Compressibility of Compacted Fills Evaluated by the Dilatometer

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The objective of this study was to investigate the relationship between the dilatometer modulus (E_D) and the constrained modulus (M) for compacted soils. An experimental program was designed using three natural soils encountered in North Carolina compacted at optimum moisture content. For the compacted soils studied, it was found that current methods for interpreting dilatometer data to predict compressibility, as determined from one-dimensional compression tests, significantly overestimated the values that were measured. On the basis of the combination of laboratory and field tests conducted, it would appear reasonable to accept the dilatometer modulus as an upper bound to the anticipated in situ constrained modulus, with the realization that values may actually be in the range of 50 to 80 percent of that value, depending on soil type.

The tangent drained constrained modulus (M) provides a localized one-dimensional modulus for a particular stress level. This modulus is defined as the slope of the linear stress-strain curve obtained from a conventional consolidation test. Marchetti *(1)* related the constrained tangent modulus to the dilatometer modulus by the equation $R_M = M/E_D$. This assumes isotropic, linear-elastic behavior and is a function of the drainage conditions under which the dilatometer modulus is determined. Equations for R_M in terms of the drained Poisson's ratio ($\bar{\mu}$) for both the drained and undrained cases are developed from the relationship of M to $\bar{\mu}$ and the drained Young's modulus ($\bar{E}$). If E_D is determined in a drained environment,

$$R_M = (1 - \bar{\mu})^2/(1 - 2\bar{\mu}) \quad (1)$$

If E_D is determined in an undrained environment,

$$R_M = (1 - \bar{\mu})/2(1 - 2\bar{\mu}) \quad (2)$$

Marchetti realized that both the in situ soil modulus and the dilatometer modulus are affected by the penetration of the blade. He therefore examined lateral earth pressure values (K_D) measured by the dilatometer. On the basis of the results of his analysis, Marchetti developed the following equations:

$$M = R_M E_D \quad (3)$$

$$R_M = 0.14 + 2.36 \log KD \qquad \text{if } I_D < 0.6 \quad (4)$$

$$R_M = R_{M,o} + (2.5 - R_{M,o}) \log K_D \qquad \text{if } 0.6 < I_D < 3.0 \quad (5)$$

with $R_{M,o} = 0.14 + 0.15\ (I_D - 0.6)$.

$$R_M = 0.50 + 2.00 \log K_D \qquad \text{if } I_D > 3.0 \quad (6)$$

$$R_M = 0.32 + 2.18 \log K_D \qquad \text{if } K_D > 10 \quad (7)$$

where the material index (I_D) is a function of soil type (the lower values are associated with clays and the higher—those above 3—with sands and other stiff soils). In all cases the value of $R_M > 0.85$.

Although Marchetti's data show significant scatter, Schmertmann *(2)* has indicated good agreement between M-values from the dilatometer and odometer tests.

For a more thorough discussion of these and other engineering parameters predicted by the dilatometer, the reader is referred the following sources: Marchetti *(1;3*, pp. 255–259), Bullock *(4)*, and Schmertmann *(2)*.

OPERATION OF THE DILATOMETER

The flat dilatometer, developed by Silvano Marchetti *(3)*, is essentially a penetration device capable of obtaining an estimate of lateral soil stiffness. The dilatometer, shown in Figure 1, uses a thin, circular, flexible membrane mounted on the side of the blade to arrive at an estimate of the lateral stiffness of the soil. The body of the dilatometer has a width of approximately 3.7 in. (95 mm) and a thickness of approximately 0.6 in. (14 mm). When at rest, the external surface of the approximately 2.4-in. (60-mm) diameter membrane is flush with the surround-

FIGURE 1 Dilatometer and control unit.

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ing flat surface of the blade. The blade is either pushed or driven into the ground and when located at the desired test depth, the membrane is inflated by means of pressurized gas through a small control unit at the ground surface. Readings are taken of the *A* pressure required to just move the membrane (related to the lateral stresses existing in the ground) and of the *B* pressure required to move its center an additional approximate 0.04 in. (1 mm) into the soil (related to soil stiffness). The movements of the membrane are measured by extensometers behind the diaphragm within the body of the device. The movements activate a signal in the control unit that tells the operator to record the pressure when the membrane just moves away from the surface of the blade (the *A* reading) and again when the membrane has moved approximately 0.04 in. into the soil (the *B* reading).

In the usual test procedure, the dilatometer is pushed into the ground and the force required for penetration is measured and recorded. At predetermined intervals (usually about 8 in.) the penetration is stopped and the membrane is inflated. Once the second pressure reading (the *B* reading) has been taken and the pressure behind the membrane is vented, the blade is advanced to the next depth and the test repeated.

Dilatometer Modulus (E_D)

The first pressure reading actually corresponds to an approximate 0.002-in. (0.05-mm) displacement of the membrane and must therefore be extrapolated back to a zero membrane displacement. Also, the pressure readings must be corrected to account for the stiffness of the membrane. The following equations enable both of these corrections to be made on the *A* and *B* readings:

$$p_0 = 1.05\,(A - Zm - \Delta A) - 0.05\,(B - Zm - \Delta B) \quad (8)$$

$$p_1 = B - Zm - \Delta B \quad (9)$$

where

A = first dilatometer reading,
B = second dilatometer reading,
ΔA = free air correction to A,
ΔB = free air correction to B,
Zm = correction for a nonzero initial gauge reading,
p_0 = corrected first reading, and
p_1 = corrected second reading.

