Use of DMT for subsurface characterization: strengths and weaknesses

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ABSTRACT: In this study, the Marchetti Dilatometer Test (DMT) was used to evaluate the soil type and properties at a site of a highway improvement project in north eastern Oklahoma. The DMT was used to determine the lateral effective stress ratio, strength parameters (i.e. cohesion, angle of internal friction), compressibility, coefficient of consolidation, and coefficient of permeability of the soil at the site. Additional laboratory tests and selected in-situ tests were conducted on the site soil. The properties obtained from the DMT have been compared to those from other laboratory and field tests including standard penetration test (SPT). Using this comparison, the strengths and weaknesses of the DMT in determining soil properties are identified and discussed.

1 INTRODUCTION

A highway improvement project is proposed on State Highway 99 (SH 99), south of Stroud, Oklahoma. The proposed highway improvement project is about one mile in length and includes the construction of a parallel alignment with two bridges across the Deep Fork River and an overflow structure. The proposed project site is located within a valley in between two hills on its north and south sides. An embankment is proposed to be constructed to achieve the desired highway grade. During the construction of the current highway that is in service, the old highway embankment located on the east side of the current highway was abandoned and was left in place. A study was undertaken to examine the feasibility of elevating the abandoned embankment to the same elevation as the current highway. The proposed project involves overcoming some geotechnical challenges: The proposed alignment is located within a flood zone. Moreover, the north part of the proposed alignment is always under water. During the construction of the current highway, both the bridge approaches and the roadway showed some settlements. In addition, the proposed pile foundations for the overflow structure require additional lateral load resistance.

In-situ testing, including several geotechnical test borings, was carried out as part of the subsurface exploration for the proposed alignment site. To obtain a continuous subsurface soil profiles and shorten the time of testing, Marchetti Dilatometer tests (DMT) were performed in several locations at the bridge approaches and roadway embankment sections. The DMT test results provided a detailed profiling of the subsurface materials and the soil parameters needed for the analysis of embankment settlement, slope stability and the lateral load resistance of the embankment foundation.

In this study, the experience of using DMT for the proposed highway improvement project is discussed. The DMT test results are compared to a selection of laboratory and in-situ test results and the accuracy of the DMT testing in determining soil mechanical properties is discussed.

2 COMPARISON OF DMT RESULTS WITH OTHER IN-SITU AND LABORATORY TEST RESULTS AT THE HIGHWAY SITE

The Marchetti Dilatometer Test (DMT) has been used as a rather simple and economical penetration test to measure in-situ soil stresses and modulus values using a series of correlations between the DMT test results and significant soil parameters. These empirical correlations have been developed by comparing the DMT test results with carefully conducted laboratory test data, large-scale chamber tests, in-situ tests (e.g. Cone Penetration Test) and field observations (Schmertmann 1988a).

