Characterization of Preconsolidated Soils in Richmond, Virginia

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The Miocene-age Calvert formation underlying Richmond is highly preconsolidated and very sensitive and requires careful evaluation for foundation design. This soil is of marine origin, and preconsolidation results from desiccation associated with several identifiable drying surfaces and overburden erosion. Major structures are typically supported within this formation by spread footings and belled caissons. The high undrained shear strength and preconsolidation pressure of the formation allow the design of high-capacity foundations. The standard penetration test N-values for the soil are typically low and not indicative of its quality. Conventional triaxial compression and consolidation tests are often utilized to obtain parameters for design of foundations. More recently pressuremeter test results have been used for foundation design. The purpose of this paper is to present a summary of available laboratory and pressuremeter test data and to characterize the engineering properties of this soil.

The stratigraphy of the Richmond area is of interest because one of the units underlying the city, the Miocene-age Calvert formation, is very sensitive and highly preconsolidated. About 30 years ago, Arthur and Leo Casagrande identified the characteristics of this unit while providing consulting foundation engineering services for several major structures in Richmond, including City Hall. Leo Casagrande (*2*) compiled their findings in a paper that became the basis for future research concerning the soil. The techniques used by the Casagrandes to identify the characteristics of the soil were classification, consolidation, and unconsolidated undrained triaxial compression tests. However, engineers at that time were relying on standard penetration test (SPT) *N*-values to determine soil properties for foundation design. The *N*-values are typically very low, ranging from about 4 to 20 for this highly preconsolidated formation where overconsolidation ratios can approach 4 because of the sensitivity of the soil, which varies from about 10 to 22. Based on *N*-values, the soil was considered to be too soft and compressible for support of major structures. Prior to this time most major structures in Richmond were founded on piles driven through this stratum or straight shaft caissons supported on rock as much as 150 to 175 ft (46 to 53 m) below the ground surface. Most recent structures have been supported on single and double under-reamed caissons founded in the clay or spread footings supported on the surface of the clay. These designs have resulted in significant foundation cost savings (*7*).

GEOLOGY

Richmond is located on the James River at the fall line, about 100 mile from the Atlantic Ocean. In the downtown area, ground surface varies from about sea level at the James River to about El 170 (52 m) to 180 (55 m) in the highest areas along Broad and Marshall streets. This upper portion of downtown Richmond is the area considered in this study (Figure 1).

Precambrian bedrock consisting of Petersburg granite underlies the downtown area and is typically at about El 30 (9 m) to −10 (−3 m). Overlying bedrock is a sequence of weathered residual soil and coastal plain sediments. The residual soil is very compact and is described as disintegrated rock. The overlying soils were deposited during various transgressions and regressions of the sea and include the very compact Eocene sand and Cretaceous sand and gravel. The Calvert formation overlies the Eocene soils and typically extends from El 60 (18 m) to about El 140 (43 m) in the upper portion of the downtown area and thus is about 80 ft (24 m) thick. Overlying the Calvert is a stratified Pleistocene terrace deposit consisting of sand, gravel, and clay layers. The clays in this formation are somewhat preconsolidated due to desiccation. The sand and gravel layers are usually compact. A typical boring log and geologic profile along Marshall Street illustrating this geologic sequence are included as Figures 2 and 3.

The preconsolidated nature of the Calvert formation likely resulted from (*a*) desiccation during periods of emergence as the Miocene sea level fluctuated and (*b*) erosion of overlying sediments during post Miocene time. The Miocene sea is estimated to have risen to maximum El 240 (73 m) (*5*). Approximately 2 mi (3.2 km) to the north of the downtown area and in a position parallel to the old Miocene shoreline, the Calvert formation has been observed at El 180 (55 m) or about 40 ft (12 m) above the top of the formation in the downtown area. Terrace deposits in the area rise to about El 230 (70 m) to 240 (73 m). Based upon this geologic evidence, it is possible to estimate that the maximum previous ground surface in the downtown area may have been as high as about El 230 (70 m).

Groundwater is located in the Cretaceous deposit at about El 40 (12 m) and is hydraulically connected to the James River. Thus, the full column of soil above this level is effective. A perched water condition is often present above the Miocene formation, and its elevation is dependent upon the amount of precipitation and level of the top of the formation.

RECENT INVESTIGATIONS

Over the intervening years since the Casagrandes' work, additional laboratory and in situ testing has been performed on this soil during investigations for numerous structures (*1,3,4,13*). In addition, the pressuremeter has been used to further characterize the soil. In 1986 Martin and Drahos (*8*) published a paper describing more recent laboratory testing data and included correlations between Menard pressuremeter (MPM) and triaxial and consolidation test results. Specifically, the paper established undrained shear strength