The difference between the two dilatometer readings may be used to obtain a modulus of elasticity. On the basis of penetration of a circularly loaded area into an elastic half-space, Marchetti *(1)* proposed that the lateral soil modulus be represented by the following expression:

$$E/(1 - \mu^2) = (2\Delta p D)/(\pi s_0) \quad (10)$$

where

s_0 = approximate 0.04-in. deflection of the center of the membrane,
Δp = difference in the corrected A and B readings,
D = 2.4-in. (60-mm) membrane diameter,
E = Young's modulus, and
μ = Poisson's ratio of the soil.

The expression $E/(1 - \mu^2)$ is then termed the dilatometer modulus, E_D.

Material Index (I_D)

The material index (I_D) is a unitless parameter that is the ratio of the difference in corrected pressure readings to a rough equivalent of the effective confining stress. It is defined by the following equation:

$$I_D = (p_1 - p_0)/(p_0 - u_0) \quad (11)$$

where u_0 is the pore-water pressure before the insertion of the blade.

Marchetti *(1)* noted that the material index was a function of grain size and soil permeability. Basically, sandy soils yield a high value of material index because as the membrane expands, drainage can occur and the increased resistance of the soil is measured by the dilatometer. Saturated clayey soils, on the other hand, do not allow for drainage or volume change. Their material index is lower because no increase in soil stiffness is detected. Empirical correlations have been developed that provide an estimate of soil type based on material index values. When plotted versus the dilatometer modulus, the material index values can also be used to predict soil densities.

Horizontal Stress Index (K_D)

The horizontal stress index is defined as

$$K_D = (p_0 - \mu_0)/\bar{\sigma}_v \quad (12)$$

where p_0 and u_0 are as previously defined in Equation 11 and $\bar{\sigma}_v$ is the vertical effective stress at the depth at which the dilatometer test is conducted.

It is at this point that a problem arises when one tries to apply these relationships to partially saturated soils. As it is not generally convenient to measure the magnitude of the negative pore pressures in the soil, it is not possible to define exactly the effective stress state. However, if the compressibility characteristics of the partially saturated sample are determined in the one-dimensional compression test, one may expect to be able to develop the relationship between M and E_D based on total stresses. This problem will be discussed later in more detail in conjunction with the presentation of the findings from this experimental program.

EXPERIMENTAL PROGRAM AND TESTING PROCEDURE

In order to evaluate the potential usefulness of the dilatometer for predicting the compressibility of compacted fills as defined

TABLE 1 SOIL CHARACTERISTICS

	Soil 1	Soil 2	Soil 3
Gradation (% passing)			
No. 4 sieve	88	97	100
No. 40 sieve	77	84	80
No. 200 sieve	43	65	54
Liquid limit (%)	46	37	57
Plasticity index (%)	3	15	24
Specific gravity	2.77	2.78	2.7
T-99 γd max (pcf)	102.4	111.0	105.5
W opt. (%)	20	16.8	18.6
T-180 γd max (pcf)	110.4	123.0	—[a]
W opt. (%)	16.8	12.2	—[a]
AASHTO classification	A-5	A-6	A-7-5

[a]Not determined.

by a one-dimensional compression test, an experimental program was designed utilizing the natural soils described in Table 1. These soils were chosen for their range of properties and significance as locally encountered materials in North Carolina. Soil 1 is a light brown silty sand with a high mica content and low plasticity. Soil 2 is a dark brown clay soil with medium plasticity. Soil 3 is a light reddish sandy silt with a significant mica content. The objective of this investigation was to establish correlations between E_D and M from one-dimensional compression tests for a range of soil types compacted at optimum moisture content.

In general, the test program may be characterized as having evaluated the following types of samples:

1. A range of sample sizes including cylindrical molds of 6-in. (152-mm) and 11-in. (280-mm) diameter and 2.8-in. (71.12-mm) Shelby tube field samples (6-in. samples predominated);
2. Moisture contents representing optimum for the compactive effort at T-99;
3. Dry densities achieved with 50 and 100 percent of the compactive effort specified in AASHTO T-99 at the optimum moisture content for the T-99 test; and
4. Soaked and unsoaked samples compacted in cylindrical molds of 6-in. diameter.

The standard preparation technique for all laboratory samples involved the air drying of soil followed by sieving through a No. 4 sieve. Any material retained on the sieve was broken down with a mortar and pestle and sieved again. The moisture content of the material was then increased with distilled water in a rotary mixer. The material was then stored in sealed plastic bags in a 100 percent humidity room for at least 72 hr to enhance moisture equilibration. All 6-in. diameter specimens were compacted by using an automatic drop weight device with a sector-shaped hammer.

After compaction, at least one sample was soaked at each energy level for all three soil types. The samples were immersed to a point slightly below the top edge of the mold to allow the water to flow upward from the bottom of the sample. All samples were soaked for at least 4 days with the recommended surcharge for a California bearing ratio (CBR) test. After the soaking, the dilatometer tests were conducted *(5)* and the water content distribution was determined.

The degree of saturation was calculated for both the initial (unsoaked) and final (soaked) conditions, with the results shown in Table 2. The increase in the degree of saturation was very small at higher compactive efforts for both the A-6 (S = 88.2 percent to S = 88.4 percent) and A-7-5 soils (S = 88.8 percent to S = 89.8 percent), but was much higher for the A-5 soil (S = 79.2 percent to S = 95.9 percent). This was probably the result of the higher permeability of the silty sand A-5 soil and the soaking technique. At the lower compactive effort the increase in the degree of saturation was much higher for all three soils because of the larger volume of voids and correspondingly higher hydraulic conductivity of the samples.