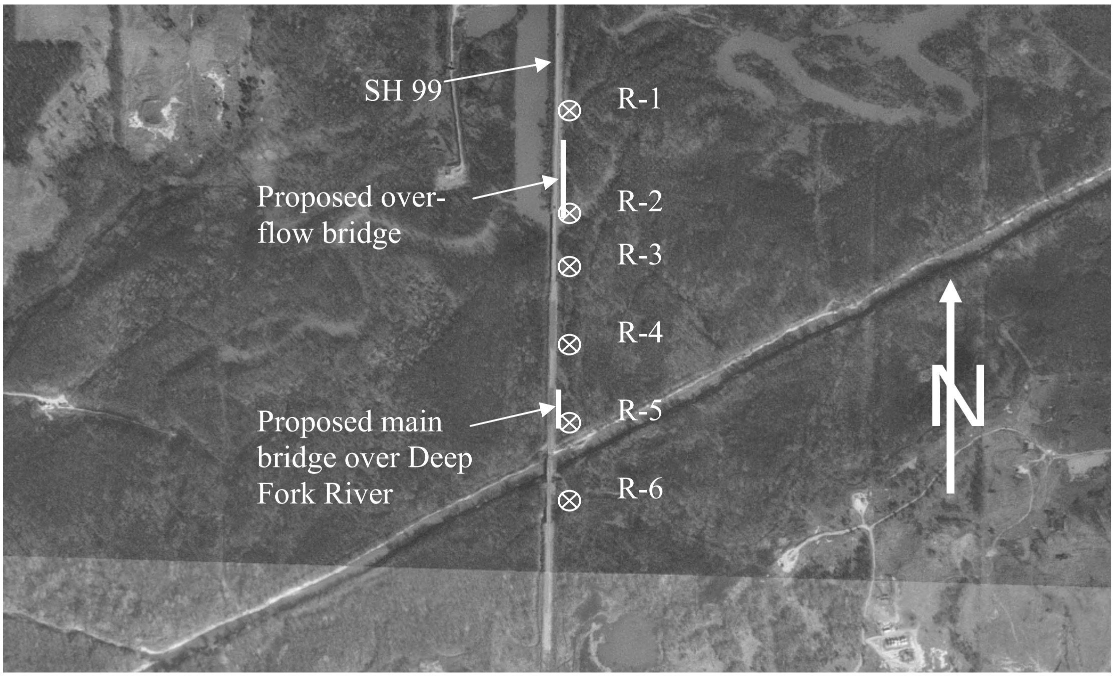

Figure 1. Location of the project site in north eastern Oklahoma and the bore-hole locations map

There are usually four DMT indices that are calculated using the DMT field data. These DMT indices are: (i) material index (I_D); (ii) horizontal strength index (K_D); (iii) dilatometer modulus (E_D); and (iv) pore pressure index (U_D). In general, the DMT indices are not directly used in the engineering design, especially since they represent data from a soil disturbed by insertion of the dilatometer blade. Rather, these DMT indices are used to correlate and interpret the soil engineering properties. For the proposed project on SH 99, the following soil engineering properties are interpreted using the correlations proposed by Marchetti and other researchers (e.g. Schmertmann 1988a): (i) soil type; (ii) lateral effective stress ratio; (iii) strength; (iv) compressibility; (v) coefficient of consolidation; and (vi) coefficient of permeability.

In the SH 99 project, six test borings were drilled on the proposed bridge approaches and roadway sections. The test borings were drilled as deep as 5 ft into the bedrock stratum. The test borings at the proposed bridge piers locations were drilled 30 ft into the bedrock stratum. Locations of the test borings are shown in Fig. 1.

DMT tests were performed adjacent to these six test borings. In addition, three DMT tests were performed at the locations of the test borings of the proposed bridge piers. Standard penetration tests (SPT) were performed in 5 ft intervals at boring locations drilled for the bridge approaches and roadway sections. Shelby tube samples were obtained from test borings R-1, R-2 and R-4 at the depth of 25 ft below the existing ground surface. The Shelby tube samples were used for laboratory testing of the site soils including soil classification tests and unconfined compression tests. SPT tests were carried out on the overburden soils and Texas Cone Penetration tests (CPT) were carried out on the bedrock stratum. The DMT tests were performed to dilatometer blade refusal. The terminal depths of the test borings and DMT tests are shown in Table 1.

Table 1. Borehole and DMT terminal depths

Boring	Borehole depths in meters (ft)	Water table at 72 hours after boring in meters (ft)	DMT terminal depth in meters (ft)
Roadway and bridge approaches			
R-1	15.2 (50.0)	2.9 (9.4)	8.2 (27.0)
R-2	18.3 (60.0)	3.4 (11.3)	14.9 (49.0)
R-3	22.9 (75.0)	3.7 (12.1)	13.1 (43.0)
R-4	25.9 (85.0)	3.5 (11.5)	15.5 (51.0)
R-5	27.4 (90.0)	3.6 (11.8)	16.2 (53.0)
R-6	29.0 (95.0)	2.4 (7.8)	9.8 (32.0)
Bridge piers			
M-5	29.0 (95.0)	5.5 (18.1)	
B-2	29.4 (96.5)	1.1 (3.5)	
B-5	29.7 (97.5)	0.9 (3.0)	

Soil samples from the SPT test sites were also tested for moisture content and soil classification (i.e. gradation and Atterberg limits). Shelby tube samples obtained were tested for unit weight, unconfined compression strength, moisture content and soil classification. Based on the DMT results, other in-situ test results and laboratory test results, the soil type, strength, compressibility, coefficient of consolidation and coefficient of permeability were determined.

2.1 *Soil Classification*

Soil classifications from DMT and the Unified Soil Classification System (USCS) are compared for borehole R-2 as shown in Table 2. The soil types in

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the DMT column are determined using the material index (I_D) from the DMT tests.

Table 2. USCS soil classifications and DMT soil descriptions for borehole R-2.

