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Comparison of Soil Properties obtained from In-Situ Tests and Laboratory: Case Study of shallow Foundation

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Abstract **–** In geotechnical engineering, in-situ penetration tests are widely used for site investigation to support analysis and design. The Standard Penetration Test (SPT) is the most common in-situ test for soil investigations in sandy soils. When it is necessary to expand the scope of investigation, geotechnical engineers typically supplement with a cheaper and quicker method such as the Cone Penetration Test (CPT) and flat dilatometer test (DMT). These tests are routinely used in geotechnical evaluations and are considered adequate for detailing soil profiles and determining soil properties. However, the correlation between the results of CPT, DMT, and soil properties is not well established yet. In this work, ground characterization and estimation of soil properties based on the combined use of in-situ tests included SPT, CPT, and DMT along with laboratory tests were conducted and evaluated. The evaluation of in-situ tests in terms of soil type, unit weight, elastic modulus, and friction angle was compared with laboratory results. To achieve the presented objectives, field and laboratory investigations were performed on a case study of shallow foundation design using general bearing capacity equation. For satisfactory design, the design must satisfy the shear and settlement criteria. These two criteria are independent to each other and must be satisfied. As results, the findings from in-situ and laboratory tests did not agree in terms of settlement calculations. The predicted bearing capacity of the case study estimated size against general failure from 1 m to 1.3m. However, the estimated settlements exceed the allowable limits, and therefore the foundation dimensions had to be suitably modified to settlement criteria.

Keywords**:** In-situ tests, soil properties, laboratory tests

1. Background

Soil sampling combined with laboratory testing is the most reliable method to determine soil properties thorough understanding of soil properties requires time consuming and costly laboratory tests. However, Sometimes due to limited budgets, tight schedules, soil properties can directly obtaining from soil field investigation report to save both time and money.

Several in-situ tests define the geostratigraphy and obtain direct measurements of soil properties and geotechnical parameters. These tests include: SPT, CPT, piezocone cone (CPTu), DMT. Each test applies different loading schemes to measure the corresponding soil response in an attempt to evaluate material characteristics, such as strength and/or stiffness [1, 2, 3].

The interpretation of in-situ geotechnical test data needs a unified approach so that soil parameters are evaluated in a consistent and complementary manner with laboratory results. At Any program or research to assist reduction of geotechnical investigation cost is valuable and should be appreciated [4, 5].

The most commonly used method for site exploration is the SPT accompanied by bore holing and laboratory testing of retrieved samples. However, this method is expensive in monetary and time cost. Consequently, in attempt to save time and money, a few numbers of tests are normally executed for site investigations. When it is necessary to increase the scope of investigation, geotechnical engineers normally supplement the bore holing with a cheaper and much quicker method such as the CPT and DMT. These tests are routinely used in geotechnical practice and are both considered adequate for detailing of soil profile and determination of soil properties [6, 7].

Predicting settlements using DMT in shallow foundations is recommended by many researchers, especially in sands, where undisturbed sampling and estimating compressibility are particularly difficult [8, 9, 10, 11, 12].

The CPT and DMT are frequently used in site characterization and determination of soil properties. Often the CPT and DMT tests are combined in order to increase the reliability of stratigraphy delineation and determination of soil properties.

Although many consider each of these in-situ tests to be adequate by themselves, the results should generally be confirmed by laboratory geotechnical investigation [2,3, 4].

CPT and DMT should be mainly used for the determination of soil profile. Neither of them measures mechanical properties of soils directly, but they can be derived based on theoretical or empirical correlations with different degree of accuracy [3, 4].

CPT is carried out directly at the site of the soil investigation and is most effective when carried out on soft clay or sandy soils. However, the data from the CPT is not sufficient to form the basis of a design, therefore the soil that has been tested through the CPT should be verified to the laboratory for further investigation [3].

If a structure settles uniformly, it will not theoretically suffer damage, irrespective of the amount of settlement. But, the underground utility lines may be damaged due to excessive settlement of the structure. In practice, such non-uniform settlements induce depending upon the permissible extent of these secondary stresses, the settlements have to be limited. If alternatively, the estimated settlements exceed the allowable limits, the foundation dimensions or the design may have to be suitably modified. Therefore, this code is prepared to provide a common basis, to the extent possible, for the estimation of the settlement of shallow foundations subjected to symmetrical static vertical loading [10, 11, 12].

Results of ground characterization and evaluation of soil properties obtained from in-situ tests and laboratory work still challenges geotechnical engineers. In this study, evaluation of in-situ tests in terms of soil type, unite weight, elastic modulus and friction angle are presented and results were compared and used in case study of shallow foundation design.

