate settlement should be expected when calculated from the DMT sounding data?

3.1 Ordinary Method: Table 2, Cols. 1 and 2, lists the writer's choice for dividing the potentially compressible soils into six sublayers (step 2). Note that the Ordinary Method part of Table 2 includes only two of the six sublayers. Ordinarily the writer would have considered, after inspection of the relative M values from the DMT sounding, that only sublayers 3 and 5 had significant compressibility and not bothered with the other sublayers. Column 11 lists the average M values from the DMT soundings for each layer (step 3). The next step 4 involves calculating the stress increase due to the footing loading. The situation closely matches that given in NAVFAC (1982, Fig. 15, p. 7.1-180) and the writer simply used the stress increases given therein. Table 2 lists these stress increases in Col. 7.

The analysis steps remaining, Nos. 5, 6 and 7 now carry forward into Table 3. Col. 5 gives the results of steps 5 and 6, with a total calculated settlement of 58.8 mm (2.32 in.). The final corrections using step 7, if any, are briefly and separately discussed in Section 3.3 herein. These corrections would apply to both the Ordinary and Special Method results in Table 3.

TABLE 1 - RECOMMENDED SETTLEMENT ANALYSIS STEPS USING DMT DATA

ORDINARY METHOD

1. Perform a DMT sounding at each settlement analysis location and determine profiles of M through the soil layers of interest.
2. Divide the compressible soils into layers and/or sublayers of similar soil type and stiffness.
3. Determine the average M value from the DMT results for each layer and sublayer in 2.
4. Calculate the vertical stress increase $\Delta\sigma_v$ at the mid-height of each layer and sublayer in 2. The Engineer can use any suitable method to calculate the vertical stress increase.
5. Calculate the 1-D settlement of each layer or sublayer using the following equation (1):

$$\text{settlement} = \frac{\text{stress increase x thickness}}{\text{modulus}} = \frac{\Delta\sigma_v}{M}(H) \quad . \; . \; . \quad (1)$$

6. Obtain the total 1-D settlement by adding all the contributions from the layers and sublayers in 5.
7. Make corrections to the settlement calculated in 6., as appropriate from Section 4.3 and any DMT experience with similar soils and loadings.

SPECIAL METHOD ADDITIONS TO STEP 4

4.1 Calculate the initial effective overburden stress σ_o' at the mid-height of each layer and sublayer in 2.

4.2 Determine the average p_c and σ_D' value from the DMT results for each layer and sublayer in 2.

4.3 Compare σ_D' vs. σ_o' (the effective overburden pressure at the time of the structure loading may not be the same as at the time of the DMT because of excavation, surcharge, dewatering, etc.).

4.4 Compare p_c and $(\sigma_o' + \Delta\sigma_v)$ and decide on which of the following cases applies to each layer or sublayer.

a. All virgin compression: use M for the normally consolidated (NC) case.
b. All recompression: use M for the OC case.
c. The stress increase spans part recompression and part virgin compression: use M from 4.5 below.

4.5 Make adjustments to the average M values in step 3, as needed. (discussed in text under 3.2 Special Method)

3.2 Special Method: This method includes the extra steps 4.1 - 4.5 listed in Table 1, the sole purpose of which is to adjust M to the average vertical effective stress during the loading that produces the settlement of interest. The extra columns in Table 2 accommodate these extra steps. The writer has also included all 6 sublayers to provide more examples.

Table 2, Col. 4, lists the best estimate of the mid-layer vertical effective stress σ_D' at the time of performing the DMTs. Usually σ_D' also closely equals the initial vertical stresss at the start of the settlement process, σ_o', and the writer has taken them equal for this example and thus completes steps 4.1 and 4.3. Col. 7 lists the average p_c values for each sublayer as obtained from the DMT results, and thus completes step 4.2. Col. 8 gives the final effective stress in the settlement process, σ_f', which equals the sum of Cols. 6 and 7. Proceed to step 4.4 by comparing cols. 6 and 7 to make the decisions as to whether the settlements will be virgin (NC), recompresion (OC) or both. Col. 10 lists each decision.