The specimen for the one-dimensional compression test was obtained after the sample was extruded from the compaction mold and cut to the section desired (vertical or horizontal or both). A consolidation test ring was then pushed into the section. The water content of the sample was determined before the test by using the trimmings and again after the test by using the entire sample. The initial wet and dry densities were then determined. The loading, unloading, and reloading stages were conducted with a load-increment ratio of 1 beginning with 1/8 tsf. Taylor's square-root-of-time-fitting method was adopted so that the time required for 90 percent consolidation (*T90*) could be determined without going too far beyond the time required for 100 percent primary consolidation (*Tp* or *T100*). Although any time-based system for evaluating the

TABLE 2 INITIAL AND AS-TESTED DEGREE OF SATURATION FOR SOAKED SAMPLES

Soil Type	Compactive Effort[a] (%)	Water Content (%) $W(c)$[b]	$W(s)$[c]	W[d]	Degree of Saturation (%) As Compacted	As Tested
A-5	50	20.0	28.7	29.24	68.4	98.2
A-6	50	17.3	21.7	23.37	73.75	92.9
A-7-5	50	19.3	21.5	24.5	78.7	87.7
A-5	100	20.0	24.0	25.0	79.2	95.9
A-6	100	17.2	17.6	19.9	88.2	88.4
A-7-5	100	19.3	19.6	21.8	88.8	89.8

[a]As specified in AASHTO T-99 test.
[b]As compacted.
[c]After soaking.
[d]From consolidation ring.

compressibility of partially saturated soils is somewhat difficult to interpret—that is, the process is not simply governed by the dissipation of excess pore pressure—the Taylor method provided a consistent and conventional format for evaluation of the data.

In order to determine the influence of sample disturbance resulting from dilatometer insertion, several one-dimensional compression tests were conducted on samples that had not been tested with the dilatometer but that had densities and water contents similar to samples that had been tested with the dilatometer.

Both soaked and unsoaked samples were prepared for each soil type. At least one soaked and one unsoaked sample at each compactive effort was tested with the dilatometer before the one-dimensional compression test was performed. The soaked samples that were not tested with the dilatometer were extruded from the mold. The moisture distribution in the sample and the corresponding degree of saturation were computed by measuring the water content of slices 1/2 in. thick. Sample heights were measured both before and after soaking.

RESULTS AND DISCUSSION

The results of the laboratory and field tests conducted in this study are presented in Tables 3 and 4. Consolidation specimens obtained from samples penetrated with the dilatometer are identified as either SFD (side facing dilatometer diaphragm) or BSD (back side of dilatometer). Dilatometer tests were performed after compaction for the unsoaked samples and after soaking for the soaked samples.

As mentioned previously in the discussion of K_D, the use of the conventional equations to predict R_M requires an estimate of the existing effective stress in order to first determine K_D. This will undoubtedly be somewhat of an inconvenience when partially saturated soils are tested in situ. In the case of the laboratory samples tested, the overburden stress is essentially zero [4 in. (102 mm) of soil cover], and the negative pore pressure accounts for the major component of the vertical effective stress. A limited study of soil suction for these soils indicated that near the optimum moisture content one might expect negative pore pressures in the range of 0.5 to 1 tsf (47.9 to 95.8 kPa). Therefore, it was determined that a reasonable

TABLE 3 DESCRIPTION OF ALL SAMPLES TESTED

Sample No. and Orientation	Soil Type	Condition as Tested	Compactive Effort[a] (%)	$W(c)$[b] (%)	$W(s)$[c] (%)	γd (pcf)	Side of Dilatometer
1-V	A-5	Soaked	50	20.0	28.6	95.5	SFD
2-V	A-5	Soaked	50	20.0	28.9	95.5	BSD
3-V	A-5	Unsoaked	50	20.0	–	95.7	BSD
4-V	A-5	Soaked	100	20.0	23.6	102.4	BSD
5-V	A-5	Soaked	100	20.0	24.2	102.1	–
6-V	A-5	Soaked	100	20.0	24.0	102.4	SFD
7-H	A-5	Soaked	100	20.0	23.8	102.1	–
8-V	A-5	Unsoaked	100	20.0	–	101.7	–
9-V	A-5	Unsoaked	100	20.0	–	101.7	–
10-H	A-5	Unsoaked	100	20.0	–	101.7	–
11-V	A-5	Unsoaked	–[d]	22.0	–	94.4	–
12-V	A-5	Unsoaked	–[d]	22.0	–	98.3	–
13-H	A-6	Unsoaked	–[e]	16.8	–	112.2	–
14-H	A-6	Unsoaked	–[e]	19.4	–	104.6	–
15-H	A-6	Unsoaked	–[e]	17.6	–	113.0	–
16-V	A-7-5	Unsoaked	50	19.3	–	100.6	BSD
17-V	A-7-5	Unsoaked	50	22.7	–	98.3	BSD
18-V	A-7-5	Unsoaked	100	19.3	–	106.3	BSD
19-V	A-7-5	Unsoaked	100	20.6	–	110.8	SFD
20-V	A-7-5	Unsoaked	100	20.6	–	110.8	SFD
21-H	A-7-5	Unsoaked	100	20.5	–	104.2	SFD
22-V	A-7-5	Unsoaked	100	20.5	–	104.2	BSD
23-V	A-6	Unsoaked	100	17.0	–	111.5	–
24-V	A-6	Unsoaked	50	16.8	–	105.9	–
25-V	A-6	Soaked	50	17.2	21.7	105.2	BSD
26-V	A-6	Soaked	100	17.2	17.6	111.6	BSD
27-V	A-7-5	Soaked	50	19.3	21.5	101.4	BSD
28-V	A-7-5	Soaked	100	19.3	19.6	106.0	SFD

Note: V = vertical orientation; H = horizontal orientation; SFD = side facing dilatometer; BSD = back side of dilatometer.

