

Comparison of DMT- and CPT-Correlated Constrained Moduli in Clayey and Silty Sands

E. Gregory McNulty¹, P.E., P.G., M.ASCE and Michael D. Harney², P.E., M.ASCE

¹Senior Engineering Manager, Parsons Transportation Group, 100 M Street SE, Washington, District of Columbia 20003; egreg.mcnulty@parsons.com

²Engineering Manager, Shannon & Wilson, 400 N 34th Street, Seattle, WA 98103, michael.d.harney@shawil.com

ABSTRACT: This paper compares constrained modulus and related data from a geotechnical engineering investigation of a 40,000 m² site in the Southeastern United States that lies within the Atlantic Coastal Plain. This study includes 47 cone penetration tests (CPTs and SCPTs) and 13 flat-plate dilatometer tests (Seismic and non-seismic DMTs) and over 80 incremental and constant rate of strain consolidation tests. This paper compares the CPT- and DMT-correlated constrained moduli and laboratory test results from co-located borings. The comparative analyses show major differences and key similarities in the correlated values; sources for these differences and similarities are discussed. This paper concludes that in contrast to the DMT, CPT/SCPT soundings and often laboratory consolidation testing underestimate key settlement parameters because of disturbance. Correlations for the investigated soil types are also presented.

INTRODUCTION

An extensive geotechnical site characterization study has been undertaken on a 40,000 m² site located in the Southeastern United States within the Atlantic Coastal Plain. The study includes field explorations, laboratory testing, development of soil properties and stratigraphy, comparative and statistical analyses of data, engineering analysis to estimate static settlement and bearing capacity, and preparation of design and construction recommendations. The field explorations include standard penetration test (SPT) borings, Cone Penetration Tests (CPT) and Seismic Cone Penetration Test (SCPT) soundings, flat plate dilatometer (DMT) measurements, and cross-hole seismic tests. This paper presents some results of the CPT, SCPT and DMT measurements, and compares constrained moduli correlated from these tests to laboratory incremental (ICON) and constant rate of strain (CRS) consolidation tests.

FIELD EXPLORATIONS

The field explorations included drilling 15 standard penetration test (SPT) mud-rotary borings, advancing 47 CPT and SCPT soundings, making flat dilatometer (DMT) measurements in 13 soundings, measuring shear and compression wave velocities at two locations using cross-hole seismic methods, and collecting bulk samples from eight, 4.5-meter deep auger borings. The typical penetration depth for this study was approximately 45 m below ground surface. Including previous subsurface explorations at the site and those completed for this study, soundings and/or borings were generally spaced on an about 15-meter grid pattern across the project site. Borings, CPTs and SCPTs, and DMTs were co-located in selected areas to facilitate data comparisons.

Based on the results of the subsurface explorations, and laboratory program, the engineering stratigraphy of the site was interpreted. CPT and SCPT explorations and SPT boring data were used to determine the thickness and presence of the engineering layers. Patterns in tip stress, sleeve stress, ratio of tip stress to sleeve stress, and pore pressure responses were used in differentiating soil layers. The site subsurface interpretation is comprised of 13 identified engineering

soil layers. These layers are generally horizontally-stratified at the site, and consist of very loose to dense silty and clayey sands. Interbeds of sandy silt and silty clay are scattered in some of the engineering layers. Table 1 summarizes some of the characteristics of the engineering layers.

Table 1. Representative characteristics of identified engineering soil layers.
(McNulty and Harney, 2010)

Layer	Average Depth to Layer (m)	USCS	Average Fines Content (%)	Average Index Properties of Fines		Average CPT Results		
				LL	PI	Corrected Tip Stress (MPa)	Pore Pressure (MPa)	Friction Ratio
1D	0	SC	23	37	18	16	0.11	2.6
1C	4.7	SP, CL	24	53	30	11	0.13	2.9
1B	7.5	SC, CL	15	41	20	7.9	0.07	2.9
1A	9.5	SC	14	39	19	3.4	0.64	3.5
2C	11.4	SM, SC	13	30	9	10	0.02	1.7
2B	15.1	SM	11	24	9	13	-0.03	0.8
2A	18.7	SP-SM	5	29	16	22	0.07	0.5
3	24.5	SC, SM	11	45	26	6.9	0.45	1.1
4	28.9	SP-SM	7	36	17	18	0.23	0.6
5C	35.3	SC	13	42	21	3.0	0.78	2.2
5B	38.1	SP-SM	9	31	9	17	0.22	0.9
5A	40.2	SC, CL	13	40	16	3.8	1.1	1.9
6	42.9	SC	16	48	20	9.7	2.9	1.7