2. Objectives

The main objective of this research is to:

- Compare soil properties obtained using existing in-situ correlations included SPT, CPT, and DMT to laboratory results,
- Evaluate design parameters from in-situ and lab testing in case study of a shallow foundation deign.

3. Methods of Measurement

In-Situ" and "Laboratory Testing" techniques represent the two principal approaches for the measurement and determination of engineering properties during geotechnical investigations.

Laboratory tests directly measure the engineering properties of soils whereas in-situ tests usually do not. However, use of empirical correlations and calibrations to convert in-situ test results to appropriate engineering properties for design purposes is a continuously growing methodology, since the determination of properties of soils as they exist in nature free from the disturbances due to sampling and laboratory handling is a useful and often necessary step toward proper design [6, 7].

A considerable quantity of data for this study was available from Florida Department of Transportation (FDOT) construction project presented by Jarushi and Cosentino [13, 14] included SPT, CPT, and DMT were conducted by the Geotechnical and Environmental Consultants while the lab tests were conducted at FDOT lab. The site is located at the central of Florida.

3.1 Laboratory program

The lab testing included tests on disturbed samples to determined natural moisture contents, grain size and hydrometer data, and Atterberg limits. Consolidated undrained Triaxial testing parameters were evaluated using undisturbed samples. Split barrel and Shelby tube samples were used to visually classify soils and to establish the soil profile. The soil samples were classified in accordance with Unified Soil Classification System (USCS). Sand was the predominate soil at this site consistently representing over 50 percent of the soil. The soil strata were classified as one of the following groups: SP-SM, and SP-SC. These soils displayed an olive green to light green color with visual descriptions ranging from clayey and silty fine sands.

3.2 In-situ Tests

Field investigations were carried out mainly through the application of SPT, CPT and DMT. These tests were performed performed at same locations within the study area and each pair of CPT, DMT and SPT was carried out as close as possible. possible.

SPT were conducted according to ASTM [15]. Boreholes for the SPT were advanced by wash boring. The split spoon sampling method was used to obtain soil samples from boreholes and disturbed representative samples were collected. Samples recovered from boreholes were stored in plastic bags which were used for laboratory testing. Based on the results of the subsurface explorations, the subsoil profile at study was primarily comprised of fine silty sand (SP-SM) particles varied from ground surface to 5 m deep. Electrical friction cone tests were performed in soundings by hydraulically advancing the cone penetrometer while signals were digitally recorded using the Hogentogler standard recording system. The CPTu soundings were conducted using 10-cm^2 piezocones, with porous filter element type 2 located at shoulder or behind the tip u_2. The CPTu test procedure followed ASTM [16] "Electronic Friction Cone and Piezocone Penetration Testing". During testing, digital channels were used to record the tip, friction, inclination and designated pore water pressure u_2 every 2 inches.

DMT soundings to produce lift-off pressures and elastic moduli were conducted according to ASTM [17]. The SPT N_{60} along with CPT results of cone and friction resistance are presented in Table 1. Table 1 also presents the DMT results.

Table 1. Raw data from in-situ tests (SPT, CPT, DMT)

Depth (m)	Ground water	Soil Type	SPT N_{60} Blows/0.30m	CPT qc (kN/m^2)	CPT Fs (kN/m^2)	P_0 (kN/m^2)	P_1 (kN/m^2)	P_2 (kN/m^2)
0-1.2		SP-SM						
2-1.2	At 1.2 m		13	8809	57	202	681	21.45
2-3			13	8900	57	280	900	21.45
3-4			13	8900	57	282	920	21.45
4-5			20	9300	57	527	2525	21.45

4. Parameters, settlements and design equations

Evaluation of geotechnical uncertainties has been a subject of interest to the geotechnical community where several studies have been performed recently under different conditions. This study is limited to evaluation of inherent soil variability of a sandy soil where three in-situ (i.e, SPT, CPT, DMT) and laboratory tests are involved in measuring soil properties. Actual field and lab data used directly to estimate soil properties which been used for foundation design. The empirical correlation and design equations used in this study are presented in Table 2. The foundation design parameters are included unit weight, friction angle and elastics modulus of soils. Table 2 also presents the settlement's based methods used along with each method. The general bearing capacity used in this study was based on general failure by Meyerhof [18].