TABLE 2 - EXAMPLE SETTLEMENT CALCULATION TABULATION BASED ON THE DMT DATA IN FIGURE 1.

1	2	3	4	5	6	7	8	9	10	11	12	13
Layer No	Top (m)	℄ (m)	σ_D' (kPa)	Soil	σ_o' (kPa)	$\Delta\sigma_v$ (kPa)	σ_f' (kPa)	p_c (kPa)	OC NC	M (MPa)	m	use M (MPa)
FOR THE ORDINARY METHOD:												
3	3.1	4.35	—	si. Cl.	—	30	—	—	—	1.6	—	1.6
5	6.7	7.45	—	cl. Si.	—	19	—	—	—	2.4	—	2.4
FOR THE SPECIAL METHOD:												
1	0.9	1.55	28	Sd.	28	67	95	580	HOC	117	-	117
						22			LOC		200	21.8
2	2.2	2.65	43	Sd.	43	48	91	65		27.4		
						26			NC		200	17.6
3	3.1	4.35	52	si. Cl.	52	30	82	46*	NC*	1.6	-	2.06
4	5.6	6.15	64	Sd.	64	23	87	60*	NC*	12.1	-	13.1
5	6.7	7.45	74	cl. Si.	74	19	93	50*	NC*	2.4	-	2.54
6	8.2	9.5	95	si. Sd.	95	12	107	420	OC	97	-	97

*The DMT correlations used interpreted these layers as, on the average, a little underconsolidated. The writer could find no physical basis for underconsolidation, and therefore attributed this interpretation to correlation errors and used the NC case for the computations. As with all tests, the engineer should use appropriate judgement when interpreting results.

The user is now ready for step 4.5, which requires the use of more detailed explanations given in Section 4. herein. Col. 13 in Table 2 gives the resulting adjusted average M values for each sublayer after using the procedures described in Section 4. These adjusted Ms are then transferred into col. 4 of Table 3 and steps 5 and 6 produce the col. 5 value of 52.7 mm (2.08 in.) for the computed ultimate consolidation settlement. In this case the Special method produced a calculated settlement about 10% less than that from the Ordinary Method. As noted in Section 4.4, the Ordinary Method can also underpredict settlement.

3.3 Corrections: The settlement calculation presented in Sections 3.1 and 3.2 applies to consolidation or volume change settlement under a perfectly flexible loaded area, in 1-D compression only. Each of these assumptions may or may not deviate significantly from reality and require some form of correction to the calculated settlement values. The length of this paper does not permit a detailed examination of each. Therefore, the reader is referred to the various pages in NAVFAC (1982) that are briefly cited below. This is a widely available reference that hopefully the reader will find convenient to use.

3.3.1 Immediate (Pseudo-Elastic) settlements: This requires Young's modulus, E. Use the ED column in Figure 1a. as equivalent to E for sands. However, the calculation for immediate settlement in sands using E is normally an alternate to using M and not an addition. For cohesive soils use the M column, with E approximately 75% M. Use the formulae and factors on pp. 7.1-211-218.

TABLE 3 - THE 1-D, CONSOLIDATION SETTLEMENT CALCULATION FOR THE EXAMPLE 6m DIAM. FLEXIBLE LOADED AREA AT THE FIG. 1 DMT SOUNDING LOCATION

1	2	3	4	5
LAYER	THICKNESS H(m)	(kPa)	M (MPa)	settlement eqn. (1) [in Table 1]
FOR THE ORDINARY METHOD:				
3	2.5	30	1.6	46.9
5	1.5	19	2.4	11.9
				58.8 mm (2.32 in)
FOR THE SPECIAL METHOD:				
1	1.3	67	117	0.7 mm
2LOC	0.9	22	21.8	0.9
2NC	0.9	26	17.6	1.3
3	2.5	30	2.06	36.4
4	1.1	23	13.1	1.9
5	1.5	19	2.54	11.2
6	2.6	12	87	0.3
				52.7 mm (2.08 in)

3.3.2 Structural Rigidity: Use Table 1 in pp. 7.1-212-213.

3.3.3 3-D effects: Page 7.1-225 provides a convenient graph to make the Skempton and Bjerrum (1957) correction for 3-D and related overconsolidation effects. See pp. 7.1-211, 216-217 for correcting for possible lateral displacement effects.