Interpretation of Test Results

Based on published relationships, several calculated and correlated soil parameters were determined as part of the data interpretation. The published correlations are generally based on a combination of theoretical and semi-empirical concepts, many of which are based on site- or region-specific information. Several published correlations for use with CPT/SCPT and DMT data were determined to be applicable to the site. For the project, correlations were selected that represent commonly-referenced procedures believed to be applicable across a wide range of subsurface conditions. Site-specific correlations and/or methods were used whenever available. The interpretation methods of constrained modulus and related parameters are presented in Table 2.

Table 2. Interpretation methods used.

Test Method	Parameter		Reference
CPT	Stress-normalized tip resistance	q_{tIN}	Schmertmann and Crapps (1988)
	Normalized friction ratio	FR	Wroth (1984)
	Pore pressure parameter	B_q	Wroth (1984)
	Soil behavior type	SBT	Robertson and Fear (1995)
	Soil behavior type index	I_c	Site-specific
	Vertical Constrained modulus	M	Mayne (2006)
DMT	Material Index	I_D	Marchetti (1980)
	Constrained modulus	M	Marchetti (1980)
	Overconsolidation ratio	OCR	Mayne (1995), Marchetti (1980)
	Effective preconsolidation Stress	σ'_p	Marchetti (1980)
	Initial vertical effective stress	σ'_{vo}	Marchetti (1980)
ICON	Incremental loading consolidation test		ASTM 2435
CRS	Constant rate of strain consolidation test		ASTM 4136

COMPARATIVE ANALYSES

Comparative analyses of field and laboratory-derived soil properties were performed to visualize and evaluate the soil properties measured, calculated, and correlated from the subsurface data collected at the site. The comparative analyses assisted in the assessment of accuracy and reliability of individual data sets. These comparisons consisted of graphs of soil parameters versus elevation and depth at paired exploration locations across the site. Nearly 250 of these comparative analyses were performed in total, for 14 different soil parameters, each at up to 35 paired exploration locations. An example of comparative analyses for M is presented in Figure 1. Some laboratory results are also presented.

STATISTICAL ANALYSES

Geotechnical engineering and index parameters for the soil were measured, calculated or correlated from field and laboratory test data. A statistical analysis of each data set and blended data set was performed to evaluate the central tendency and variability of the soil properties for each soil layer. Statistical analyses were performed for 19 different parameters for each of the 13 interpreted engineering soil layers.

The results of the statistical analyses were visualized using a series of “box-and-whisker” plots. Box-and-whisker plots were selected to compare relative distributions between engineering layers because measures of central tendency, variability, and overall range are apparent. The