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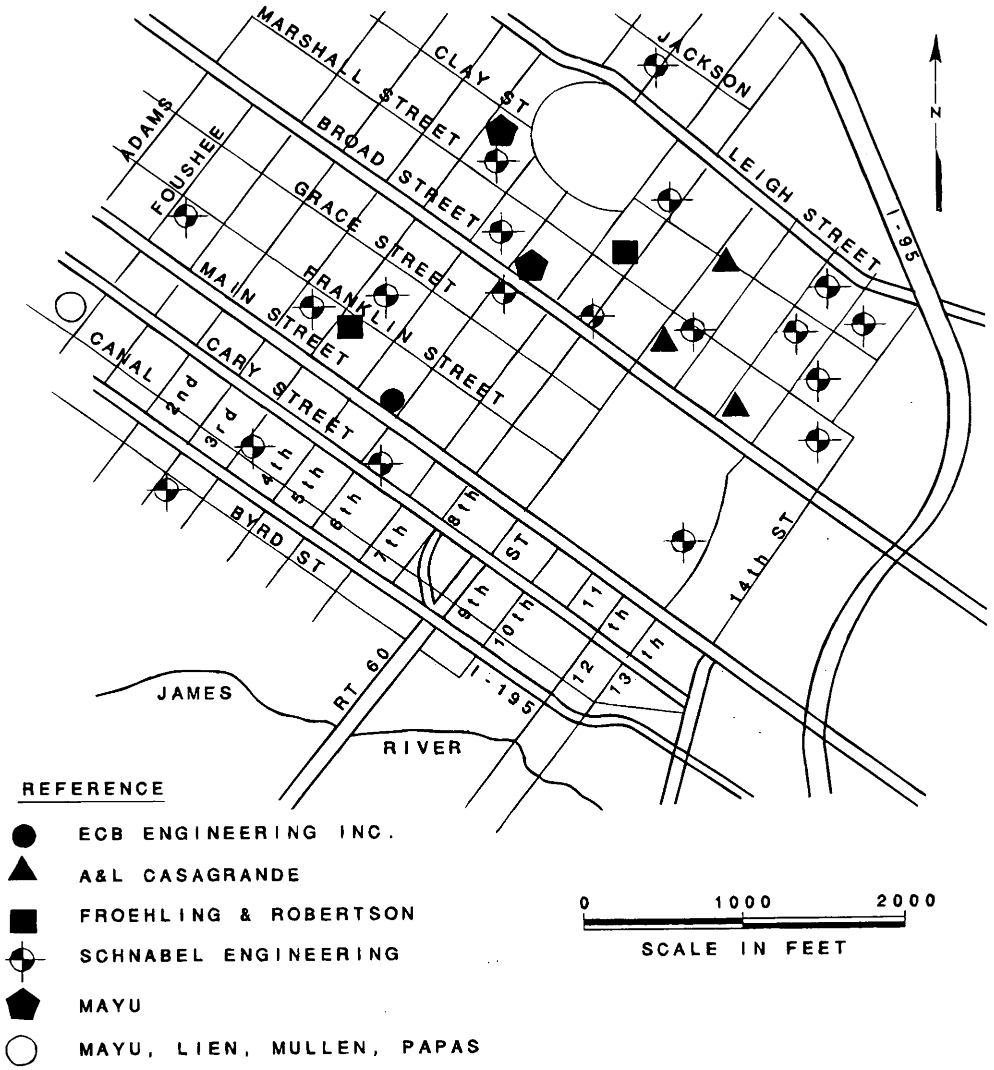

FIGURE 1 Map of upper portion of downtown Richmond (1 ft = 0.305 m).

from the pressuremeter limit pressure based on correlations with unconsolidated-undrained triaxial compression tests.

Mayu (*10*), Mullen (*11*), Lien (*6*), and Pappas (*12*) have also performed additional pressuremeter tests in the soil. They each used the self-boring pressuremeter (SBPM) and the MPM to evaluate soil modulus, undrained shear strength, and the earth pressure coefficient at rest, K_0. Mullen also performed tests with the dilatometer and cone penetrometer. These data from in situ tests suggest the undrained shear strength and soil modulus to be higher than that obtained by conventional laboratory testing of undisturbed tube samples.

The clays in the formation tend to be highly plastic. Mayu (*10*) evaluated the clay mineralogy of one sample of the clay and found the following constituents:

Constituent	*Percent*
Mica	25
Kaolinite	10
Smectite	55
Phyllosicates	9
Quartz	1

The high percentage of smectite, which includes montmorillonite, provides the characteristic high plasticity of these soils.

SAMPLE DATA BASE

This study summarizes the results from over 200 samples tested in the laboratory from undisturbed tube and block samples and over 70 pressuremeter tests. These data represent 24 sites in downtown Richmond as shown in Figure 1. The data were developed from the references listed in the previous section. Most of the laboratory test results were obtained from 3-in. diameter tube samples, which compose about 80 percent of the samples. Both shear strength and consolidation test results are included for these samples. About 20 percent of the tube samples were 2-in. in diameter and were used to perform shear strength testing. Shear strength and consolidation results from four 5-in. diameter tube samples and three block samples are also included.

SAMPLE QUALITY

One issue of concern when estimating shear strength and compression properties of stiff and hard consistency clays from laboratory tests is the disturbance that occurs during both sampling and sample

ELEV (FT)	STRATA DESCRIPTION GROUND SURFACE EL 150 FT	SPT	REMARKS
141	SAND FILL, SOME BRICK & CINDERS - BROWN & BLACK	7 7	FILL
132	WELL GRADED SAND WITH CLAY - BROWN (SC)	54 18 12	PLEISTOCENE ▼ (PERCHED)
121	SILT - BROWN (ML)	6 6 9	UPPER MIOCENE (CALVERT FORMATION)
60	FAT CLAY WITH SAND - GRAY (CH)	12 7 14 12 16 16 20 11 17 12 13 14 13 13	LOWER MIOCENE (CALVERT FORMATION)
38	SILTY SAND WITH CEMENTED SAND LAYERS - BROWN & GRAY (SM)	89 21 100/0.7 100/0.8 38	EOCENE ▼
12	SILTY SAND WITH GRAVEL - GREEN (SM)	100/0.3 100/0.6 91 93 100/0.3	CRETACEOUS
-10	DISINTEGRATED ROCK - GRAY	100/0.8 100/0.7 100/0.3 100/0	PRECAMBRIAN
-15	HARD SLIGHTLY FRACTURED GRANITE ROCK	REC 100%	

▼ = WATER TABLR
SPT = STANDARD PENETRATION TEST
REC = RECOVERY
100/0.3 = SPT BLOWS/FT

FIGURE 2 Typical test boring (1 ft = 0.305 m).