3.3.4 Secondary and creep: Requires other than DMT data to evaluate such effects.

3.3.5 Aging: The evaluation of this effect requires DMT or other types of data over a period of time.

3.3.6 Summary: Pseudo-elastic settlements, lateral displacements, and creep-secondary effects all tend to increase settlement. Rigidity, overconsolidation and aging effects tend to decrease settlement. Unless the Engineer has some reason to consider that one or more of these effects will have a major impact on the problem, it might be assumed that these effects all approximately cancel and that the results of the analysis described in Sections 3.1 and 3.2 provide an adequate answer without the refinements of Section 3.3.

4. CONSTRUCTING THE M VS. σ_v' GRAPHS

This section divides the problem into four cases; NC in all soils, highly overconsolidated (HOC) in all soils, lightly overconsolidated (LOC) clay and peat and LOC silt and sand. The values of M obtained for Col. 13 in Table 2 refer to the average values that apply to each layer or sublayer, and each may require its own graphical construction or the mathematical equivalent of such a construction. The constructions are shown in Figures 3a through 3d and are discussed individually. The double, open lines shown in these figures indicate the Ordinary (constant-M) Method used in Section 3.1.

The suggested M-graph construction procedures are admittedly oversimplified and can only roughly estimate the actual, unknown relationship between M and σ_v'. Nevertheless, the writer recommends their use in the absence of superior information. They should be adequate for most settlement analysis purposes in ordinary sands, silts, clays and organic soils.

4.1 The highly OC case: Figure 3a illustrates this case. The writer recommends the following construction steps: 1) Plot the M-σ_D' point "1", 2) check the reasonableness of m, which = M, compared to the ranges given in Figure 2. The OC value of m should exceed these NC reference values. 3) construct a horizontal line (constant M) through the point "1" in Figure 3a.