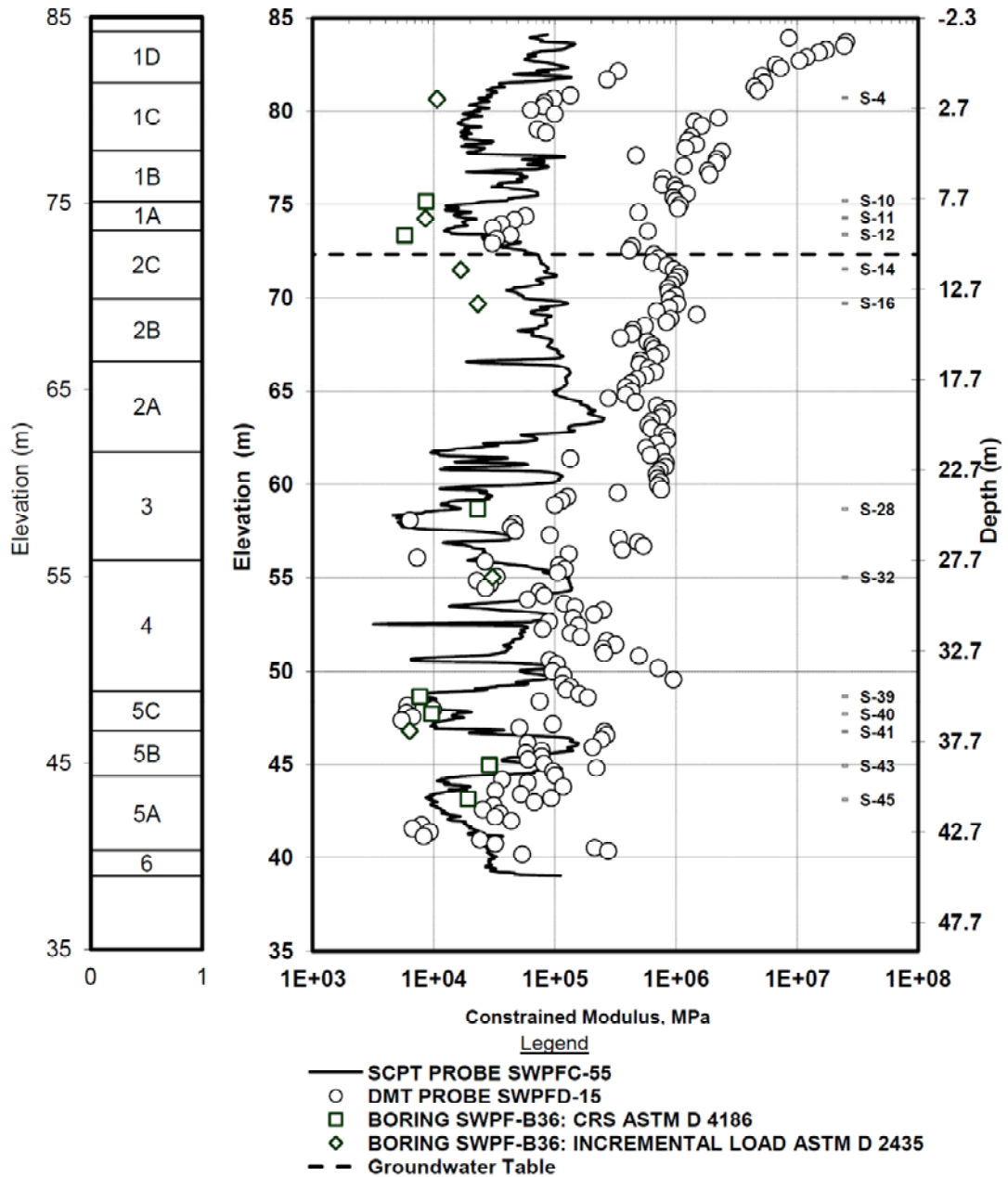


Figure 1. Comparative analysis of constrained modulus for a paired set of CPT, DMT, and laboratory consolidation results (Boring B36, SCPT C55, and DMT D15).

box-and-whisker plots show median (vertical bar), inter-quartile range (shaded boxes), and minimum and maximum data range (whiskers). The median is defined as the data point such that there are an equal number of values larger and smaller than that data point. For an odd number of data points, the median is the middle value. For an even number of data points, the median is the mean of the two middle values. The inter-quartile range divides the data set into quarters. For example, the first quartile is a value that has 25 percent of the observations below its value (Johnson, 2000).

Confidence intervals that are based on the standard deviation do not provide a representative

measure of spread about the central tendency if the underlying distribution is far from normal. As can be observed from the box plots, some of the distributions are skewed; therefore, other measures of variability or dispersion about the central tendency are more appropriate. For some data sets, the sample size was too small to calculate meaningful confidence limits.