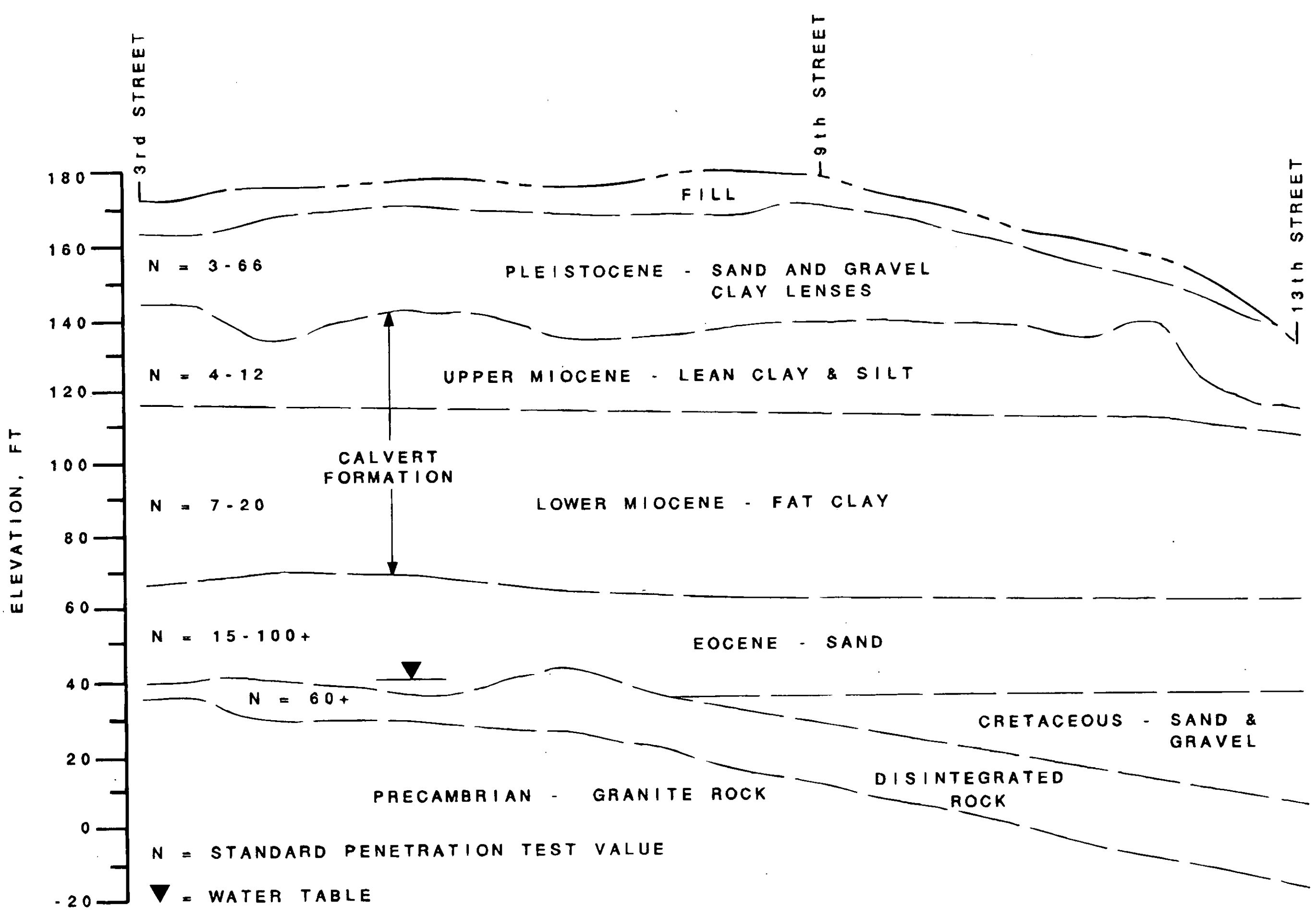

FIGURE 3 **Profile along Marshall Street (1 ft = 0.305 m).**

extrusion in the laboratory. Block samples would be expected to experience less disturbance than 5-in. diameter tube samples and the 5-in. and 3-in. diameter tube samples likewise should experience less disturbance than the smaller 2-in. diameter samples. The area ratio A_r may be used to estimate sample disturbance and is defined as follows:

$$A_r(\%) = [(D_o^2 - D_i^2)/D_i^2] \times 100$$

where D_o is the outside diameter of the sample and D_i is the inside diameter of the sample.

The term "undisturbed" is generally used for a sample obtained with a sampling tube for which the area ratio is equal to or less than 10 percent. The area ratios for the types of samples tested are as follows:

Sample Type	*Area Ratio (%)*
2-in. tube	13.7
3-in. tube	8.9
5-in. tube	5.2
Block	~0

The 2-in. sample exceeds the 10 percent limit. The block samples are designated as approximately zero since they are obtained by cutting from the ground. From the area ratios it is obvious that the block sample should be far superior to the 3-in. or 5-in. tube samples. Less-disturbed samples should produce higher-quality results when tested for shear strength and consolidation properties. The preconsolidation pressure and compression index would be expected to be higher for comparable samples that have experienced less disturbance. Likewise the shear strength would be expected to be higher and strain at failure lower under less-disturbed conditions. Only three block samples and four 5-in. diameter tube samples are included in the data base. These samples are identified in the test results presented below for comparison with results for 2-in. and 3-in. diameter tube samples.

The pressuremeter test has the advantage of being performed in situ, and the soils surrounding the test should be less affected by disturbance. The SBPM should also subject the soils to less disturbance than the MPM, since the two-step process of excavating the hole and replacement with the MPM is not required. This is also true for the dilatometer and cone penetrometer tests.

LABORATORY TESTING

The data base includes index property, consolidation, undrained shear strength, and soil modulus test data. The data are discussed under these topic headings below for clarity.

Index Properties

Index property tests for purposes of this paper include moisture content, fines content (percentage passing the No. 200 sieve), plasticity index, and density. Wet density is used in overburden calculations since the full column of soil is effective. Dry density is more meaningful with respect to strength and compressibility properties.

The Miocene-age soils were previously divided into two strata (*2*). The upper Miocene extends from about El 140 (43 m) to 120 (37 m). The lower Miocene extends below this level to about El 60 (18 m). All boundaries vary up to about ±10 ft (3 m) across the area included in the study. The results of these tests are plotted in Figures 4–6.

The moisture content of the upper Miocene typically ranges from about 30 to 40 percent as shown in Figure 4. The range for the lower Miocene is about 40 to 60 percent between about El 120 (37 m) and 100 (30 m). Below this level the moisture content ranges much more widely from about 40 to 90 percent. Thin beds of sand occur occasionally in the lower Miocene. Moisture contents are typically lower in these thin layers, approximating the values of the upper Miocene. The average values for each of these layers are 34.9 percent for the upper Miocene, 48.6 percent for the upper portion of the lower Miocene above about El 100, and 61.4 percent for the remainder of the lower Miocene as shown by the vertical lines on Figure 4.

The upper Miocene has a much lower fines content, typically ranging from about 30 to 60 percent. The fines content in the lower Miocene ranges from about 70 to 100 percent, but the majority of samples have more than 85 percent fines with no change indicated at El 100 (30 m). The average for the upper Miocene is 45.1 percent and for the lower Miocene, 91.2 percent.