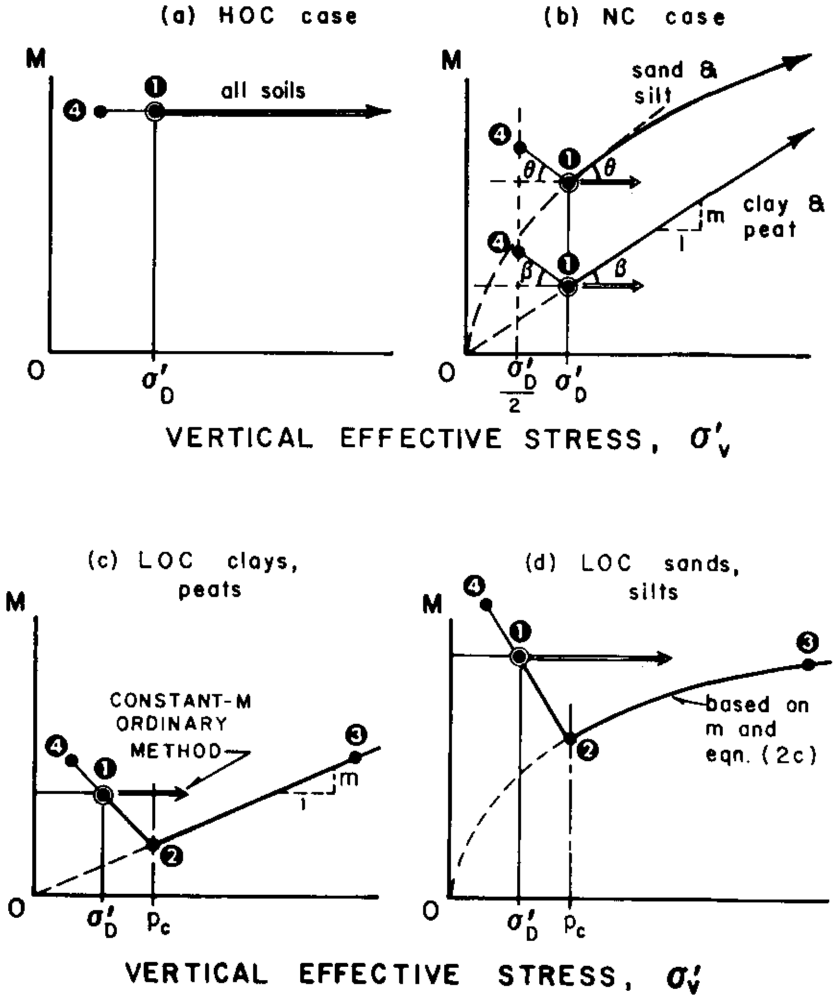


FIGURE 3 - SUGGESTED CONSTRUCTIONS FOR THE ADJUSTMENT OF M FROM THE DMT TO OTHER MAGNITUDES OF VERTICAL EFFECTIVE STRESS

This means that the Engineer can consider the soil as so highly overconsolidated that the subsequently applied stress increase will not approach the p_c point and that M can be considered independent of σ_v'.

4.2 The NC case: Figure 3b presents the construction for this case. The writer recommends the following steps: 1) plot the M-σ_D' point "1", 2) Calculate m according to either eqn. (2a) or (2c), depending upon soil type. Check for reasonableness of m in accord with the reference values in Figure 2. 3) if reasonable, proceed; if not, either look for an explanation and use as tested, or retest if judged appropriate. 4) Use either eqn. (2a) or (2c) to extend the graph in the direction of higher stress levels. 5) construct a line, in the direction of lower stress levels to 0.5 σ_D' at point "4" using the angle (θ or β) to the horizontal equal to that for stresses higher than σ_D'. Use supplemental test data for evaluating recompression M at less than 0.5 σ_D' (applies to all cases). Note that the Ordinary Method with NC soils involves the use of too-low values of M and will tend to overpredict settlement (as in Table 3).

4.3 Lightly OC clay and organic soils: Figure 3c presents the construction for this case. The writer recommends the following steps: 1) plot the M vs. σ_D' point "1", 2) estimate m using either Figure 2b, or eqn. (2b) with assmed values of e and C_c from the virgin compression data correlations presented on p. 7.1-224 of NAVFAC (1982). 3) Calculate M at p_c using this m and eqn. (2a) and plot as pt. "2". 4) fit a line with slope m through point "2" and the origin, 5) construct the line 1-2-3 as an estimate of how M varies with increasing effective stress, 6) Line 2-1 can then be extended backward to cover the recompression range to 0.5 σ_D' by the line 1-4.

Sometimes the shape of the curve between points 1-2-3 can be evaluated from other DMT data in the same sounding or at the same site. For example, the same clay may become progressively less overconsolidated and even become normally consolidated with depth and thus provide data for successive points along the 1-2 or 1-2-3 portion of the construction.

4.4 Lightly OC silt and sand: Figure 3(d) illustrates this construction. The writer recommends the same steps as in Section 4.3 and Figure 4c, with the change that instead of fitting a straight line through point "2" in accord with eqn. (2a), one fits a parabola through point "2" in accord with eqn. (2c).

Note that the use of the Ordinary Method with LOC soils usually involves the use of a too-high M below the p_c stress and thus will tend to underpredict settlement.

5. ACCURACY COMPARISONS

The following comparisons should help the reader evaluate the accuracy that might be expected from settlement analyses based on data from DMT soundings and the correlations in current use. The following sections consider soil properties and then overall results of settlement analyses.

5.1 p_c and M comparisons: Table 4 presents comparisons between p_c and M values as determined from the DMT compared to high quality oedometer tests, or large calibration chamber tests, or backfigured field test settlement measurements. Table 4 presents averages, standard deviations and ranges for clay and organic soils and for sand and silt. The compilation in this table suggests that the DMT will usually provide p_c and M values adequate for most ordinary work, with good averages but with considerable spread.