Box-and-whisker plots were developed for (a) all data sources for each parameter for each soil layer; and (b) all soil layers for each soil parameter and data source. An example of a box-and-whisker plot for all data sources for the constrained modulus in a specific unit is shown in Figure 2. Figures 3 and 4 present the constrained modulus for all layers using the CPT-based correlation and DMT-based correlation, respectively. Similar plots were developed for every soil layer. In Figure 2, CV denotes the coefficient of variation, N denotes the number of samples in the population, and XHL denotes crosshole sonic logging.

DISCUSSION

Potential sources of bias

In the selection of the design M's, the uncertainty in the data source from direct measurements, calculations or empirical correlations, was evaluated. In the comparative and statistical analyses, biases were observed in the data source or data sets for a given soil property. The observed differences or bias among data sets for M could be the scatter imbedded in the measurement technique, subsurface conditions, or the empirical correlations used to estimate some of the soil properties. These potential sources of bias tend to limit the ability to make conclusions regarding the relative accuracy and precision between two data sources or sets and the source of the bias.

The various data sources were assumed to be reliable as they all have been extensively used throughout the field of geotechnical engineering. Strict quality assurance procedures were followed during the field explorations and laboratory testing to increase the confidence in the reliability of these tests.

However, in the laboratory, two significant sources of biases were observed late in the CRS laboratory testing programs that were not part of or not controlled by the quality assurance program. First, upon extrusion, the soil specimens quite noticeably expanded and separated vertically into individual lens of material along thin layers of sand. Second, the CRS lab technician used a thick aluminum blade to trim the soil specimens and roughly pushed the consolidation ring into the soil. By contrast, the ICON lab technician used a wire soil cutter and gently handled the specimens. The failure to use a wire soil cutter and delicately treat the CRS soil specimens caused significant mechanical disturbance of the consolidation test specimens. Hence, all the CRS tests appeared to have significant laboratory induced disturbance as their stress-strain curves were more rounded than the ICON stress-strain curves. ICON test specimens likely incurred at least the disturbance produced by extrusion from the Shelby tubes.

The in situ soundings were advanced at distances of 1.5 to 8 meters or more apart. Changes in subsurface conditions over this distance could have contributed to the bias between two data sets of the same soil property.

Empirical correlation equations used for the project were obtained were developed by various researchers in the cited references. Empirical relationships are based on a database of soil properties that generally exhibit scatter. The final predictive correlation equation is only one best-fit estimate of that soil property, and there is a distribution (or scatter) of data about that estimate. The estimate could represent the average, lower bound, upper bound, or some other value depending on the interest of the author. For example, one empirical correlation equation using inputs from CPT estimates M lower than that from the DMT in part because CPT shears at the ultimate or critical shear strain while the DMT shears at a strain about three orders of magnitude lower (Figure 5, Mayne, 2001). Figure 2, shows that the DMT moduli reach into the small shear-

strain range of the CHT constrained moduli and lies in a range at least one order of magnitude greater than either the CPT and laboratory consolidation test measurements of constrained modulus.

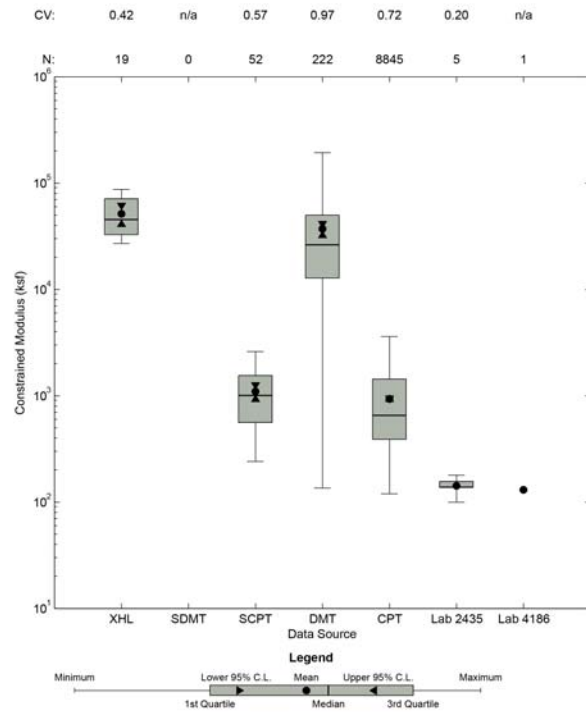


Figure 2. Box-and-whisker statistical visualization for constrained modulus correlated from all data sources for soil layer 1C, including ICON and CRS consolidation tests.