Dry and wet densities are also distinctly different as would be expected based on the variation in moisture and sand content. Dry density values range from about 80 to 100 pcf (1281 to 1602 kg/m^3) for the upper Miocene and average 85.5 pcf (1370 kg/m^3). The lower Miocene ranges from 50 to 80 pcf (801 to 1281 kg/m^3) with a distinct change in density at about El 100 (30 m). Above this level the values range from 60 to 80 pcf (961 to 1281 kg/m^3) and average 73.2 pcf (1173 kg/m^3). Below this level the dry density drops to a range of about 50 to 70 pcf (801 to 1121 kg/m^3) with an average of 61.4 pcf (984 kg/m^3). Wet density values illustrate a similar variation.

The liquid limit and plasticity index are also distinctly different in the two strata. The liquid limit and plasticity index are much higher in the lower Miocene. Typical liquid limits range from about 30 to 60 in the more sandy upper Miocene and 50 to 110 for the lower Miocene. Plasticity index values range from about 10 to 40 for the upper Miocene and 30 to 70 for the lower Miocene.

The samples in the upper Miocene typically classify clayey sand (SC) to sandy lean clay (CL) as shown in Figure 5. The lower Miocene typically classifies as fat clay (CH). Casagrande (*2*) noted that these soils contain colloidal organic matter and that samples should be air-dried prior to Atterberg limit testing. Oven drying of samples results in a reduction in liquid limit and thus the plasticity index. The samples that plot below the A-line in Figure 5 are probably not representative of the strata properties. These results are likely due to improper testing procedures.

These index properties confirm that the Miocene formation should be separated into two strata, described above as upper and lower, with the boundary at about EL 120 (37 m). In addition, these data suggest that consideration should be given to further dividing the lower Miocene at about El 100 (30 m). This concept is supported by the data discussed below.

Consolidation Test Data

Consolidation tests are widely used to evaluate the deformation characteristics of these soils. The soils generally exhibit preconsolidation pressures (P_c) well in excess of the existing overburden pressures (P_o) as noted in Figure 6.

The ground surface grades at the locations of the borings where samples were obtained vary from about El 140 (43 m) to 180 (55 m). The overburden pressures for all samples were normalized for evaluation purposes using a ground surface grade of El 180 (55 m), the typical ground surface grade in the upper portion of downtown Rich-