[a]As specified in AASHTO T-99 test.
[b]As compacted.
[c]After soaking.
[d]Statically compacted in 11 in. mold to density shown.
[e]Field-compacted Shelby tube sample.

TABLE 4 CONSTRAINED MODULUS AND DILATOMETER MODULUS VALUES FOR ALL SAMPLES TESTED

Sample No. and Orientation	M (tsf) by Stress Level 0.5 tsf	1.5 tsf	4.5 tsf	E_D (tsf)
1-V	30.0	36.4	68.0	45.0
2-V	23.0	27.0	86.0	45.0
3-V	95.0	95.6	108.0	107.0
4-V	45.0	55.0	109.0	107.0
5-V	50.0	53.5	95.0	–
6-V	52.0	56.5	105.0	107.0
7-H	48.0	52.0	103.0	–
8-V	61.0	61.7	110.0	103.0
9-V	60.0	75.0	100.0	–
10-H	120.0	101.0	130.0	–
11-V	76.0	55.6	88.0	111.0
12-V	80.0	69.4	80.0	118.0
13-H	140.0	210.0	304.0	200.0
14-H	130.0	188.7	275.0	189.0
15-H	150.0	227.3	325.0	200.0
16-V	135.0	125.0	150.0	176.0
17-V	73.0	87.0	120.0	118.0
18-V	122.0	157.0	215.0	205.0
19-V	100.0	160.0	225.0	233.0
20-V	138.0	172.0	220.0	233.0
21-H	220.0	160.0	150.0	205.0
22-V	80.0	130.0	200.0	205.0
23-V	140.0	125.0	145.0	223.0
24-V	125.0	55.0	85.0	161.0
25-V	110.0	67.0	76.0	52.0
26-V	140.0	100.0	110.0	132.0
27-V	50.0	75.0	125.0	132.0
28-V	68.0	105.0	175.0	212.0

Note: V = vertical orientation; H = horizontal orientation.

way to depict the data would be to evaluate the constrained modulus at several stress levels to ensure that the actual effective stress in the sample during the dilatometer test was bracketed. Table 4 is a summary of the M-values calculated at stress levels of 0.5, 1.5, and 4.5 tsf and the corresponding E_D-value for each of the samples tested. These values were used to determine the correlations between M and E_D as shown in Figures 2 through 8.

Correlations between the dilatometer modulus and the constrained modulus were developed at three different stress levels. These relationships are presented in the following groups: each of the three soil types, all unsoaked samples, all soaked samples, and all samples with vertical orientation. It should be noted that each point plotted does not represent a separate sample, but an individual one-dimensional compression test. Therefore, one E_D-value often corresponds to several M-values when more than one consolidation test specimen was trimmed from a given sample.

Duplicate Tests

A typical curve of log stress versus percent strain for each of the one-dimensional compression test specimens (Specimens 1 through 28) was plotted for loading, unloading, and reloading. To indicate the consistency of the results, duplicate specimens were taken from the same compacted mold. These results are plotted together as shown in Figures 9 through 12. The agreement is seen to be quite good, although there are some differences in the unloading-reloading stages.

Effect of Mold Size

For the A-5 soil, several one-dimensional compression tests were conducted on specimens taken a few inches away from the dilatometer blade penetration in the 11-in. diameter mold. The constrained modulus values were consistent with those obtained on specimens from the 6-in. diameter mold (+5 to 20 percent). The dilatometer moduli from Specimens 11 and 12 (E_D = 111.0 tsf and E_D = 118.0 tsf) are very close to that of Specimen 3 (E_D = 107.0 tsf). At the same time the constrained modulus values from the specimen in the 11-in. mold were slightly lower than those from the smaller mold, which is probably due to the higher water content of the specimen in the 11-in. mold [W_n = 22.0 percent in the 11-in. diameter mold as compared with W_n = 20.0 percent in the 6-in. diameter mold (see Tables 3 and 4)].

Blade Penetration Effects

In order to evaluate the effect of blade penetration in the sample, one-dimensional compression tests were performed on specimens obtained from two identical samples having the same water content and dry density. The dilatometer test (blade penetration) was conducted on one sample, whereas one-dimensional compression tests were performed on specimens from both samples. The constrained modulus values from the sample penetrated with the dilatometer were only slightly higher than those from the sample that was not penetrated. For example, Specimen 6 was tested with the dilatometer and had

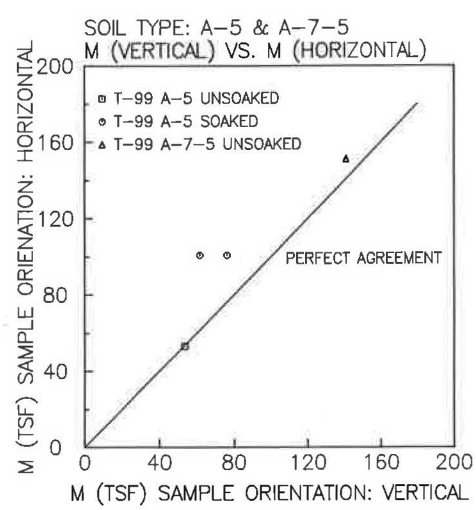

FIGURE 2 Comparison of constrained moduli from vertical and horizontal specimens.