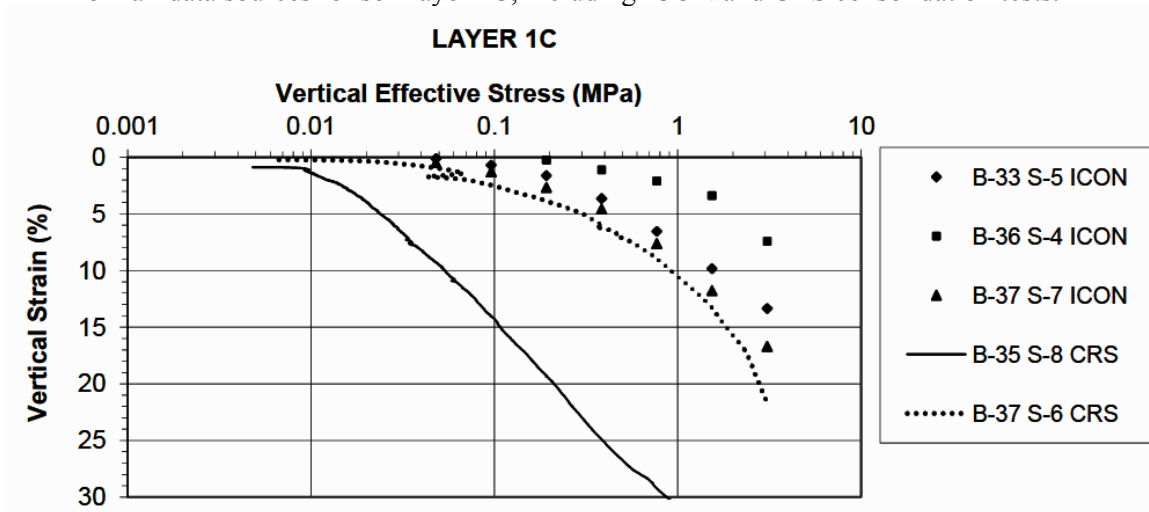


Figure 3. Laboratory ICON and CRS test stress-strain curves for soil layer 1C; CRS curves suggest significant disturbance, believed to be caused by extrusion and trimming of soil specimens.