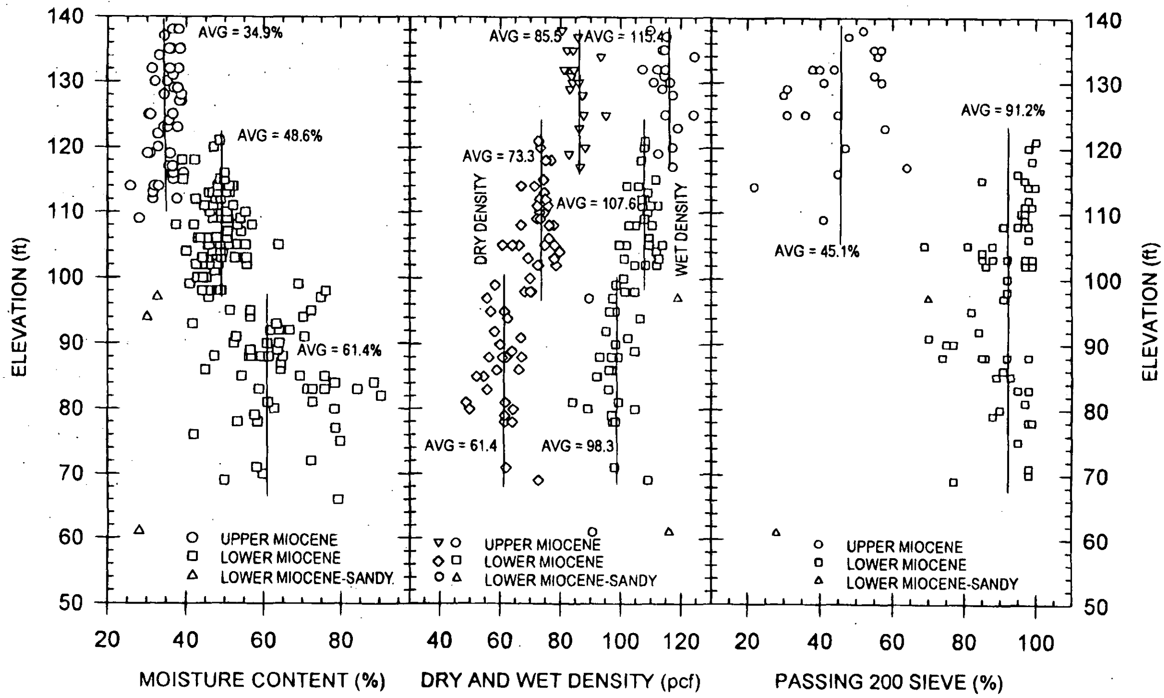

FIGURE 4 **Moisture content, density, and gradation (1 ft = 0.305 m).**

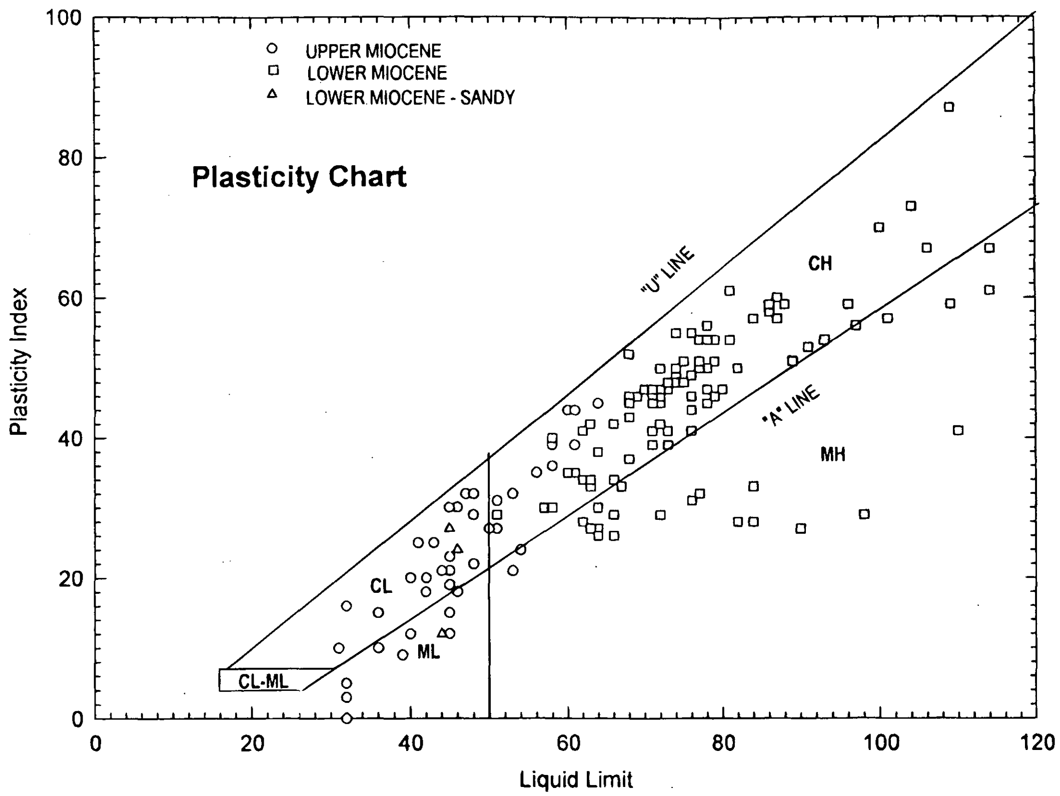

FIGURE 5 Atterberg limits (1 ft = 0.305 m).

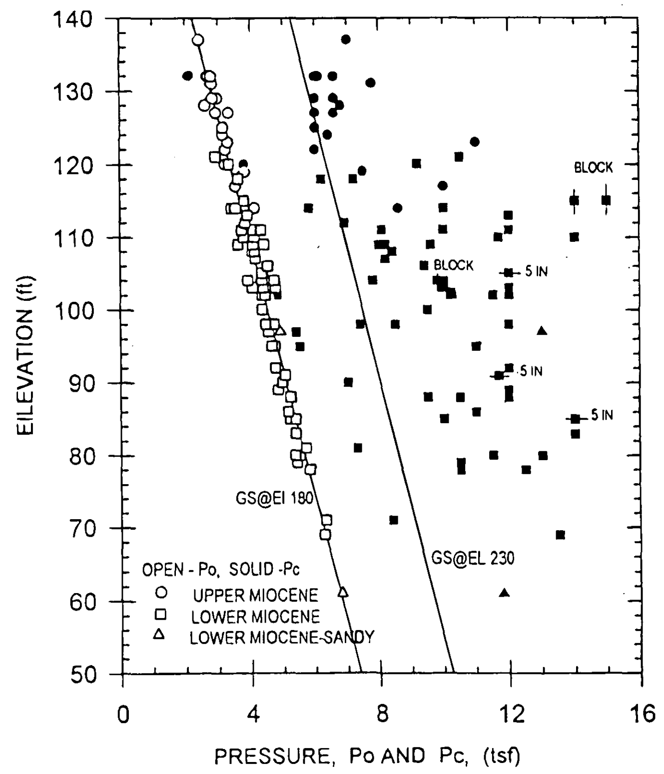

FIGURE 6 Consolidation test data (1 ft = 0.305 m, 1 tsf = 0.1 MN/m^2).

mond. This normalized overburden pressure was also used to calculate the normalized overconsolidation ratio (OCR) for all the sites in the downtown area as shown in Figure 6. This approach allows the comparison of other data from all sites with the normalized OCR.

The maximum ground surface elevation in this part of Richmond in past geologic history was likely about El 230 (70 m) as discussed above. Note that the maximum past pressures for the vast majority of samples exceed the El 230 (70 m) line thus indicating the appropriateness of this assumption. Two possible explanations for why the preconsolidation pressures plot to the left of the El 230 line are (*a*) that the samples tested were disturbed or (*b*) that the ground surface may not have been as high as assumed.

The wide variation of the maximum past pressures is believed to be due to old surfaces of drying that occurred during the regressions of the Miocene sea. This effect is most noticeable in the more plastic soils with higher fines content of the lower Miocene, as would be expected, since they are more susceptible to the effects of surface tension.

The normalized OCR data are illustrated in Figure 7. These data indicate that the strata between about El 100 (30 m) and 120 (37 m) in the lower Miocene have higher normalized OCR values than the strata below El 100 (30 m). This suggests that the strata should be suitable for support of somewhat higher foundation bearing pressures than the remaining portion of the lower Miocene below El 100 (30 m). This also supports the idea that the lower Miocene should be separated into two distinct strata.

The initial void ratios are also presented in Figure 7. The initial void ratios are somewhat higher for the lower Miocene than the