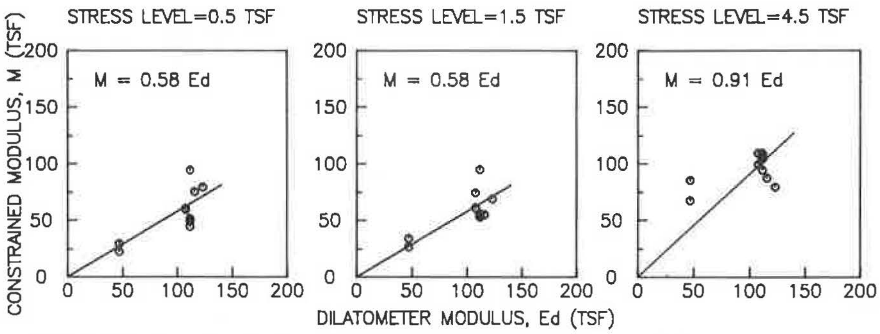

FIGURE 3 Constrained modulus versus dilatometer modulus for A-5 soil.

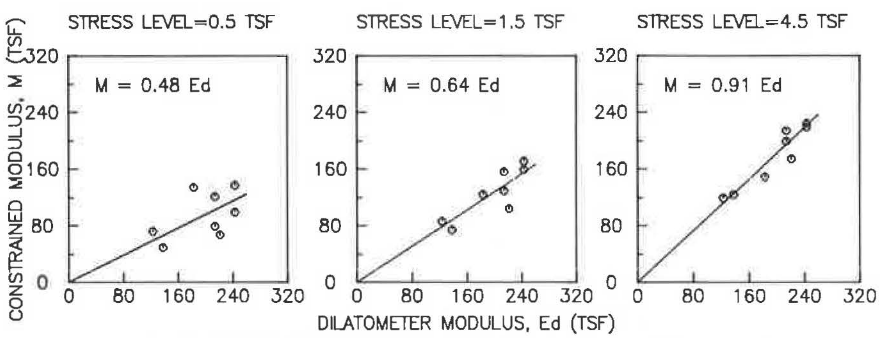

FIGURE 4 Constrained modulus versus dilatometer modulus for A-7-5 soil.

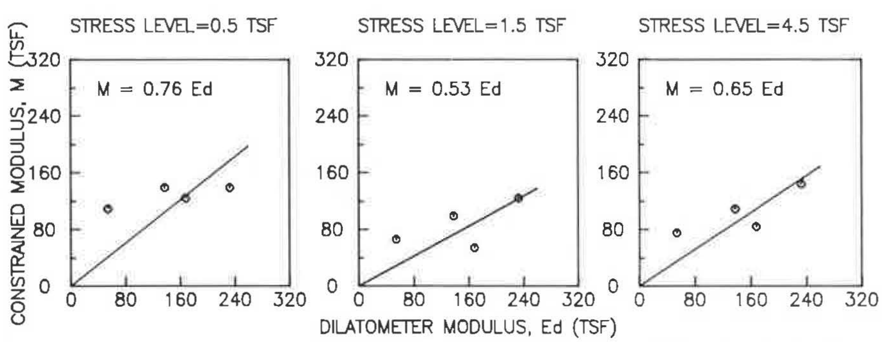

FIGURE 5 Constrained modulus versus dilatometer modulus for A-6 soil.

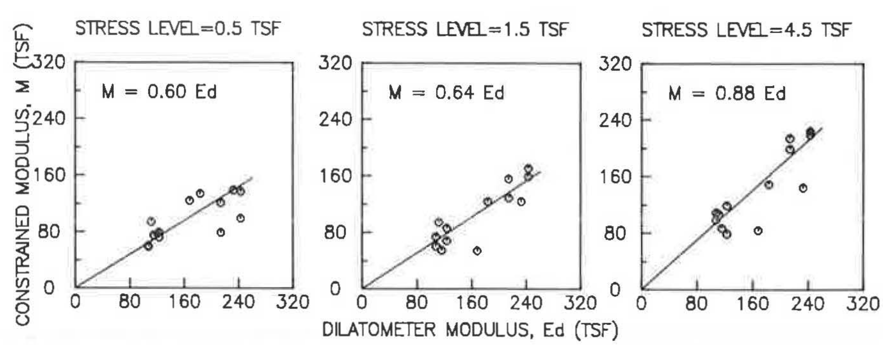

FIGURE 6 Constrained modulus versus dilatometer modulus for all unsoaked samples.

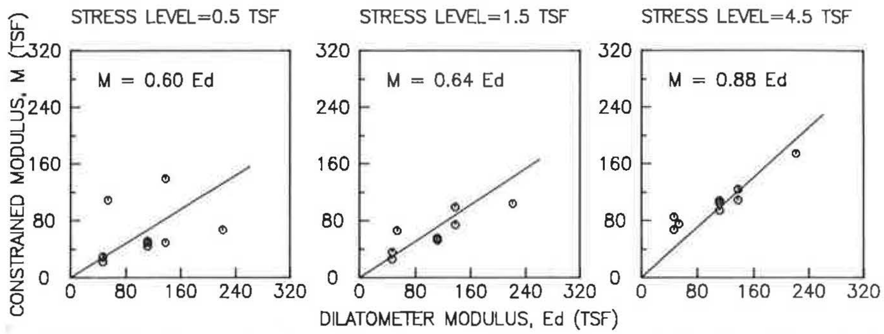

FIGURE 7 Constrained modulus versus dilatometer modulus for all soaked samples.

