EVALUATION OF TEXAS CONE PENETROMETER TEST TO PREDICT UNDRAINED SHEAR STRENGTH OF CLAYS

by

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This thesis is dedicated to the author's parents, brother and entire family.

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ABSTRACT

EVALUATION OF TEXAS CONE PENETROMETER TEST TO PREDICT UNDRAINED SHEAR STRENGTH OF CLAYS

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The cone penetration test used in Texas is termed as Texas cone penetrometer (TCP), which works on dynamic principles similar to those of SPT, i.e. a hammer is used to drive the cone device for a preset depth of penetration of 12 inches. Results are typically reported in the form of N12 values. Correlations between N12 and soil strength properties are currently used by the TxDOT to determine in situ strength properties of soils prior to any infrastructure design.

A research study was initiated to evaluate the existing shear strength predicting correlations used by TxDOT and its applicability for soils from various regions of Texas with different geologies and stress histories. Database of TCP

and Texas triaxial test results performed over the last ten years by TxDOT in Dallas and Fort Worth districts was compiled to obtain the necessary data for the current research. This thesis research then focused on evaluating the existing correlations and developed improved correlations to predict strength properties of stiff clays from Dallas and Fort Worth regions of Texas.

The currently used relationship between the penetrometer test N12 value and undrained shear strength was found to be lower bound for the data obtained from Dallas and Fort Worth regions. Hence, improved correlations were established between TCP test results and undrained shear strength for cohesive soils via statistical regression methods. Comparisons of undrained shear strength predicted by these new correlations with both measured strength and predicted undrained shear strength by the current geotechnical manual showed the reliable and improved predictions by the recommended model for stiff clays. These correlations still need to be evaluated with more independent TCP data to further validate their interpretations.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Subsurface exploration studies including in situ test methods have been used to evaluate penetration resistance of soil. The penetration resistances of test devices are used to classify, and then characterize subsoils. In the United States, the most commonly used penetration devices are the standard penetration test (SPT), the cone penetration test (CPT), and the dynamic cone penetrometer (DCP). One of the in situ tools commonly used for this process in the state of Texas is cone penetrometer, generally referred as Texas cone penetrometer (TCP).

In general, static (CPT) and dynamic cone penetrometers (DCP) provide cone resistances in different units, such as pounds per square inch for CPT and centimeters per blow for DCP. The penetration test used in Texas, Texas cone penetrometer, measures the number of blows to drive the cone for preset depth of penetration. This device has been used in site investigations including foundation and bridge explorations. This device works on dynamic principle similar to SPT, i.e. a hammer is used to drive the cone device for a preset value of penetration.

Texas cone penetrometer (TCP) test and their correlations have been used to predict undrained shear strength of clayey soils. These correlations are useful as they provide a quick and simple way to determine soil shear strength without sampling and laboratory testing. Limited research was performed in 1974 and 1977 to develop these correlations between TCP N-values and shear strength parameters.

It should be noted that these correlations were based on TCP tests conducted predominantly in the upper gulf coast region of Texas. These correlations are currently used by the TxDOT for geotechnical design purposes. Some limitations exist such as the applicability of these correlations for soils from other regions in Texas and the need to continuously update the existing correlations with more recent test data. Hence, in order to evaluate the current correlations for soils from different regions of Texas, a research study was initiated at three universities, The University of Texas at Arlington, University of Houston and Lamar University. This thesis research is a part of The University of Texas at Arlington investigations and hence focused on developing correlations for soils from Dallas and Fort Worth region of Texas.

1.2 Objectives

In order to accomplish the present research objective of developing TCP or modifying TCP based strength correlations, a few specific objectives were established. These were:

- To develop a soil database for Texas soils, containing information from the tests carried out for TxDOT projects in the last 10 years.
- To attempt the possibility of unified soil classification using the TCP tests values.
- To evaluate the existing correlations between the Texas cone penetrometer (TCP) test values and undrained shear strength.
- To develop improved correlations for interpreting undrained shear strength of CL and CH soils from Dallas and Fort Worth districts.
- To develop software to predict the undrained shear strength using the new correlations developed in this study, and include provisions to incorporate any new correlations to be developed in the future.

1.3 Methodology

A database of Dallas and Fort Worth soils was collected and developed which contained information pertaining to TCP tests carried out by TxDOT over the last ten years, starting from 1994. This database, in the future, could be expanded with information from soils from the remaining districts in Texas. Software termed as 'EXTRACT' was developed to expedite the process of data compilation from the traditionally used wincore software files.

Four statistical analyses were made to analyze the data for possible soil classification using TCP N-values. An attempt to perform soil classification based on TCP parameter was made without using Atterberg limits and particle size data. This attempt was made on both Dallas and Fort Worth districts' data and an outcome of this attempt is comprehensively analyzed and discussed.

The correlations currently used by TxDOT to predict the undrained shear strength is evaluated. Later, three empirical models to predict undrained shear strength using TCP-N values were developed. Localized correlations were developed for Dallas and Fort Worth soils. In addition to the TCP N –values, the effect of depth as a parameter to better predict undrained shear strength was addressed. The developed models' interpretations were compared with laboratory measured properties. Based on the analysis, a few correlations are recommended for future usage. A new software named TCPSoft was also developed to predict undrained shear strength based on the recommended correlations from the present study.

1.4 Thesis Organization

This thesis report comprises of seven chapters:

Chapter 1 provides an introduction, research objectives, and an overview of the thesis organization.

Chapter 2 presents the literature review on history and significance of penetration tests. Various types of penetration tests currently in use in the United States are discussed. Results from past research conducted on TCP are discussed in this chapter.

Chapter 3 summarizes the methods developed to collect the data from Dallas and Fort Worth districts of TxDOT and compile them. Salient features of the software “EXTRACT” developed to extract data from boring logs and compile them in Microsoft excel files are also explained.

Chapter 4 presents the statistical analysis of data to study the possibility of soil classification using TCP N-values. Four statistical approaches are presented to determine procedures to classify soils using TCP N-values.

Chapter 5 provides an evaluation of existing correlations to predict undrained shear strength currently used by TxDOT. Three methods to develop new correlation to predict the undrained shear strength using TCP N-values are discussed. All three models are evaluated and the appropriate method to predict undrained shear strength is recommended for future usage.

Chapter 6 covers the development of the software “TCPSoft” to predict the undrained shear strength. Microsoft Visual Basic application software was used as the front end. A database was created using Microsoft Access to store the constants required to run the program. Salient features of this database based software are discussed. Examples are provided to illustrate the working of the software.

Chapter 7 provides summary and conclusions from the present research. Recommendations for future research needs are also discussed.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

In the present research an attempt is made to modify the existing correlations to predict the shear strength of soils using the Texas cone penetrometer (TCP) N values. Background on this method and existing correlations presented in this chapter were collected from previous research reports, journals, conference articles, and online resources.

An introduction to in situ penetration tests was first described, followed by a description of various types of dynamic and static penetration tests currently used in geotechnical practice. A comparative study among SPT, CPT, and TCP tests has been presented, followed by the applications of these methods to interpret various soil characteristics including undrained shear strength parameters. The later part of the chapter focuses on the past research results from TCP as well as a review of existing correlations to predict undrained shear strength properties.

2.2 Historical Background of Penetration Tests

Unlike other branches of civil engineering which evolved by theoretical analysis and then applied to the field problems, geotechnical engineering has evolved from practice and field observations of soils in embankments and foundations (Desai, 1970). A series of laboratory tests simulating field conditions were developed to determine shear strength and other properties of soils. The results of these tests would be representative of the field condition only if in situ conditions could be exactly reproduced or simulated (Desai, 1970). This process is difficult since the structure of soil specimens attained by natural field and artificial laboratory compactions is rarely similar (Desai, 1970). This necessitates development of field testing methods and equipments to determine the in situ properties of soils with established consistency. Soil sounding or penetration testing is one of these field methods.

Probing with rods through weak ground to locate a firmer stratum has been practiced since about 1917 (Meigh, 1987). Soil sounding or probing consists of forcing a rod into the soil and observing the resistance to penetration (Coyle and Bartoskewitz, 1980). According to Hvorslev (1949), the oldest and simplest form of soil sounding consists of driving a rod into the ground by repeated blows of a hammer, where the given number of blows (N) required per foot penetration of the rod may be used as an index of penetration resistance and the parameter is correlated directly with foundation response parameters. The numerical value would not only depend on the characteristic of the soil, but also on diameter, length and weight of probing devices in relation to weight and drop of the hammer.

Variation of the resistance indicates dissimilar soil layers, and the numerical values of this resistance permit an estimate of some of the physical and engineering properties of the strata (Hvorslev, 1949). Table 2.1 gives a basic understanding of different sounding methods for different soil types based on measured penetration resistance and friction along the rod.

Table 2.1 Typical Soil Types and Sounding Properties (Bondarik, 1967)

Type of Soil	Penetration Resistance	Friction Along the Rod	Applicable Sounding Devices
Fine, coarse gravel	Very great	Insignificant or none	Heavy dynamic penetrometers without casting
Sandy soil	Changes according to density	Considerable below ground water level	Dynamic penetrometers with widened sounding heads (below groundwater level with casing), static penetrometers
Silty soil	Depends on density and moisture content	Not great	Static and dynamic penetrometers
Clayey soil	Varies with consistency, decreases with increasing moisture content	Great, increases with increasing moisture content	Static penetrometers, dynamic penetrometers with casting
Silty organic soil	Very small or zero	May be considerable	Static and dynamic penetrometers with casing

Compiled by Bondarik (1967) based on the work by Schultze and Knausberger (1957)

Use of the penetrometer evolved because of the need to acquire data from the subsurface soils which was not obtainable by any other means (Hamoudi et al., 1974). Considerable gains in efficiency, economy, and time are achieved by using in-situ devices such as the standard penetration test (SPT) and cone penetration test (CPT), dilatometer, pressuremeter, and shear vane (Jamiolkowski et al., 1985).

The use of impact type hammer-driven cone penetrometers has been largely limited to drilling applications where standard drilling tools like split-spoon samplers have been used as penetrometers (Swanson, 1950). Impact type hammer-driven penetrometers provide the best historical database and are extremely inexpensive. They are, however, hampered by a lack of accuracy due to the numerous sources of errors which can occur during the test, equipment variability, and test repeatability. Also, infrequent sampling is provided by dynamic penetrometers which may lead to possible sample disturbance during the test.

On the other hand, static penetrometers provide more accurate test results and enhanced test repeatability. Static penetrometers provide continuous data without sample disturbance. However, they have been limited by their economic viability and their limitations in the ranges of soil resistance that can be measured with them (Fritton, 1990; Vyn and Raimbault, 1993).

2.3 Penetration Tests Presently in Use

Four types of penetration tests currently practiced in the United States are described in the following sections.

2.3.1 Standard Penetration Test (SPT)

The standard penetration test (SPT) was developed around 1927, and is the most widespread dynamic penetration test practiced in the United States. Since 1958, the SPT has been standardized as ASTM method 1586 with periodic updates. SPT is an economical means to obtain subsurface information. The test involves driving the standard split-barrel sampler into the soil and counting the number of blows (N) required for driving the sampler to a depth of 150 mm each, for a total of 300 mm. The test is stopped early in case of a refusal which may arise from the following conditions:

1. 50 blows are required for any 150 mm increment
2. 100 blows are obtained to drive 300 mm
3. 10 successive blows produce no advance in penetration

In 1996, Bowles estimated around 85-90% of conventional designs in North America were made using SPT. In 1961 Meigh and Nixon reported the results of various types of in situ tests at several sites and concluded that the SPT gives a reasonable, if not somewhat conservative, estimate of the allowable bearing capacity of fine sands. The results of the SPT can usually be correlated in a general way with the pertinent physical properties of sand (Duderstadt, 1977). Peck, Hanson, and Thornburn (1953) reported a relationship between the

N value and the angle of shearing resistance, Φ', which has been widely used in foundation design procedures dealing with sands. According to their literature, several researchers have also reported a correlation between SPT N-values and unconfined compressive strength of cohesive soils (Sowers and Sowers, 1951; Terzaghi and Peck, 1967; and United States Department of the Interior, 1960)

2.3.2 Cone Penetration Test (CPT)

The CPT was introduced in the Netherlands in 1932 and has been referred to as static penetration test, or quasi-static penetration test, or Dutch sounding test (Meigh, 1987). The cone penetration test (CPT) is a simple test that is now widely used in lieu of the SPT and this test is recommended for soft clays, soft silts, and in fine to medium sand deposits (Kulhawy and Mayne, 1990). The test consists of pushing a standard cone penetrometer with 60˚ apex angle into the ground at a rate of 10 to 20 mm/s and then recording the resistances offered by the tip and cone sleeve. The test is not well adapted to gravel deposits and stiff/hard cohesive deposits (Bowles, 1996). The CPT test has been standardized by the American society of testing and materials as ASTM D 3441.

2.3.3 Dynamic Cone Penetrometer (DCP)

The dynamic cone penetrometer (DCP) originally developed by Sowers, is another impact based in situ device. Acar and Puppala (1991) studied the use of dynamic penetrometer for evaluating compaction quality in fills constructed with a boiler slag. The DCP is simple, economical, requires minimum maintenance, and can be used even in inaccessible sites. It also provides continuous assessment of the in situ strength of the pavement base and underlying subgrade layers without the need for digging the existing pavement as in the case of California Bearing Ratio field Test (Chen et al., 2001). Since its inception, the Dynamic cone penetrometer (DCP) has been used in several countries such as Australia, New Zealand, and United Kingdom. A few DOT's in the USA including Texas, California, and Florida have also used this device for pavement in situ investigations. The DCP has proven to be an effective tool in the assessment of in situ strength of pavements and subgrade and can also be used for QC/QA in pavement construction (Nazzal, 2002). The DCP results can be correlated to various engineering properties such as CBR, shear strength of soils, soil classification, Elastic Modulus (E_S), and Resilient modulus (M_R) (Nazzal, 2002).

2.3.4 Texas Cone Penetrometer (TCP)

The state of Texas currently uses a sounding test similar to the SPT during its foundation exploration work. The Texas cone penetrometer (TCP) is a dynamic penetration test similar to the SPT and practiced by the Texas Department of Transportation (TxDOT) to determine the allowable shear values of foundation materials encountered in bridge foundation exploration work for design purposes.

2.4 History and Development of TCP

According to the Geotechnical Manual (2000), TCP was developed by the bridge foundation soils group under the wings of the bridge division with the help of materials, tests, equipment, and the procurement division of the DOT. This was an effort to bring consistency in soil testing to determine soil and rock load carrying capacity in foundation design, which was lacking prior to the 1940's. The first use of TCP dates back to 1949, the first correlation charts and test procedure was first published in the Foundation Exploration and Design Manual in the year 1956. These correlations were modified slightly in 1972 and 1982 based on accumulated load test data for piling and drilled shafts (Geotechnical Manual, 2000).

2.4.1 TCP Equipment and Testing Procedure

The TCP test (Tex-132-E) is a standardized test procedure by TxDOT. The TCP test is an in situ test which has been calibrated over the years and its consistency is well established (Geotechnical Manual, 2000). The following apparatuses as shown in Figures 2.1 and 2.2 are required to run the TCP test:

1. Hammer, 170 ± 2 lb. with a 24 ± 0.5 in. drop
2. Drill stem, sufficient to accomplish boring to the desired depth
3. Anvil, threaded to fit the drill stem, and slotted to accept the hammer
4. Conical driving point, 3 in. in diameter with a 2.50 in. long point

The driving point is to be manufactured from AISI 4142 steel. The point is to be heated in an electric oven for 1 hour at 1550 to 1600 degrees Fahrenheit. Point is plunged into approximately 25 gallons of tempering oil and moved continuously until adequately cooled (Geotechnical Manual, 2000).

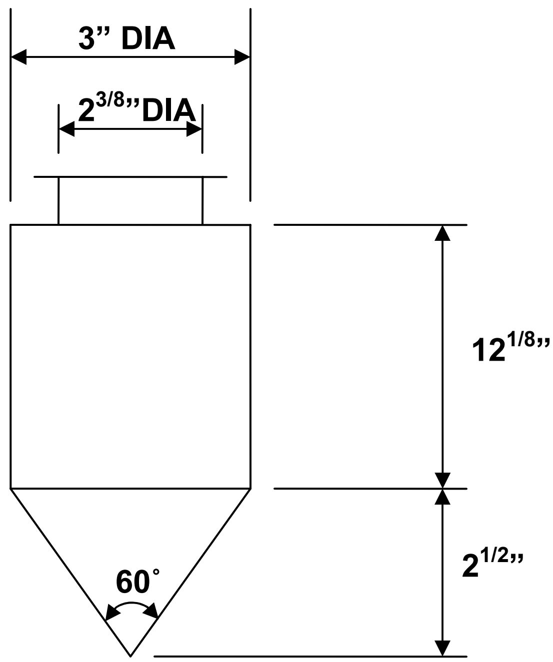

Figure 2.1 Details of Conical Driving Point of TCP (Not to Scale)

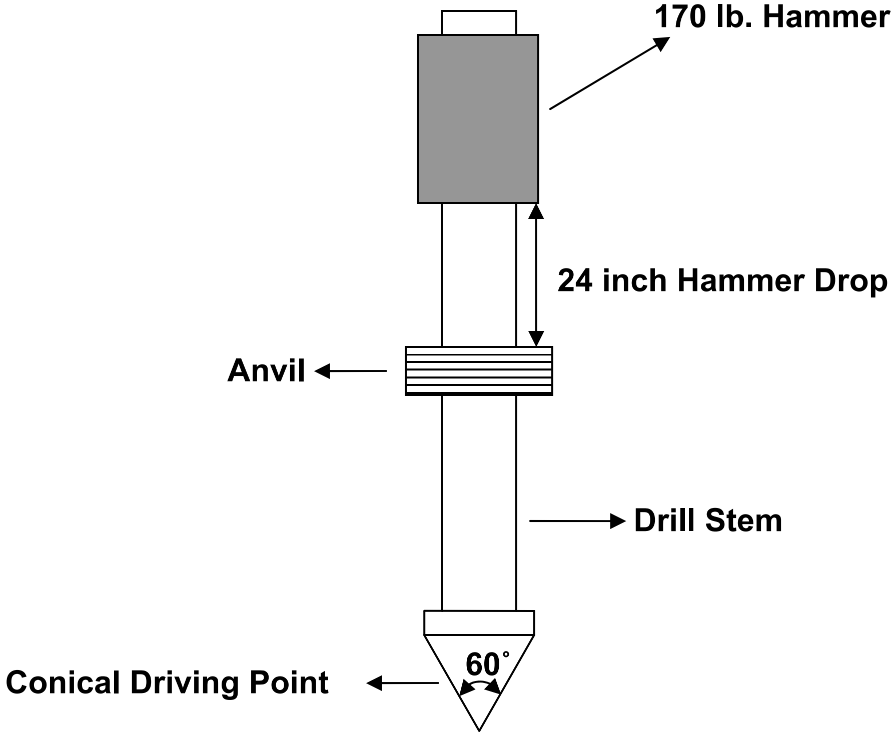

Figure 2.2 Details of the Texas Cone Penetrometer (Not to Scale)

Figure 2.3 Close-Up View of Cone Tip between Tests

Figure 2.4 TCP Hammers – Fully Automatic on Left; Automatic Trip on Right (Geotechnical Manual, 2000)

The test consists of dropping of a 170 lb. hammer to drive the 3 inch diameter penetrometer cone attached to the stem. The penetrometer cone (Figures 2.1 to 2.5) is first driven for 12 inches or 12 blows, whichever comes first and is seated in soil or rock. The test is started with a reference at this point. N-values are noted for the first and second 6 inches for a total of 12 inches for relatively soft materials and the penetration depth in inches is noted for the first and second 50 blows for a total of 100 blows in hard materials.

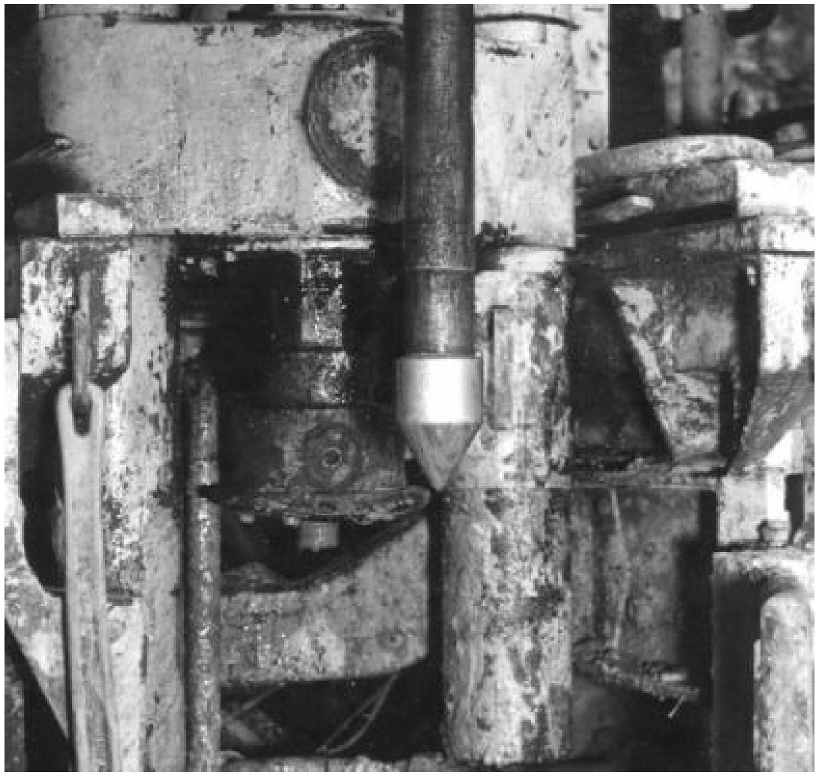

Figure 2.5 TCP Cone Tip (Geotechnical Manual, 2000)

2.4.2 TCP and Shear Strength

Shear strength is one of the most important of engineering properties of soils (Schmertmann, 1975). Schmertmann (1975) described the importance of shear strength to geotechnical engineers by stating that in situ shear strength would probably be the one property that design engineers needed for design purposes. The load carrying properties of soils is usually dependent on its shear strength.

TxDOT presently uses the Texas triaxial method (Tex-118-E) to determine the shear strength of soils for its design purposes. The shear strength results from the Texas triaxial tests have been correlated with the results from the ASTM method of triaxial testing during past studies and are provided in section 2.6 of this chapter. However, during routine subsurface investigations, laboratory tests for determining soil shear strength are often omitted due to the additional expense involved. The TCP test is routinely used as the primary means for predicting soil shear strength at bridge sites.

2.5 SPT, CPT and TCP - A Comparison

As discussed earlier, SPT and TCP work on a similar driving method. In SPT, soil samples are recovered by the split-spoon sampler, while in TCP no sample is recovered. CPT and SPT resemble in shape, but the TCP is larger in diameter compared to CPT. Based on these qualities of SPT, CPT, and TCP, it can be interpreted that TCP is a hybrid of SPT and CPT.

Tables 2.3, 2.4, 2.5 and 2.6 present the existing correlations of SPT, CPT, and TCP at different soil density classifications. In addition to extensive literature review, a table similar to the one compiled by Vipulanandan et al. (2004) in the proposal for TxDOT project 0-4862 was used to compile these tables. From Tables 2.3 and 2.4, it can be noted that the main parameters in SPT and CPT are blow count (N) and end bearing (q_c) respectively. It can also be seen from Tables 2.3 and 2.4 that TCP has not been correlated to some soil properties.

The relationship developed by Touma and Reese (1969) between SPT and TCP in cohesive and cohesionless soils is presented in Tables 2.5 and 2.6. The relative difference in N values of SPT and TCP at different soil density classifications is also presented in these two tables.

Studies by Meyerhoff (1956) and Lamb and Whitman (1969) were used as the source for typical values for friction angle (Φ) and dry density (D_r) (%), respectively in Table 2.3. For TCP, presently there is a difference in soil density classification, as shown in Table 2.2 and Figure 2.6.