Table 2. Correlations and Design Equations used in this study

Test	Soil Parameters	Equation	Author
CPT	Unit weight kN/m³	$\frac{\gamma}{\gamma w} = 0.27[logR_f] + 0.36\left[log\frac{qc}{pa}\right] + 1.236$	Robertson (2009)
	Friction angles (degree)	$\acute{\emptyset} = \tan^{-1}[0.38 + 0.27log(\frac{qc}{\acute{\sigma o}})$	Ricceri et al., (2002)
	Elastic Modulus(kN/m²)	$Es = 2.5\ q_c$	Schmertmann (1978)
	Settlements (mm)	$S = 2.3\frac{H}{qc/\sigma_0}\ \log_{10}\left(\frac{\sigma_0 + \Delta\sigma}{\sigma_0}\right)$	De Beer & Martens (1957)
SPT	Unit weight kN/m³	$\gamma_{moist} = 16.0 + 0.1\ N_{60}\ \ (KN/m^3)$	Peck et. al., (1974)
	Friction angles (degree)	$\acute{\emptyset} = 27.1 + 0.3\ N60 - 0.00054N60^2$ Correlation between corrected N_{SPT} and friction angle from effective stress	Peck, Hanson, Thornburn (1974) From Peck et al., 1974)
	Elastic Modulus(kN/m²)	$Es = \alpha N_{60}Pa$ $Es=300(N+6)$	Kulhawy& Mayne (1990) Bowles, J.E., 2002
	Settlements (mm)	$Se = \frac{2q_{net}}{N_{60}Fd}\left(\frac{B}{B+0.3}\right)^2$	Meyerhof (1965) Modified by Bowles (1977)
		$\frac{Se}{BR} = \propto_1\propto_2\propto_3\left[\frac{1.25\left(\frac{L}{B}\right)}{0.25+\left(\frac{L}{B}\right)}\right]^2\left(\frac{B}{BR}\right)^{0.7}\left(\frac{q'}{Pa}\right)$	Burland& Burbridge's (1985)
DMT	Unit weight kN/m³	Chart for unit weight	After Schmertmann, (1986)
	Friction angles (degree)	$\emptyset = 31 + \frac{Kd}{0.236 + 0.066Kd}$	Ricceri et al., 2002
	Elastic Modulus(kN/m²)	$Es = (1 - \mu 2)ED$	Schmertmann, 1986)
	Settlements (mm)	$S_{DMT} = \sum\frac{\Delta\delta V}{M_{DMT}}\Delta Z$	Marchetti 1997
	General Bearing Capacity	$q_{\ u} = c'N_cF_{cs}F_{cd}F_{ci} + qN_qF_{qs}F_{qd}F_{qi} + \frac{1}{2}\gamma BN_\gamma F_{\gamma s}F_{\gamma d}F_{\gamma i}$	Meyerhof (1963)

5. Accuracy of existing correlations

Natural inherent of soil variability and transformation uncertainties were evaluated in relation to SPT, CPT, DMT and Triaxial tests. The total uncertainty was determined relative to each method and comparison based on estimated design parameters was made.

5.1 Estimating Soil Parameter using SPT Data

Soil parameter were calculated based on empirical correlations presented in Table 2 included unit weight, friction angle and elastic modules. Table 3 presents the results derived from with SPT using corrected N values.

Table 3. Estimated Design parameters from SPT Test

Depth "m"	Ground water	SPT N-Value	SPT N_{60}	Ø SPT Degree	γ SPT (KN/m^3)	E (Kpa)	Used Ø AVG	Used γ AVG
0-1.2		11	14	31	17.4	5182.4	°31	°17
1.2-2	At 1.2 m	12	13	31	17.3	4935		
2-3		12	13	31	17.3	4935		
3-4		14	13	31	17.3	4935		
4-5		18	20	33	18	6557.9		

5.2 Estimating Soil Parameter using CPT Data

Soil parameter included unit weight, friction angle and elastic modules, were calculated based on empirical correlations mentioned in Table 2. Theses parameters were obtained from direct CPT data. Table 4 shows the results derived from with CPT using cone resistance or friction ratio.

Table 4. Estimated Design parameters from CPT Test

Depth "m"	Ground water	CPT q_c (kPa)	CPT f_s (kPa)	Ø SPT Degree	γ SPT (KN/m^3)	E (KPa)
0-1.5						
1.2-2	At 1.2 m	8809	57	37	18.5	22022
2-4		8900	57	37	18.5	22250
3-4		8900	57	37	18.5	22250
4-5		9300	57	37	18.5	23250

5.3 Estimating Soil Parameter using DMT Data

DMT data was used to calculate the soil parameter based on empirical correlations using equation mentioned in Table 2. These parameters were also obtained from direct DMT data. Table 5 shows the results obtained from with DMT correlation using findings of DMT test.

Table 5. Estimated design parameters from DMT Test

Depth "m"	Ground water	ED (kPa)	Ø Degree	γ SPT (kN/m^3)	E (kPa)
0-1.2				17.8	
2-1.2	At 1.2 m	16620	38	18.4	15242
2-2		21557	37	18.4	19617
3-4		22093	36	18.4	20104
4-5		69280	40	19.4	63044

5.4 Estimating Soil Properties from Laboratory Tests

Soil sampled recovered from bore holes were individually assessed and classified based on dry sieve analysis. Sieve analysis was performed on each soil sample. These soils contain appreciable amounts of fines. According to the unified soil classification system, the soils can be symbolized as SP-SM. Table 6 shows parameters from Triaxial test results included unit weight, friction angle and elastic modulus.