Depth in meters (ft)	DMT Soil Class	USCS Soil Class
4.9 (16)	Sand	Silty Sand
6.1 (20)	Clayey Silt	Sandy Lean Clay
6.4 (21)	Silt	
7.6 (25)	Silt	Sandy Lean Clay
7.9 (26)	Silty Clay	
9.1 (30)	Silty Sand	Silty Sandy Lean Clay
9.4 (31)	Silt	
10.7 (35)	Silty Clay	Silty Sand
11.0 (36)	Silty Sand	
12.2 (40)	Silty Sand	Silty Sand
12.5 (41)	Silty Sand	
13.7 (45)	Silty Sand	Silty Sand
14.0 (46)	Silty Sand	

As shown in Table 2, the soil classifications from the DMT test results and the USCS using the laboratory test results do not exactly match. The soil classification using I_D can be expected to yield different results from the sieve analysis (Schmertmann 1988a). The parameter I_D is an indicator of the soil mechanical behavior, similar to a *rigidity index*. Thus, the DMT results can misidentify silt as clay or vice versa. For example, if a clay soil exhibits a stiff response to the DMT test, it may be interpreted as silt according to its I_D value. However, it has generally been shown that the DMT soil classifications are capable of identifying the basic soil type, such as sandy soils or clayey soils (Schmertmann 1988a). The I_D parameter from DMT was also used to estimate the unit weight of the soils. A comparison of the DMT and laboratory test results is shown in Table 3.

Table 3. Predicted unit weight of soil samples from DMT and laboratory tests.

Borehole	Sample depth in meters (ft)	Laboratory unit weight in kN/m^3 (pcf)	DMT unit weight in kN/m^3 (pcf)
R-1	3.0-3.5 (10-11.5)	14.9 (94.9)	17.6 (112.3)
R-2	6.1-6.6 (20-21.5)	18.1 (115.5)	17.2 (109.2)
R-4	6.1-6.6 (20-21.5)	16.3 (103.6)	17.2 (109.2)
	9.1-9.6 (30-31.5)	16.5 (104.9)	17.2 (109.2)
	15.2-15.7 (50-51.5)	16.4 (104.3)	16.7 (106.1)
R-5	7.6-8.1 (25-26.5)	15.4 (98.0)	17.6 (112.3)
	15.2-15.7 (50-51.5)	16.2 (103.0)	17.6 (112.3)
R-6	7.6-8.1 (25-26.5)	17.0 (108.0)	17.6 (112.3)

As shown in Table 3, the unit weight values from the DMT test results are notably different from the laboratory test results in boreholes R-1 and R-5. For example, the DMT results overestimate the soil unit weight at Borehole 1 by about 18%. In other boreholes, the unit weight values from the DMT results are closer to the laboratory test results. For the most part, the soil unit weight from the interpretation of DMT results can be viewed as a reasonable approximation of the value expected from the more accurate laboratory tests and a preferred alternative to the use of lookup tables. As explained by Marchetti (1980), the unit weight is a soil property that is estimated empirically using the DMT I_D parameter. As a result, similar to soil classification, the estimated soil unit weight from the DMT results could be different from those from laboratory testing of the soil.

2.2 *Soil Strength*

Shelby tube soil samples were procured for clayey soils to perform unconfined compression tests. The values for the cohesion of clayey soils and the friction angle of sandy soils were determined using the data obtained from DMT, unconfined compression tests (clayey soils only) and SPT tests. These properties are presented in Tables 4 and 5.

Table 4. Comparison of cohesion values from laboratory and DMT test results.

Borehole	Depth (ft)	Unconfined compression test cohesion (psf)	DMT cohesion (psf)
R-1	7.6-8.2 (25-27)	32.0 (668)	N/A*
R-2	7.6-8.2 (25-27)	45.1 (941)	26.8 (560)
R-4	7.6-8.2 (25-27)	92.1 (1922)	72.8 (1520)

* N/A: Inconclusive

Table 5. Comparison of friction angle values of sandy soils from SPT and DMT test results.

Borehole	Depth (ft)	SPT Friction Angle (°)	DMT(°) (ϕ)	DMT (ϕ)(°) (adjusted**)
R-2	10.7 (35)	30.7	43.6	40
	12.2 (40)	31.1	45.6	41
	13.7 (45)	28.2	OOR*	OOR*
R-5	9.1 (30)	28.1	40.2	37
	10.7 (35)	28.1	40.0	37
R-6	9.1 (30)	29.3	38.3	36
B-5	6.1 (20)	31.7	45.8	41
	9.1 (30)	29.1	47.4	42
	12.2 (40)	30.4	OOR*	OOR*
	13.7 (45)	29.6	OOR*	OOR*
	15.2 (50)	30.2	OOR*	OOR*
	16.8 (55)	32.3	OOR*	OOR*

* OOR: Out of Range ** Equation 1.