Table 2.2 Soil Density Classification for TCP (Geotechnical Manual, 2000)

Soil Density or Consistency			
Density (Granular)	**Consistency (Cohesive)**	**TCP (blows/feet)**	**Field Identification**
Very Loose	Very Soft	0 to 8	Core (height twice diameter) sags under own weight
Loose	Soft	8 to 20	Core can be pinched or imprinted easily with finger
Slightly Compacted	Stiff	20 to 40	Core can be imprinted with considerable pressure
Compacted	Very Stiff	40 to 80	Core can be imprinted slightly with fingers
Dense	Hard	80 to 5”/100	Core cannot be imprinted with fingers but can be penetrated with pencil
Very Dense	Very Hard	5”/100 to 0”/100	Core cannot be penetrated with pencil

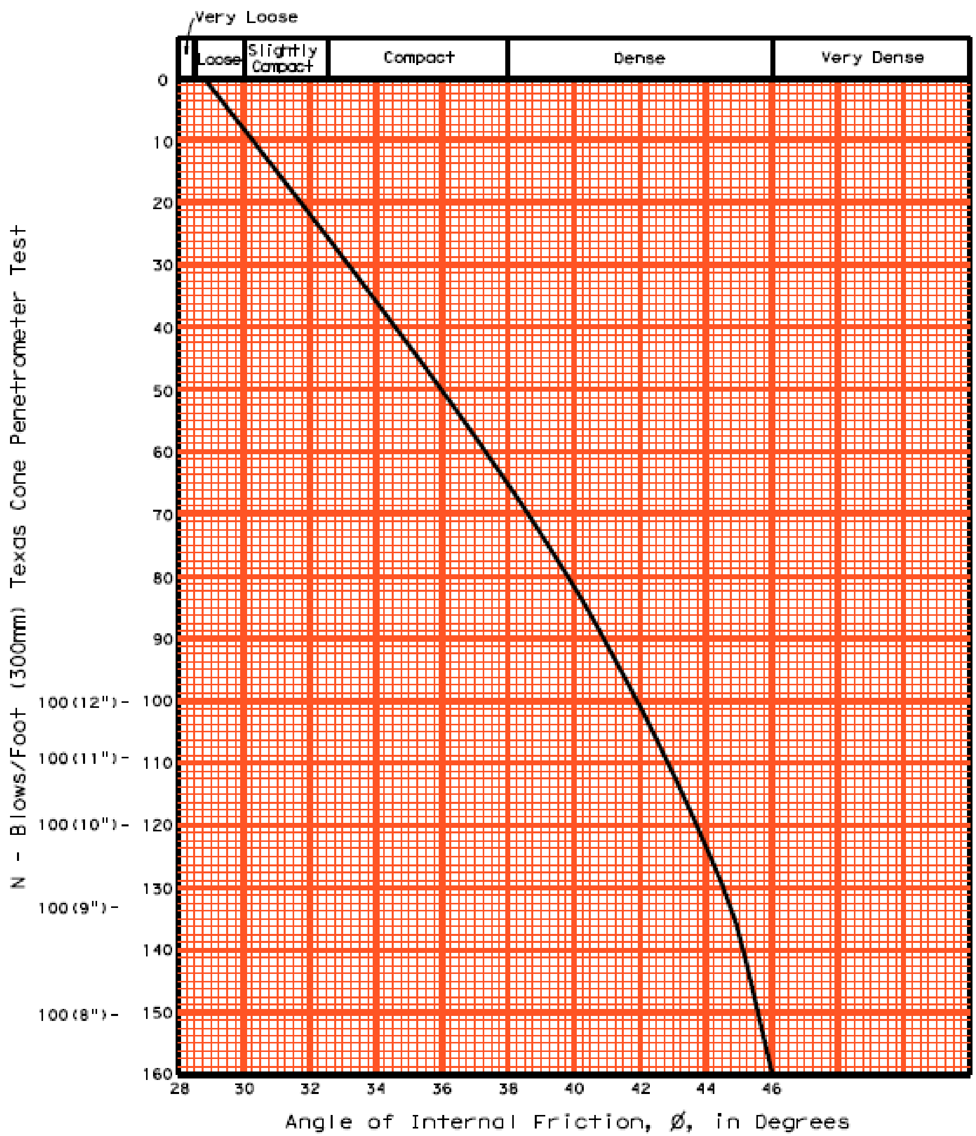

Figure 2.6 Soil Density Classification for TCP (Geotechnical Manual, 2000)

Table 2.3 Existing Correlations for Cohesionless Soils in SPT, CPT and TCP (After Vipulanandan et al., 2004)

Soil Classification		Typical Values	SPT	CPT	TCP
Very Loose	Φ	< 30˚	$\tan^{-1}\left[\frac{N_{SPT}}{12.2+20.3\frac{\sigma'_{VO}}{Pa}}\right]^{0.34}$ (Schmertmann, 1975)	$\tan^{-1}\left[0.1+0.38\log\frac{q_c}{\sigma'_{VO}}\right]$ (Kulhawy and Mayne, 1990)	28˚ - 29˚ in Figure 4.1 of TxDOT Manual (Geotechnical Manual, 2000)
	D_r (%)	0 to 15	$f\left(N,\sigma'_{VO},OCR,C_U\right)$ (Marcuson and Bieganousky, 1977)	Cone Tip Resistance $\left(\frac{q_c}{P_a}\right)$, < 20	Not Available
Loose	Φ	30˚ to 35˚	$\tan^{-1}\left[\frac{N_{SPT}}{12.2+20.3\frac{\sigma'_{VO}}{Pa}}\right]^{0.34}$ (Schmertmann, 1975)	$\tan^{-1}\left[0.1+0.38\log\frac{q_c}{\sigma'_{VO}}\right]$ (Kulhawy and Mayne, 1990)	29˚ - 30˚ in Figure 4.1 of TxDOT Manual (Geotechnical Manual, 2000)
	D_r (%)	15 to 35	$f\left(N,\sigma'_{VO},OCR,C_U\right)$ (Marcuson and Bieganousky, 1977)	Cone Tip Resistance $\left(\frac{q_c}{P_a}\right)$, 20 to 40	Not Available
Medium	Φ	35˚ to 40˚	$\tan^{-1}\left[\frac{N_{SPT}}{12.2+20.3\frac{\sigma'_{VO}}{Pa}}\right]^{0.34}$ (Schmertmann, 1975)	$\tan^{-1}\left[0.1+0.38\log\frac{q_c}{\sigma'_{VO}}\right]$ (Kulhawy and Mayne, 1990)	30˚ - 38˚ in Figure 4.1 of TxDOT Manual (Geotechnical Manual, 2000)

Table 2.3 - *Continued*

Medium	D_r (%)	35 to 65	$f\left(N, \sigma'_{VO}, OCR, C_U\right)$ (Marcuson and Bieganousky, 1977)	Cone Tip Resistance $\left(\frac{q_c}{P_a}\right)$, 40 to 120	Not Available
Dense	Φ	40° to 45°	$\tan^{-1}\left[\frac{N_{SPT}}{12.2+20.3\frac{\sigma'_{VO}}{Pa}}\right]^{0.34}$ (Schmertmann, 1975)	$\tan^{-1}\left[0.1+0.38\log\frac{q_c}{\sigma'_{VO}}\right]$ (Kulhawy and Mayne, 1990)	38° - 46° in Figure 4.1 of TxDOT Manual (Geotechnical Manual, 2000)
	D_r (%)	65 to 85	$f\left(N, \sigma'_{VO}, OCR, C_U\right)$ (Marcuson and Bieganousky, 1977)	Cone Tip Resistance $\left(\frac{q_c}{P_a}\right)$, 120 to 200	Not Available
Vey Dense	Φ	> 45°	$\tan^{-1}\left[\frac{N_{SPT}}{12.2+20.3\frac{\sigma'_{VO}}{Pa}}\right]^{0.34}$ (Schmertmann, 1975)	$\tan^{-1}\left[0.1+0.38\log\frac{q_c}{\sigma'_{VO}}\right]$ (Kulhawy and Mayne, 1990)	Not Available
	D_r (%)	85 to 100	$f\left(N, \sigma'_{VO}, OCR, C_U\right)$ (Marcuson and Bieganousky, 1977)	Cone Tip Resistance $\left(\frac{q_c}{P_a}\right)$, > 200	Not Available

Table 2.4 Existing Correlations for Cohesive Soils in SPT, CPT and TCP (After Vipulanandan et al., 2004)

Soil Classification		SPT	CPT	TCP
Very Soft	C_U	$C_U / P_a \approx 0.29 N_{SPT}^{0.72}$ (Hera, et al., 1974)	$C_U = \frac{q_C - \sigma_{VO}}{N_K}$	$C_{U(ASTM)} = 0.067\ N_{TCP}$ (CH Soils) $C_{U(ASTM)} = 0.054\ N_{TCP}$ (Silty CL Soils) $C_{U(ASTM)} = 0.053\ N_{TCP}$ (Sandy CL Soils)
	OCR	$OCR = 0.58 N_{SPT}$ (Mayne and Kemper, 1984)	$OCR = 0.32(q_T - \sigma_{VO} / \sigma_{VO})$ (Mayne, 1991)	Not Available
Soft to Medium	C_U	$C_U / P_a \approx 0.29 N_{SPT}^{0.72}$ (Hera, et al., 1974)	$C_U = \frac{q_C - \sigma_{VO}}{N_K}$	$C_{U(ASTM)} = 0.067\ N_{TCP}$ (CH Soils) $C_{U(ASTM)} = 0.054\ N_{TCP}$ (Silty CL Soils) $C_{U(ASTM)} = 0.053\ N_{TCP}$ (Sandy CL Soils)
	OCR	$OCR = 0.58 N_{SPT}$ (Mayne and Kemper, 1984)	$OCR = 0.32(q_T - \sigma_{VO} / \sigma_{VO})$ (Mayne, 1991)	Not Available
Stiff	C_U	$C_U / P_a \approx 0.29 N_{SPT}^{0.72}$ (Hera, et al., 1974)	$C_U = \frac{q_C - \sigma_{VO}}{N_K}$	$C_{U(ASTM)} = 0.067\ N_{TCP}$ (CH Soils) $C_{U(ASTM)} = 0.054\ N_{TCP}$ (Silty CL Soils) $C_{U(ASTM)} = 0.053\ N_{TCP}$ (Sandy CL Soils)

Table 2.4 - *Continued*

Stiff	OCR	$OCR = 0.58 N_{SPT}$ (Mayne and Kemper, 1984)	$OCR = 0.32(q_T - \sigma_{VO}/\sigma_{VO})$ (Mayne, 1991)	Not Available
Very Stiff	C_U	$C_U / P_a \approx 0.29 N_{SPT}^{0.72}$ (Hera, et al., 1974)	$C_U = \frac{q_C - \sigma_{VO}}{N_K}$	$C_{U(ASTM)} = 0.067\ N_{TCP}$ (CH Soils) $C_{U(ASTM)} = 0.054\ N_{TCP}$ (Silty CL Soils) $C_{U(ASTM)} = 0.053\ N_{TCP}$ (Sandy CL Soils)
	OCR	$OCR = 0.58 N_{SPT}$ (Mayne and Kemper, 1984)	$OCR = 0.32(q_T - \sigma_{VO}/\sigma_{VO})$ (Mayne, 1991)	Not Available
Hard	C_U	$C_U / P_a \approx 0.29 N_{SPT}^{0.72}$ (Hera, et al., 1974)	$C_U = \frac{q_C - \sigma_{VO}}{N_K}$	$C_{U(ASTM)} = 0.067\ N_{TCP}$ (CH Soils) $C_{U(ASTM)} = 0.054\ N_{TCP}$ (Silty CL Soils) $C_{U(ASTM)} = 0.053\ N_{TCP}$ (Sandy CL Soils)
	OCR	$OCR = 0.58 N_{SPT}$ (Mayne and Kemper, 1984)	$OCR = 0.32(q_T - \sigma_{VO}/\sigma_{VO})$ (Mayne, 1991)	Not Available

Table 2.5 Existing Correlations between SPT and TCP for Cohesionless Soils

Soil Classification	$\mathbf{N_{SPT}}$	$\mathbf{N_{TCP}}$	**Relationship between SPT & TCP**
Very Loose	0 to 4	0 to 8	$N_{SPT} = 0.5\ N_{TCP}$
Loose	4 to 10	8 to 20	$N_{SPT} = 0.5\ N_{TCP}$
Medium	10 to 30	20 to 60	$N_{SPT} = 0.5\ N_{TCP}$
Dense	30 to 50	60 to 100	$N_{SPT} = 0.5\ N_{TCP}$
Very Dense	> 50	> 100	$N_{SPT} = 0.5\ N_{TCP}$

Table 2.6 Existing Correlations between SPT and TCP for Cohesive Soils

Soil Classification	$\mathbf{N_{SPT}}$	$\mathbf{N_{TCP}}$	**Relationship between SPT & TCP**
Very Soft	< 2	< 3	$N_{SPT} = 0.7\ N_{TCP}$
Soft to Medium	2 to 8	3 to 11	$N_{SPT} = 0.7\ N_{TCP}$
Stiff	8 to 15	11 to 21	$N_{SPT} = 0.7\ N_{TCP}$
Very Stiff	15 to 30	21 to 43	$N_{SPT} = 0.7\ N_{TCP}$
Hard	> 30	> 43	$N_{SPT} = 0.7\ N_{TCP}$

2.6 Review of Past Research on TCP

TCP tests are routinely carried out since they are required for investigation of foundation materials encountered during foundation exploration for TxDOT projects. Therefore, a large amount of data from these tests can be made available from past reports, drilling logs, and other sources by TxDOT. Limited research was done during 1974 to 1977 to correlate TCP N-values to shear strength parameters. These studies were carried out especially in the upper gulf coast region. The research objectives and results of these studies along with references are presented in Tables 2.7 and 2.8.

Table 2.7 Review of Past Research Reports on TCP

Report Year	Authors	Research Objective	Research Findings
1974	Hamoudi, M.M., Coyle, H.M., Bartokewitz, R.E.	To develop improved correlations between the TCP N-value and the unconsolidated - undrained shear strength of homogeneous CH, CL, and SC groups of cohesive soils	$C_{U(ST)} = 0.60\ C_{U(TAT)}$ $C_{U(TAT)} = 0.11\ N$ (Homogeneous CH soils) $C_{U(TAT)} = 0.02\ N$ (CH soils with secondary structure) $C_{U(TAT)} = 0.10\ N$ (Silty CL soils) $C_{U(TAT)} = 0.095\ N$ (Sandy CL soils) $C_{U(ST)} = 0.070\ N$ (Homogeneous CH soils) $C_{U(ST)} = 0.018\ N$ (CH soils with secondary structure) $C_{U(ST)} = 0.063\ N$ (Silty CL soils)

Table 2.7 - *Continued*

1974 (Continued)	Hamoudi, M.M., Coyle, H.M., Bartokewitz, R.E.		$C_{U(ST)} = 0.053\ N$ (Sandy CL soils) $C_{U(ST)} = 0.1\ N_{SPT}$ (Homogeneous CH soils) $C_{U(ST)} = 0.09\ N_{SPT}$ (Silty CL soils) $C_{U(ST)} = 0.076\ N_{SPT}$ (Sandy CL soils) *Where:* $C_{U(ST)}$ = Shear Strength from ASTM standard test $C_{U(TAT)}$ = Shear Strength from Texas triaxial test N = TCP blow count N_{SPT} = SPT blow count
1975	Cozart, D.D., Coyle, H.M., Bartoskewitz, R.E.	To develop improved correlations between the TCP test N - value and drained shear strength of cohesionless soils	$N_{SPT} = 0.5\ N_{TCP}$ $S = 0.114 + 0.20N$ (tsf) If the boundary condition (S = 0, when N = 0) is stipulated, the equation is;

Table 2.7 - *Continued*

1975 (Continued)	Cozart, D.D., Coyle, H.M., Bartoskewitz, R.E.		S = 0.022N (tsf) P' = 0.150 + 0.026N γ = 107.78 + 0.24 N_{TCP} (Relatively poor correlation) *Where:* N_{TCP} = TCP blow count N_{SPT} = SPT blow count S = Shear Strength P' = Effective overburden pressure γ = Unit weight (pcf)
1977	Duderstadt, F.J., Coyle, H.M., Bartoskewitz, R.E.	1) To develop an improved correlation between the N-value from TCP test and: • the unconsolidated – undrained shear strength of cohesive soils • drained shear strength of cohesionless soil 2) To attempt the development of a correlation between the TCP N–value and unit side friction and unit point bearing for driven and bored piles	Table 2.7

Table 2.8 Research Findings of the 1977 Research Report

Objectives	Research Findings
Correlations for cohesive soils	$C_{U(ASTM)} = 0.58\ C_{U(TAT)}$ $C_{U(TAT)} = 0.11\ N_{TCP}$ (Homogeneous CH Soils) $C_{U(TAT)} = 0.11\ N_{TCP}$ (Silty CL Soils) $C_{U(TAT)} = 0.095\ N_{TCP}$ (Sandy CL Soils) $C_{U(ASTM)} = 0.067\ N_{TCP}$ (Homogeneous CH Soils) $C_{U(ASTM)} = 0.054\ N_{TCP}$ (Silty CL Soils) $C_{U(ASTM)} = 0.053\ N_{TCP}$ (Sandy CL Soils) $C_{U(ASTM)} = 0.096\ N_{SPT}$ (Homogeneous CH Soils) $C_{U(ASTM)} = 0.076\ N_{SPT}$ (CL Soils) $N_{SPT} = 0.7\ N_{TCP}$ *Where:* $C_{U(ASTM)}$ = Shear Strength from ASTM standard test (tsf) $C_{U(TAT)}$ = Shear Strength from Texas triaxial test N_{TCP} = TCP blow count N_{SPT} = SPT blow count

Table 2.8 - *Continued*

Correlations for cohesionless soils		$N_{SPT} = 0.5\ N_{TCP}$ $S = 0.021\ N_{TCP}$ (SP, SM, and SP-SM soils) $P' = 0.172 + 0.023\ N_{TCP}$ $\gamma = 111.0 + 0.231\ N_{TCP}$ $S = 0.041\ N_{SPT}$ *Where:* N_{SPT} = SPT blow count N_{TCP} = TCP blow count S = Drained shear strength (tsf) γ = Unit weight (pcf)
Unit side friction and unit point bearing	**Driven Piles**	$f_s = 0.031\ N_{TCP}$ (Cohesive Soils) $f_s = 0.033\ N_{TCP}$ (Cohesionless Soils) $q_c = 0.103\ N_{TCP}$ (Cohesive Soils) $q_c = 1.330\ N_{TCP}$ (Cohesionless Soils) *Where:* N_{TCP} = TCP blow count f_s = Unit side friction (tsf) q_c = Unit point bearing (tsf)
	Bored Piles	$f_s = 0.022\ N_{TCP}$ (Cohesive Soils) $f_s = 0.014\ N_{TCP}$ (Cohesionless Soils) $q_c = 0.32\ N_{TCP}$ (Cohesive Soils) $q_c = 0.10\ N_{TCP}$ (Cohesionless Soils) *Where:* N_{TCP} = TCP blow count f_s = Unit side friction (tsf) q_c = unit point bearing (tsf)

Note: The correlations for unit side friction and unit point bearing for both driven and bored piles were developed using a limited amount of data. Therefore, these correlations were considered preliminary and no conclusions were made on these correlations. Additional data and research were recommended to be added to the data used in the 1977 report to come up with final correlations.

Based on past research, TxDOT presently uses the chart shown in Figure 2.7, and the same is presented as equations in Table 2.9 to predict the shear strength of soils using TCP N-values for its foundation design purposes. The chart is designed to predict ½ shear strength; hence, it has a factor of safety of 2 incorporated in it. The TCP values may be used without any correction to determine the shear strength using this chart. The TCP test does not require consideration of groundwater since it is conducted in the ground (in situ) (Geotechnical Manual, 2000).

As discussed earlier, the TCP test is the primary means of determining the soil shear strength by TxDOT for routine subsurface investigations. For this reason, a better correlation between the TCP N-values and soil shear strength could result in significant financial savings in the design and construction of earth structures built by TxDOT. Hence, as part of this research, an attempt was made to develop new correlations between TCP parameters and shear strength and the results are presented in the latter chapters.

Table 2.9 Design Chart to Predict Shear Strength for Foundation Design Using TCP N-values; Presently Used by TxDOT (Geotechnical Manual, 2000)

Soil Type	**Constants – C**	**Design Shear Strength (0.5 × Cohesion) (tsf) = N/C**	**Ultimate or Full Undrained Shear Strength or Cohesion (tsf) = N/(0.5 ×C)**
CH	50	N/50	N/25
CL	60	N/60	N/30
SC	70	N/70	N/35
OTHER	80	N/80	N/40

Where;

N = N12 – Number of blows/12”

2.7 Summary

The history and origin of different types of penetrometers have been discussed. A brief description of the design and working of different types of penetrometers presently in use in the US are mentioned. Introduction to the design, working, and present use of the Texas cone penetrometer has been provided. A comparison between the TCP, SPT, and CPT has been made and discussed. Correlations of TCP from past studies and design chart presently used by TxDOT for use of TCP N-values to predict shear strength have been summarized.

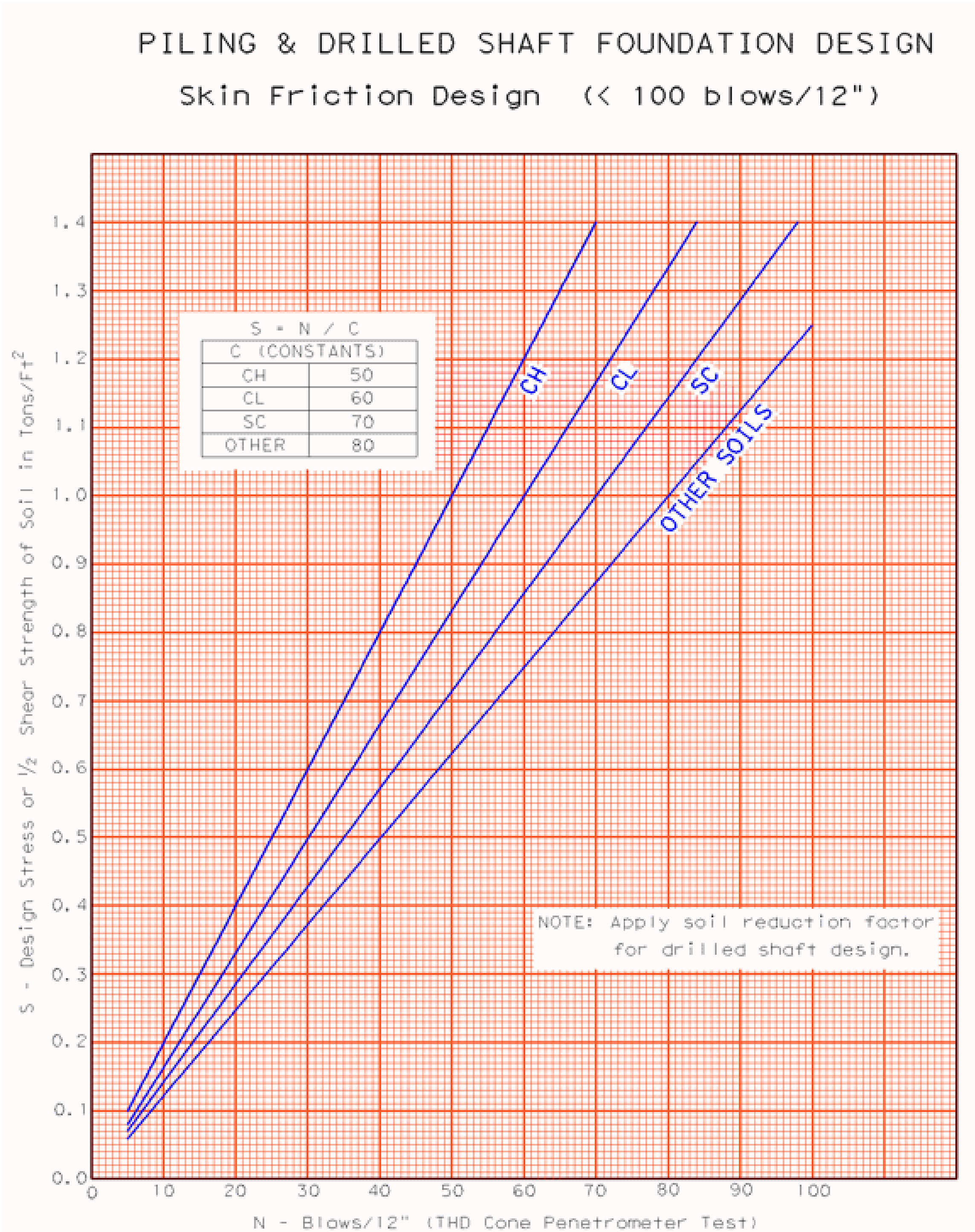

Figure 2.7 Design Chart to Predict Shear Strength for Foundation Design Using TCP N-values; Presently Used by TxDOT (Geotechnical Manual, 2000)

CHAPTER 3
DATA COLLECTION, EXTRACTION AND COMPILATION

3.1 Introduction

This chapter elucidates methods developed to collect and compile data from Dallas and Fort Worth districts for the present research. Salient features of the software developed to extract data from boring logs and compile them in Microsoft excel files are explained. Details about the information collected to develop a database management system of Texas soils are also discussed.

3.2 Research Data Collection

This section explains the data pertaining to various soil properties that are required in the present research. Documentation of TCP test results (Tex-132-E) and Texas triaxial test results (Tex-118-E) are first discussed. This is followed by a description of various methods followed to collect the available data from the Dallas and Fort Worth districts of TxDOT.

3.2.1 TCP and Shear Strength Data

TCP tests (Tex-132-E) are conducted on a routine basis by TXDOT to determine the allowable shear strength values of subsoils for design purposes and also to characterize sites and design foundations. This test is typically conducted by the TxDOT prior to routine design work related to geotechnical projects including embankments. These TCP tests are either conducted by the department itself; or contracted out to outside testing agencies.

The undrained shear strength property predictions based on TCP N-values are conservative and these predictions are typically lower than the laboratory measured similar property. Therefore, laboratory testing of soils is always recommended to determine undrained shear strength of soils. TxDOT currently uses the Texas triaxial test method (Tex-118-E) to determine the undrained shear strength of soils in laboratory setting. However, such practice is expensive and time consuming. Hence, at most of the sites, TxDOT primarily uses the TCP test as the primary means to predict the shear strength of soils.

The results of the TCP tests are normally input into a software named as Wincore (version 3). At construction sites where laboratory shear strength testing was performed, data from Texas triaxial test method (Tex-118-E) are also inputted into the Wincore 3.0 software. Wincore is software used to analyze and report soil borings in accordance to TxDOT standards. In addition, it can also be used for foundation design purposes. The Department normally documents a hard copy of these results, while the Wincore files are deleted after a period of time in accordance to the district requirements. A typical drilling log is shown in Figures 3.1 & 3.2.

3.2.2 Data Limitation, Data Evaluation, and Research Groups

As per the recommendations of TXDOT, it was decided to collect the TCP data of last 10 years, beginning from 1994. Since the TCP test is used across the

Texas, a large amount of data from TCP tests was available. The available data was screened first to ensure that it does contain triaxial test strength results. Further, to expedite the research, three universities were involved to collect the data required for the study. The state of Texas was grouped into three sectors. The following research teams were responsible for collecting data from each group:

1. The University of Texas at Arlington team – North and west Texas (Including Dallas, Fort Worth and Austin)
2. The University of Houston team – Central and south central Texas (Including Houston and San Antonio)
3. Lamar University team – East Texas (Including Beaumont)

3.2.3 Data Collection

A major portion of the TCP and Texas triaxial test results from Fort Worth district were available in hard copy format. This was available as boring logs similar to the ones shown in Figures 3.1 & 3.2. A few boring logs were available as soft copies stored as Wincore files. Data for the last 10 years starting from 1994 to present was collected. The data were then manually entered into the database created in Microsoft Excel. The data available in Wincore files were extracted by the software developed during this study. The details of this software are explained in greater depth in section 3.3 of this chapter. Similarly, the Dallas district's boring logs from Wincore were converted by the developed software into the database for Dallas district.