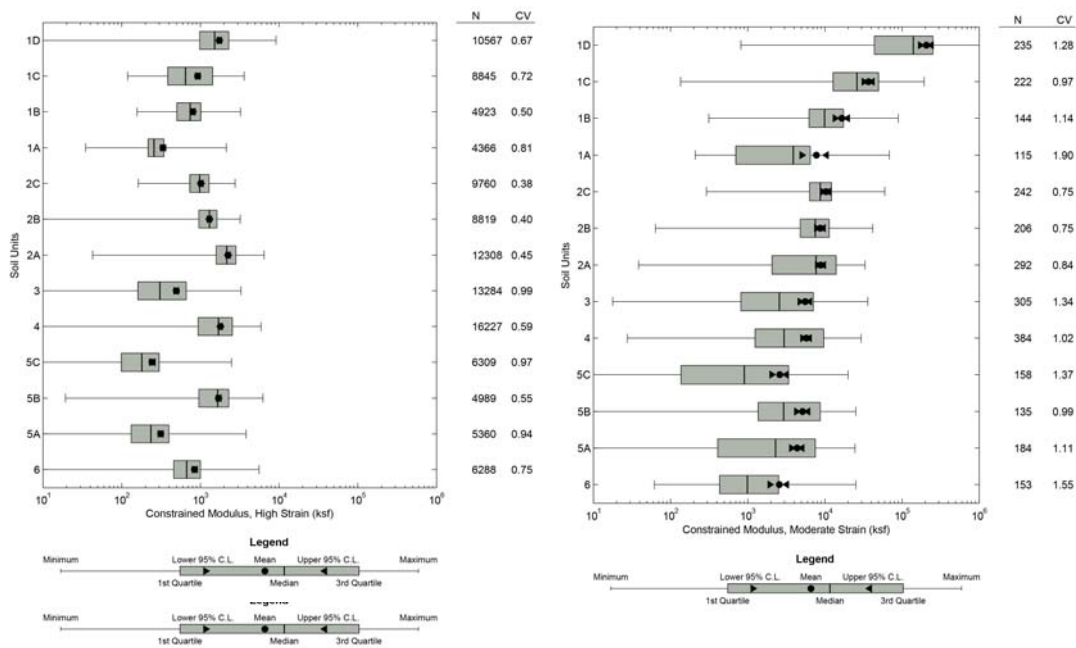


Figure 4. Box-and-whisker statistical visualization for constrained modulus from CPT (high shear strain) and DMT (moderate shear strain) for all soil layers.

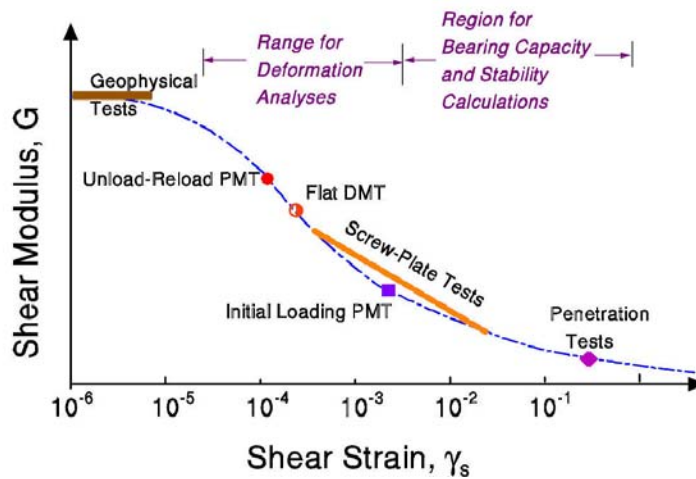


Figure 5. Conceptual illustration of shear modulus reduction, hence disturbance, incurred by various method of in – situ testing and their corresponding appropriate use for geotechnical analyses (Mayne, 2001).

Constrained modulus

At 14 paired test locations, M estimated from CPT has been compared with those determined from ICON and CRS consolidation tests performed on undisturbed samples from the nearest SPT borings. Direct-push Shelby tubes, pitcher barrel samplers, or hydraulically-operated fixed-piston samplers were used, depending on the soil type sampled. At six paired test locations, M estimated from DMT were compared with those determined from ICON and CRS tests performed on undisturbed samples from the nearest SPT borings.

The M estimated from the ICON and CRS laboratory tests compares favorably with the CPT-correlated values below the groundwater table, but generally is higher above the groundwater table. In particular, the high shear strains at which the CPT operates seems to confirm that both the ICON and CRS soil specimens experienced significant disturbance. The larger constrained moduli in the engineering layers above the groundwater table are likely due to the significant overconsolidation caused by desiccation in Layers 1D and 1C.

The DMT generally measures constrained moduli an order of magnitude greater than those from the other data sets, it reduces only slightly M for the relatively loose engineering layers 3, 5A, and 5C, and is more sensitive to changes in the stiffness of the soil. Unit weight tests on samples retrieved from these layers indicate relatively loose soils, and other in-situ tests (e.g., CPT) and laboratory consolidation tests indicate lower M in these layers. Because of the apparent complete remolding of the soil matrix by the CPT (particularly at the hard bottom of engineering layer 4 before entering the “soft zones” starting at 5C) and disturbance in the laboratory due to sample extrusion, the DMT M were used in the engineering analyses to compute settlement.

Preconsolidation stress and overconsolidation ratio

Figure 6 compares the preconsolidation stress and overconsolidation ratios determined by the DMT versus those derived from ICON and CRS tests using the Becker and Casagrande methods to determine ranges of minimum and probable estimates. These data suggest that the DMT estimates a preconsolidation stress that equals or often greatly exceeds those estimated by the Casagrande or Becker methods; note that the Casagrande method depends on the selection of point of maximum curvature that often does not exist or is difficult to determine. Typically, the data suggest that the Becker probable stress agrees better with the DMT estimates of P_c . By contrast, the CPT significantly underestimates the overconsolidation ratio because the high shear strain at which the CPT operates erases all stress history and obliterates the structure of the soil.