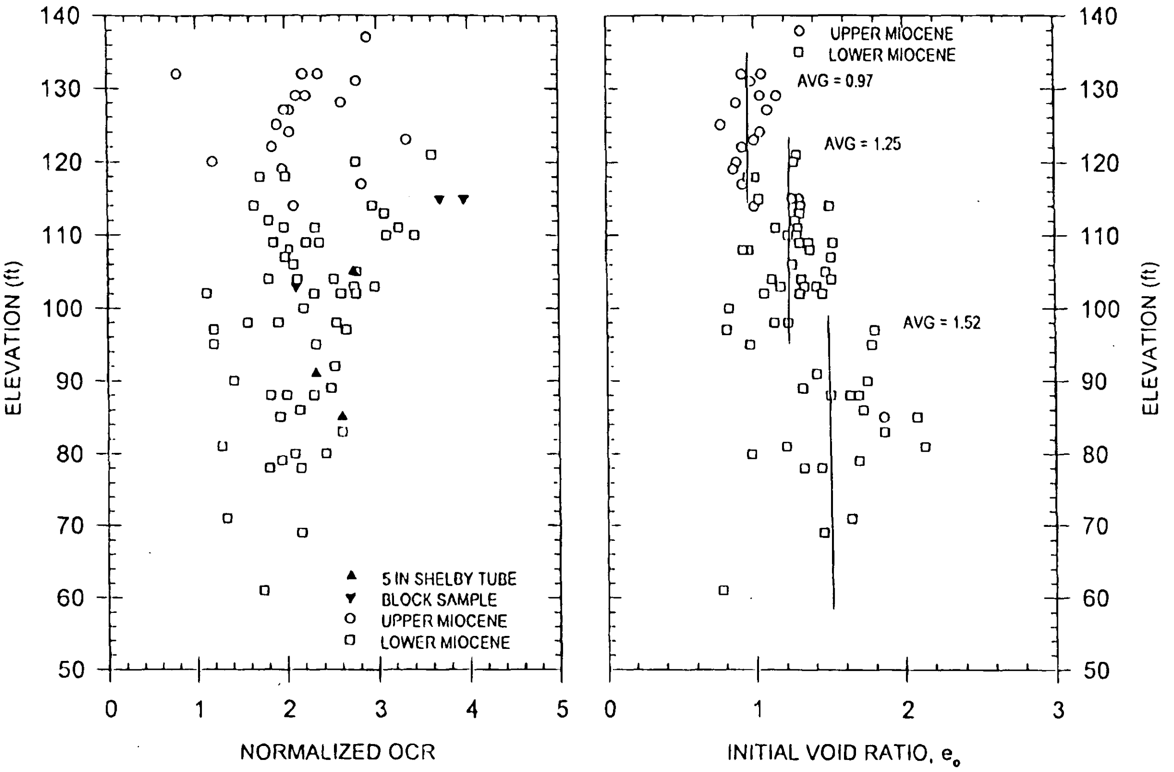

FIGURE 7 Normalized OCR and initial void ratio (1 ft = 0.305 m).

upper Miocene. The portion of the lower Miocene between about El 100 (30 m) and 120 (37 m) exhibits somewhat lower initial void ratios as would be expected based on the data presented above including the higher density and normalized OCR values associated with this stratum. The average e_0 value is 0.97 for the upper Miocene, 1.25 for the lower Miocene above about El 100, and 1.52 for the remainder of the lower Miocene. The average values for the three zones are shown by the vertical lines on Figure 7.

The variation of the compression (C_c) and recompression (C_r) indices with liquid limit and void ratio are illustrated in Figure 8. The equations for the linear regression trend lines are included in the figures and are as follows.

Compression Index

$C_c = 0.0326(LL - 43.4)$ $C_c = 1.79(e_0 - 0.808)$

Recompression Index

$C_r = 0.00045(LL + 11.9)$ $C_r = 0.05(e_0 - 0.444)$

These equations may be used for preliminary estimates of C_c and C_r in lieu of actual test data. The ratio C_r/C_c based on these equations is about 1/25 or very high. Typical values range from about 1/5 to 1/10.

Results for the 5-in. tube and block samples are noted in Figures 6–8. The estimate of the preconsolidation pressure would be expected to improve with reduction in sample disturbance. Direct comparisons cannot be made, since samples were not obtained side by side but, rather continuously, down the hole. However, five of the six block and 5-in. tube samples tested are in the highest range of preconsolidation pressures and normalized OCR values, suggesting that these samples are likely to be less disturbed. All 5-in. diameter tube and block samples were obtained in the lower Miocene formation.

Figure 8 illustrates the position of the six 5-in. and bulk samples tested versus all samples. The C_c values would be expected to be higher for less disturbed samples with similar properties, but the values for these samples do not illustrate this trend. The recompression index should be little affected by sample disturbance since these values were calculated from unload-reload cycles.

Soil Modulus

Soil modulus data were developed from both triaxial and pressuremeter tests. The triaxial test data represent tangent modulus values measured at 50 percent of peak stress and are shown in Figure 9. Because the triaxial test samples from undisturbed tube samples undergo more disturbance and test smaller amounts of soil, the values are typically lower than pressuremeter values, ranging from 100 to 400 tsf (10 to 40 MN/m^2). The 5-in. diameter tube sample tests are generally at the upper edge of the unconsolidated, undrained (UU) and consolidated, undrained (CU) data from undisturbed tube samples. Triaxial testing done on the block samples that have experienced less disturbance recorded higher results, which ranged from 600 to 1000 tsf (60 to 100 MN/m^2).

The MPM is lowered into a preformed hole where the soil has slight to moderate disturbance caused by the drilling process and insertion techniques. These tests were slightly higher than the triaxial tests and ranged from 100 tsf (10 MN/m^2) to approximately 1300 tsf (130 MN/m^2). The highest modulus values were calculated from the