DRILLING LOG

1 of 2

WinCore
Version 3.0

County	Navarro	Hole	SB-9	District	Dallas
Highway	I-45	Structure	retainer walls	Date	05/06/02
CSJ	0093-01-076	Station	10072+90	Grnd. Elev.	318.00 ft
		Offset		GW Elev.	22.00 ft

Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
			CLAY, dark gray, gravelly, moist (CL)							
316.			CLAY, gray, moist (CL)							
										2.0
314.			CLAY, dark brown, moist (CL)							2.0
5										1.25
										2.0
311.			CLAY, dark gray, moist (CL)							2.25
										2.25
				7.8	10.39	33.8	79	50	118.9	
				17.8	13.05	33.0			119.4	2.25
				27.8	11.97	33			121.2	
10										2.5
										2.25
										2.5
										2.5
										2.5
15										2.25
302.		1 (6) 3 (6)	CLAY, gray, calcareous, moist (CL)							2.0
20		6 (6) 8 (6)								

Remarks: water level at completion was 10' on 05-06-02 at 3 pm, 24 hour water level was 5' on 05-07-02 at 2pm, level from surface

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Ricardo Garcia   Logger: James S   Organization: W.E.S. T Inc

C:\Documents and Settings\hxv7394\My Documents\Desktop\Test Data.clg

Figure 3.1 Typical Drilling Log

DRILLING LOG

WinCore
Version 3.0

County	Navarro	Hole	SB-9	District	Dallas
Highway	I-45	Structure	retainer walls	Date	05/06/02
CSJ	0093-01-076	Station	10072+90	Grnd. Elev.	318.00 ft
		Offset		GW Elev.	22.00 ft

Elev. (ft)	Depth	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
				CLAY, gray, calcareous, moist (CL)							
297.				CLAY, light brown, moist (CL)							
295.				CLAY, tan, wet (CL)							
293.	25		2 (6) 2 (6)	CLAY, tan, gray, sandy, moist (SC)							
288.	30		1 (6) 2 (6)	CLAY, tan, sandy, moist (SC)							
285.5				CLAY, gray, sandy, moist (SC)							
283.	35		16 (6) 50 (6)	CLAY, gray, moist (CL)							
281.				SHALE, gray, moist							
	40		50 (2.25) 50 (1)								

Remarks: water level at completion was 10' on 05-06-02 at 3 pm, 24 hour water level was 5' on 05-07-02 at 2pm, level from surface

Any ground water elevation information provided on this boring log is representative of conditions existing on the day and for the specific location where this information was collected. The actual groundwater elevation may fluctuate due to time, climatic conditions, and/or construction activity.

Driller: Ricardo Garcia Logger: James S Organization: W.E.S. T Inc

C:\Documents and Settings\hxv7394\My Documents\Desktop\Test Data.clg

Figure 3.2 Typical Drilling Log

3.3 Data Extraction From Wincore 3.0 to Microsoft Excel Format

The Wincore 3.0 software documents boring log and various test results including TCP data from each site. The software developed here, termed as EXTRACT was used to extract data from Wincore 3.0 to Microsoft Excel format. The code for implementing this program as a Macro in Microsoft excel is attached in Appendix E of thesis. A few details of the file extraction process are described in this section.

3.3.1 Wincore 3.0 Software

Five different screens of Wincore document the information from various test results. Each of these screens would request the user's input results from various types of tests performed at each site. Details of these screens are:

1. Project Data – Details about the site and project information
2. Hole Data – Information about the boring hole and personnel involved
3. Strata Data – Details about the different layers of strata in the boring hole
4. TCP Data – Stores TCP test results
5. Laboratory Data – Records results from various laboratory tests

Typical figures of these screens of Wincore software are shown in Appendix A as Figures A.1, A.2, and A.3. The information recorded in Wincore would then be available for print out as a boring log, similar to the one shown in Figures 3.1 and 3.2. The boring log shown here in Figures 3.1 and 3.2 is the hard copy of the information stored in the Wincore file shown in Figures A.1 to A.3. TxDOT documents these files with various codes that identify the project as per the location near to the Interstate or state highway.

3.3.2 EXTRACT - Software Developed to Extract Data

A software program, EXTRACT was developed to extract the information stored in the Wincore files to convert and then transfer them into excel file. The intent of this program development is minimizing the tedious manual entry process and reduces the errors involved in the manual entry process.

Visual basic editor in Microsoft excel was used to develop this software in the form of a macro. When invoked, the macro enables the extraction and conversion process

3.3.3 Typical Extraction Process

Two buttons, READ DATA and CLEAR DATA, are provided in the software. The READ DATA button can be used to choose a Wincore file from different files available in a directory. Once the user selects a Wincore file, the program extracts all the information stored in the file, and the information is then converted into excel format. The macro was developed such that the data from the five input screens of Wincore file are stored in five separate worksheets in excel. Typical screens of the developed software showing the extracted data in Microsoft excel format are shown in Figures B.1 to B.5 in Appendix B.

The CLEAR DATA button can be used to delete all the information stored in a particular excel file. Once the user clicks on the CLEAR DATA button, any information stored in excel file would be deleted. Hence, the user needs to be careful when using this option in the software.

3.4 Data Compilation

The details of the database system developed to compile the data collected from different TxDOT districts and thus create a soil database management system for Texas soils is described in the following section.

3.4.1 Primary Key (PK) and Foreign Key (FK)

Five tables were created in five different worksheets and were used to store information collected from the TxDOT districts. Each of these five tables is assigned a Primary key (PK). This key would be used to identify information carried over to the next table. Each Primary key (PK) will be converted into a Foreign key (FK) in the later tables. For example, Boring Hole ID is the Primary key (PK) in Table 4. In Table 5, Boring Hole ID will turn out to be the Foreign key (FK). Thus information corresponding to a boring hole in Table 4 is linked to the information in Table 5 by the analogous Boring Hole ID. Similarly, information from all five tables is linked and can provide easy access to review information from a particular project site or a particular boring hole. Both the Primary key (PK) and the Foreign key (FK) are clearly identified in all five tables. The information stored in each of these five tables and a brief explanation of each type of data is described in Tables 3.1 to 3.5. Typical screens showing the template of the tables to compile data are shown in Figure C.1 to C.8 in Appendix C.

Table 3.1 Details of Table 1 of Soil Database for the Study

Table 1 of Database – Work Group	
Name	**Definition**
Work Group ID (PK)	An ID for each work group
Group Name	A Individual Name for each work group
Assigned User	An assigned name for each work group
Phone Number	Phone number of the work group
Email	Email address of the work group

Table 3.2 Details of Table 2 of Soil Database for the Study

Table 2 of Database – Zip Code	
Name	**Definition**
Zip Code (PK)	Zip Code of the work site
City/Town	City/Town of the work site
State	State of the work site
County	County of the work site

Table 3.3 Details of Table 3 of Soil Database for the Study

Table 3 of Database – Site	
Name	**Definition**
CSJ (Site ID) (PK)	An ID number of the work site. This is of the form XXXX-YY-ZZZ; where the first four digits designates the Highway number, the next two digits specify the Section number, and the last three digits represent the Job number
Project Name or Number	A common name or number of the work site
Structure Location or Address	Physical address of the work site
City	City of the work site
State	State of the work site
Zip Code (FK)	Zip Code of the work site
County	County of the work site
Work Group ID (FK)	ID of the work group collecting the data
Data Source	Source of the data

Table 3.4 Details of Table 4 of Soil Database for the Study

Table 4 of Database – Field Test	
Name	**Definition**
Boring Hole ID (PK)	An ID number of the boring hole
CSJ (Site ID) (FK)	The boring hole must be related to a work site represented by CSJ
Station	Station
Offset (ft)	Offset
Ground Elevation (ft)	Ground of the boring hole at the depth datum. Elevations are positive upward, measured from the elevation datum
Groundwater table Elevation (GWT)	Groundwater table elevation
Date	Date of the drilling job
Total Borehole Depth (ft)	The depth is measured from the depth datum of the hole and is positive downward, as measured along the hole alignment
Driller	Name of the Driller
Logger	Name of the Logger
Organization	Name of Organization performing the job

Table 3.5 Details of Table 5 of Soil Database for the Study

Table 5 of Database – Test	
Name	**Definition**
Test ID (PK)	An ID number of the work group for the Test table (Example: UTA01, UH01, LAR01)
Boring Hole ID (FK)	An ID number of the boring hole
Depth	The measured depth to the sample where the test was performed at each boring hole
Classification	The soil classification used to describe the layer
First N6 or N1	The number of blows required for the TCP to penetrate the first 6 inches
Second N6 or N2	The number of blows required for the TCP to penetrate the second 6 inches
Penetration for the first 50 blows	Penetration for the first 50 blows if the penetration is less than 6 inches for any of the 6 inch increments
Penetration for the second 50 blows	Penetration for the second 50 blows if the penetration is less than 6 inches for any of the 6 inch increments
Pocket penetrometer	Pocket penetrometer readings
Triaxial test method	The type of triaxial test performed (Example: Texas triaxial test (TAT), ASTM triaxial test (ST)
Lateral pressure (psi)	Lateral pressure from the triaxial test

Table 3.5 – *Continued*

Deviator stress (psi)	Deviator stress from the triaxial test
Specific gravity	Specific gravity measured
D10	Grain diameter corresponding to 10 percent passing
D50	Grain diameter corresponding to 50 percent passing
Uniformity (Cu)	A coefficient describing the degree of uniformity of the grain size distribution. This coefficient is defined as the ratio of D60 over D10
Curvature (Cz)	A coefficient describing the degree of curvature of the grain size distribution. This coefficient is defined as the ratio of D30 times 2 over D60 times D10
% Pass 200 Sieve	The percentage of fines by weight passing the No. 200 sieve
% Pass 10 Sieve	The percentage of fines by weight passing the No.10 sieve
% Pass 4 Sieve	The percentage of fines by weight passing the No. 4 sieve
Natural Moisture Content (MC)	The in-situ moisture content of the soil generally expressed in percent
Liquid Limit (LL)	The water content of the soil at the arbitrary boundary between the semi-liquid and plastic states generally expressed in percent

Table 3.5 – *Continued*

Plastic Limit (PL)	The water content of the soil at the arbitrary boundary between the plastic and semi-solid states generally expressed in percent
Plasticity Index (PI)	Plasticity index is Liquid Limit-Plastic Limit
Total Unit Weight (Wet Density) (pcf)	Total unit weight
Compression Index (C_c)	Compression index (C_c) from the consolidation test
Coefficient of Consolidation (C_v)	Coefficient of consolidation (C_v) from the consolidation test
OCR	Over consolidation ratio (OCR) from the consolidation test
Date Last Updated	The date of the last update of data in the table
Assessment	An assessment of information relevant to the lab test

3.5 Volume of Data Collected for Research

Details of the volumes of information collected for each soil type from both Dallas and Fort Worth districts are listed in the following. The number of data points, the number of N12 results from TCP tests, and the number of measured shear strength (C_m) data from the Texas triaxial tests are reported in this section.

3.5.1 Data Collected From Dallas District

Tables 3.6 to 3.8 list the volume and details of information collected for Dallas district projects. A total of 15,339 data points were collected from the Dallas district. The distribution of these data into the four major types of soils considered for design by TxDOT is already detailed in Table 3.6. Of these 15,339 data points, 2,554 data points were under-classified and identified as clays, without further classification into CL or CH groups. Details of the data of under-classified clays are listed in Table 3.7. Also, 9,154 data points were identified as “Other Soils”, which included different types of soils. Distribution of “Other Soils” in Dallas district is listed in Table 3.8.

Table 3.6 Details of Dallas District Database for Study

CLASSIFICATION	DATA POINTS	N12 DATA	SHEAR STRENGTH (C_m) DATA
CL	1936	1496	55
CH	677	461	12
SC	1018	952	4
Other Soils	9154	1130	3
Total	**15339**	**6267**	**74**

Note: Total includes data points of clay and clay (fill) shown in Table 3.7

Table 3.7 Clay and Clay (Fill) Data in Dallas District Database

CLASSIFICATION	DATA POINTS	N12 DATA	SHEAR STRENGTH (C_m) DATA
Clay	2243	1949	0
Clay (Fill)	311	279	0

Table 3.8 Classification of Other Soils in Dallas District

CLASSIFICATION	DATA POINTS	N12 DATA	SHEAR STRENGTH (C_m) DATA
Asphalt & Asphalt (Fill)	11	6	0
Bentonite	1	0	0
Limestone	3576	117	0

Table 3.8 – *Continued*

Clayey Shale	1	0	0
Concrete	2	2	0
Debri (Cement & Wood)	1	0	0
Fill	24	24	0
Gravel	28	21	0
Road Base	2	2	0
Sand	962	471	0
Sand (Fill)	6	6	0
Sandstone	72	8	0
Severely Weathered Shale & Weathered Shale	4	0	0
Shale	4403	464	3
Shaly Clay	3	1	0
Weathered Limestone & Crushed Limestone	48	8	0

3.5.2 Data Collected From Fort Worth District

The volume and details of data collected from Fort Worth district is listed in Tables 3.9 to 3.11. A total of 5859 data points were collected from the Fort Worth district. Of these 5859 data points, 998 data points were without further classification into CL or CH, and were just identified as clays. Majority of the data points were identified as “Other Soils”, which is listed in Table 3.11.

Table 3.9 Details of Fort Worth District Database for Study

CLASSIFICATION	**DATA POINTS**	**N12 DATA**	**SHEAR STRENGTH (C_m) DATA**
CL & CL (Fill)	718	597	0
CH & CH-CL	239	119	0
SC & SC-SM	254	83	0

Table 3.9 – *Continued*

Other Soils	3650	749	0
Total	**5859**	**2378**	**10**

Note: Total includes data points of clay and clay (fill) shown in Table 3.10

Table 3.10 Clay and Clay (Fill) Data in Fort Worth District Database

CLASSIFICATION	DATA POINTS	N12 DATA	SHEAR STRENGTH (C_m) DATA
Clay	912	749	6
Clay (Fill)	86	81	4

Table 3.11 Classification of Other Soils in Fort Worth District

CLASSIFICATION	DATA POINTS	N12 DATA	SHEAR STRENGTH (C_m) DATA
Cemented Sand	7	3	0
Clay Shale &	3	2	0
GC & GP	3	3	0
Gravel,	29	19	0
Lignite &	1379	48	0
ML	10	3	0
Mudstone	3	0	0
Pavement	2	1	0
Sand & Sand (Fill)	1021	542	0
Sandstone	225	8	0
Sandy Shale	9	0	0
Shale	889	99	0
Shaly Clay	10	2	0
Silt	15	1	0
Siltstone	24	0	0
Silty Clay & Silty	15	15	0
SM	4	1	0
SP	2	2	0

3.6 Summary

This chapter explains the methods followed by TxDOT to document results obtained from various testing. The development of the database to compile the TCP and geotechnical data collected from different TxDOT districts for the present research is explained. The prominent features of the software developed to extract data from the Wincore files and then store them in Microsoft excel files are presented. Finally, details of data collected from Dallas and Fort Worth districts are provided.

CHAPTER 4

DATA ANALYSIS, RESULTS AND DISCUSSION: SOIL CLASSIFICATION

4.1 Introduction

Statistical analysis of data collected from the Dallas and Fort Worth districts of TxDOT are described in this chapter. The use of TCP data for possible soil classification is discussed. Four approaches used to statistically analyze the data for possible soil classification and these results are described here.

4.2 Soil Classification

Results from the TCP tests are currently being used to predict the allowable shear strength values of soils for design purposes. The primary objective of the research was to develop new and improved correlations between the TCP N value and undrained shear strength. To perform this study, large volumes of data starting from early 1994 to the latest available were collected from Dallas and Fort Worth districts of TxDOT. The data collected from these two districts contained a considerable amount of soils which were either not classified or under-classified (instead of classifying them as CL or CH, they are classified as clay).

A total of 15,340 data points were collected from the Dallas district, and 16.6% of those were found to be broadly classified. Of the 5859 data points collected from Fort Worth, 17% of data were broadly classified. Several of these data points contained undrained shear strength data pertaining to these broadly classified soils. The soils relating to these data points required further classification so that the data could be used in the correlation development to predict undrained shear strength. This necessitated the classification of these soils. Hence, an attempt is made here to first study the classification of soils based on TCP data. It should be noted here that no such classification in the literature were either attempted or performed using TCP's N values.

During the TCP test, the number of blows for the first six inches (N1) and the second six inches (N2) are recorded separately. This number indirectly indicates the type of soil encountered in exploration (Geotechnical Manual, 2000). Summation of N1 and N2 gives the total number of blows required for 12 inches (N12). In granular materials, the number of blows for the second increment is significantly greater than the first, whereas in clays, the number of blows for N1 and N2 is generally about the same (Geotechnical Manual, 2000).

Other than basic or simple identification of soil types, classification of soils into various USCS symbols including CL or CH required additional laboratory basic testing including particle size information and Atterberg limits. Since only TCP values are available, no attempt is made to include these additional parameters in the present classification methods. An attempt was first made to group TCP N values into four major soil classification categories. These four soil types and their basic properties are shown in Table 4.1.

Table 4.1 Typical Soil Properties of Natural Clay
(TxDOT Geotechnical Manual, 2000)

Category	Soil Type
CL	High plasticity clays, LL≥50
CH	Low plasticity clays and silt clay mixtures, LL<50
SC	Sand-Clay mixtures
OTHER	All other soils and rocks

4.3 Data Analysis for Soil Classification

The collected data that has classification results from both districts were grouped into four major categories as shown in Table 4.1. Then, this data was used to study the possibility of classifying them based on TCP N values. In an effort to determine the best and most reliable procedure to classify the soils, the following four statistical approaches were followed. These were:

1. Best linear fit lines through the TCP data
2. Linear fit lines passing through the data and the origin
3. 95% Confidence interval level based on N1 and N2
4. 95% Confidence interval based on the ratio of N2/N1 and depth

Results from each approach for both districts are presented here.

Tables 4.2 present TCP data points used in this research.

Table 4.2 Data Points Used from Dallas and Fort Worth Districts

District	Soil Type	Data Points
Dallas	CL	1435
	CH	451
	SC	950
	OTHERS	882
Fort Worth	CL	1936
	CH	677
	SC	1018
	OTHERS	9154

After analysis, it was found that less than 10% of the N12 values of CL and CH soils had a blow count of more than 100. Currently, the TCP test results are primarily being used to determine the allowable shear values for design purposes, and TxDOT discarded N12 values more than 100 for the determination of shear strength in their design projects since such high blow counts indicate a strong soil in the ground.

4.3.1 Approach 1 - Best Linear Fit Lines

An XY scatter plot between N1 and N2 was plotted for each of the four types of soils. To differentiate between the four types of soils, four different approaches explained earlier were chosen to represent each type of soil.

Linear trend lines which best fit the data points for each type of soil as per Approach 1 were plotted on the scatter plot. Different patterns were used to represent the trend lines corresponding to the four soil types. The results of best fit linear trend lines for each soil type from the Dallas and Fort Worth districts are presented in Figures 4.1 and 4.2, respectively. The equations and the coefficient of determination (R^2) of the trend lines for four soil types are shown in Tables 4.3 and 4.4. No noticeable difference in trend lines can be noted between these four soils from Dallas district (Figure 4.1). It should be noted from Table 4.3 that there is no significant difference in the values slopes amongst the trend lines for CL and CH soils.

The results of best linear fit lines of Approach 1 for the Fort Worth district showed slightly visual variations in trend lines among four soil types, which is slightly better than those noted for Dallas district soils. The variations in slopes were, however, too small to make a conclusive and precise soil classification. Further examination of this data showed that majority of soil data were located or plotted in the overlapping zones among different soil types. Hence, this approach of using linear best fit lines through N1 and N2 results did not result in tangible methods for soil classification.

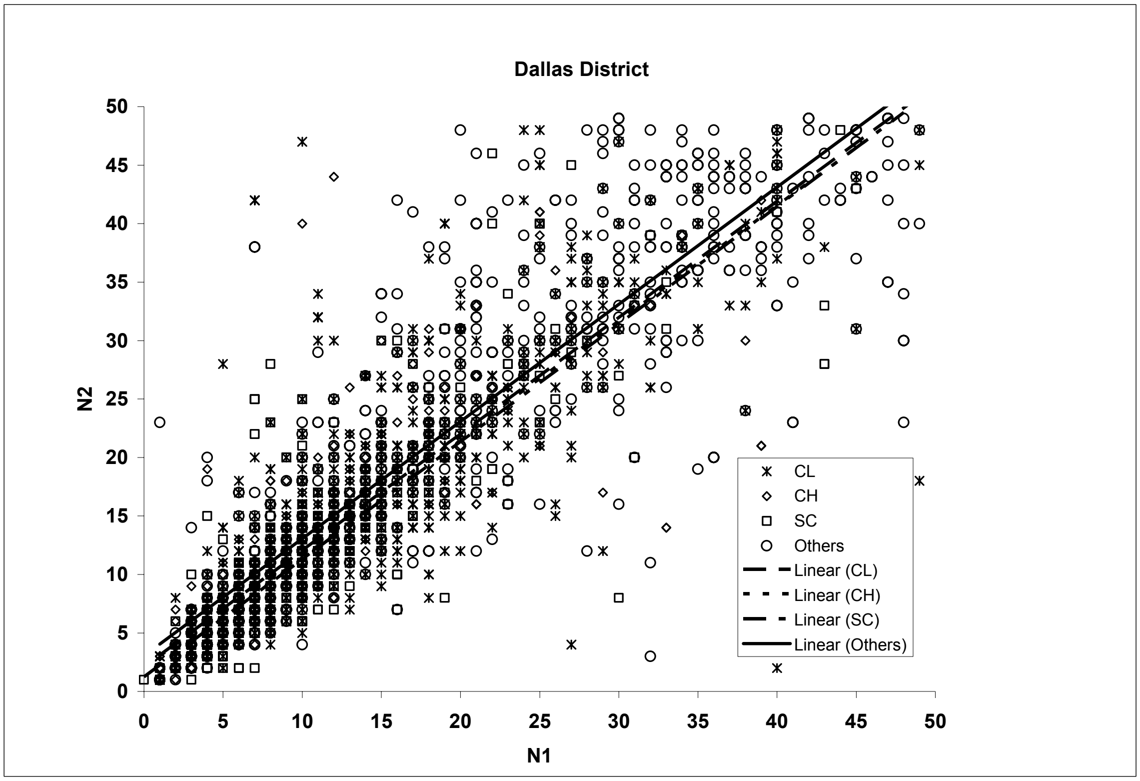

Figure 4.1 Best Fit Linear Lines for Four Types of Soils – Dallas District

Table 4.3 Equations and R^2 for Best Fit Linear Lines – Dallas District

Soil Type	Equation	R^2
CL	N2 = 0.99 × N1 + 2.12	0.76
CH	N2 = 0.99 × N1 + 2.02	0.71
SC	N2 = 1.01 × N1 + 1.24	0.77
OTHERS	N2 = 1.00 × N1 + 3.05	0.80

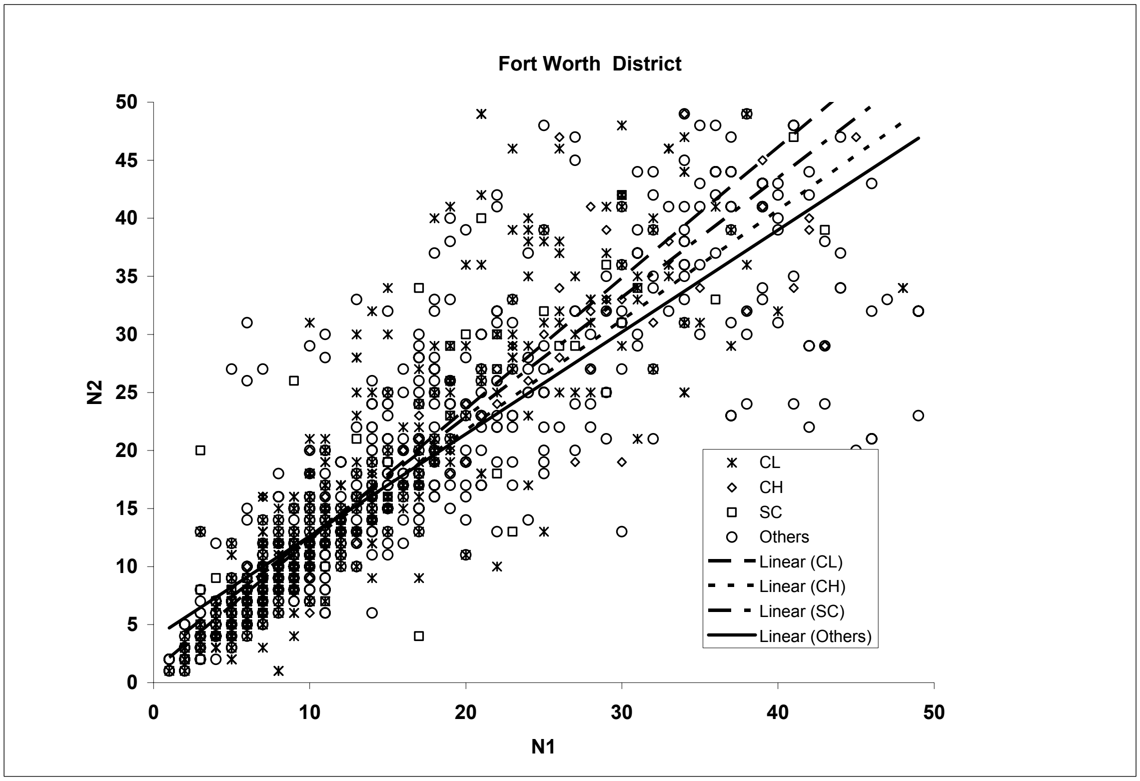

Figure 4.2 Best Fit Linear Lines for Four Types of Soils – Fort Worth District

Table 4.4 Equations and R^2 for Best Fit Linear Lines – Fort Worth District

Soil Type	Equation	R^2
CL	N2 = 1.13 × N1 + 1.03	0.80
CH	N2 = 0.95 × N1 + 2.78	0.82
SC	N2 = 1.03 × N1 + 2.25	0.79
OTHERS	N2 = 0.88 × N1 + 3.83	0.73

4.3.2 Approach 2 - Linear Fit Lines Passing Through Origin

Linear trend lines for each type of soil passing through the origin of each soil type were followed on the same data. Figures 4.3 and 4.4 present Approach 2 analyses results for Dallas and Fort Worth soils, respectively. The derived equations and R^2 values are shown in Tables 4.5 and 4.6 respectively.