CONCLUSIONS

Constrained moduli correlated from multiple data sources at a site composed of silty and clayey sands have been compared. Comparisons were performed among results correlated from different in-situ techniques (i.e., CPT and DMT) and among correlated M and laboratory ICON and CRS consolidation tests. Because of the observed disturbance incurred during extrusion and trimming of the consolidation test specimens, the CPT’s high strain/high disturbance M correlated M well with laboratory measurements. In particular, the flattened stress strain curves from the CRS consolidation tests suggest that their soil specimens experienced the most disturbance. In addition, engineering management leadership in instituting consistent training of lab technicians in proper equipment and specimen handling could help reduce these disturbance issues.

The DMT-correlated M for all soil layers, particularly above the water table, exceeded the CPT and consolidation test values by an order of magnitude or more. DMT-correlated M ’s generally measured the highest OCR, even in the looser layers. In the looser layers, the DMT-correlated M and OCR did not exhibit a reduction, as would be expected for a technique that protects soil structure and stress history in the surrounding in-situ soil (Schmertmann, et al., 1986).

It appears that the DMT, not the CPT, should be used to estimate M in-situ and be used for settlement design analyses.

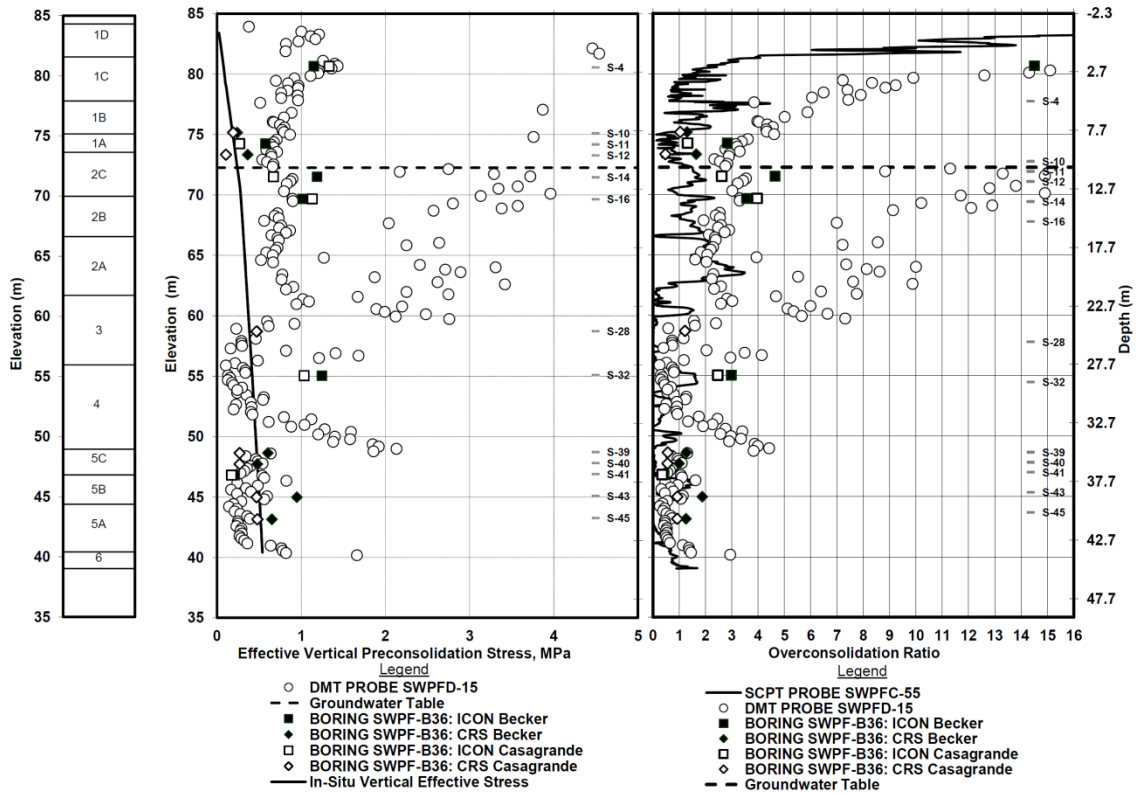


Figure 6. Comparison of preconsolidation stress and overconsolidation ratios from DMT, ICON and CRS tests, and CPTs.