TABLE 4 - SUMMARY OF COMPARISONS BETWEEN DMT & OTHER (BELIEVED SUPERIOR) TESTS FOR SOIL COMPRESSIBILITY PROPERTIES

[DMT-other)/(other]%

	p_c		M	
	clay+org.	sd.+si	clay+org.	sd+si
No. comparisons	17	5	22	7
average	+7%	+10%	-11%	+1%
std. dev.	28%	23%	40%	20%
range high	+32%	+53%	+55%	+20%
range low	-40%	-14%	-79%	-29%
Range in ave. DMT values (bars, 100 kPa, 1 tsf)	0.4 to 8	0.04 to 2	1.5 to 440	10 to 2000

5.2 Settlement comparisons: Table 5 presents, in no special order, a summary of all the DMT-calculated and measured settlement comparisons currently (Feb 86) available to the writer. They include a considerable variety of soil types ranging from peat to hard clay, and settlements ranging from 3 to 2850 mm (0.2 to 112"). The following subsections provide some background information:

5.2.1 Tampa Skyway Bridge main piers: A very heavy structure in Florida with drilled shaft foundations into and over a HOC clay and with approximately 50% of the loading now in place. M_{DMT} about 3 to 5 times greater than M from oedometer tests, probably because the M values are too high for adequate rigidity in conventional oedometer equipment. The DMT blade was advanced by driving with an SPT hammer, which produces conservative M_{DMT} (see 5.2.5). Very refined (including 3-D finite element) calculations were used for the predictions, which included immediate settlement. Ref. Sonnenfeld, et.al. (1985) for some of the DMT and other data.

TABLE 5 - COMPARISONS BETWEEN DMT-CALCULATED AND MEASURED SETTLEMENTS

No. 5.2.	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.

5.2.2 Jacksonville Power Plant: This case involved heavy loading over a 21 acre site in Florida on sands densified by dynamic compaction and compaction grouting. The loadings are now about 80% complete, and the DMT and measured settlements are for these loadings. The data in Table 5 result from averaging 3 structures, with individual DMT/meas. settlement ratios of 0.91, 1.17 and 1.12. Ref. Schmertmann, et. al. (1986).

5.2.3 Lynn Haven Factory: A fill and floor slab in Florida placed over peaty sands, produced settlement and a lawsuit. The investigation had to be completed quickly, with maximum of 2 days at the site. The DMT was chosen because the testing and analysis could be completed quickly. Ref. S&C file (1983).

5.2.4 British Columbia Research Embankment: The DMT soundings were made after a test embankment was constructed over Fraser River peat and organic clays, 30 km from Vancouver, by the British Columbia Dept. of Highways. The project also involved extensive additional research testing and instrumentation by the University of B.C. Calculations by the writer suggested that the Ordinary Method would have badly undercalculated settlement because of the much lower stresses at the start of loading than at the time of DMT. The measured settlement includes an adjustment for lateral displacements. Ref. Brown (1983).

5.2.5 Fredricton (Canada) Bank: This especially informative case involves two adjacent sites. At one, the engineers performed a plate load test in the surface sand, and also measured the settlement contribution of the sand under a 4.6 m (15 ft) surcharge. At the other they monitored the settlement performance of a nine storey bank building placed on a raft foundation near the bottom of the sand layer, just above a uniform, 30 m (100 ft) thick deposit of overconsolidated (perhaps only by light cementation) yet very sensitive clayey silt which becomes nearly quick when disturbed. It has average plasticity and liquidity indices of approximately 10% and 1.0, resp.

DMTs were performed at the bank site through the sand and 5 m (16 ft) into the clayey silt, using both the SPT hammer and a quasi-static push to advance the DMT blade. The driven DMTs disturbed the clayey silt and yielded M values that averaged 1/4 the average M from the pushed tests. Only the modulus results from the pushed DMTs were used to compute the case 5c settlement. The computation also includes the assumption that the tested top 5 m is representative of the entire 30 m thickness, and an 0.9 factor for the Skempton-Bjerrum (1956) 3D-OCR effects.

Twenty one odeometer tests over the upper 20 m (66 ft) of the clayey silt gave an average M = 5.0 MPa (52 tsf), much less than the average M_{DMT} = 16.8 MPa (175 tsf) . A similar but conventional analysis using undisturbed sampling and lab testing would have predicted settlements more than 6 times those measured! While the DMT predicted much more accurately than the laboratory based method, this case does provide a warning that soils with a sensitive structure may be less compressible before the insertion of the DMT blade vs. after the disturbance from insertion. However, such disturbance does produce a conservative result. Refs. Landva (1981) and Valsangkar, et. al. (1985).