Similar classification problems were encountered in this approach as the best fit lines passing through origin of four soil types have similar slopes for both districts, though slightly different for Fort Worth district soils. This slight difference does not lead to any classification of these soils. This implies that majority of the present results overlapped each other for various soil types, making this approach ineffective to use for soil classification.

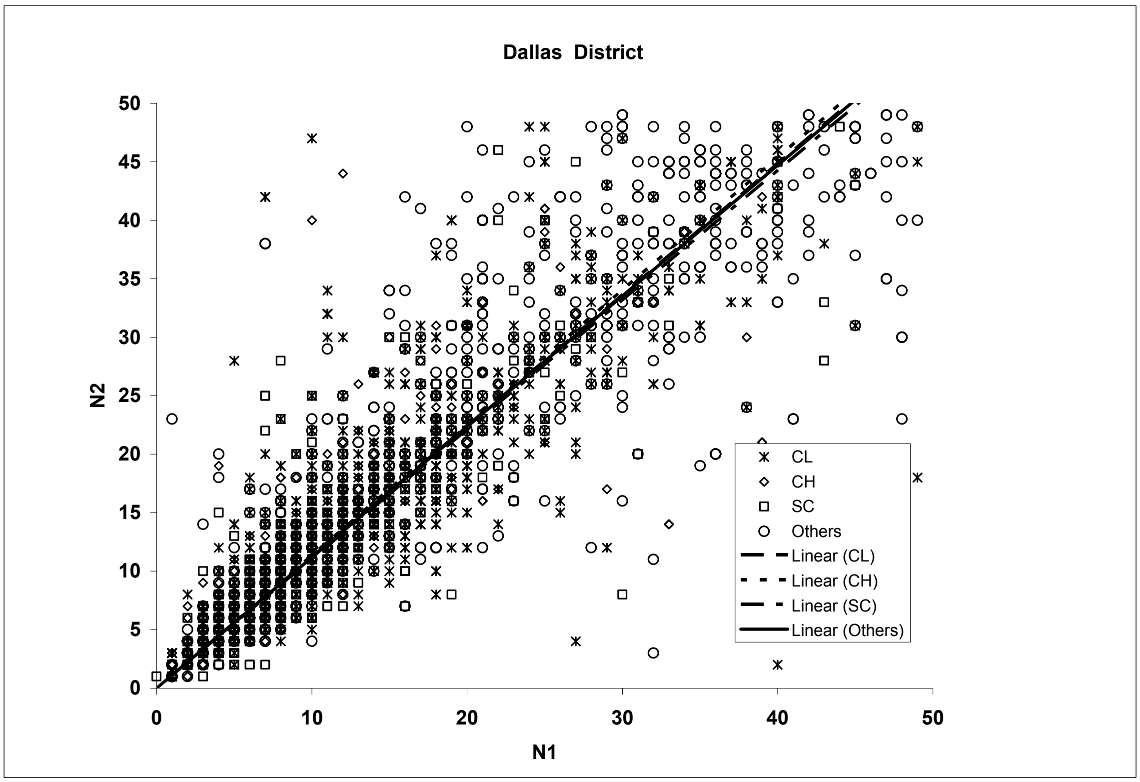

Figure 4.3 Linear Fit Lines from the Origin for Four Types of Soils – Dallas District

Table 4.5 Equations and R^2 for Linear Fit Lines from the Origin - Dallas District

Soil Type	Equation	R^2
CL	N2 = 1.12 × N1	0.74
CH	N2 = 1.13 × N1	0.68

Table 4.5 – *Continued*

SC	N2 = 1.11 × N1	0.76
OTHERS	N2 = 1.12 × N1	0.79

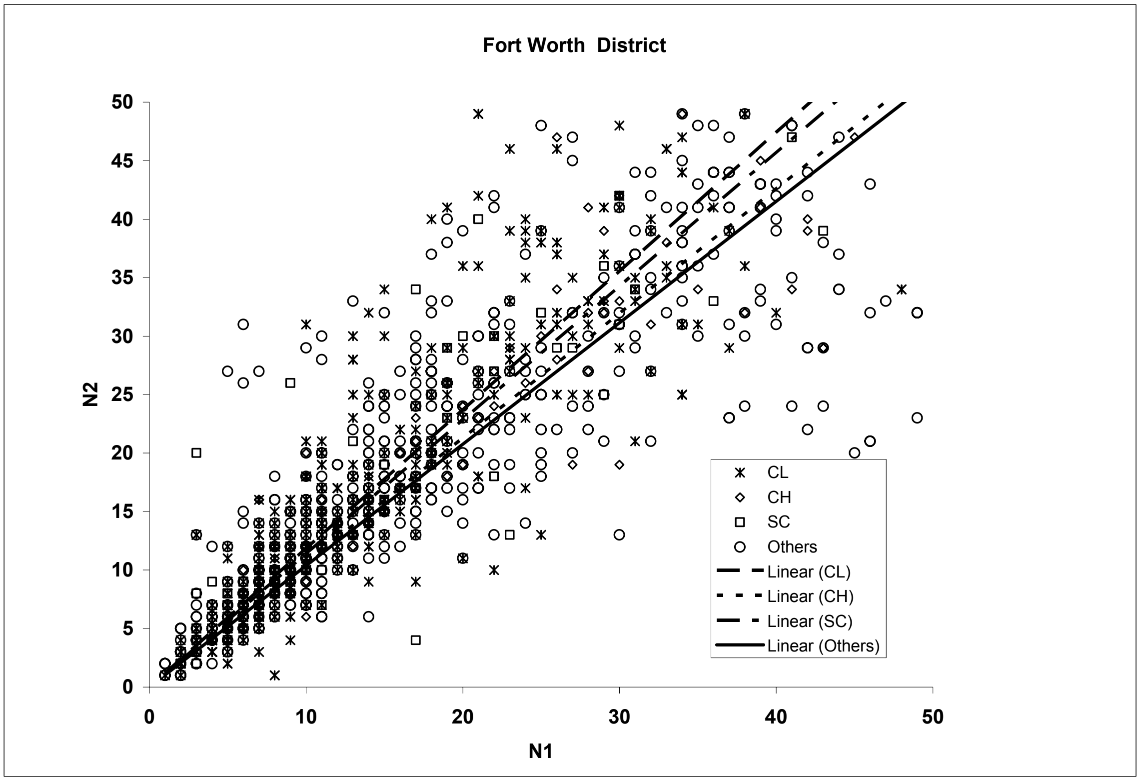

Figure 4.4 Linear Fit Lines from the Origin for Four Types of Soils – Fort Worth District

Table 4.6 Equations and R^2 for Linear Fit Lines from the Origin – Fort Worth District

Soil Type	**Equation**	**R^2**
CL	N2 = 1.19 × N1	0.80
CH	N2 = 1.06 × N1	0.80
SC	N2 = 1.14 × N1	0.77
OTHERS	N2 = 1.04 × N1	0.69

The use of the number of blows for the first six inches (N1), and the number of blows for the second six inches (N2) did not yield methods for soil classification. Two other statistical analyses utilizing 95% of confidence interval were used to study the possibility of using different forms of TCP data to classify the soils.

4.3.3 Approach 3 - 95% Confidence Interval Based on N1 and N2

This third approach was used to address the possibility to classify the soils based on N1 and N2 values from the TCP tests. Figure 4.5 and Table 4.7 present the results of this approach from the Dallas district. The N1 values were split into four groups based on the N1 values and the following criteria:

- $0 \leq N1 \leq 10$
- $10 < N1 \leq 20$
- $20 < N1 \leq 30$
- $30 < N1 \leq 50$

The mean and standard deviation of the corresponding N2 values was calculated for the four soils irrespective of their blow count numbers. The outliers were eliminated (those that lie beyond mean $\pm$ 1 standard deviation). The number of data points used after the outliers were eliminated has been presented in Table 4.7. The upper and lower limit 95% confidence interval was calculated from the mean and standard deviation results based on the following:

- 95% Upper limit confidence interval = Mean + 2 • SD
- 95% Lower limit confidence interval = Mean – 2 • SD

The results for all types of soils were plotted in an XY scatter chart with smooth lines representing mean, upper and lower limit confidence intervals (Figure 4.5). This approach, as in the case of previous two approaches, followed similar trends with minor difference among soil types. The bands representing different soil groups also overlapped each other, and hence making it impractical to classify soils.

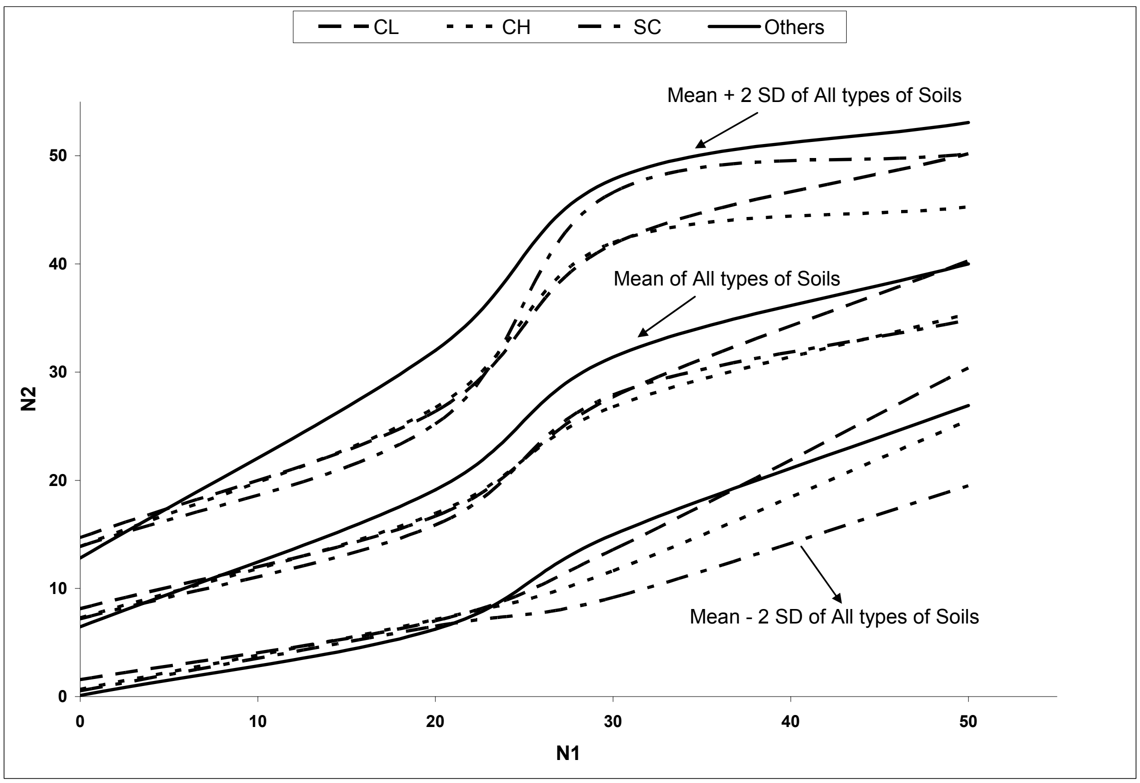

Figure 4.5 95% Confidence Interval of Four Types of Soils Based on N1 and N2-Dallas District

Same approach was followed for Fort Worth district soils, and their results are presented in Table 4.8, and graphically represented in Figure 4.6. The results produced noticeably similar trends as the Dallas district with little or no significant difference amongst the soil groups. This reconfirms the limitations of this approach to develop soil classification strategy based on N1 and N2 values.

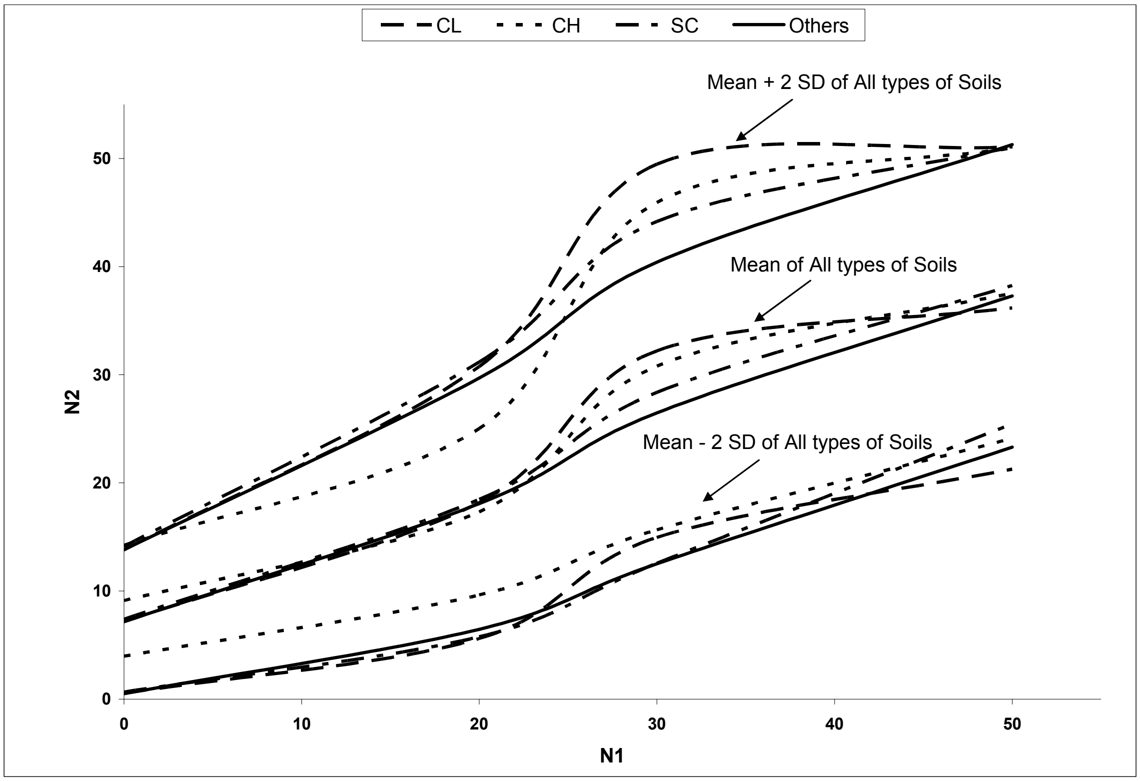

Figure 4.6 95% Confidence Interval of Four Types of Soils Based on N1 and N2-Fort Worth District

Table 4.7 Mean and Standard Deviation of N2 for Corresponding N1 – Dallas District

Soil Type	N1	Data Points	Mean of N2	SD of N2	Mean + 2 • SD	Mean – 2 • SD
CL	**0 to 10**	845	8.13	3.28	1.56	14.70
	11 to 20	421	16.68	4.85	6.99	26.37
	21 to 30	105	27.69	7.06	13.57	41.81
	31 to 50	80	40.29	4.95	30.39	50.19
CH	**0 to 10**	311	7.27	3.30	0.66	13.87
	11 to 20	96	16.93	4.90	7.12	26.73
	21 to 30	20	26.79	7.58	11.62	41.96
	31 to 50	12	35.40	4.93	25.54	45.26
SC	**0 to 10**	752	7.20	3.33	0.55	13.85
	11 to 20	142	15.85	4.67	6.51	25.20
	21 to 30	26	27.89	9.36	9.17	46.61
	31 to 50	11	34.83	7.67	19.49	50.18
OTHERS	**0 to 10**	331	6.46	3.18	0.11	12.81
	11 to 20	201	19.12	6.44	6.24	32.00
	21 to 30	141	31.39	8.21	14.98	47.81
	31 to 50	159	40.00	6.54	26.92	53.08

Table 4.8 Mean and Standard Deviation of N2 for Corresponding N1 – Fort Worth District

Soil Type	N1	Data Points	Mean of N2	SD of N2	Mean + 2 • SD	Mean - 2 • SD
CL	0 to 10	347	7.17	3.31	0.54	13.80
	11 to 20	118	18.18	6.29	5.60	30.75
	21 to 30	55	32.20	8.63	14.94	49.46
	31 to 50	28	36.17	7.45	21.26	51.08
CH	0 to 10	42	9.10	2.56	3.97	14.22
	11 to 20	30	17.32	3.85	9.62	25.02
	21 to 30	18	30.79	7.57	15.65	45.93
	31 to 50	12	37.54	6.72	24.11	50.97
SC	0 to 10	39	7.38	3.37	0.65	14.12
	11 to 20	16	18.47	6.36	5.76	31.18
	21 to 30	10	28.36	7.90	12.56	44.17
	31 to 50	3	38.25	6.40	25.46	51.04
OTHERS	0 to 10	231	7.17	3.33	0.51	13.83
	11 to 20	193	18.08	5.81	6.46	29.70
	21 to 30	69	26.47	6.97	12.52	40.42
	31 to 50	84	37.29	6.99	23.31	51.28

4.3.4 Approach 4 - 95% Confidence Interval Based on the Ratio of N2/N1 and Depth

The final approach (approach 4) used a totally different one, as this approach used the ratios of N1 and N2 values and depth to classify soils. In the Dallas district, depth information was grouped into five categories based on the following criterion:

- $0 \leq \text{Depth} \leq 10$
- $10 < \text{Depth} \leq 30$
- $30 < \text{Depth} \leq 50$
- $50 < \text{Depth} \leq 70$
- $\text{Depth} > 70$

After eliminating outliers (those that lie beyond mean ± 1 standard deviation), the ratios of N2/N1 were calculated with the rest of the data in each group. It was expected that different soil types would lead to a different and unique N2/N1 ratio, and a confidence interval could be developed based on this property. The total number of data points used in the analysis is presented in Table 4.9. Mean and standard deviations of the N2/N1 ratios were calculated and presented in the same table. Both upper and lower limits of 95% confidence intervals were calculated from the mean and standard deviation based on the following criterion:

- 95% Upper limit confidence interval = Mean + 2 • SD
- 95% Lower limit confidence interval = Mean – 2 • SD

The results were plotted in a line graph with markers representing mean, upper and lower limits of each soil type. These results of Dallas district are presented in Table 4.9 and Figure 4.7. This method also followed similar trends with no major differences in ratios among the present four soil types (CL, CH, SC and others). The mean and standard deviation of N2/N1 ratios at different depths were similar for all soils.

A similar procedure with a slight variation in depth was followed to analyze the data from Fort Worth district. The geological formation in Fort Worth district was hard and rocky at shallow depths when compared to Dallas district. This resulted in shallower bore holes and lesser data at greater depths. In Fort Worth, the analysis depth was separated into three categories based on the following criteria:

- $0 \le$ Depth ≤ 10
- $11 <$ Depth ≤ 30
- Depth > 30

The results from Fort Worth district are presented in Figure 4.8 and Table 4.10. The results produced noticeably similar trends as the Dallas district with little or no significant difference in N2/N1 ratios amongst the soil groups. This implies that this final approach also results in no method to classify the soils based on TCP N values.

Several reasons could be attributed to this phenomenon. Large scatter in soils for the same depth, mean results being same for each soil type and the empirical nature of this analysis, and use of TCP parameters alone make it impractical to use the present approach to classify subsoils.

Table 4.9 Mean and Standard Deviation of N2/N1 Ratios at Different Depths – Dallas District

Soil Type	Analysis Depth	Data Points	Mean of N2/N1	SD of N2/N1	Mean + 2 • SD	Mean – 2 • SD
CL	**0 to 10**	756	1.23	0.38	1.99	0.46
	11 to 30	566	1.24	0.36	1.96	0.52
	31 to 50	83	1.22	0.20	1.63	0.82
	51 to 70	15	1.36	0.37	2.11	0.61
	> 70	6	1.27	0.19	1.64	0.90
CH	**0 to 10**	217	1.23	0.48	2.19	0.27
	11 to 30	141	1.31	0.42	2.15	0.47
	31 to 50	41	1.31	0.33	1.98	0.65
	51 to 70	26	1.29	0.27	1.83	0.75
	> 70	18	1.32	0.47	2.26	0.38
SC	**0 to 10**	486	1.17	0.38	1.93	0.41
	11 to 30	366	1.21	0.33	1.87	0.56
	31 to 50	63	1.25	0.39	2.03	0.47
	51 to 70	8	1.24	0.32	1.89	0.59
	> 70	10	1.21	0.22	1.65	0.76
Other Soils	**0 to 10**	294	1.24	0.49	2.22	0.25
	11 to 30	312	1.24	0.34	1.93	0.55
	31 to 50	193	1.35	0.62	2.58	0.12
	51 to 70	48	1.20	0.32	1.84	0.55
	> 70	34	1.17	0.33	1.83	0.51

Table 4.10 Mean and Standard Deviation of N2/N1 Ratios at Different Depths – Fort Worth District

Soil Type	Analysis Depth	Data Points	Mean of N2/N1	SD of N2/N1	Mean + 2 • SD	Mean – 2 • SD
CL	0 to 10	285	1.23	0.38	2.00	0.47
	11 to 30	230	1.21	0.29	1.79	0.62
	> 30	46	1.24	0.36	1.96	0.53
CH	0 to 10	45	1.22	0.38	1.98	0.46
	11 to 30	54	1.12	0.23	1.57	0.67
	> 30	10	1.06	0.22	1.51	0.61
SC	0 to 10	47	1.24	0.40	2.03	0.44
	11 to 30	21	1.28	0.48	2.23	0.32
	> 30	7	1.16	0.24	1.63	0.68
Other Soils	0 to 10	221	1.18	0.48	2.14	0.22
	11 to 30	253	1.23	0.44	2.11	0.35
	> 30	131	1.21	0.54	2.28	0.14

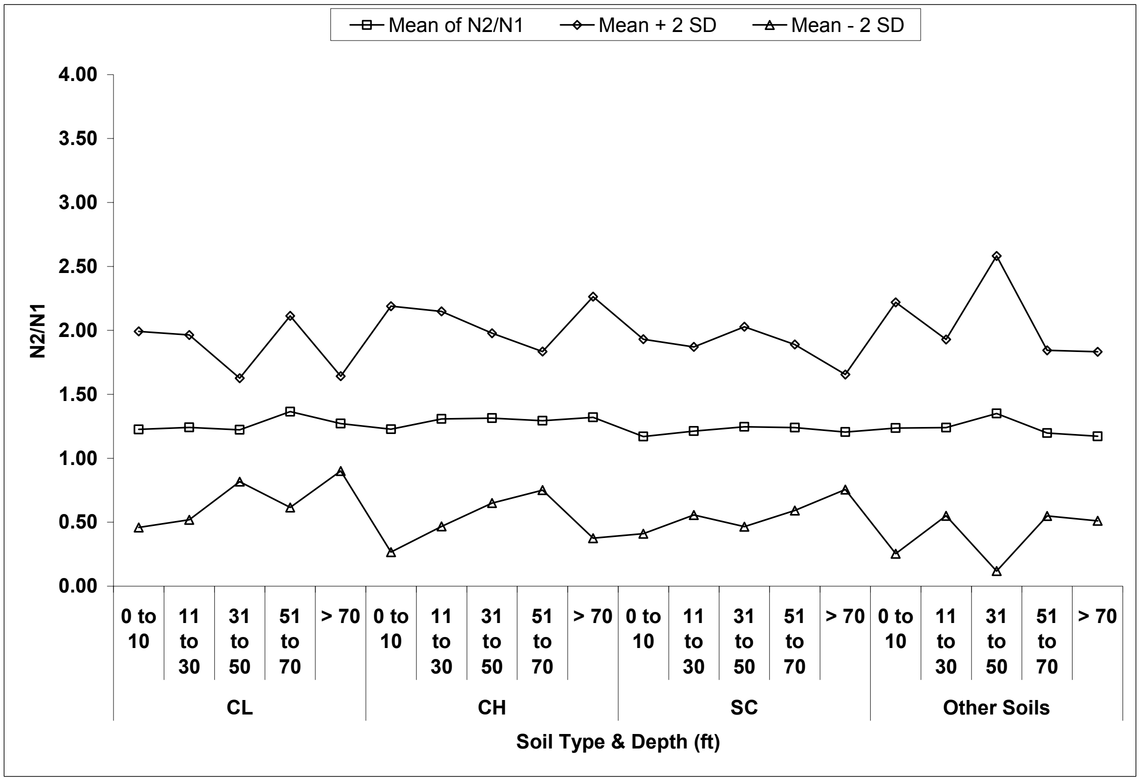

Figure 4.7 95% Confidence Interval Based on N2/N1 Ratios at Different Depths – Dallas District

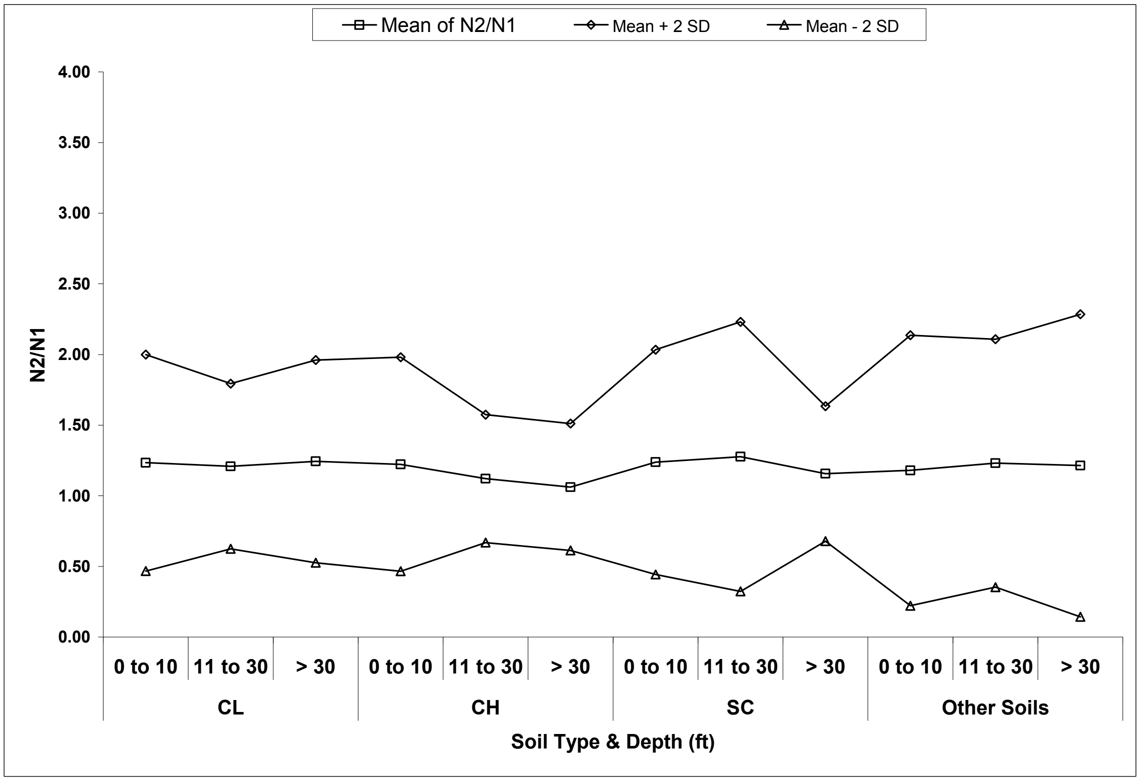

Figure 4.8 95% Confidence Interval Based on N2/N1 Ratios at Different Depths – Fort Worth District

4.4 Soil Classification - Summary

Four approaches were followed to analyze data for possible soil classification using TCP test values. All variables, including N2/N1 ratios and depth information have been considered. In most cases, little or no significant difference was noted amongst the present four soils. Hence, none of these approaches could confidently be used to classify soils into four major categories.