As shown in Table 4, in test boring R-1 at a depth of 25-27 ft, DMT yields an inconclusive cohesion value. Based on the interpretation of DMT results, the soil at this depth is classified as clayey silt with the I_D value greater than 0.6 (Marchetti 1980). The data reduction software program developed by Marchetti (1980) to simplify the interpretation of

DMT data appears to be incapable of interpreting the cohesion value for soils with I_D values greater than 0.6. However, the program provides an option to change the default range of values for I_D to predict the soil cohesion value. In this study, the default range of values for I_D was changed in the program (in test boring R-1) and as a result, the clayey soil at 25-27 ft in the test boring R-1 was found to have a cohesion value of 550 psf. Table 4 shows that the DMT test results underestimate the predicted cohesion values for clayey soils by about 400 to 500 psf compared to the values from unconfined compression tests. However, in the absence of more accurate laboratory test results, DMT results could be used as preliminary values for the soil strength properties.

The correlation between the horizontal stress index (K_D) from DMT test results and the undrained shear strength of cohesive soils has been confirmed by several different studies (e.g. Kamei, 1995). However, Powell and Uglow (1988) stated that this correlation is suitable for *young* clay deposits and suggested that for *old* clay deposits, either (a) the existing correlations for that soil type can be used, or (b) if only limited amount of new data is available, a new correlation could be derived by drawing a straight line through the new data parallel to the Marchetti correlation line. Fig. 2 shows the Marchetti correlation line for undrained shear strength of cohesive soils.

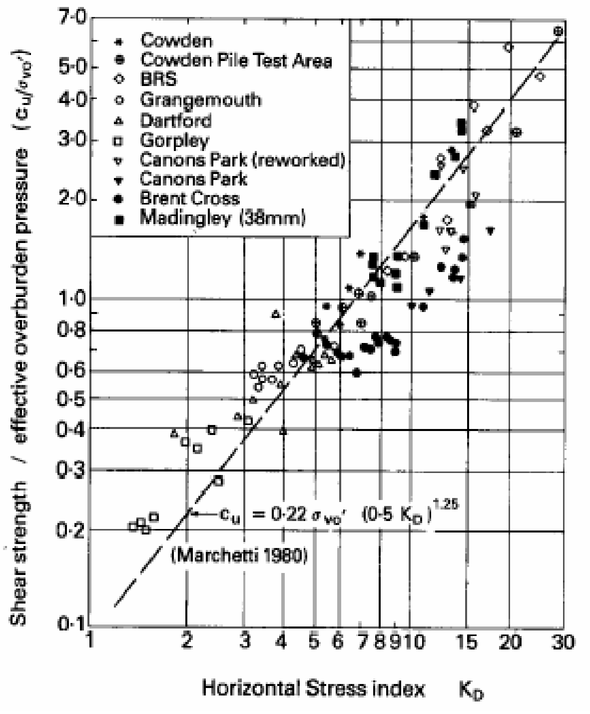

Figure 2. Shear strength/effective overburden pressure vs. horizontal stress Index, K_D (Powell and Uglow, 1988)

In Table 5, the soils internal friction angle values are estimated from the SPT tests using the correlations between the SPT data and the soils friction angle values as given by Peck, Hanson and Thornburn (1974). The SPT results are corrected for the influence of the effective overburden pressure (Liao and Whitman, 1986). The term OOR in Table 5 refers to the fact that the data reduction program provided by Marchetti (1980) is not capable of calculating the soil friction angle value using the available correlation formulae. Once the calculated friction angle value for sandy soils is greater than 50^o, the program automatically terminates the calculation. Hence such case is shown as OOR (i.e. out of range) in the table.

The (plane-strain) DMT friction values in Table 5 have been downward adjusted to determine equivalent traiaxial friction values using the following equation (Schmertmann 1988b):

$$\phi_{tr} = 32 + 2(\phi_{ps} - 32)/3 \qquad [1]$$

As shown in Table 5, the DMT correlations overpredict the friction angle values for the sandy soils compared to the SPT results. Part of the reason for the difference between the friction angle values determined from the two approaches can be attributed to the difference in the degree of sensitivity of the test results to the test procedures. Overall, DMT test results are perceived to be less sensitive to the test procedure and would require fewer corrections compared to the SPT results. At the same time, it is also possible that the proposed correlations between the DMT results and soil friction angle values are not suitable for the subsurface conditions of the SH 99 project site. Marchetti (1997) noted that the DMT results in a number of earlier studies have overpredicted the friction angle value of sandy soils. Therefore, these values could be non-conservative if used at the site of the proposed SH 99 project.