5.2.6 Ontario (Canada) peat: Hayes (1983) presented an example of the settlement of a roadway embankment over peat. He then added another case over peat from his company's files. Ref. Hayes (1985).

5.2.7 Miami peat: The writer has an additional settlement prediction experience with peat in Florida, involving the settlement of a 1.2 m (4 ft) square plate test on a surface 1.2 m (4 ft) thick peat layer. The peat had an OC crust and varied from HOC at the surface to NC at the bottom. Ref. S&C file (1983).

5.2.8 Peterborough (Canada) industrial plant and apartment building: Both sites involved loose sands and silts, with SPT N-values of 5 to 15. Hayes also reports he had 4 other cases with settlements ranging from 8 to 30 mm where he found close agreement with settlements predicted using the DMT data. He wrote "We are now quite confident that the dilatometer test data can be used to produce reasonable and accurate settlement predictions." Ref. Hayes (1983).

5.2.9 Peterborough (Canada) Liquid Storage Tank Pad: The loading has temporarily reached 100% of the maximum expected. The predicted ultimate settlement is 30 mm at the perimeter of the pad. In Oct 85 the average perimeter settlement was 23 mm, but consolidation of a 4 m (13 ft) thick clay layer at a depth of 10 m is continuing. The projected ultimate settlements are 28 to 33 mm. Ref. Hayes (1985).

5.2.10 Linkoping, Sweden, plate load tests: Performed in dense silty sand by the Swedish Geotechnical Institute. G. Sallfors performed the DMTs and settlement analyses. Ref. Sallfors (1986).

5.2.11 Sunne, Sweden, 2 storey house: Monitoring points placed on the basement walls showed settlements of 5 and 3 mm for the first and second floor loadings, vs. 6 and 4 mm predicted in advance. Ref. Sallfors (1986).

5.2.12 Summary: Based on the 16 comparisons listed in Table 5, the average predicted/measured ratio for settlement equals a conservative 1.18, with a standard deviation = 0.38, and extremes of 0.71 and 2.23. Excluding the 2.23 extreme in 5.2.5c would give 1.11, 0.26, and 0.71-1.67, respectively. The Ordinary Method used

in 13 of these comparisons usually produces acceptable results, but occasionally the situation calls for correcting M for the effects of different effective stress levels. Note the wide range of soils (sands, silts, clays and peats) and the wide range of settlement magnitude involved (3 to 2850 mm) wherein the dilatometer gave reasonable settlement predictions. Although more research and experience will doubtless further improve the correlations, the DMT has already proven reliable for the calculation of foundation settlements.

6. SUMMARY AND CONCLUSIONS

6.1 The DMT quickly and economically provides good stratigraphic and soil property data for the computation of settlement.

6.2 The method of analysis for converting DMT data to settlement involves the application of a simple and general stress-strain equation (1) for one-dimensional compression.

6.3 Because the DMT determines M values at only the insitu effective stress, using such M in settlement analyses may require special adjustment to the different effective stress levels that apply to the problem under investigation. However, the Ordinary Method of analysis that omits this adjustment usually suffices.

6.4 As with other methods of analysis, the DMT settlement calculation method recommended herein may require correction for such effects as pseudo-elastic settlement, structural rigidity, 3-D effects, creep and aging. However, these may often be assumed to cancel each other.

6.5 The DMT appears to predict the relevant soil properties for settlement analysis with an average error of approximately 10%, and a standard deviation of approximately 30%. The ratio of calculated/measured settlement for the sixteen examples listed herein averages 1.18, with a standard deviation of 0.38. The soils involved in these cases include peats, loose to dense sands and silts, soft to hard clays, and mixtures thereof, from a wide spectrum of location and geologic origin.

6.6 A DMT sounding can usually provide the data needed for the calculation of expected settlement with an accuracy adequate for most practical purposes.

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