CHAPTER 5
DATA ANALYSIS, RESULTS AND DISCUSSION:
SHEAR STRENGTH CORRELATIONS

5.1 Introduction

In this chapter, efforts are made to evaluate existing correlations currently used by TxDOT to predict the shear strength. Limitations in these existing correlations are explained. An attempt is then made to develop new and localized correlations for Dallas and Fort Worth districts. Three different methods are followed to develop improved statistical correlations to predict shear strength of soils using TCP N values. The effect of depth on the correlations to predict shear strength of soils has been explained by the correlations developed both with and without depth as an independent variable. In conclusion, evaluations of the newly developed correlations is performed, which resulted in a reasonably good correlation developed between undrained shear strength and Texas cone resistance to penetration, N12, values for CL and CH soils of both Dallas and Fort Worth districts.

5.2 TCP and Shear Strength

Geotechnical engineers consider shear strength as one of the most important engineering properties of soils (Schmertmann, 1975). The load-carrying capacity of soils is usually dependent on the shear strength of soil and

Hence this strength parameter is used in both foundation and geotechnical designs. In the laboratory, the shear strength of soils can be determined by various methods including triaxial, direct shear and the UCS test method. Laboratory testing is conducted on undisturbed samples obtained during foundation exploration.

Shear strength test results obtained from laboratory tests usually underestimate soil strength due to disturbances to soil samples during sampling and difficulties in the simulation of natural field environment (Geotechnical Manual, 2000). Hence, foundation capacities determined using the present bearing capacity models is usually conservative (Schmertmann, 1975). The in situ shear strength of soils is usually needed or recommended during geotechnical investigations or during early stages of construction projects in order to better assess or characterize site conditions for designing foundation systems for infrastructure.

TxDOT currently uses Texas triaxial test method (Tex-118-E) to determine undrained shear strength of soils in the laboratory conditions. However, as explained earlier, during routine subsurface investigations, laboratory tests for determining the soil shear strength are often unrealistic, expensive and time consuming. The strength test results are sometimes on high side, which may result in premature failures of the civil infrastructure. Hence, TxDOT primarily uses the TCP test (Tex-132-E) method as the primary means to predict the in situ shear strength of soils required in the design of deep foundations.

The TCP test (Tex-132-E) is an in situ test that has been calibrated over the years and its consistency has been well established. TCP tests are routinely performed by TxDOT to determine the allowable shear strength values for design purposes. This test uses empirical correlations to predict strength properties of soils. The TCP test does not require consideration of groundwater to predict the strength properties of soils since it is conducted in the ground (in situ) (Geotechnical Manual, 2000).

TxDOT currently uses a chart shown in Figure 2.7 or Table 2.9 of Chapter 2 to predict undrained shear strength or cohesion of soils using TCP N-values. The chart is designed to predict ½ shear strength, i.e., with a safety factor of 2 incorporated in it. In this chart, the TCP values may be used without any correction to determine the undrained shear strength. In the present study, shear strength predicted by the current TxDOT geotechnical manual method is represented by (C_{PO}).

In this research, an attempt was made to first evaluate the existing method and then develop new correlations between TCP N values and shear strength of soils. Three new models (C_{P1}, C_{P2}, C_{P3}) were attempted here to develop these improved correlations. All three models were evaluated and based on these results, one model was recommended for future usage.

The chart currently used by TxDOT is designed to predict ½ the shear strength of soils, by including a factor of safety on soil strength measurements. The measured undrained shear strength (C_m) parameter from Texas triaxial tests represents the ultimate or full shear strength. In order to bring uniformity to these undrained shear strengths used in both measurement and prediction methods, the undrained shear strength predicted by the existing TxDOT geotechnical method (C_{PO}) has been multiplied by 2 to represent the ultimate or full undrained shear strength, which is equivalent to the measured shear strength of clays.

5.3 Data Analysis for Shear Strength Correlations

As mentioned earlier, large volumes of TCP and laboratory strength data were collected from both Dallas and Fort Worth TxDOT district offices. Tables 5.1 and 5.2 present the total number of data points collected from each of these districts for shear strength analysis. Total numbers of N12 data from the TCP test and corresponding measured shear strength (C_m) from the Texas triaxial tests of each of these districts have also been presented in these tables.

Undrained shear strength data required to conduct statistical analysis was available only for CL and CH soils from the Dallas district, and Clay (CL and CH) from the Fort Worth district. Clays from the Fort Worth district were not classified into CL or CH groups. Therefore, in this study, statistical analysis was performed separately for CL and CH soils from Dallas district and for combined ‘Clay’ (CL and CH are grouped) from Fort Worth district.

Expansive clays found in the Dallas - Fort Worth region are over-consolidated in nature. Map showing the geology of DFW is shown in Figure 5.1. Different colors in the map represent various geological formations in the metroplex region. Extensive legend of different colors in this map is provided in Appendix D.

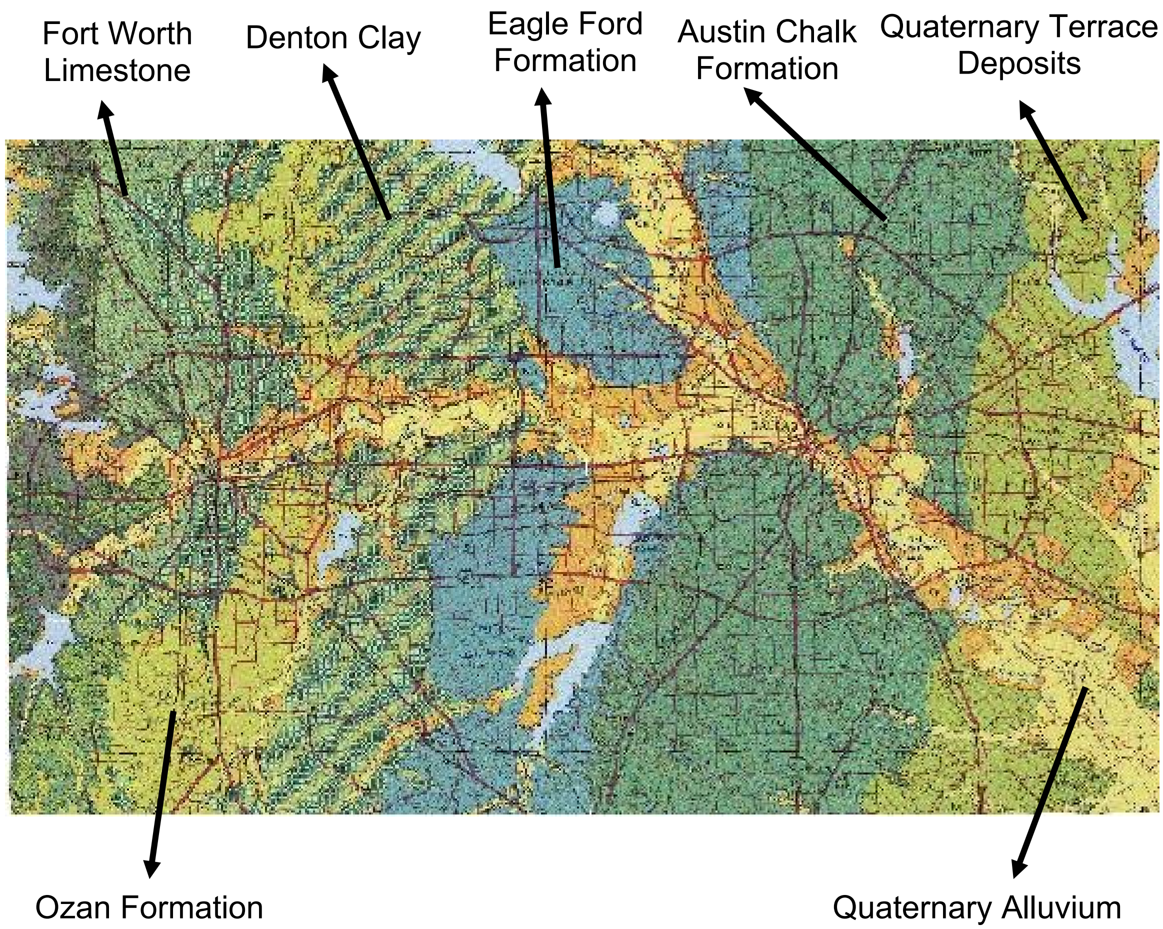

Figure 5.1 Map Showing Geology of DFW (TCEQ, 2004)

It is apparent that the geology of Dallas region is different from Fort Worth region. Hence, to understand the effects of geological variations on undrained shear strength, the current correlation used by the TxDOT is evaluated for Dallas and Fort Worth districts, separately. Also, attempts to develop new correlations are confined to both districts' soils in separate form.

5.4 Factors Affecting Resistance to Penetration, N

The relationship between undrained shear strength and resistance to penetration, N, is not always constant. Hence, it is necessary to discuss a few factors affecting these parameters before any attempt to develop new correlations.

The ease with which the cone penetrates the subsoil is represented by the magnitude of the N value. Hamoudi et al. (1974) reported that the moving of a cone penetrometer created a cavity, which moves in both lateral and upward directions. The extent of these movements is probably dependent upon soil type, degree of compactness, overburden pressure, and degree of saturation (Hamoudi et al., 1974). Desai (1970) reported that the upward displacement of subsoil will occur until a certain depth or surcharge pressure is reached which will no longer permit such displacement. At depths, where the upward displacement becomes small, the lateral displacement will form an important part of the total displacement (Desai, 1970).

In impervious and saturated cohesive soils below water table, the resistance to penetration of the cone is mostly attributed to its skin friction and resistance of pore water (Sanglerat, 1972). Desai (1972) and Sengupta and Aggarwal (1966) reported that the friction was appreciable in loose sands and all types of clay soils as well as those in stratified deposits. The diameter of the cone used in the studies by Desai (1972), Sengupta and Aggarwal (1966) was either equal to or smaller than the drill pipe that was attached to the cone. The

TCP cone is larger in diameter than the drill pipe to which it is attached (Hamoudi et al., 1974). This can be seen in Figures 2.2, 2.3 and 2.5 of Chapter 2. Therefore, the side contact area is relatively small and the side friction is likely to be small when compared to the point resistance (Hamoudi et al., 1974).

Based on all these factors, it would be appropriate to correct the N-values obtained from TCP for depth and soil type effects. Further, the factors which affect the N-value are obviously inter-related, and it is difficult, if not impossible, to isolate a single, most important factor (Hamoudi et al., 1974).

5.5 Evaluation of Existing Correlations for TCP

The correlations currently used by TxDOT to predict the undrained shear strength are evaluated in the following sections.

5.5.1 Dallas District

Comparisons between the resistance to penetration for 12 inches (N12) and measured undrained shear strength (C_m) at various depths for CL and CH soils from the Dallas district are presented in Figures 5.2 and 5.3. The geotechnical manual currently does not include depth as a parameter to predict the undrained shear strength of soils. Depth was, however, included as a parameter in this scatter chart to observe any noticeable difference in predicted shear strength values at various depths. In this scatter chart, the predicted shear strength at different depths is represented by a unique pattern. Further, the existing geotechnical manual line which predicts the undrained shear strength of CL and CH soils has been multiplied by 2 and included in these plots.

It can be interpreted from these charts that the present TxDOT method to predict the undrained shear strength underestimates the shear strength in most cases. However, in a few cases, the geotechnical manual method also overestimates the undrained shear strength. From these plots it is clear that the current geotechnical manual method is not the most realistic representation of the shear strength of soils from Dallas district.

Table 5.1 Data Points Used for the Study from Dallas District

Soil Type	N12	Measured Shear Strength (C_m) With N12 Match
CL	1496	55
CH	461	12
SC	952	4
OTHERS	1130	3

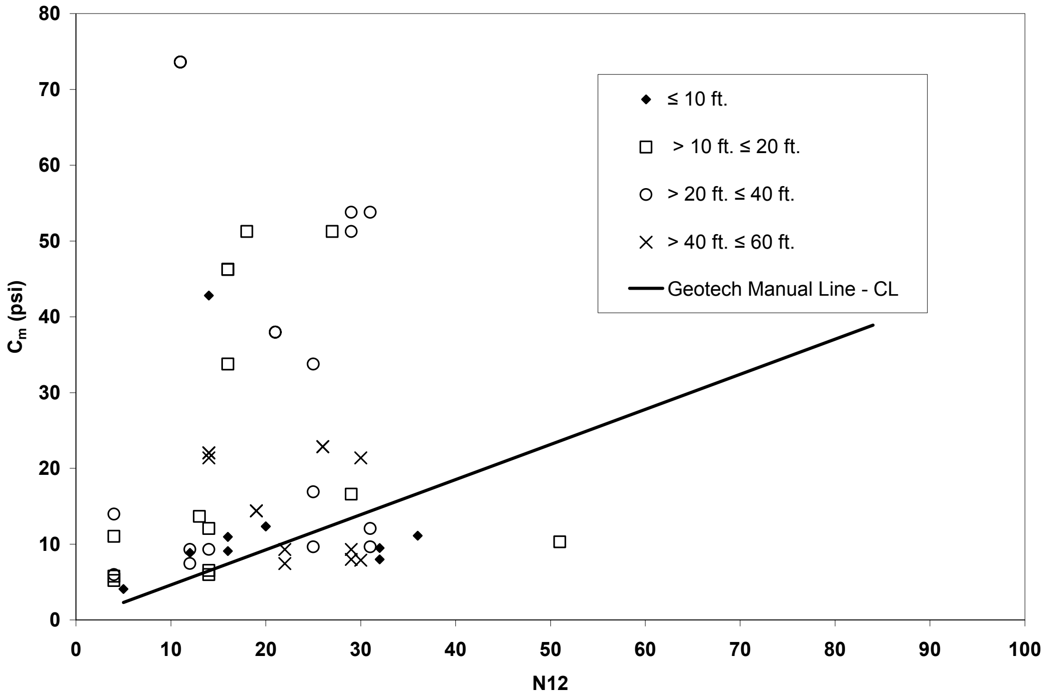

Figure 5.2 Measured Shear Strength (C_m) and N12 at Each Depth for CL – Dallas District

Table 5.2 Data Points Used for the Study from Fort Worth District

Soil Type	**N12**	**Measured Shear Strength (C_m) With N12 Match**
CL	597	0
CH	119	0
SC	83	0
OTHERS	749	0
Broadly Classified	830	10

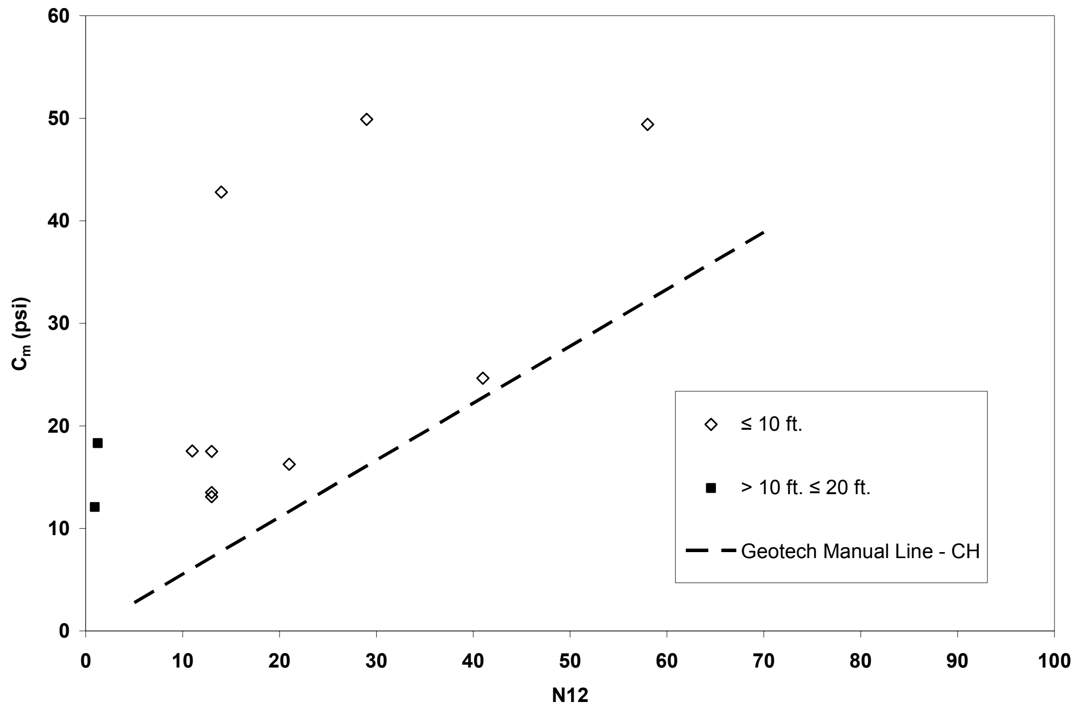

Figure 5.3 Measured Shear Strength (C_m) and N12 at Each Depth for CH – Dallas District

5.5.2 Fort Worth District

No shear strength data from the Texas triaxial testing was available for either CL or CH soil types separately. Since the attempt to classify the soils based on N1 and N2 values proved futile, an effort has been made to develop correlations for clays (combining CL and CH) from the Fort Worth district. Comparisons between the resistance to penetration for 12 inches, N12 and measured undrained shear strength (C_m) at various depths for clay (CL and CH) soils from the Fort Worth district are presented in Figure 5.4. The current geotechnical manual predictions for full undrained shear strength of both CL and CH soils are also included in the same figure.

Assuming that the measured shear strength (C_m) values from the Texas triaxial tests are either CL or CH, it can be interpreted from these charts that the present TxDOT method overestimates the undrained shear strength in most cases for any of these two types of soil. Very few of the predicted shear strength values are close to the measured shear strength. Similar to the variation of the results from the Dallas district, the current geotechnical manual methods for CL and CH did not provide accurate representation of the undrained shear strength of soils Fort Worth district.

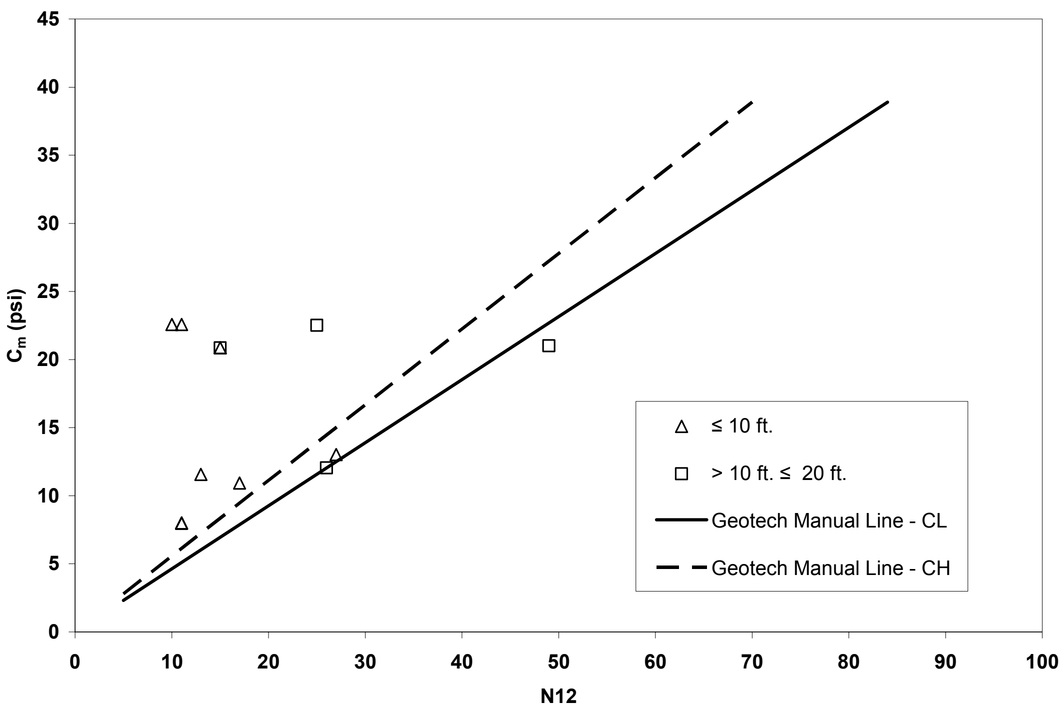

Figure 5.4 Measured Shear Strength (C_m) and N12 at Each Depth for CL and CH- Fort Worth District

The following sections describe the modeling of the present research utilizing the collected database.

5.6 TCP and Shear Strength Correlations without Depth – Model 1 (C_{P1})

It is well known that soil is a complex engineering material and the geological formations vary vertically and horizontally from region to region. This variation in soil properties can be attributed to various geologic, environmental, mineralogical, and chemical processes that take place during the formation of soil deposits. The in situ soil properties will also vary both vertically and horizontally due to depositional variations. Hence, the use of generalized correlations to predict soil properties like shear strength for soils of all geologic formations is not always possible should be dealt with caution. Where applicable, the use of local calibrations is preferred over broader and generalized correlations (Mayne and Kemper, 1984; Orchant et al., 1988; Kulhawy and Mayne, 1990).

For this reason, in the present research, an attempt has been made to develop localized correlations between TCP test parameters and undrained shear strength properties of soils of Dallas and Fort Worth districts.

5.6.1 Correlations without Depth (C_{P1}) - Dallas District

An XY scatter plot between N12 values and their corresponding measured shear strengths (C_m) was plotted for CL and CH soils. A linear trend line which best fit the data points was established for each type of soil. The best fit linear lines along with their equations and R^2 values for the two types of soils from the Dallas district are shown in Figures 5.5 and 5.6 respectively.

To represent the undrained shear strength predicted by the current TxDOT method, the geotechnical manual lines to predict the undrained shear strength (full shear strength) of CL and CH types of soils has been added to these scatter plots. This would also help to make any possible comparisons with correlation developed by model 1 in the present study. To differentiate between geotechnical manual lines for different soil types, different patterns were chosen to represent each soil type. Same patterns were used to represent CL and CH type of soils in the previous section of this chapter.

In the chart, it can be seen that the model 1 correlation (C_{P1}) for CL type soil was significantly higher than the existing geotechnical manual line to predict the undrained shear strength. Therefore, it can be interpreted that the current geotechnical manual method underestimates the shear strength for CL soils from Dallas district, implying that the measured shear strength is larger than the one predicted by TxDOT geotechnical manual. Moreover, the linear fit trend line showed a very poor coefficient of determination (R^2) value of 0.001. In a regression equation, the R^2 value measures the proportion of variation in Y that is best explained by the independent variable X (Berenson et al. 2002). In this correlation, the dependent variable Y is undrained shear strength and independent variable X is N12 values from TCP tests. A low value of 0.001

implies that the correlation is very poor at best. This very low value is explained by the large variability of N12 values used in the correlation development.

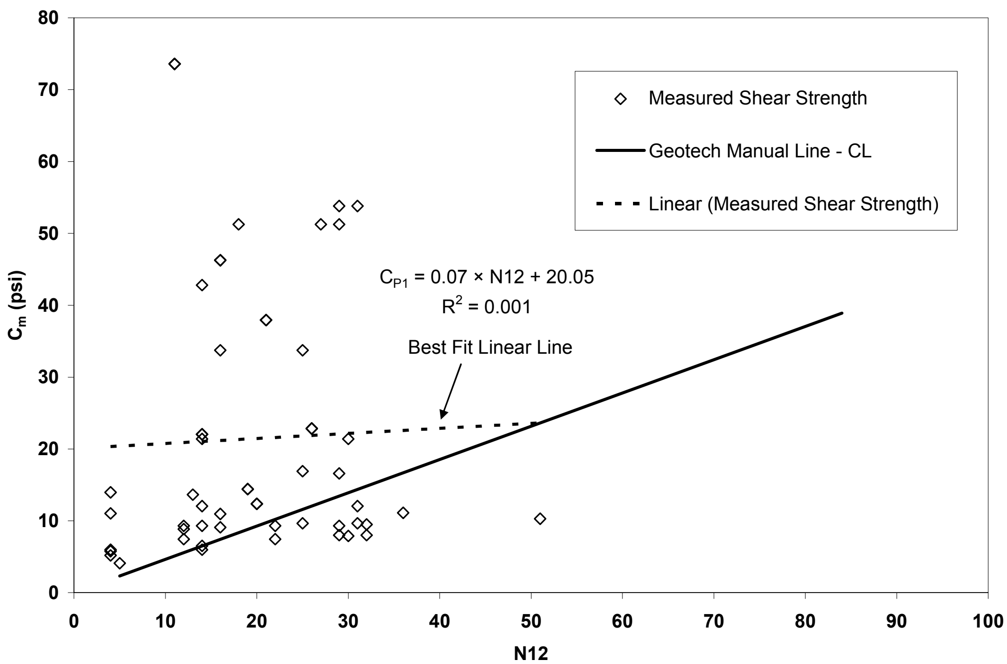

Figure 5.5 Best Fit Linear Line between Measured Shear Strength (C_m) and N12 for CL – Dallas District

The model 1 correlations (C_{P1}) for CH soils showed results similar to CL soils from Dallas district. The new correlation developed to predict the undrained shear strength was significantly higher than the existing geotechnical manual line. Though the model 1 correlations for CH soils showed an improved and better R^2 value of 0.32, it was still a low value with poor dependability. As a result, the correlation could not be used to predict shear strength of CH soils from Dallas district.