Table 6. Soil parameters from laboratory Results

Depth "m"	Ground water	Ø Degree	γ (KN/m^3)	E (kPa)
0-1.5		34	16	
1.2-2	At 1.2 m	33	16.7	4935
2-3		35	17	4935
3-4		33	17.3	4935
4-5		34	17.3	6557

6. Comparison of obtained Soil properties

Table 7 presents of Comparison of soil parameters from laboratory test results with in-situ tests. It can be observed from Table 7 that with a variation of elastic modulus from 5000 kPa to 22022 kPa while the friction angle ranged from 31 to 37 degree.

Table 7. Average Laboratory vs. Estimated In-situ Parameters

Tests	Ø Degree	γ (KN/m^3)	E (KPa)
Standard Penetration Test "SPT"	31	17	5000
Cone Penetration Test "CPT"	37	18.5	22022
Dilatometer Test "DMT"	37	18.6	18320
Triaxial Laboratory	34	17	5340

7. Case Study of Square Shallow Foundation

To perform uncertainty of design parameters, a case study of square shallow foundation is presented. Satisfactorily, shallow foundations must have two main characteristics; to be safe against overall shear failure in the soil that supports them them and cannot undergo excessive displacement.

The presented results in Table 8 combined use of in-situ along with laboratory in a square shallow foundation design where 1000 kN is applied using factor of safety of 3. Prediction of settlement of case this study was based on methods presented in Table 2. The general bearing capacity used in this evaluation was based on general share failure developed by Meyerhof [15].

It was noticed that the results of in-situ and laboratory did not agreed in term of settlement purpose. The initial estimation of the footing based on share failure ranged in size from 1m x 1m to 1.3m x 1.3m which agreed reasonably well on general failure criteria, however, settlements were found to be unsatisfactory and size was modified for settlement criteria to size of 1.8m using in-situ design parameters and up to 3m using laboratory results.

The findings from in-situ and laboratory tests did not agree in terms of settlement calculations, which showed settlement, over 200 mm considered excessive. As the size modified to 1.8m, the in-situ tests agreed well showed that settlements predicted are generally in good agreement within allowable.

Table 8. In situ and laboratory investigations

Test	Estimated Size B*B (m)	Settlement calculation methods (mm)						[a]Recommended Size Based on Allowable Settlement (m x m)
		Strain influence factor method [19]	Theory of Elasticity, Bowles 1987 [18]	Meyerhof SPT Modified by Bowles [6]	Burland& Burbridge's (1985) SPT [18]	De Beer & Martens (1957 CPT [20]	Marchetti (1997) DMT [8,9]	
Standard Penetration Test "SPT"	1.2 X 1.2	244mm	74mm	34mm	81mm			1.8 x 1.8 $se < 25mm$
Cone Penetration Test "CPT"	1.0 x 1.0	61mm	24mm	-	-	16mm		1.8 x 1.8 $se < 25mm$
Dilatometer Test "DMT"	1.0 x 1.0	73mm	63mm	-	-		27mm	1.8 x 1.8 $se < 25mm$
Laboratory Test "LAB" Triaxial Test	1.3 X 1.3	210mm	83mm	-	-			3 x 3 $se < 25mm$
[a]Recommended size was estimated based on worst settlement method and its satisfied allowable settlement of 25mm								

8. Conclusion

The interpretation of in-situ geotechnical test data needs a unified approach so that soil parameters are evaluated in a consistent and complementary manner with laboratory results. At any program assisting reduction of geotechnical investigation cost is valuable and should be appreciated. Results of ground characterization and evaluation of soil properties obtained from in-situ tests and laboratory work were compared. Evaluation of in-situ tests in terms of unit weight, elastic modulus and friction angle are presented and results were compared and used in case study of shallow foundation design.

The results showed that the combined use of CPT and DMT can be a useful addition to defining ground profile and material properties. Thus, they can significantly improve the reliability of a geotechnical desgn in low-cost manner.

The findings from in-situ and laboratory tests did not agree in terms of settlement calculations. The predicted bearing capacity agreed in estimating footing size against general failure from 1 m to 1.3m. However, for satisfactory design, foundation must satisfy the shear and settlement criteria. These two criteria are independent to each other and must be satisfied and therefore, the estimated size was modified to 1.8m x 1.8m so that the in-situ tests agreed well showed that settlements in good agreement within allowable.

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