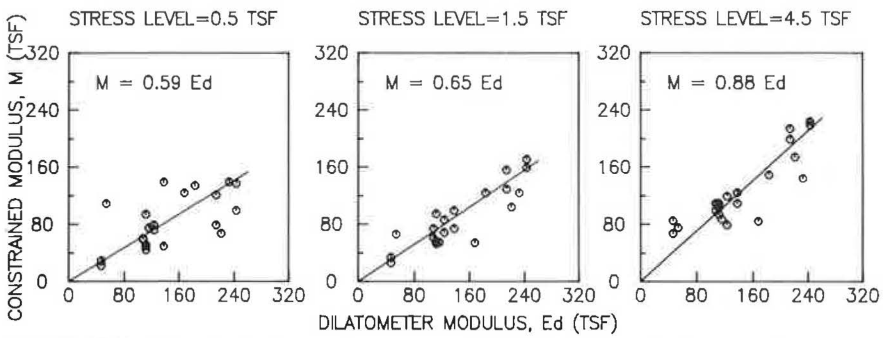

FIGURE 8 Constrained modulus versus dilatometer modulus for all samples.

an $M = 52.0$ tsf at the 0.5-tsf stress level, $M = 56.5$ tsf at the 1.5-tsf stress level, and $M = 105.0$ tsf at the 4.5-tsf stress level. Specimen 5, which was not penetrated with the dilatometer, had corresponding values of $M = 50.0$, 53.5, and 95.0 tsf. In comparison with the difference between all duplicate specimens tested, these values are not considered significantly different.

One-dimensional compression tests were also performed on samples obtained from both sides of the dilatometer to investigate the effect of the 1-mm expansion of the dilatometer diaphragm during testing. From Table 4 one can compare the data from Samples 1 and 2 and also from Samples 4 and 6. At a low stress level the constrained modulus on the sample from the side facing the dilatometer (SFD) is somewhat higher than

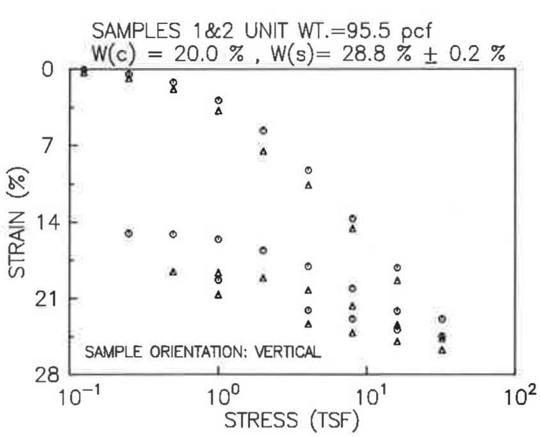

FIGURE 9 Strain versus log stress for Specimens 1 and 2.

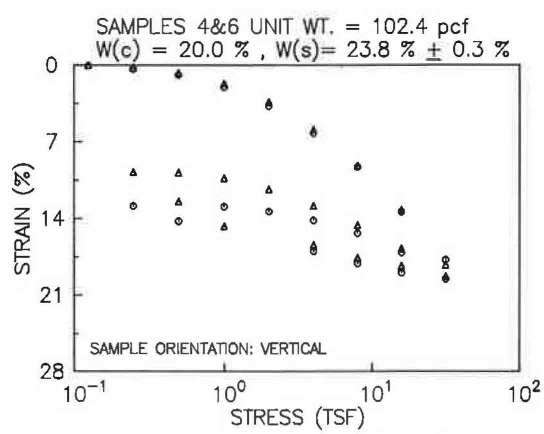

FIGURE 10 Strain versus log stress for Specimens 4 and 6.

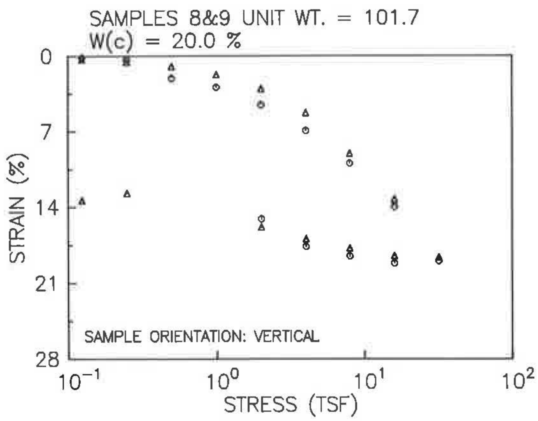

FIGURE 11 Strain versus log stress for Specimens 8 and 9.

that obtained from the sample from the back side of the dilatometer (BSD). At higher stress levels the constrained modulus on the SFD, however, is lower than that on the BSD. As the difference in constrained modulus values for specimens taken from duplicate samples ranges from 5 to 20 percent, it is not possible to conclude that a predictable difference in constrained modulus values was caused by the diaphragm expansion. This is logical because the insertion of the blade has already caused a 7-mm lateral displacement of the soil.

These test results indicate that the soil structure of the as-compacted material is stable enough that insertion of the dilatometer blade causes little change in the lateral stiffness of the soil. On this basis it was concluded that for the soils tested, the data can be used without significant concern for the influence of sample disturbance effects.

Effect of Soaking

In order to show the influence of an increased degree of saturation caused by soaking on the relationship between the constrained modulus and dilatometer response, the pertinent data from Tables 3 and 4 are reorganized and presented in Tables 5 and 6. A brief review of these tables shows that, in general, soaking causes both the resultant E_D- and M-values to be lower. However, for most of the data, the decrease in both stiffnesses is similar in magnitude, so that the ability to predict the constrained modulus from the dilatometer modulus would not be significantly limited by a lack of knowledge of the saturation state of the soil. The data contained in Tables 3 and 4 are shown in Figures 3 through 8.