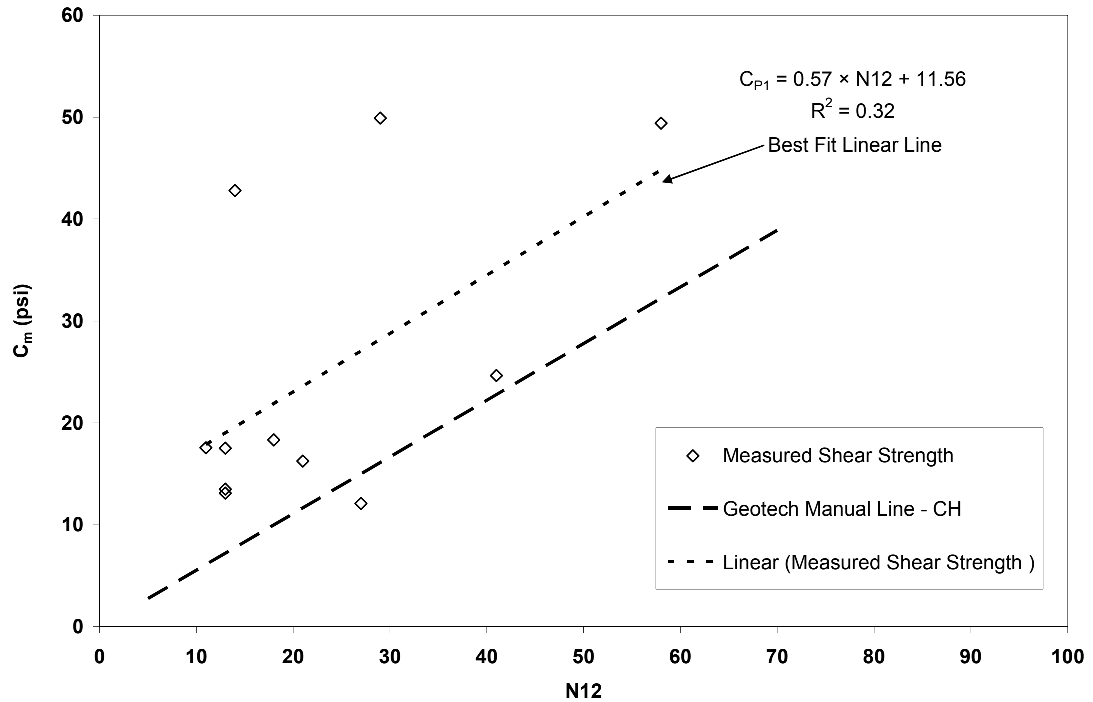

Figure 5.6 Best Fit Linear Line between Measured Shear Strength (C_m) and N12 for CH – Dallas District

5.6.2 Correlations without Depth (C_{P1}) - Fort Worth District

The Fort Worth district had no measured shear strength (C_m) data for either CL or CH soils, separately. Therefore, statistical analysis was performed on both soils grouped under broadly classified clay (i.e. without sub classification into CL and CH) from this district.

An XY scatter plot between N12 and measured sheared strength (C_m) expressed in pounds per square inch (psi) was plotted for CL and CH soils. A linear trend line which best fit the N12 values and undrained shear strength of soil was established in an attempt to develop model 1 correlations. The existing geotechnical manual line to predict the undrained shear strength of both CL and CH types of soils has been added to the chart in Figure 5.7.

Similar problems were encountered as the new best fit lines to predict the undrained shear strength for CL and CH soils have similar R^2 values for both districts, though slightly different for Fort Worth district. The model 1 correlations showed a very low R^2 value of 0.11 for soils from Fort Worth district.

Therefore, model 1 correlations developed to predict undrained shear strength (C_{P1}) using TCP N values showed poor results for soils from both districts. This implies that this method cannot be used to predict the undrained shear strength of soils using TCP test results. Hence, further attempts have been made to develop new model correlations. Models 2 and 3 are these new attempts to develop better correlations to predict undrained shear strength.

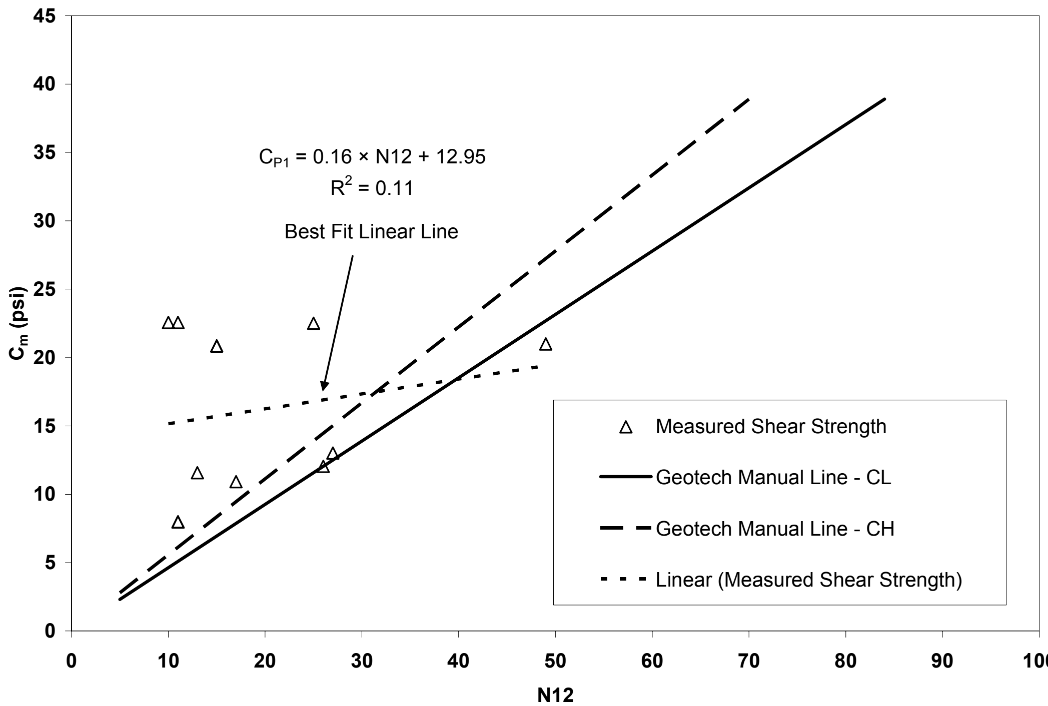

Figure 5.7 Best Fit Linear Line between Measured Shear Strength (C_m) and N12 for CL and CH – Fort Worth District

5.7 TCP and Shear Strength Correlations with Depth – Model 2 (C_{P2}) and Model 3 (C_{P3})

Figures 5.3 to 5.5 showed variations in measured shear strength (C_m) versus N12 values at different depths. From these figures, it can be interpreted that the undrained shear strength is not linearly varying against N12 values. These results seem to be influenced by the depths at which tests are conducted. The depth effects have not been accounted for in the current TxDOT geotechnical manual approach (C_{PO}). Hence, the two new models, models 2 and 3 are attempted to develop correlations to predict undrained shear strength as a function of both N12 and depth.

5.8 Correlations with Depth – Research Methodology

The first step in developing new correlations based on N12 and depth data was to place soils into different groups with similar properties. Based on inputs from TxDOT engineers and various consultants to TxDOT, a research methodology was developed to analyze the present data for the two soil types; CH and CH. Model 2 and Model 3 correlations were developed using multiple linear regression analysis. The equations were of the form:

$$C_{P2} \text{ or } C_{P3} = A_1 \pm (A_2 \times N12) \pm (A_3 \times D)$$

Where:

C_{P2} = Predicted Undrained shear strength using model 2 correlations and expressed in pounds per square inch (psi)

C_{P3} = Predicted Undrained shear strength using model 3 correlations and expressed in pounds per square inch (psi)

N12 = Number of blows/12” (≤100)

D = Depth in feet

A_1, A_2, A_3 = Multiple linear regression constants

Table 5.3 present the methodology developed to develop both Model 2 and Model 3 correlations.

Table 5.3 Method Developed to Analyze Data and Develop Equations

District	Soil Type	Depth (ft.)	N12	Model
Each TxDOT District	Each Soil Type	Entire Depth	All N12 Values	Model 2 (C_{P2})
		Depth ≤ 20	N12 ≤ 10	Model 3 (C_{P3})
			10 < N12 ≤ 15	
			15 < N12 ≤ 40	
			40 < N12 ≤ 70	
			70 < N12 ≤ 100	
		20 < Depth ≤ 40	N12 ≤ 10	
			10 < N12 ≤ 15	
			15 < N12 ≤ 40	
			40 < N12 ≤ 70	
			70 < N12 ≤ 100	
		40 < Depth ≤ 60	N12 ≤ 10	
			10 < N12 ≤ 20	
			20 < N12 ≤ 40	
			40 < N12 ≤ 70	
			70 < N12 ≤ 100	
		Depth > 60	N12 ≤ 10	
			10 < N12 ≤ 20	
			20 < N12 ≤ 40	
			40 < N12 ≤ 70	
			70 < N12 ≤ 100	

5.8.1 Correlations with Depth – CL - Dallas District

Table 5.4 presents both model correlations developed for CL soils from the Dallas district. The R^2 values and standard error estimate (S.E.E.) corresponding to each correlation have also been included in the table. The figure numbers showing the comparison of results between the predicted shear strength (C_{P2} or C_{P3}) from the new correlations and the measured shear strength (C_m) has also been listed in this table.

Figures 5.8 to 5.15 are presented to show the comparisons between measured shear strength (C_m) and predicted shear strength (C_{P2} or C_{P3}) for CL soils from Dallas district. All figures have a solid line in the middle, which represents 1:1 line. Any data close to this line indicates that both measured shear strength (C_m) and predicted shear strength (C_{P2} or C_{P3}) are close to each other. Two dotted lines that represent ± 30% of predicted shear strength (C_{P2} or C_{P3}) are also included. Results close to the top dotted line indicate the predicted shear strength is higher than the measured shear strength by 30%, whereas results close to the bottom dotted line indicate that the predicted shear strength is lower than the measured shear strength by 30%. In all cases, the measured shear strength (C_m) is obtained from Texas triaxial (Tex-118-E) tests conducted on the field samples collected from various depths. In the entire analysis, the measured shear strength (C_m) was regarded as true shear strength of soils.

The results from model 2 correlations are presented in Figure 5.8. This graph shows a significant scatter, indicating considerable variations between predicted undrained shear strength (C_{P2}) and measured shear strength (C_m). A statistic is used to measure the variability of the actual Y values from the predicted Y values. The standard deviation to measure the variability of each observation around the line of regression is called the standard error of the estimate (Berenson et al., 2002). In these models, the Y values are the predicted and measured undrained shear strength. The standard error of the estimate can be used to determine whether a correlation can be used to make statistically significant inference of future Y values (Berenson et al., 2002). A standard error estimate of 18.51 and a very low R^2 value of 0.005 for model 2 correlations indicate that this equation developed with no separation of data based on either N12 and depth data predicted poorly for CL soils from the Dallas district.

Reasons for the variations from model 2 predictions can be attributed to several factors. This model uses a single equation for all of the N12 values, not distinguishing between N12 values at different depths in the analysis. As discussed earlier in the chapter, measured shear strength (C_m) showed significant variation for similar N12 values at different depths. This could explain the variations between the measured and predicted undrained shear strengths.

In model 3, several correlations were developed for CL soils from the Dallas district for different depths and N12's. The R^2 values of these correlations ranged from 0.66 to 0.94, indicating better correlation with the model 3 attributes. The standard error estimate of model 3 correlations ranged from 1.41 to 13.87, indicating good characteristic. The results have been presented in Figures 5.9 to 5.15. These figures indicate that most of the predictions from model 3 are close to the measured test results. This can be interpreted from the results being close to the 1:1 line or scattered within the ± 30% lines.

Most predictions from the current TxDOT method are either underestimated or overestimated, whereas the newly introduced correlations of model 3 provided good undrained shear strength predictions for CL soils. It should be noted here that these comparisons are not comprehensive enough to suggest these correlations could be used for routine practice. More such evaluations with independent TCP data will further refine these correlations and enhance the confidence of practitioners to use such correlations.

Table 5.4 Model 2 (C_{P2}) and Model 3 (C_{P3}) Correlations Developed for CL Soils in Dallas

Depth (ft.)	N12	Equation	R^2	Standard Error of Estimate	Results in Figure
Entire Depth	All N12 Values	C_{P2} = 18.50 + (0.048 × N12) + (0.070 × Depth)	0.005	18.51	5.8
Depth ≤ 20	N12 ≤ 10	C_{P3} = - 6.27 + (1.71 × N12) + (0.25 × Depth)	0.75	2.66	5.9
	10 < N12 ≤ 15	C_{P3} = -136.60 + (15.10 × N12) - (3.27 × Depth)	0.92	5.03	5.10
	15 < N12 ≤ 40	C_{P3} = 14.30 - (0.88 × N12) + (2.31 × Depth)	0.66	11.48	5.11
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A
20 < Depth ≤ 40	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	C_{P3} = 1230.20 - (45.30 × N12) - (16.80 × Depth)	0.92	13.87	5.12
	15 < N12 ≤ 40	C_{P3} = -103.40 + (3.48 × N12) + (1.90 × Depth)	0.64	9.87	5.13
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A
40 < Depth ≤ 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	C_{P3} = 53.70 - (1.88 × N12) - (0.09 × Depth)	0.94	1.41	5.14
	20 < N12 ≤ 40	C_{P3} = - 44.50 - (1.56 × N12) + (1.95 × Depth)	0.73	4.47	5.15
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A
Depth > 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	Not Available	N/A	N/A	N/A
	20 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A

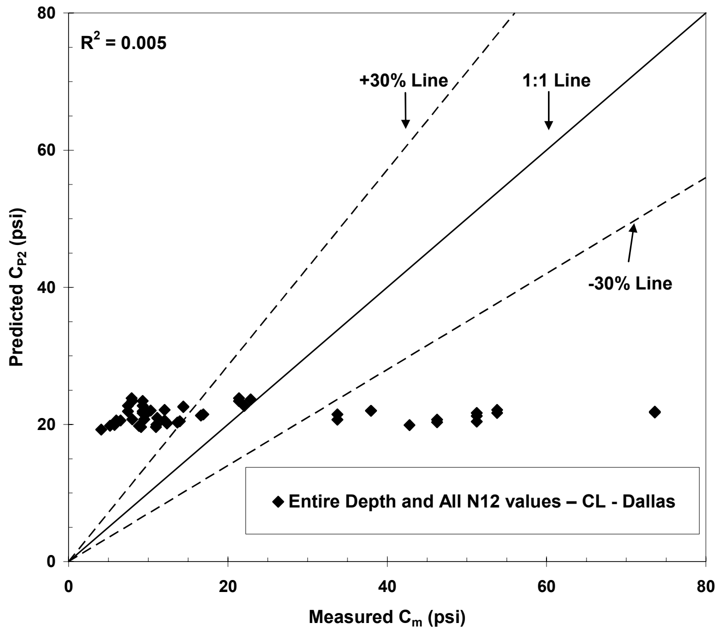

Figure 5.8 Comparisons between Measured and Predicted Shear Strength for Entire Depth and All N12 Values – CL – Dallas (Model 2)

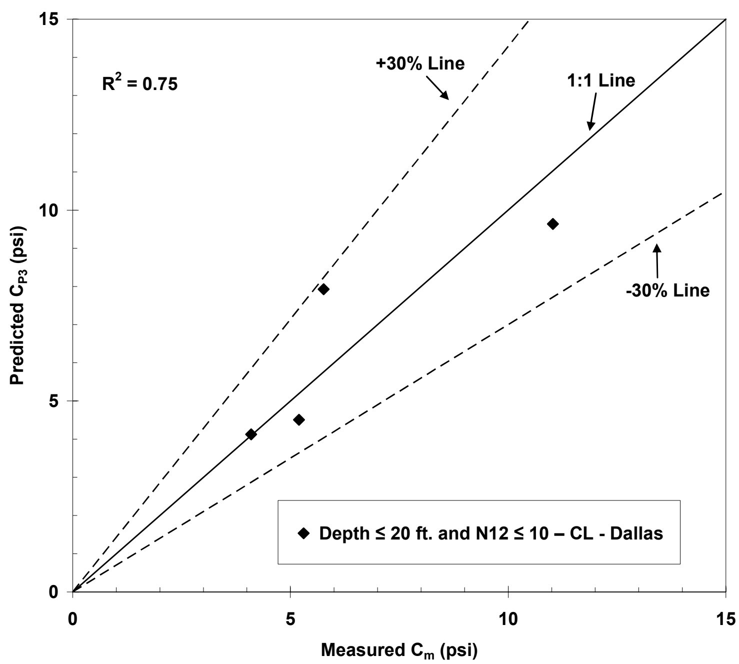

Figure 5.9 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and N12 ≤ 10 – CL – Dallas (Model 3)

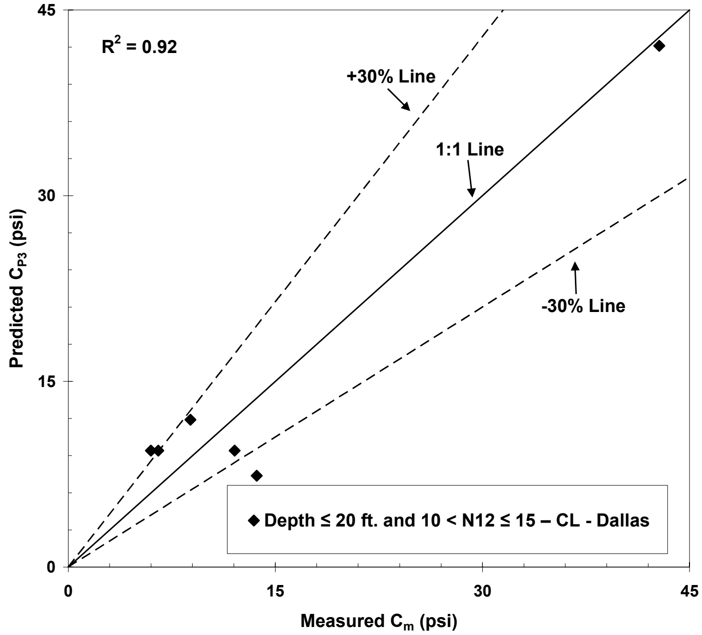

Figure 5.10 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and 10 < N12 ≤ 15 – CL – Dallas (Model 3)

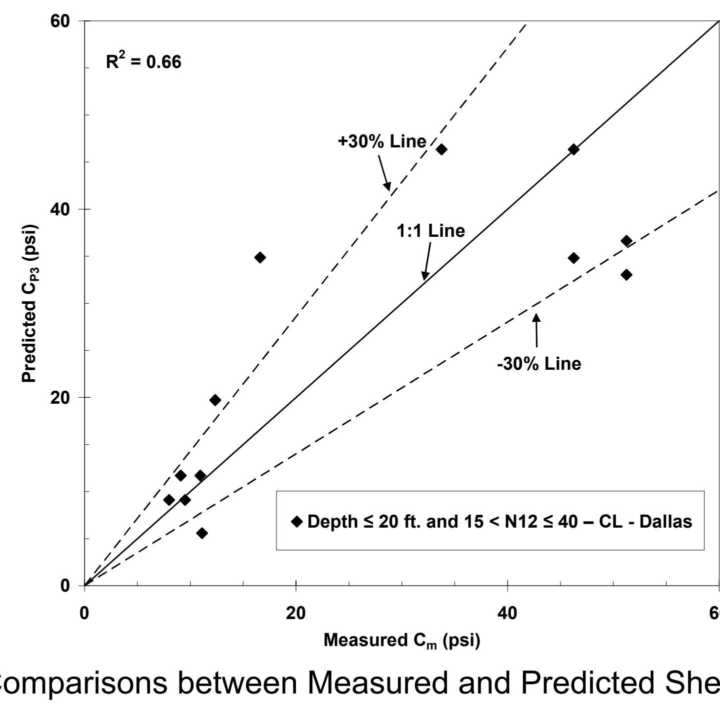

Figure 5.11 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and 15 < N12 ≤ 40 – CL – Dallas (Model 3)

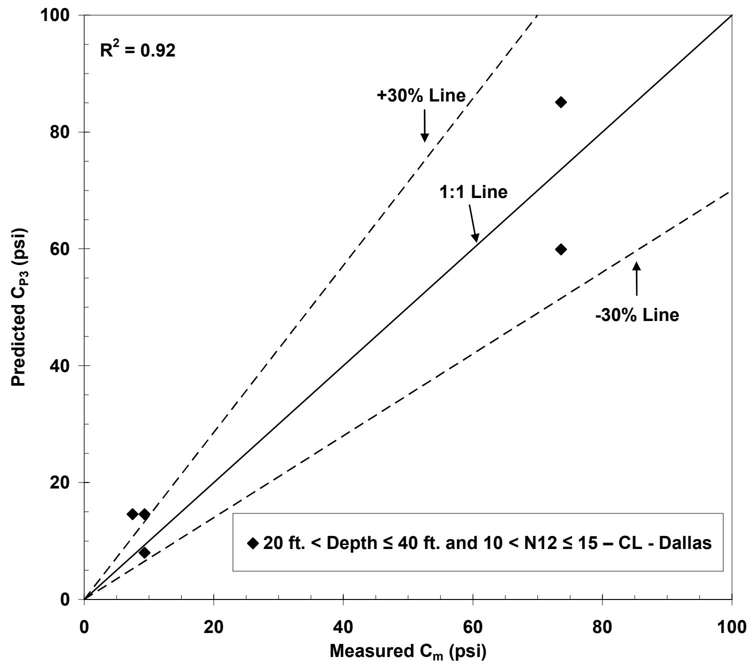

Figure 5.12 Comparisons between Measured and Predicted Shear Strength for 20 ft. < Depth ≤ 40 ft. and 10 < N12 ≤ 15 – CL – Dallas (Model 3)

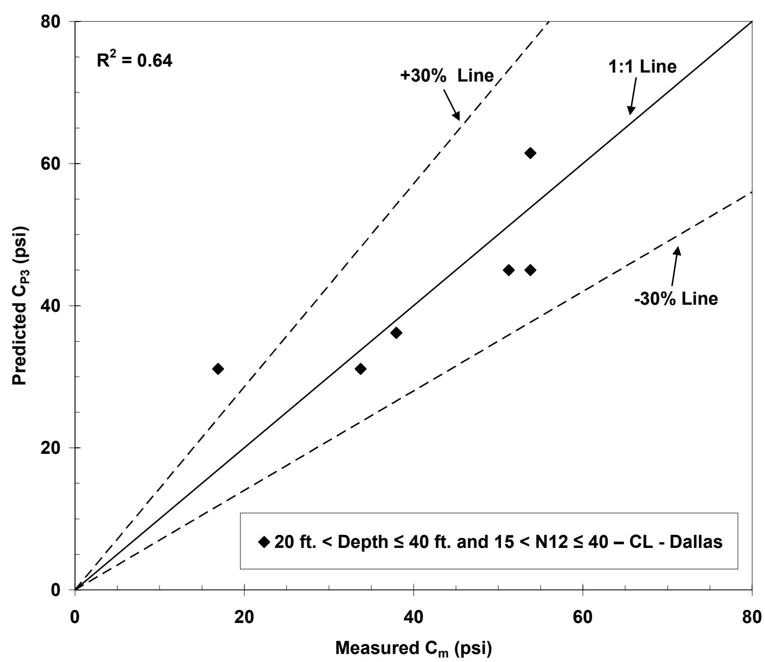

Figure 5.13 Comparisons between Measured and Predicted Shear Strength for 20 ft. < Depth ≤ 40 ft. and 15 < N12 ≤ 40 – CL – Dallas (Model 3)

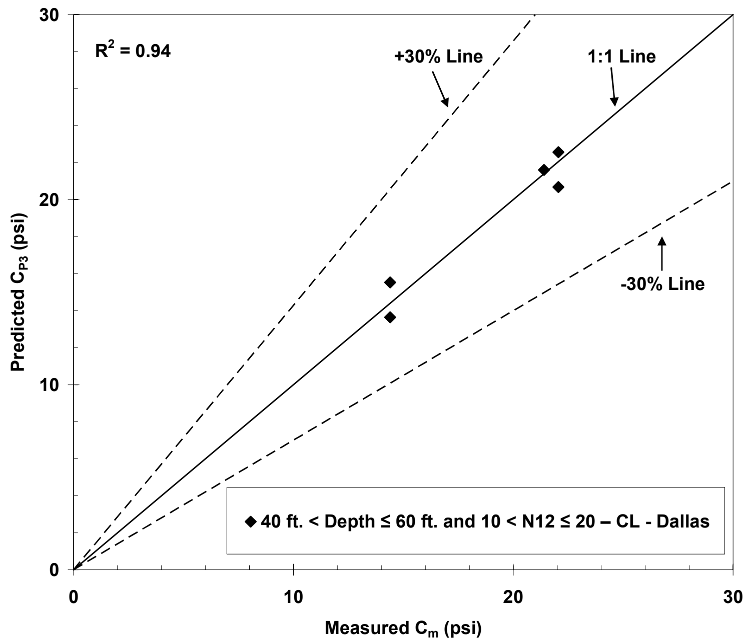

Figure 5.14 Comparisons between Measured and Predicted Shear Strength for 40 ft. < Depth ≤ 60 ft. and 10 < N12 ≤ 20 – CL – Dallas (Model 3)

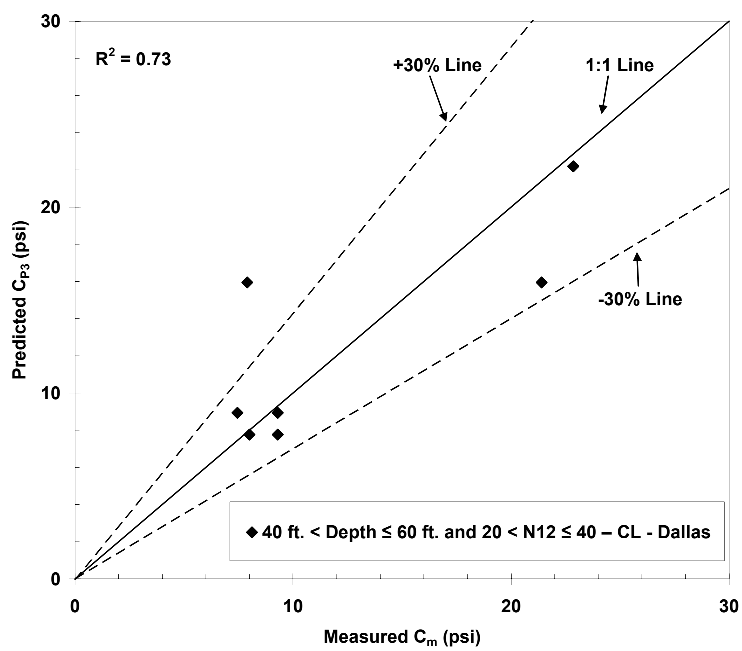

Figure 5.15 Comparisons between Measured and Predicted Shear Strength for 40 ft. < Depth ≤ 60 ft. and 20 < N12 ≤ 40 – CL – Dallas (Model 3)

5.8.2 Correlations with depth – CH - Dallas District

Model 2 and model 3 correlations developed for CH soils from Dallas district are presented in Table 5.5. The R^2 values and standard error estimate of the new correlations from both models, and the figure numbers showing the results of the new correlations have also been included in the table.