2.3 *Compressibility*

The consolidation settlement of the highway embankment was predicted using the coefficient of compressibility of the subsurface soils predicted from DMT test results and an empirical formula proposed by Skempton (Das, 1998) using the SPT test data (Table 6)..

The Skempton's empirical approach using SPT results is based on the correlations between the soil shear strength and its stress history (FHWA 2002). From these correlations, the over-consolidation ratio (OCR) of the soils and the magnitudes of the embankment consolidation settlement were estimated using the undrained shear strength values of the soils. The DMT results were used to predict the tangent drained constrained modulus of the soils (M) and the magnitude of the consolidation settlement using Janbu's method (Schmertmann, 1988a).

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Table 6. Consolidation settlement underneath the proposed SH99 highway embankment based on DMT test results and Skempton's empirical formula (C_c=0.009*(LL-10)).

	Estimated consolidation settlement in mm (in)	
Borehole	Skempton's empirical formula using SPT data	DMT results
R-1	5 (0.21)	5 (0.18)
R-2	4 (0.17)	15 (0.58)
R-3	35 (1.37)	39 (1.52)
R-4	32 (1.27)	44 (1.73)
R-5	24 (0.93)	23 (0.90)
R-6	15 (0.60)	N/A*
B-2	546 (21.5)	244 (9.59)

* N/A: Not enough information for analysis.

Results shown in Table 6 indicate that the predicted values for the consolidation settlement at boreholes R-1 through R-5 are comparable, with a maximum difference of about 0.5 in. However, the predicted results for the consolidation settlement at borehole B-2 are significantly different. Comparison of the laboratory and in-situ test results indicated that the subsurface soils at locations R-1 through R-6 are much stiffer and stronger than subsurface soils at location B-2. This is because boreholes R-1 through R-6 are located on the abandoned old highway, i.e. on the subsurface soils that had been consolidated due to the weight of the old highway embankment. However, boring B-2 is located in the flooded area and the subsurface soils in that location are extremely soft.

To determine the accuracy of the predicted consolidation settlements, the settlement analysis carried out in this study was compared to the analysis that had been carried out during the construction of the current highway alignment by the Oklahoma Department of Transportation (ODOT). Based on the information provided by ODOT, the predicted consolidation settlement of the current highway built in the flooded zone was about 14 in. Because the height of the proposed embankment is less than the height of embankment placed during the construction of current highway, the expected magnitude of the consolidation settlement underneath the proposed highway embankment is less than the value of 14 in that was predicted for current highway embankment. Therefore, the predicted magnitude of the consolidation settlement for the proposed embankment from DMT test results (Table 6) is considered to be reasonable.

2.4 *Coefficients of Consolidation and Permeability*

The OCR and the pre-consolidation pressure (P_c) values for Borehole B-2 were calculated in order to evaluate the accuracy of the OCR values predicted from DMT results. This borehole was selected because the subsurface soils in this location were softest. The P_c and OCR values for the B-2 location are presented in Fig. 3. The P_c test results shown in Fig. 3 indicate that the subsurface soils (i.e. at shallower depths) at the borehole B-2 location are, for the most part, normally consolidated clayey soils.

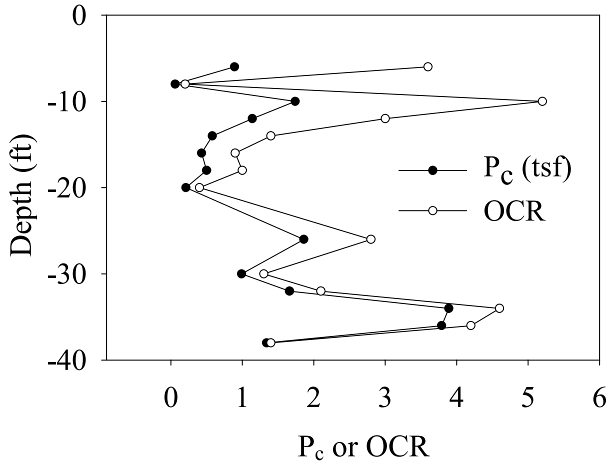

Figure 3. Variations of OCR and P_c with depth in borehole B-2.