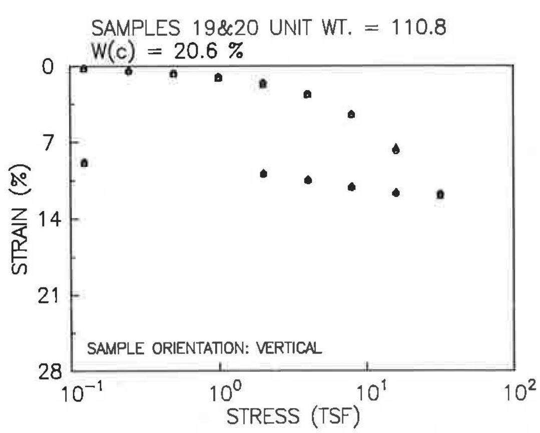

FIGURE 12 Strain versus log stress for Specimens 19 and 20.

Influence of Specimen Orientation

In Figure 2 the constrained moduli for both horizontal and vertical samples taken from the same mold are compared. These results show somewhat higher modulus values for several of the horizontal specimens when compared with those of the corresponding vertical specimens. The expansion of the dilatometer membrane measures the lateral stiffness of the soil, which is represented in this research by the vertical samples. These results indicate that the data obtained from the dilatometer may be considered a reasonable estimate of the vertical stiffness for the compacted soils tested.

Dilatometer Modulus Versus Constrained Modulus

In Figure 3 a plot of M versus E_D is presented for all tests conducted on the A-5 soil (soaked and unsoaked specimens). A straight line equation for a line passing through the origin (zero) by linear regression was used to model the relationship. Figures 4 and 5 show the relationship of the constrained modulus versus the dilatometer modulus for the A-7-5 and A-6 soils, respectively.

Figures 6 and 7 are summary plots for the unsoaked and soaked samples, respectively. A linear relation for a straight line passing through the origin was used for all data points. The resulting equations are shown on each figure.

Figure 8 is a summary plot for all the samples tested. The linear relations for straight lines passing through the origin are also given. The slopes based on data from all samples are very close to those corresponding to the unsoaked condition.

It would be of significant benefit if an initial estimate of the constrained modulus could be made directly from the field dilatometer test results without regard to soil type and moisture condition. This would be analogous to Marchetti's equation for predicting R_M when K_D is greater than 10 (Equation 7).

In order to develop this relationship, the slopes of all M-E_D relationships were plotted as a function of stress level, and the results are shown in Figure 13. In general, the coefficient relating the dilatometer modulus to the constrained modulus (R_M) is an increasing function of stress level (i.e., the slope increases with stress level). The following section presents the data generated on undisturbed field samples of the A-6 soil and aids in the interpretation of this relationship.

Field Tests and Field Samples

In order to further explore the relationship between the constrained modulus and the dilatometer modulus, three one-dimensional compression tests were conducted on specimens

TABLE 5 CHARACTERISTICS OF SOAKED AND UNSOAKED SAMPLES

Sample No. and Orientation	Soil Type	Condition as Tested	Compactive Effort[a] (%)	$W(c)$[b] (%)	$W(s)$[c] (%)	γd (pcf)	Side of Dilatometer
1-V	A-5	Soaked	50	20.0	28.6	95.5	SFD
3-V	A-5	Unsoaked	50	20.0	–	95.7	BSD
4-V	A-5	Soaked	100	20.0	23.6	102.4	BSD
8-V	A-5	Unsoaked	100	20.0	–	101.7	–
9-V	A-5	Unsoaked	100	20.0	–	101.7	–
25-V	A-6	Soaked	50	17.2	21.7	105.2	BSD
24-V	A-6	Unsoaked	50	16.8	–	105.9	–
26-V	A-6	Soaked	100	17.2	17.6	111.6	BSD
23-V	A-6	Unsoaked	100	17.0	–	111.5	–
27-V	A-7-5	Soaked	50	19.3	21.5	101.4	BSD
17-V	A-7-5	Unsoaked	50	22.7	–	98.3	BSD
28-V	A-7-5	Soaked	100	19.3	19.6	106.0	SFD
18-V	A-7-5	Unsoaked	100	19.3	–	106.3	BSD

Note: V = vertical orientation; SFD = side facing dilatometer; BSD = back side of dilatometer.
[a]As specified in AASHTO T-99 test.
[b]As compacted.
[c]After soaking.

trimmed from undisturbed Shelby tube samples of the A-6 soil obtained in a field investigation of a 15-ft (4.8-m) compacted embankment in Research Triangle Park (RTP), North Carolina. The test data were analyzed and the constrained modulus at each of the three stress levels is plotted versus the field dilatometer reading at the depth from which each of the samples was obtained. These data are shown in Figure 14, which allows the determination of an appropriate slope for each stress level, as previously discussed for Figure 13.

Figure 15 shows the R_M-values generated from Figure 14 in conjunction with those from the laboratory tests on each of the three soils. The field samples show a greater rate of increase of R_M with stress level than the laboratory-compacted specimens; however, even these values are significantly lower than those that would be predicted from Marchetti's equations. For example, the average I_D-value obtained for all tests on the A-6 soil was 1.37. Using Equation 5 and an estimate of K_D based on the existing overburden stress at a depth of 10 ft (approximately 3 m), the calculated R_M-value is around 2.3. As it is doubtful that the appropriate stress level for any of the tests would be greater than the 1.5-tsf value, it appears that using Marchetti's equations may overestimate the stiffness of compacted soils by a significant amount.