REFERENCES

- Becker, D.E., Crooks, J.H., Been, K., and Jefferies, M.G. (1987). "Work as a criterion for determining in situ and yield stresses in clays. *Can. Geotech. J.*, 24(4), 549-564.
- Casagrande, A. (1936). "The Determination of the Pre-Consolidation Load and Its Practical Significance," Discussion D-34, *Proceedings of the First International Conference on Soil Mechanics and Foundation Engineering, Cambridge*, Vol. III, pp. 60– 64.
- Johnson, R.A., 2000, *Miller & Freund's probability and statistics for engineers*, 6th ed.: New Jersey, Prentice hall.
- Marchetti, Silvano, 1980, "In situ tests by flat dilatometer." *J. Geotech. & Geoenv. Eng Journal of the Geotechnical Engineering Division*, v. 106, no. GT3, p. 299-321
- Marchetti, Silvano, 1997, The flat dilatometer: Design applications, keynote lecture, in Third International Geotechnical Engineering Conference, Cairo, Egypt, 1997, *Proceedings: Cairo, Egypt, Cairo University*, p. 421-448, available: <http://www.marchetti-dmt.it/>.
- Mayne, P., 2001, *Stress-strain-strength-flow parameters from enhanced in-situ tests. Proceedings, International Conference on In-Situ Measurement of Soil Properties & Case Histories In-Situ 2001, Bali, Indonesia, May 21-24, 2001*, p. 27-48.
- Mayne, P., 2006. Interrelationships of DMT and CPT readings in soft clays, *Proceedings of the 2nd International Flat Dilatometer Conference*.
- McNulty, E.G. and Harney, M.D., 2010. "Comparison of CPT- and DMT-correlated effective

- friction angle in clayey and silty sands,” *Proceedings of the 2nd International Conference on Cone Penetration Testing*, Huntington Beach California, May 10-12.
- Robertson, P.K. and Campanella, R.G., 1983, Interpretation of cone penetration tests, part I: sand: *Canadian Geotechnical Journal*, v. 20, no. 4, p. 718-733.
- Robertson, P.K. and Fear, C.E., 1995, Liquefaction of sands and its evaluation, in Ishihara, Kenji, ed., Earthquake geotechnical engineering, *The First International Conference on Earthquake Geotechnical Engineering, IS-Tokyo '95, Tokyo, 1995, Proceedings: Rotterdam, A. A. Balkema.*
- Schmertmann, J.H., 1975, Measurement of in-situ shear strength, in *ASCE Specialty Conference on In-Situ Measurement of Soil Properties*, v. 2, pp. 57-138.
- Schmertmann, J.H., , W. Baker, R. Gupta, and K. Kessler, 1986, CPT/DMT QC of Ground Modification at a Power Plant, *Proceedings of In Situ '86 GT Div., ASCE, June 23-25, 1986 Blacksburg, VA*
- Schmertmann, J. H., and D. Crapps, 1988, Guidelines for Using the CPT, CPTU and Marchetti DMT for Geotechnical Design: DMT test methods and data reduction, Rep. No. FHWA-PA-87-014-84-24, *Pennsylvania. Dept. of Transportation. Office of Research and Special Studies, United States. Federal Highway Administration.*
- Senneset, K.; Sandven, R.; and Janbu, N., 1989, Evaluation of soil parameters from piezocone tests: *Transportation Research Record no. 1235, p. 24-37.*
- Wroth, C.P., 1984, The interpretation of in situ soil tests: *Geotechnique*, v. 34, no. 4, p. 449-489.