Figures 5.16 to 5.18 are presented to show the comparison between the measured shear strength (C_m) and the predicted shear strength (C_{P2} or C_{P3}) of the new correlations. Similar to the charts plotted for CL soil type, all figures have one solid line in the middle which represents the 1:1 line. On either side of the solid line are two dotted lines which represent ± 30% of predicted shear strength (C_{P2} or C_{P3}).

Figure 5.16 presents a comparison between the measured shear strength and the predicted shear strength from model 2 correlations for CH soils from the Dallas district. The chart shows a significant scatter of results similar to the results for CL soil type from the Dallas district. The correlations showed a very low R^2 value of 0.32. Standard error estimate of model 2 correlation was 13.71. This confirms the observation made for CL soils from Dallas district. To paraphrase, model 2 correlations developed with no separation of data based on either N12 values or depth of testing gives very poor results for both types of soils in the Dallas district.

The results from model 3 for CH soils from the Dallas district are presented in Figures 5.17 and 5.18. The results from model 3 showed excellent predictions. R^2 values of the two correlations developed using model 3 were 0.72 and 0.98, indicating great dependability. The standard error estimates of these two correlations were 2.23 and 15.99 respectively. High standard error was attributed to fewer data points being used to develop the correlation. However, both correlations are considered reasonable to provide appropriate strength predictions due to high R^2 values.

Figures 5.17 and 5.18 also indicate that most of the shear strength values predicted by model 3 correlations are close to the measured test results. This can be seen from figures showing comparisons between predicted shear strength (C_{P3}) and measured shear strength (C_m). The predicted shear strengths are close to 1:1 line and most of the data points are scattered within the ± 30% lines.

The reasons for the variations in model 2 predictions can be attributed to the same factors as those discussed for CL soil type. This model uses a single equation for all the N12 values. It does not distinguish between similar N12 values at different depths in the analysis. This factor was mainly attributed to the high variations between measured and predicted shear strengths.

Model 3, which required the use of separate correlations based on depth of testing and N12 data showed good predictions. The reasons for this could be attributed to the same factors given for the results from CL soil type of the Dallas district. More independent TCP data are still needed to validate these correlations.

Table 5.5 Model 2 (C_{P2}) and Model 3 (C_{P3}) Correlations Developed for CH Soils in Dallas

Depth (ft.)	N12	Equation	R^2	Standard Error of Estimate	Results in Figure
Entire Depth	All N12 Values	C_{P2} = 11.60 + (0.57 × N12) - (0.006 × Depth)	0.32	13.71	5.16
Depth ≤ 20	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	C_{P3} = -18.70 + (1.39 × N12) + (4.14 × Depth)	0.98	2.23	5.17
	15 < N12 ≤ 40	C_{P3} = 7.37 + (2.03 × N12) - (2.29 × Depth)	0.72	15.99	5.18
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A
20 < Depth ≤ 40	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	Not Available	N/A	N/A	N/A
	15 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A
40 < Depth ≤ 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	Not Available	N/A	N/A	N/A
	20 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A
Depth > 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	Not Available	N/A	N/A	N/A
	20 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A

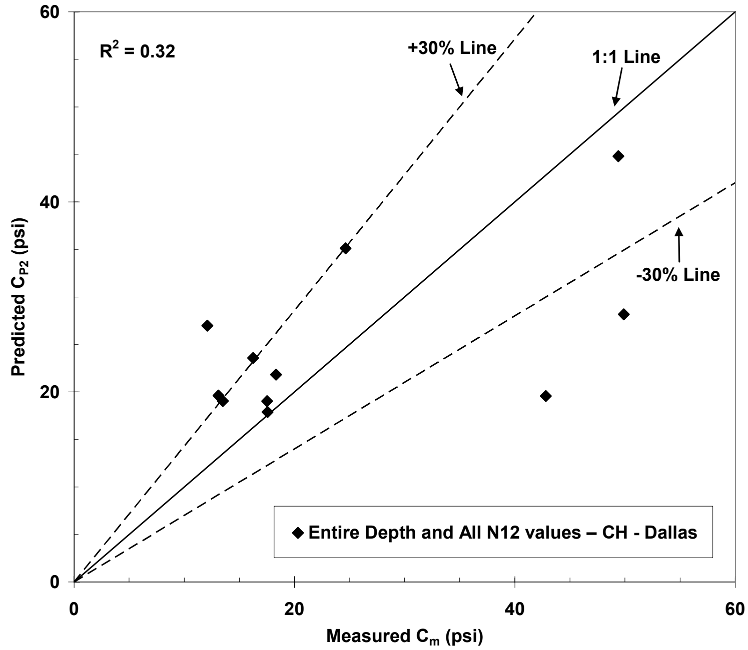

Figure 5.16 Comparisons between Measured and Predicted Shear Strength for Entire Depth and All N12 values – CH – Dallas (Model 2)

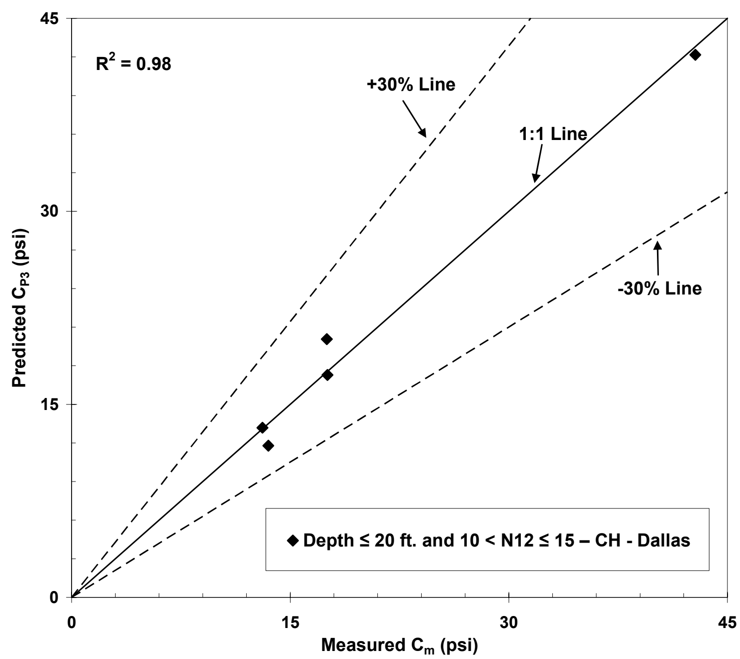

Figure 5.17 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and 10 < N12 ≤ 15 – CH – Dallas (Model 3)

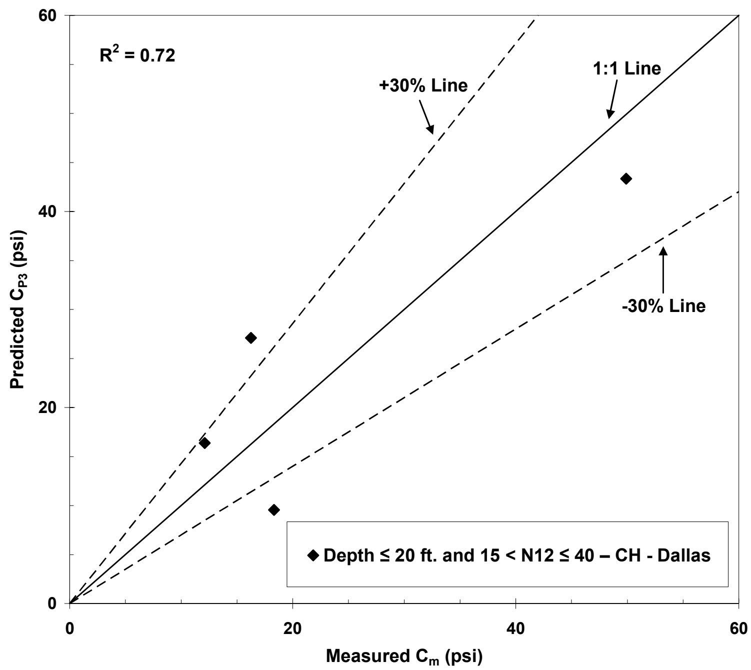

Figure 5.18 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and 15 < N12 ≤ 40 – CH – Dallas (Model 3)

5.8.3 Correlations with Depth – CL and CH - Fort Worth District

The correlations developed for CL and CH soil types from Fort Worth district based on two models (2 and 3) are presented in Table 5.6. The R^2 values of the correlations have also been included in the table.

Figure 5.19 presents a comparison between measured shear strength and predicted shear strength from model 2 correlations for clays from the Fort Worth district. The model 2 correlations have a very low R^2 value of 0.23 and a standard error estimate of 5.95. This indicates that the predicted shear strength (C_{P2}) of model 2 is significantly different from the actually measured shear strength (C_m) which can be graphically seen in Figure 5.19. Overall, it can be concluded that the model 2, which uses a single correlation for all N12 values and depth data, should not be used to predict undrained shear strength for clayey soils.

The results from model 3 correlations for Fort Worth clays are presented in Figures 5.20 and 5.21. The R^2 values of both correlations were 0.84 and 0.81, respectively. The standard error estimates of these two correlations were 2.23 and 15.99, respectively. The high R^2 values and a low standard error of estimate of these two correlations indicate these are good to moderate correlations. Most of the predicted shear strength values are close to the corresponding measured test results. Reasons explained earlier for these prediction trends are also valid in the case of Fort Worth clays.

Table 5.6 Model 2 (C_{P2}) and Model 3 (C_{P3}) Correlations Developed for CL and CH Soils in Fort Worth

Depth (ft.)	N12	Equation	R^2	Standard Error of Estimate	Results in Figure
Entire Depth	All N12 Values	C_{P2} = 15.70 - (0.69 × N12) + (1.28 × Depth)	0.23	5.95	5.19
Depth ≤ 20	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	C_{P3} = 136.20 - (12.60 × N12) + (7.53 × Depth)	0.84	3.99	5.20
	15 < N12 ≤ 40	C_{P3} = -3.95 - (4.74 × N12) + (9.54 × Depth)	0.81	3.30	5.21
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A
20 < Depth ≤ 40	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	Not Available	N/A	N/A	N/A
	15 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A
40 < Depth ≤ 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	Not Available	N/A	N/A	N/A
	20 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A
Depth > 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	Not Available	N/A	N/A	N/A
	20 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A

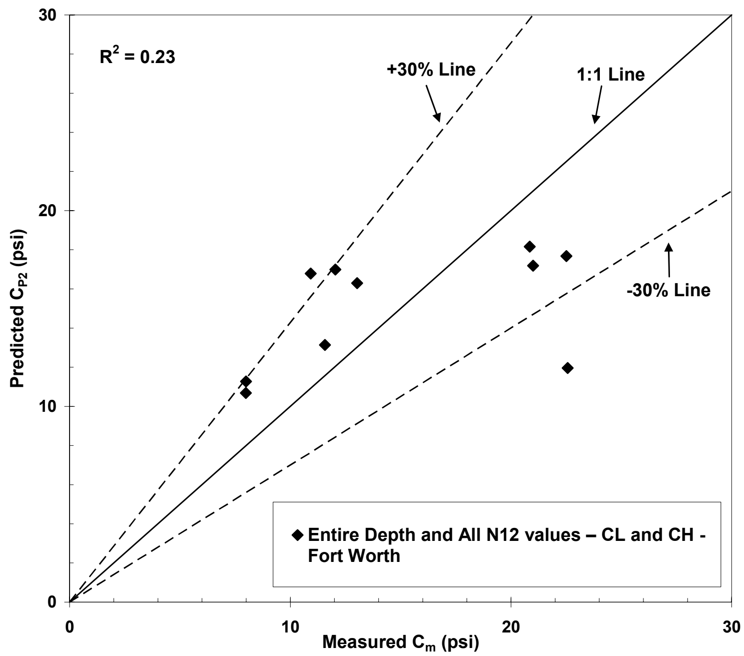

Figure 5.19 Comparisons between Measured and Predicted Shear Strength for Entire Depth and All N12 values – CL and CH - Fort Worth (Model 2)

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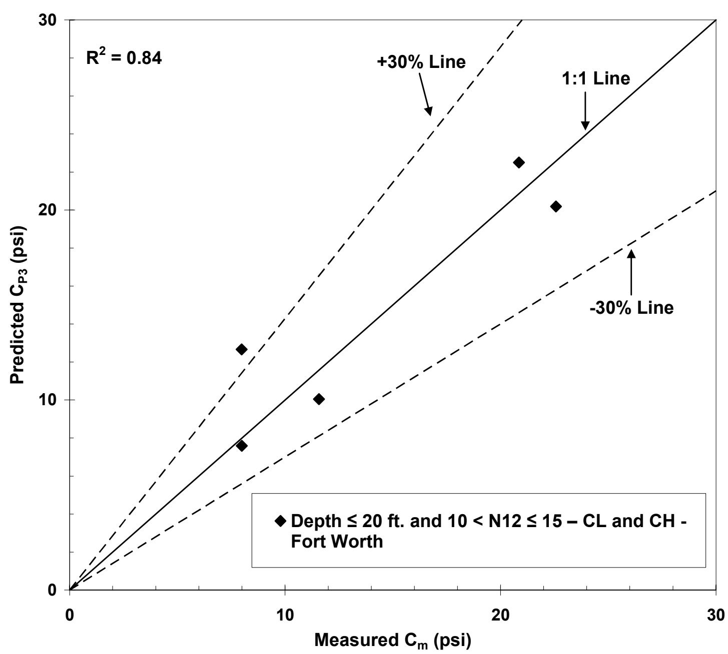


Figure 5.20 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and 10 < N12 ≤ 15 – CL and CH - Fort Worth (Model 3)

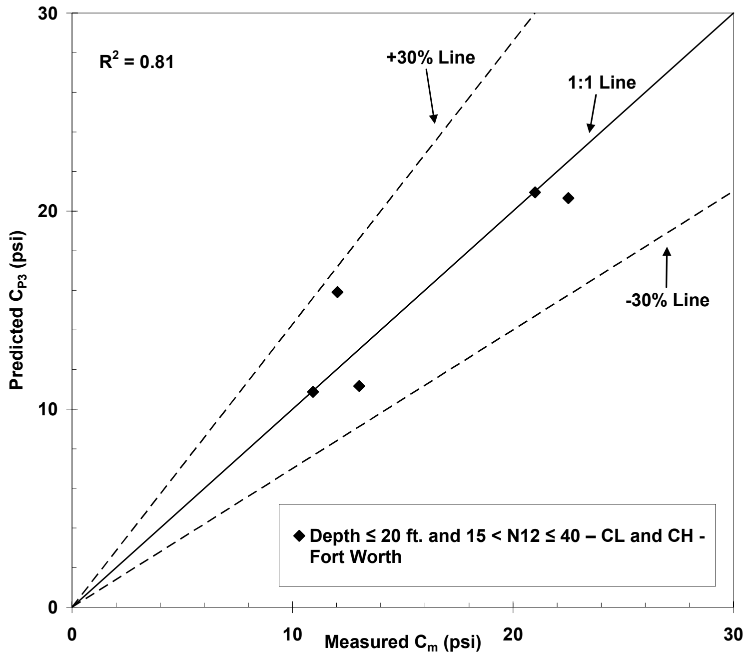


Figure 5.21 Comparisons between Measured and Predicted Shear Strength for Depth ≤ 20 ft. and 15 < N12 ≤ 40 – CL and CH - Fort Worth (Model 3)

5.9 Comparisons between Model 3 Correlations (C_{P3}) and Existing TxDOT Geotechnical Manual Method (C_{PO})

Model 3 correlations (C_{P3}) provided the best strength predictions amongst the three models developed in this study. To further understand the effectiveness in the predictions provided by model 3 correlations, comparisons of undrained shear strength predicted by model 3 correlations (C_{P3}) and undrained shear strength predicted by the current TxDOT charts (C_{PO}) are presented. The measured shear strength (C_m) obtained by the Texas triaxial method has been used as the basis of comparison between these two methods.

The ratios of predicted to measured shear strengths for all cases are used to make a comparison. Averages and standard deviations of these ratios are then determined for both CL and CH soils from Dallas district. The comparison for CL and CH soils are summarized and presented in Tables 5.7 and 5.8, respectively.

The average ratios between predicted and measured shear strengths for model 3 correlations are 0.95 and 0.93 for CL and CH soils, respectively. Their standard deviations are 0.20 and 0.27, respectively. On the other hand, the average ratios of predicted to measured shear strengths for the current TxDOT method are 0.54 and 0.53 for CL and CH soils, respectively. Their standard deviations are 0.45 and 0.37, respectively. From these ratios and corresponding standard deviation, it is clear that model 3 correlations provided reasonable and improved strength predictions over the current TxDOT method.

Further, Figures 5.22 and 5.23 present comparisons of undrained shear strength predicted by these two methods (Model 3 and Current TxDOT) for CL and CH soils from the Dallas district, respectively. This figure clearly illustrates that most of the predictions from model 3 correlations are close to the measured test results. This can be inferred because the predicted shear strengths by Model 3 are close to 1:1 line and a few of them are scattered within the ± 30% lines. The figure also shows that a high percentage of under-predicted shear strengths by the TxDOT geotechnical manual method due to the fact the manual methodology correlations did not account for over consolidation effects.

Comparisons between the predicted shear strengths provided by the two methods clearly illustrate the improved performance of model 3 correlations over the current method. Reliable predictions of undrained shear strength are obtained with the inclusion of depth as a parameter to predict undrained shear strength using TCP N values. Further, by using separate correlations for different N12 values and corresponding depth of testing, undrained shear strengths can be better predicted with a higher degree of precision than those provided by the current method.

Table 5.7 Comparison between Research Results and Current TxDOT Geotechnical Manual Method Undrained to Predict Shear Strength of Soils; Dallas District – Soil Type - CL

Soil Type	N12	Depth	C_m (psi) - Measured Shear Strength	C_{PO} (psi) - TxDOT Geotechnical Manual	C_{P3} (psi) - Research Results	Ratio of (C_{PO}/C_m)	Ratio of (C_{P3}/C_m)
CL	4	16	5.20	1.85	4.51	0.36	0.87
	7	16	11.03	3.24	9.64	0.29	0.87
	5	7.5	4.10	2.32	4.13	0.56	1.01
	13	16	13.65	6.02	7.38	0.44	0.54
	14	10	42.80	6.48	42.10	0.15	0.98
	14	20	12.05	6.48	9.40	0.54	0.78
	27	20	51.25	12.50	36.63	0.24	0.71
	16	20	46.25	7.41	46.36	0.16	1.00
	32	10	9.50	14.82	9.11	1.56	0.96
	11	40	73.6	5.09	59.9	0.07	0.81
	12	40	9.30	5.56	14.6	0.60	1.57
	14	35	9.30	6.48	8	0.70	0.86
	21	35	37.95	9.72	36.18	0.26	0.95
	25	25	33.75	11.58	31.10	0.34	0.92
	31	30	53.80	14.35	61.48	0.27	1.14

Table 5.7 – *Continued*

	15	50	22.05	6.95	20.69	0.31	0.94
	14	60	21.40	6.48	21.60	0.30	1.01
	19	45	14.4	8.80	13.65	0.61	0.95
	22	45	7.45	10.19	8.93	1.37	1.20
	26	55	22.85	12.04	22.19	0.53	0.97
	29	50	8	13.43	7.76	1.68	0.97

Average of Ratios:

TxDOT Geotechnical Manual (C_{PO}/C_m) = 0.54

Research Results (C_{P3}/C_m) = 0.95

Standard Deviation of:

TxDOT Geotechnical Manual (C_{PO}/C_m) = 0.45

Research Results (C_{P3}/C_m) = 0.20

Table 5.8 Comparison between Research Results and Current TxDOT Geotechnical Manual Method to Predict Undrained Shear Strength of Soils; Dallas District – Soil Type - CH

Soil Type	N12	Depth	C_m (psi) - Measured Shear Strength	C_{PO} (psi) - TxDOT Geotechnical Manual	C_{P3} (psi) - Research Results	Ratio of (C_{PO}/C_m)	Ratio of (C_{P3}/C_m)
CH	13	3	13.5	7.22	11.79	0.54	0.87
	11	5	17.56	6.11	17.29	0.35	0.98
	14	10	42.8	7.78	42.16	0.18	0.99
	29	10	49.9	16.11	43.34	0.32	0.87
	18	15	18.325	10.00	9.56	0.55	0.52
	27	20	12.1	15.00	16.38	1.24	1.35

Average of Ratios:

TxDOT Geotechnical Manual (C_{PO}/C_m) = 0.53

Research Results (C_{P3}/C_m) = 0.93

Standard Deviation of:

TxDOT Geotechnical Manual (C_{PO}/C_m) = 0.37

Research Results (C_{P3}/C_m) = 0.27

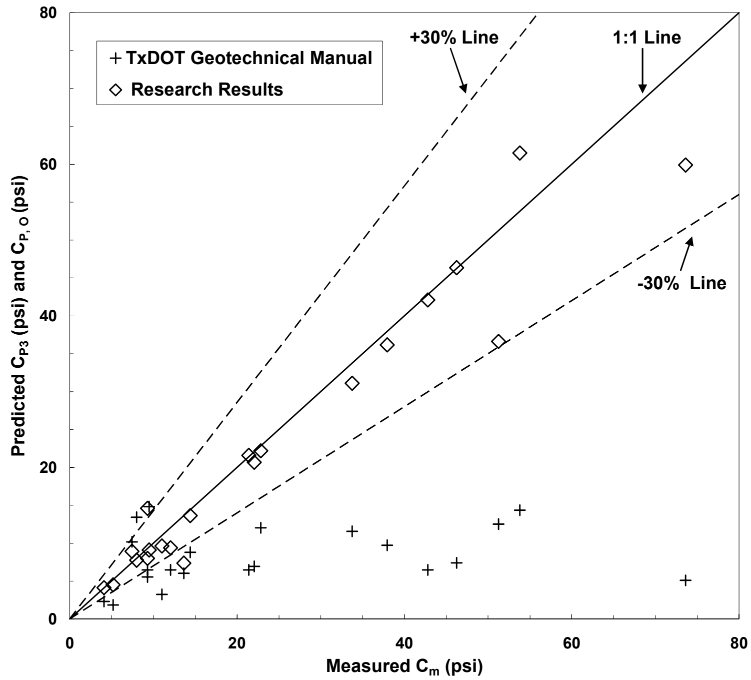


Figure 5.22 Comparisons between Measured and Predicted Shear Strength from TxDOT Geotechnical Manual and Research Results for CL – Dallas District

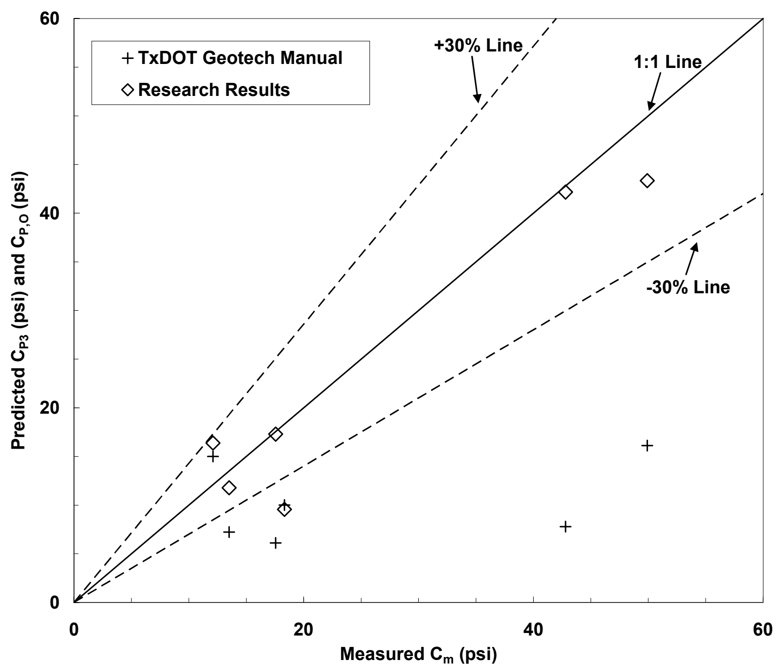


Figure 5.23 Comparisons between Measured and Predicted Shear Strength from TxDOT Geotechnical Manual and Research Results for CH – Dallas District

5.10 Shear Strength Correlations – Summary

From the present research, it is apparent that there are many factors which affect the TCP N-value and predicted shear strength. For a given soil type, therefore, the undrained shear strength cannot be predicted using a single parameter or by a single correlation with different variables. This theory is supported in the correlations developed as model 1 and model 2 for CL and CH soil types from the Dallas and Fort Worth districts. The need for separate correlations to predict the undrained shear strength based on N12 values and depth of testing is evidently necessary. This requirement has been established through the correlations developed from model 3 for both soil types from the Dallas and Fort Worth districts. Conclusively, the use of model 3 correlations would result in more accurate predictions of undrained shear strength values which would result in more economical and less conservative designs. The effectiveness of the new correlations over the current geotechnical manual method has been established in section 4.9 of this chapter.