On the basis of the results of this experimental investigation, it would appear reasonable to accept the dilatometer modulus as an upper bound to the anticipated in situ constrained modulus, with the realization that values may actually be in the range of 50 to 80 percent of that value, depending on soil type.

SUMMARY AND CONCLUSIONS

In this research, the relationship between the dilatometer modulus and the constrained modulus from the one-dimensional

TABLE 6 CONSTRAINED MODULUS AND DILATOMETER MODULUS VALUES FOR SOAKED AND UNSOAKED SAMPLES

Sample No. and Orientation	M (tsf) by Stress Level			E_D
	0.5 tsf	1.5 tsf	4.5 tsf	(tsf)
1-V	30.0	36.4	68.0	45.0
3-V	95.0	95.6	108.0	107.0
4-V	45.0	55.0	109.0	107.0
8-V	61.0	61.7	110.0	103.0
9-V	60.0	75.0	100.0	–
25-V	110.0	67.0	76.0	52.0
24-V	125.0	55.0	85.0	161.0
26-V	140.0	100.0	110.0	132.0
23-V	140.0	125.0	145.0	223.0
27-V	50.0	75.0	125.0	132.0
17-V	73.0	87.0	120.0	118.0
28-V	68.0	105.0	175.0	212.0
18-V	122.0	157.0	215.0	205.0

Note: V = vertical orientation.

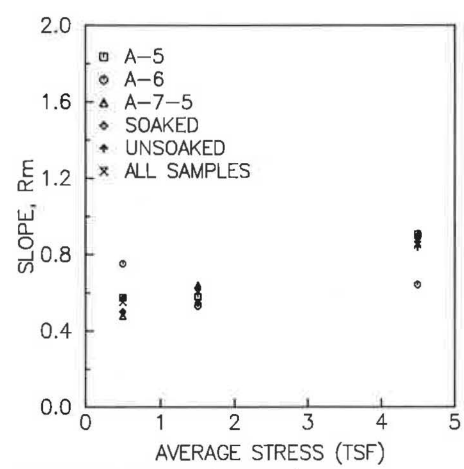

FIGURE 13 Ratio relating dilatometer modulus to constrained modulus versus stress level for laboratory samples.

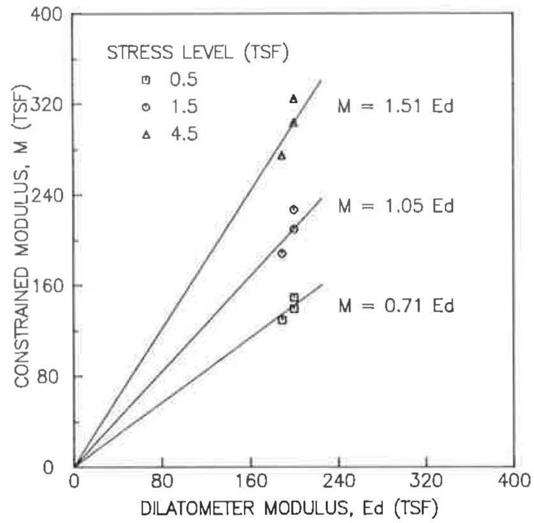

FIGURE 14 Constrained modulus versus dilatometer modulus as a function of stress level for A-6 field samples.

compression test for three different soils encountered in North Carolina has been studied.

On the basis of the results of the experimental test program reported, the following conclusions are advanced:

1. For the compacted soils studied it was found that current methods for interpreting dilatometer data to predict compressibility, as determined from one-dimensional compression tests, significantly overestimated the values that were measured. On the basis of the combination of laboratory and field tests conducted, it would appear reasonable to accept the dilatometer modulus as an upper bound to the anticipated in situ constrained modulus, with the realization that values may actually be in the range of 50 to 80 percent of that value, depending on soil type.

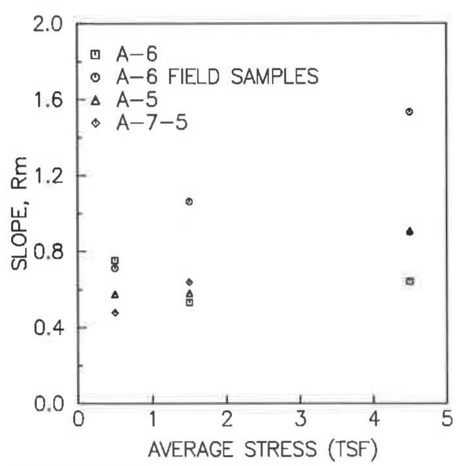

FIGURE 15 Ratio relating dilatometer modulus to constrained modulus versus stress level for laboratory and field samples.

2. A laboratory technique was utilized by which dilatometer penetration tests were performed in CBR molds (6-in. diameter), after which the one-dimensional compression test specimens were obtained, so that both pieces of data were obtained from the same specimen. Although the boundary conditions appear unfavorable in the small mold, the results of the one-dimensional compression tests were consistent with those duplicate samples in which the dilatometer was not penetrated.

3. Limited one-dimensional compression tests on Shelby tube samples (field-compacted material) of the A-6 soil show a relatively higher influence of stress level on the constrained modulus for the same dilatometer modulus than on the laboratory-compacted sample. Further study should emphasize the correlation between field dilatometer tests and laboratory tests on Shelby tube or other undisturbed samples of partially saturated soils, which more closely represent in situ conditions.

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