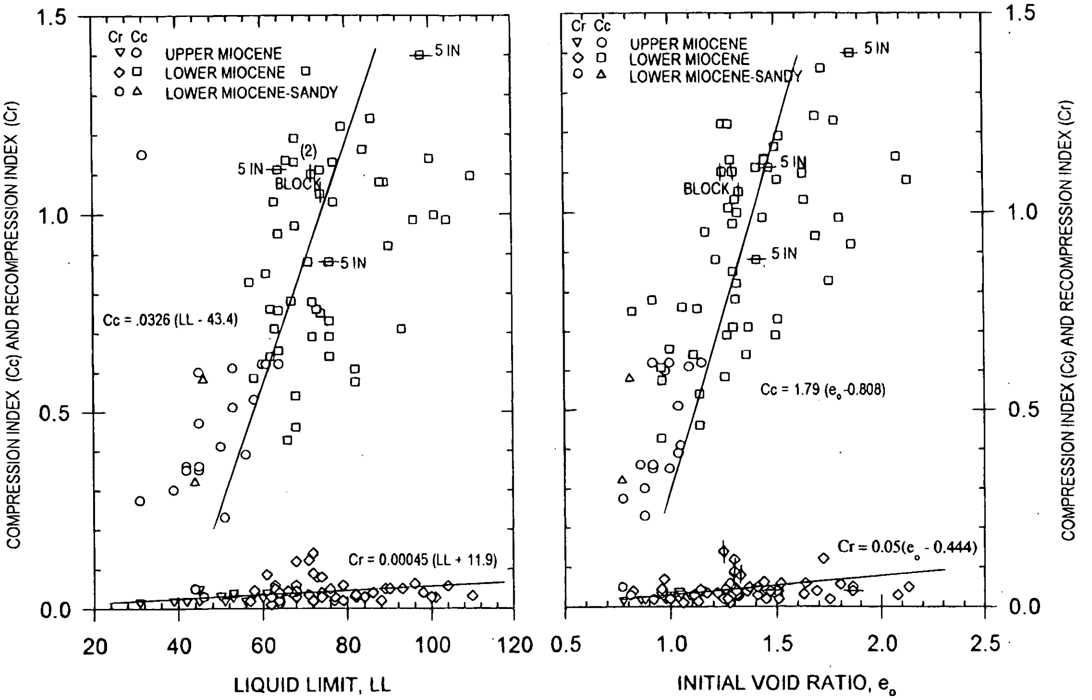

FIGURE 8 **Variation of C_c and C_r with liquid limit and initial void ratio.**

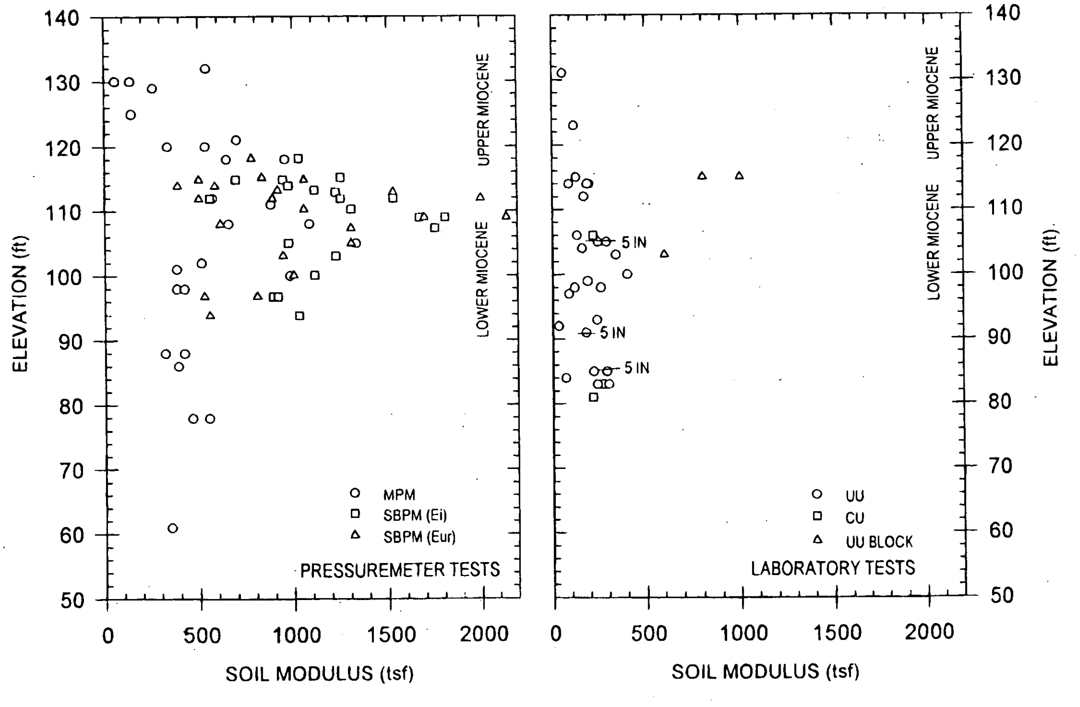

FIGURE 9 **Soil modulus versus elevation (1 ft = 0.305 m, 1 tsf = 0.1 MN/m²).**

SBPM, which causes the least disturbance to the soil as it drills its own hole to the level being tested. The probe membrane expands pneumatically and uses three strain arms 120 degrees apart in the middle of the probe to measure the membrane displacement during expansion. The SBPM tests provide an initial modulus value (E_i) from a tangent to the steepest portion of the initial loading curve and a value from subsequent unload reload curves (E_{ur}). The SBPM tests produced the highest initial modulus values, ranging from approximately 500 tsf (50 MN/m^2) to peak values near 1800 tsf (180 MN/m^2).

It should be noted that the highest soil modulus values were found above El 100, again confirming the significance of this upper portion of the lower Miocene.

Shear Strength

The majority of the laboratory undrained shear strength, s_u, test data represent UU triaxial compression and unconfined compression (Q) tests as indicated in Figure 10. The UU tests were performed at or near a confining stress equal to the overburden pressure under the assumption that K_0 equals about one. K_0 values have been shown to range from 1 to 2 for the upper Miocene and 2 to 8 for the lower Miocene on the basis of SBPM tests (*6*). These are very high values. Equations for estimating K_0 from OCR data, such as those developed by Mayne and Kulhany (*9*), suggest that K_0 would be in the range of about 0.75 to 1.25. The use of $K_0 = 1$ for the UU test appears conservative based on the SBPM tests, and the resulting s_u values should be lower than those from the in situ tests.

The typical values for s_u in the upper Miocene range between about 0.5 and 1.0 tsf (0.05 and 0.1 MN/m^2) with the triaxial and in situ test results in the same range. The values for the lower Miocene range from about 1.0 to 7.0 tsf (0.1 to 0.7 MN/m^2). The in situ tests are typically higher than the triaxial results. Once again the results are higher in the lower Miocene above El 100 (30 m). The very high s_u values would not be expected based on SPT N values. The usual s_u correlations with N-values would suggest s_u values of between 0.5 and 1.0 tsf and (0.05 and 0.1 MN/m^2) as opposed to 1.0 to 7.0 tsf (0.1 to 0.7 MN/m^2).

The block and 5-in. diameter tube samples are in the upper range of laboratory s_u values and these are indicative of less disturbance. This is not true for the MPM because of the built-in bias by using correlations with triaxial test results to estimate S_u as previously described (*8*).

The s_u values also increase with reduced strain at failure but with much scatter as illustrated in Figure 11. Typically failure strain values are less than 6 percent for the lower Miocene formation. Block samples produced the highest s_u values with $s_u = 5$ tsf (0.5 MN/m^2) at 1 percent strain at failure.

SUMMARY AND CONCLUSIONS

The Miocene-age formation in downtown Richmond is unique in that it is both highly preconsolidated and sensitive but not fissured. Standard penetration test N values typically underestimate the soil quality, and laboratory or in situ testing are required for accurate assessment of the soil properties. The data base presented herein includes results from a variety of sources including tests from over 200 undisturbed samples and over 70 pressuremeter tests. The reader is referred to the various figures for specific ranges of data for various soil properties. The conclusions may be summarized as follows.