However, the OCR values from DMT tests are less than 1 only at isolated depths (e.g. from 15 ft to approximately 22 ft). The predicted OCR values down to the depth of about 15 ft are mainly greater than 1, which is unexpected considering that these soils are very soft and have continuously been under water. Nonetheless, it can be observed in Fig. 3 that the variations of the OCR (from DMT results) and P_c with depth are very similar in shape. This is consistent with the remark made by Marchetti (1997) that DMT results could be used to obtain a reasonable first order approximation of the soil OCR values and their variation with depth. However, it is imperative that engineers interpret the DMT soil information from any site tested very carefully.

In addition to the regular DMT, a DMTC test was carried out (Robertson et al. 1988) by monitoring the dissipation of pore pressure with time to determine the coefficient of consolidation (C_v) of the clayey soils (Table 7). However, due to the lack of laboratory test results, the predicted C_v values could not be compared to the values from other test methods.

Table 7. C_v values predicted from DMTC tests.

Borehole	R-2	R-3	R-4	R-5
			Layer 1: 0.063	
C_v m2/day	0.132	0.014	(0.685)	(0.01)
(ft^2/day)	(1.427)	(0.156)	Layer 2: 0.009	0.113
			(0.100)	

* N/A: Not enough information for analysis.

As shown in Table 7, the predicted C_v values for different boreholes vary over a wide range. Even though these coefficients are not verified using other test methods, they provide a basis to estimate the values for the coefficient of consolidation and coefficient of permeability of the soils. For example, values of coefficient of consolidation for the Chicago Clay vary in the range between 0.085 ft^2/day and 0.428 ft^2/day (Das, 1998). The predicted values for the coefficient of consolidation in Table 7 are comparable to this range of values.

3 CONCLUSIONS

The use of DMT as an alternative in-situ testing to conventional subsurface drilling, laboratory testing and other in-situ test methods to obtain soil information for engineering analysis and design has been explored. Based on a comparison of the actual field results from a project site on State Highway 99 (SH 99) in northeastern Oklahoma and the available correlations, the following conclusions are drawn about using DMT as an in-situ testing method:

(i) More work is needed to improve the soil density and description charts (Powell and Uglow, 1988). In general, the DMT test results can be used to determine the soil type and unit weight. However, the actual descriptions and values may need some correction and refining. As indicated by Marchetti (1997), DMT results usually provide a reasonable soil description. However, in the range of cohesive soils, DMT sometimes misidentifies silt as clay and vice versa. Such misread was encountered in some of the boreholes of the project site described in this study. It is understood that the parameter I_D from the DMT tests is primarily an indicator of the mechanical behavior of soils, and therefore may not completely yield consistent results with the sieve analysis. For the most part, however, the DMT results yield reasonably accurate soil density values and are a preferred alternative to the use of lookup tables for engineering analysis and design.

(ii) It was found that the DMT results can be used to predict the undrained shear strength of cohesive soils with reasonable accuracy. However, the correlations proposed for the DMT data are valid for soils with I_D values less than 0.6. The data reduction program provided by Marchetti (2002) has an option to modify the range of variation for the I_D parameter to use the correlation. It was found in this study that allowing I_D to assume values as great as 1.0 would provide reasonable results for the undrained shear strength of cohesive soils. However, further study is needed to validate the admissible range of values for the I_D parameter in order to predict the undrained shear strength of the cohesive soils more accurately.

(iii) It was found that the friction angle values for sandy soils using the DMT test results were overestimated compared to the values obtained from the SPT tests. Therefore, the soil friction angle values from the DMT tests would be non-conservative if used for the SH 99 project site.

(iv) The proposed highway embankment consolidation settlement was estimated using the tangent drained constraint modulus (M) and was compared to an empirical formula proposed by Skempton (Das, 1998), which is based on the standard penetration test results. In addition, the predicted consolidation settlement magnitude from previous subsurface exploration during the construction of the current highway was obtained from ODOT. The magnitude of consolidation settlement predicted from DMT results was found to be reasonably close to the value predicted by ODOT. It was found that Skempton's empirical formula using the standard penetration test results tend to over-predict the magnitude of consolidation settlement.

(v) The variations of the OCR (from DMT results) and pre-consolidation pressure values with depth were found to be very similar in shape. It was concluded that the DMT results could be used to obtain a reasonable first order approximation of the soil OCR values and their variation with depth. However, it is imperative that engineers interpret the degree of consolidation of the soil at a given site based on the OCR values from DMT test results very carefully.

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