1. Previous studies identified upper and lower Miocene layers based on gradational properties and this is confirmed. The upper layer, which typically extends from about El 120 to 140 (37 to 43 m), is more sandy and varies from clayey sand (SC) to sandy lean clay (CL). The lower layer from about El 60 to 120 (20 to 37 m) has a high fines content and usually classifies as fat clay (CH).
2. The test data suggest that a third layer consistently exists at the top of the lower Miocene layer between about El 100 and 120 (30 and 37 m). This layer was previously identified as an old drying surface at specific sites. The layer typically has higher normalized OCR values, lower initial void ratios, and higher shear strength and soil modulus values than the soils below or above.
3. In situ testing with the MPM and the SBPM generally provide higher soil modulus and undrained shear strength values than conventional triaxial testing of undisturbed samples for both the upper and lower Miocene formations. Only the block samples produced results similar to the in situ test results.

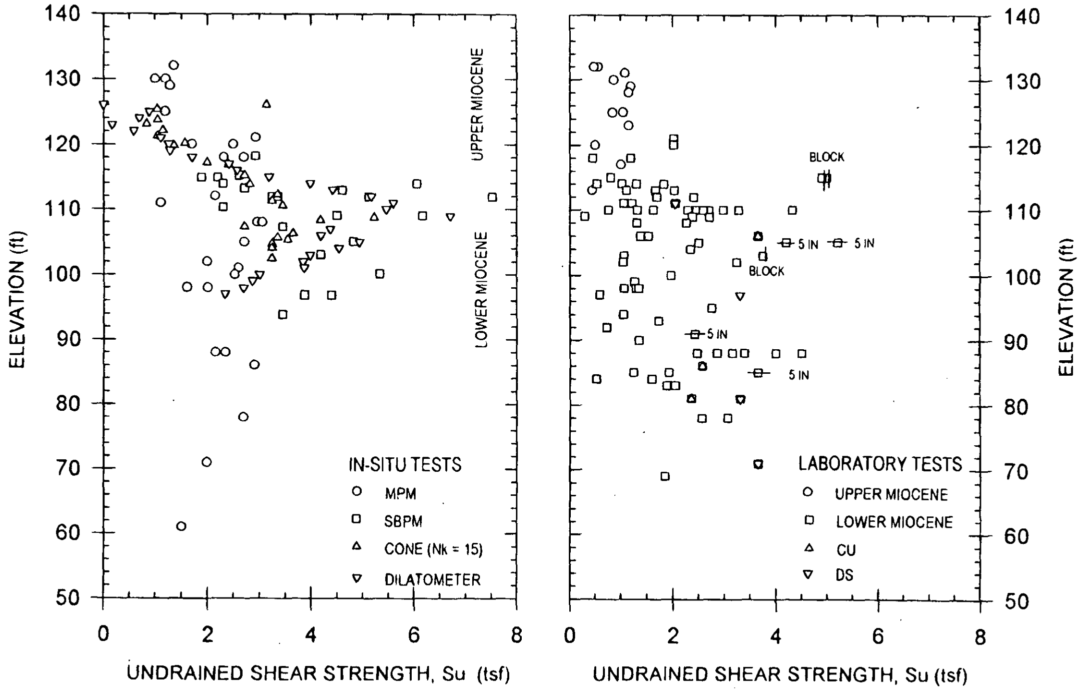

FIGURE 10 Undrained shear strength versus elevation (1 ft = 0.305 m, 1 tsf = 95.8 kN/m^2).

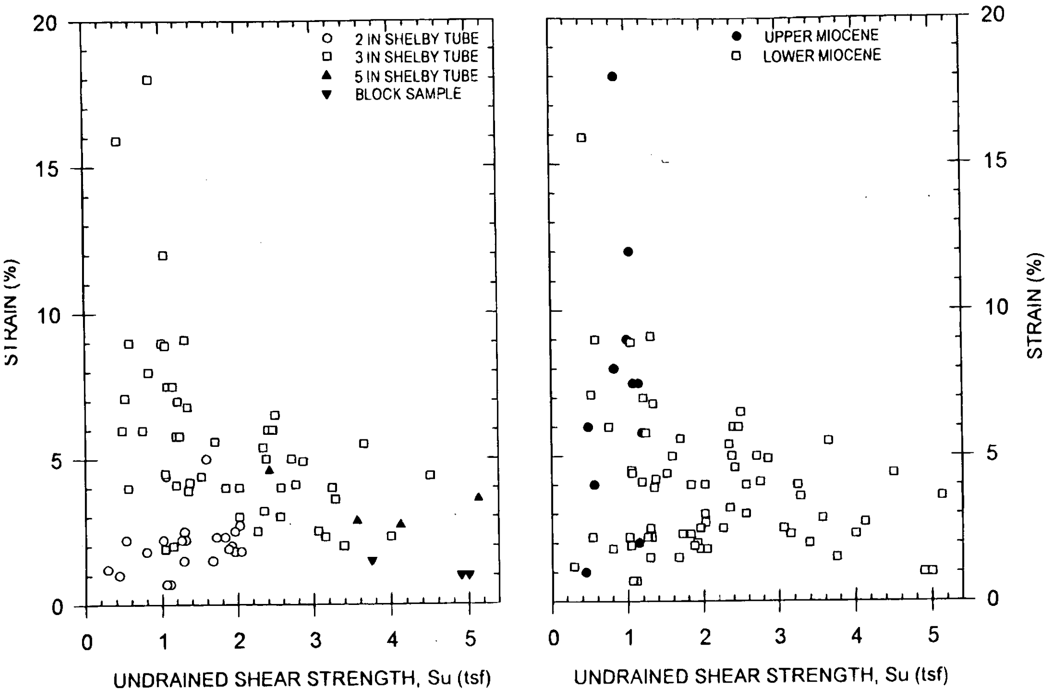

FIGURE 11 **Undrained shear strength versus strain at failure (1 tsf = 95.8 kN/m^2).**

4. Sample disturbance does have a major impact on laboratory test results for both undrained shear strength and compression properties. Based on the area ratio the block samples and 5-in. diameter tube samples should be the least disturbed and in fact generally do produce higher-quality results than smaller-diameter tube samples. Only the block samples produced results similar to the in situ test results for undrained shear strength and soil modulus. The block samples also produced the highest estimates of preconsolidation pressure.

5. Equations for C_c and C_r in terms of liquid limit and initial void ratio are presented. Due to the scatter in the data, these equations should only be used for preliminary estimates of these indices.

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