Localized correlations have proven to produce better results than the broader, more generalized correlations used by TxDOT. Although correlations developed through the research methodology have shown promising results, more field testing and analysis of data is needed for the development of better correlations.

Table 5.9 Recommendations for Correlations Developed with Depth for CL Soils in Dallas District

Depth (ft.)	N12	Equation	R^2	S.E.E	Recommendation
Entire Depth	All N12 Values	$C_{P2} = 18.50 + (0.048 \times N12) + (0.070 \times Depth)$	0.005	18.51	x
Depth ≤ 20	N12 ≤ 10	$C_{P3} = -6.27 + (1.71 \times N12) + (0.25 \times Depth)$	0.75	2.66	✓
	10 < N12 ≤ 15	$C_{P3} = -136.60 + (15.10 \times N12) - (3.27 \times Depth)$	0.92	5.03	✓
	15 < N12 ≤ 40	$C_{P3} = 14.30 - (0.88 \times N12) + (2.31 \times Depth)$	0.66	11.48	✓
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A
20 < Depth ≤ 40	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	$C_{P3} = 1230.20 - (45.30 \times N12) - (16.80 \times Depth)$	0.92	13.87	✓
	15 < N12 ≤ 40	$C_{P3} = -103.40 + (3.48 \times N12) + (1.90 \times Depth)$	0.64	9.87	✓
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A
40 < Depth ≤ 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	$C_{P3} = 53.70 - (1.88 \times N12) - (0.09 \times Depth)$	0.94	1.41	✓
	20 < N12 ≤ 40	$C_{P3} = -44.50 - (1.56 \times N12) + (1.95 \times Depth)$	0.73	4.47	✓
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A
Depth > 60	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 20	Not Available	N/A	N/A	N/A
	20 < N12 ≤ 40	Not Available	N/A	N/A	N/A
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤	Not Available	N/A	N/A	N/A

Note: x - Not Recommended; ✓- Recommended

Table 5.10 Recommendations for Correlations Developed with Depth for CH Soils in Dallas District

Depth (ft.)	**N12**	**Equation**	**R^2**	**S.E.E**	**Recommendation**
Entire Depth	All N12 Values	$C_{P2} = 11.60 + (0.57 \times N12) - (0.006 \times Depth)$	0.32	13.71	x
Depth ≤ 20	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	$C_{P3} = -18.70 + (1.39 \times N12) + (4.14 \times Depth)$	0.98	2.23	✓
	15 < N12 ≤ 40	$C_{P3} = 7.37 + (2.03 \times N12) - (2.29 \times Depth)$	0.72	15.99	✓
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A

Note: x - Not Recommended; ✓- Recommended

Table 5.11 Recommendations for Correlations Developed with Depth for CL and CH Soils in Fort Worth District

Depth (ft.)	**N12**	**Equation**	**R^2**	**S.E.E**	**Recommendation**
Entire Depth	All N12 Values	$C_{P2} = 15.70 - (0.69 \times N12) + (1.28 \times Depth)$	0.23	5.95	x
Depth ≤ 20	N12 ≤ 10	Not Available	N/A	N/A	N/A
	10 < N12 ≤ 15	$C_{P3} = 136.20 - (12.60 \times N12) + (7.53 \times Depth)$	0.84	3.99	✓
	15 < N12 ≤ 40	$C_{P3} = -3.95 - (4.74 \times N12) + (9.54 \times Depth)$	0.81	3.30	✓
	40 < N12 ≤ 70	Not Available	N/A	N/A	N/A
	70 < N12 ≤ 100	Not Available	N/A	N/A	N/A

Note: x - Not Recommended; ✓- Recommended

CHAPTER 6

DEVELOPMENT OF SOFTWARE - TCPSoft

6.1 Introduction

This chapter provides information on various details of the software development to predict the undrained shear strength using TCP N values. Salient features and limitations of the developed software are discussed. These features include provisions to incorporate new correlations developed in the future for soils other than those developed in the present study. Two examples are provided to illustrate various input options available to the user to interpret the undrained shear strength of different soils from various districts.

6.2 Background and Software Objective

In civil engineering, the use of specialized software has resulted in faster computations and reliable designs with an enhanced quality of results. Specialized software is being used for civil engineering purposes such as infrastructure design, slope stability analysis, AutoCAD drawing applications, pre and post construction monitoring, quality control and quality assurance tasks (QC/QA), and project cost analysis (Besana and Austriaco, 1996; O'Neil et al. 1996; Udo-Inyang and Chen 1997). Likewise in this study, specialized software to predict the undrained shear strength of soils from different districts of Texas has been developed. This software uses the Texas cone penetrometer N value and the depth of testing as input parameters to predict undrained shear strength.

Localized correlations to predict undrained shear strength were developed, which were documented in the previous chapter. Several new correlations were developed using N12 and depth attributes for both Dallas and Fort Worth districts. The selection of the appropriate correlation to be used for a given conditions of a project site can be time-consuming and can lead to human errors. The main objectives of TCPSoft program development were to make these new correlations easy to use, expedite the process to predict the shear strength, and eliminate any possible human errors in selecting the appropriate correlations for a given set of TCP test values. Since the correlations used in this software are already evaluated, the use of this software can enhance the confidence of the user. However, more independent data verification will enhance the confidence of the user in this approach.

6.3 Software Model

Visual basic, an application software part of the Microsoft visual studio .NET Professional 2003 was used to develop the software. The code to implement this program is attached in Appendix F of thesis. The database used for correlation development was in Microsoft Access and any changes to the data may alter the correlations. The TCPsoft program is developed by taking account of these changes and any new correlations developed can be easily incorporated in the software.

The features of TCPSoft include localized predictions for both TxDOT districts. Since this study was limited to CL and CH soils from the Dallas and Fort Worth districts, current use of this software is limited to these two soil types from the districts. The model used by TCPSoft to use different correlations from different districts and for various soil types is shown in Table 6.1.

Table 6.1 Model Followed by TCPSoft to Use Developed Correlations

District	Soil Type	Depth (ft.)	N12
Each TxDOT District	Each Soil Type	≤ 20	≤ 10
			> 10 ≤ 15
			> 15 ≤ 40
			> 40 ≤ 70
			> 70 ≤ 100
		> 20 ≤ 40	≤ 10
			> 10 ≤ 15
			> 15 ≤ 40
			> 40 ≤ 70
			> 70 ≤ 100
		> 40 ≤ 60	≤ 10
			> 10 ≤ 20
			> 20 ≤ 40
			> 40 ≤ 70
			> 70 ≤ 100
		> 60	≤ 10
			> 10 ≤ 20
			> 20 ≤ 40
			> 40 ≤ 70
			> 70 ≤ 100

6.3.1 Salient Features of TCPSoft

Salient features of TCPSoft include provisions to incorporate any new correlations developed for soil types that are not currently included in the present research. This can be done by including details of new correlations in the database. Provisions have been made to incorporate them in the software.

The database used in the software has been designed with 3 different forms. These three forms are:

1. District form
2. Soil Type form
3. Formula form

The district form lists the seven TxDOT districts with a unique district ID designated to represent each district. The districts that are listed in this form would be available for selection from the scroll down menu in the input screen. The main objective of this form is to make provisions for future correlations that are developed for districts other than these seven districts already included in this form. If, in the future, correlations for any new district are developed, the corresponding district name would be included in the form. A new district ID would be designated for such a district. Once details for any new district are added in this form, the district would be available for input from the scroll down menu.

The soil type form lists the four soil types currently considered by TxDOT for design purposes. The soil types that are listed in this form would be available for selection from the scroll down menu in the input screen. A unique soil type ID has been used to represent each soil type. In the future, any new soil type that may be considered for design purposes can be added to the four already provided in the list. A new soil type ID would be designated for any additional soil type. Once details for a new soil type are added in this form, the soil type would be available for input from the scroll down menu.

The formula form is the most important form and is used to store and retrieve the constants required to run the program. Correlations developed in the present study are listed in this form shown in Figure 6.3. A unique formula ID has been used to represent each soil type. This form contains the constants from the correlations for different soil types from various TxDOT districts. The conditions under which a particular correlation can be used are listed in this form. These conditions are used by the software to select a particular correlation to be used for any input conditions. Any new correlation developed in the future can be added to the existing database by simply providing details of different constants in the formula form. A new formula ID would be designated to any new correlation.

A simple procedure has been followed to input the constants from the correlations into the database. The three forms and the method followed to input the constants for correlations developed in the present study are shown in Figures 6.1, 6.2, and 6.3. Explanations of various terms used in the three forms are given in Table 6.2.

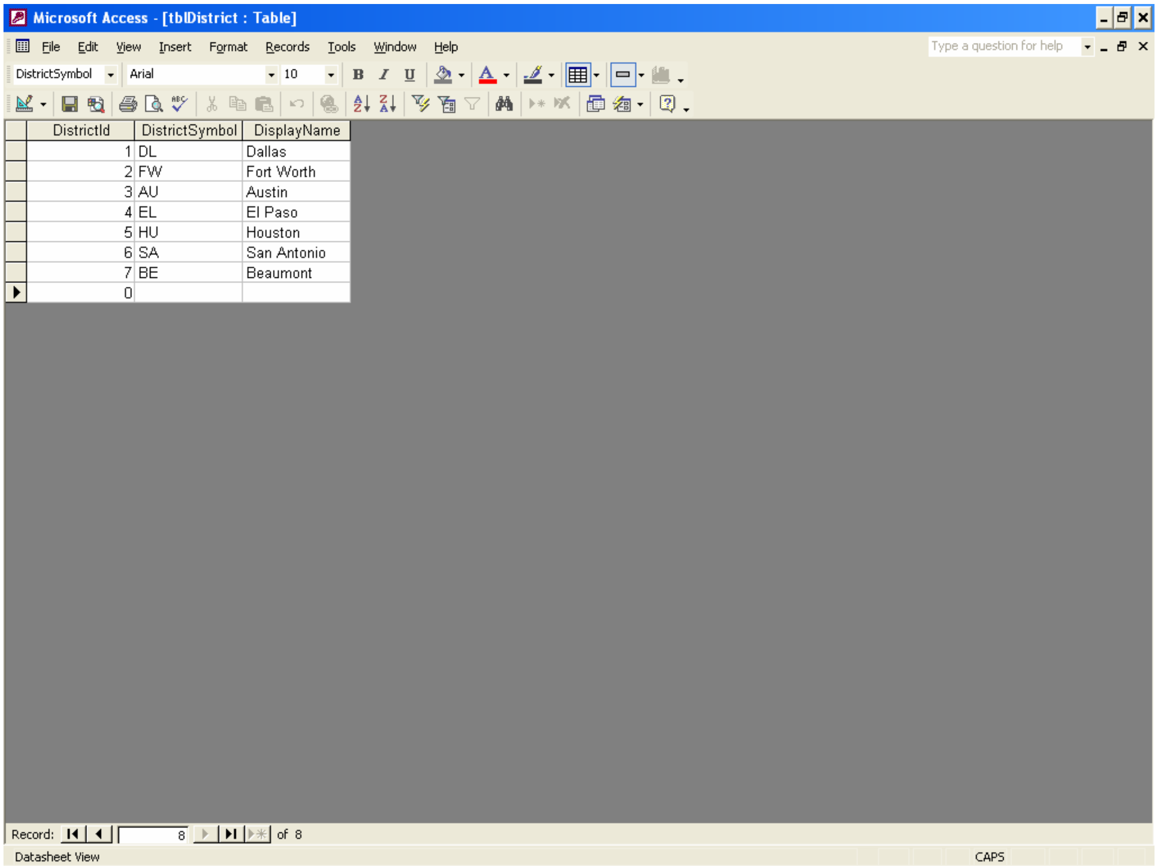


Figure 6.1 District Form: District ID's and Symbols Used to Identify the Different Districts in the Database

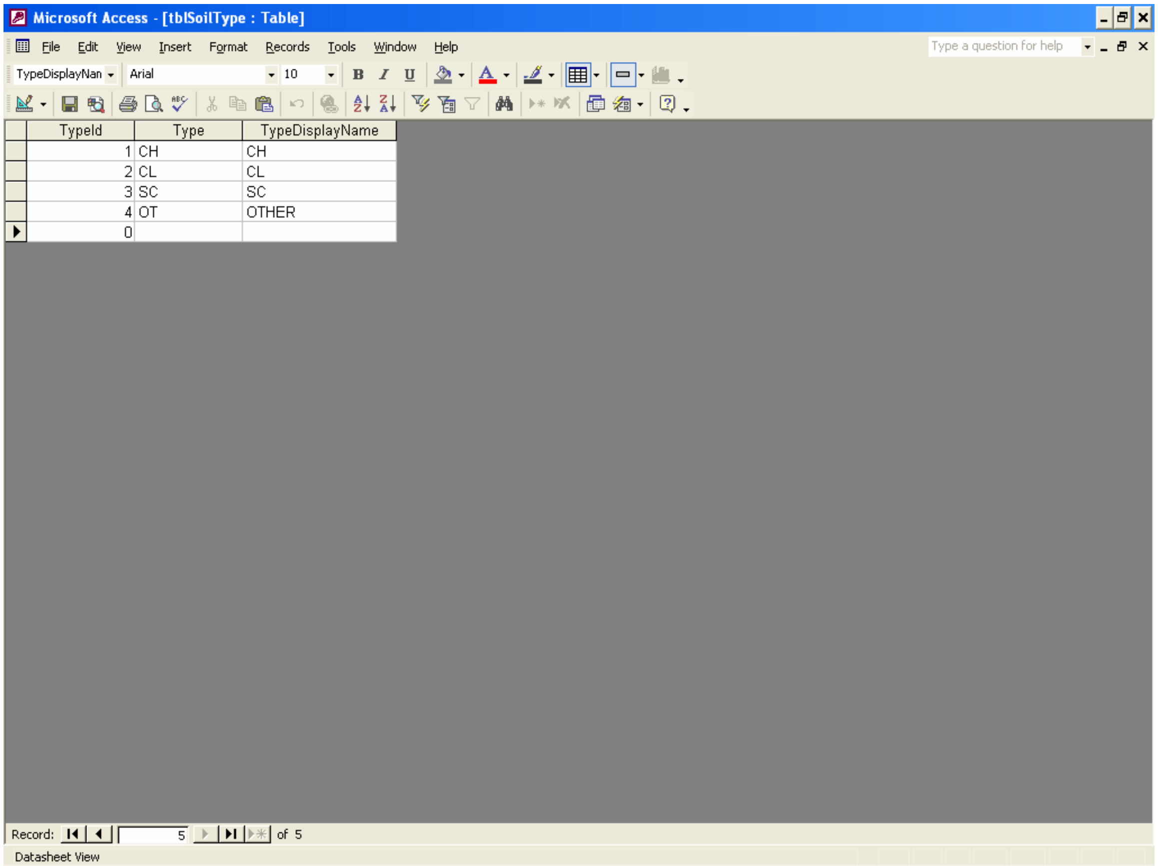
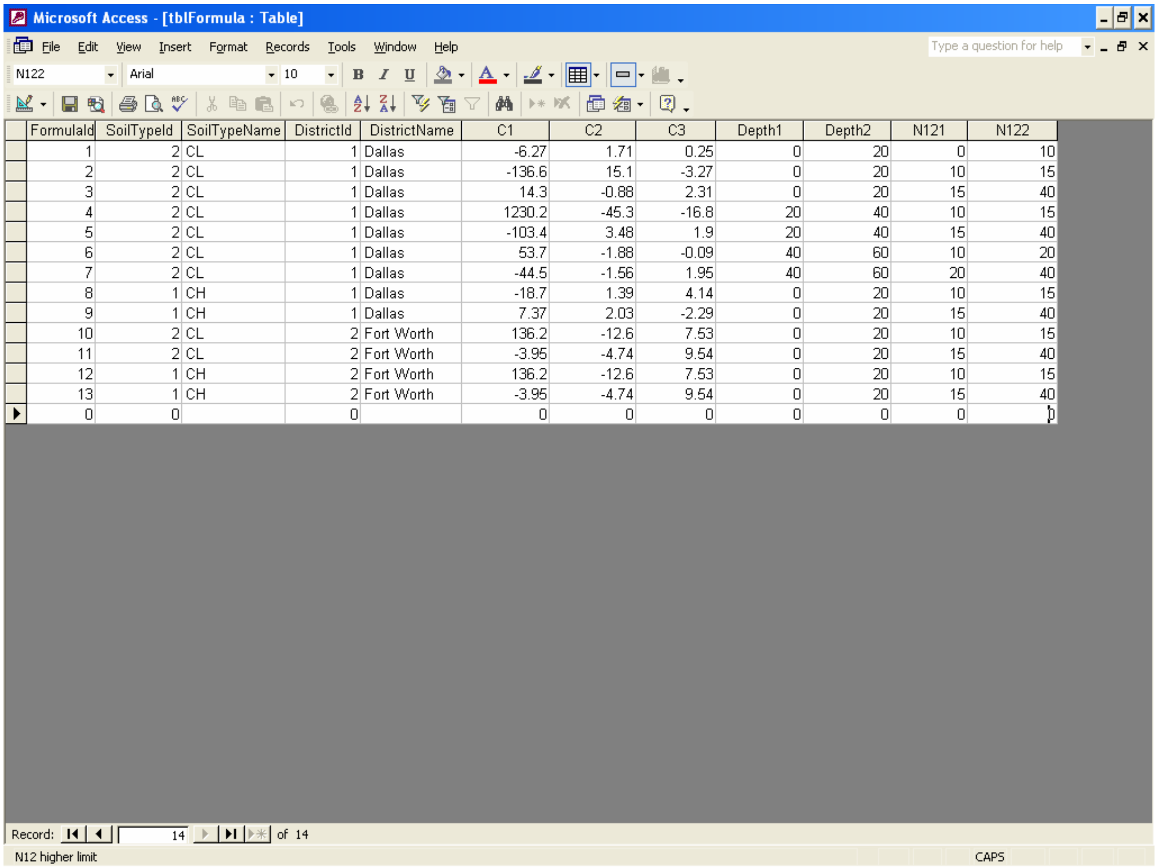


Figure 6.2 Soil Type Form: Soil Type IDs and Symbols Used to Identify the Different Soil Types in the Database



FormulaId	SoilTypeId	SoilTypeName	DistrictId	DistrictName	C1	C2	C3	Depth1	Depth2	N121	N122
1	2	CL	1	Dallas	-6.27	1.71	0.25	0	20	0	10
2	2	CL	1	Dallas	-136.6	15.1	-3.27	0	20	10	15
3	2	CL	1	Dallas	14.3	-0.88	2.31	0	20	15	40
4	2	CL	1	Dallas	1230.2	-45.3	-16.8	20	40	10	15
5	2	CL	1	Dallas	-103.4	3.48	1.9	20	40	15	40
6	2	CL	1	Dallas	53.7	-1.88	-0.09	40	60	10	20
7	2	CL	1	Dallas	-44.5	-1.56	1.95	40	60	20	40
8	1	CH	1	Dallas	-18.7	1.39	4.14	0	20	10	15
9	1	CH	1	Dallas	7.37	2.03	-2.29	0	20	15	40
10	2	CL	2	Fort Worth	136.2	-12.6	7.53	0	20	10	15
11	2	CL	2	Fort Worth	-3.95	-4.74	9.54	0	20	15	40
12	1	CH	2	Fort Worth	136.2	-12.6	7.53	0	20	10	15
13	1	CH	2	Fort Worth	-3.95	-4.74	9.54	0	20	15	40
0	0		0		0	0	0	0	0	0	0

Figure 6.3 Formula Form: Procedure Followed to Input the Constants in the Database for the Correlations Developed for Different Soil Types from Different Districts

Table 6.2 Details of Constants in the Database and their Definitions

Name	Definition
Formula ID	An ID for the corresponding correlation
Soil Type ID	An ID designated for each soil type, as shown in Figure 6.2
Soil Type Name	Soil Type for which the correlation can be used

Table 6.2 – *Continued*

District ID	An ID designated for each district, as shown in Figure 6.1
District Name	District for which the correlation can be used
C1	Constant 1 in the Multiple Linear Regression correlation
C2	Constant 2 in the Multiple Linear Regression correlation
C3	Constant 3 in the Multiple Linear Regression correlation
Depth 1	Lower limit of depth for which the correlation can be used
Depth 2	Upper limit of depth for which the correlation can be used
N121	Lower limit of N12 for which the correlation can be used
N122	Upper limit of N12 for which the correlation can be used

6.4 Data Inputs

Although the results derived by TCPSoft have been tested, they still require final approval from a designated professional engineer for design purposes. The developer assumes no responsibly of the results produced by this software. A disclaimer screen pops up upon opening the program, and requires the user to agree to the terms listed for any further use of the software. This screen is shown in Figure 6.4. Incorporation of this feature is necessary due to the high variability of the source data collected from both districts.

The four input parameters required to predict the undrained shear strength of soils are listed in Table 6.3. A scroll down menu has been provided to select the soil type and district for which the undrained shear strength is required. Since there could be several different values for depth of testing and N12 values from the TCP test, no scroll down menu has been for provided for these two input parameters. The user must input the N12 value and depth of testing as noted during the TCP test. After inputting the required parameters, the user clicks on the “Calculate” button to get the output from the software. The input screen is shown in Figure 6.5. Figure 6.6 shows the current options available for selection in the soil type and district scroll down menus.

Table 6.3 Details of Data Input in TCPSoft

INPUT PARAMETERS	**INPUT OPTIONS**
SOIL TYPE	CH, CL, SC, OTHER SOILS *(Scroll down menu)*
DISTRICT	Dallas, Fort Worth, Austin, El Paso, Houston, San Antonio, Beaumont *(Scroll down menu)*
DEPTH (Ft.)	*User Inputs values*
N12	*User Inputs values*

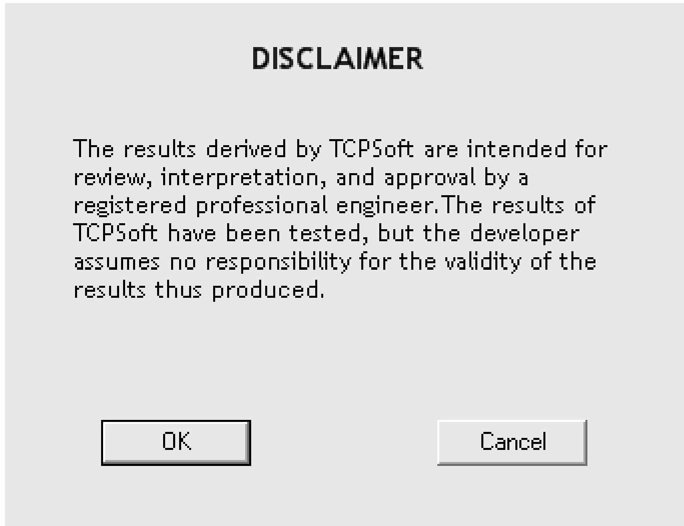


Figure 6.4 Typical Screen Showing the Disclaimer in TCPSoft Software

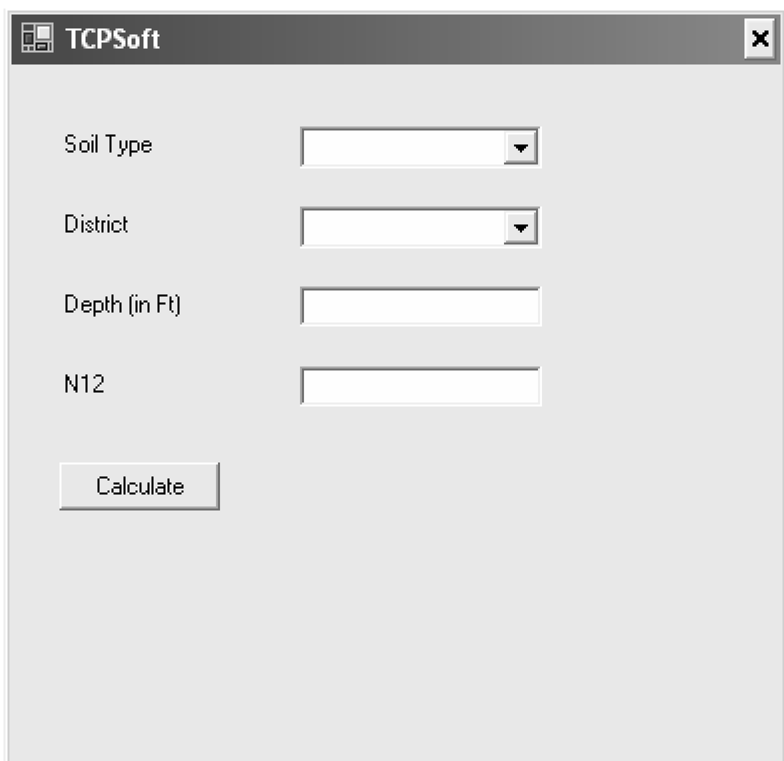


Figure 6.5 Typical Screen Showing the Input Options in TCPSoft Software

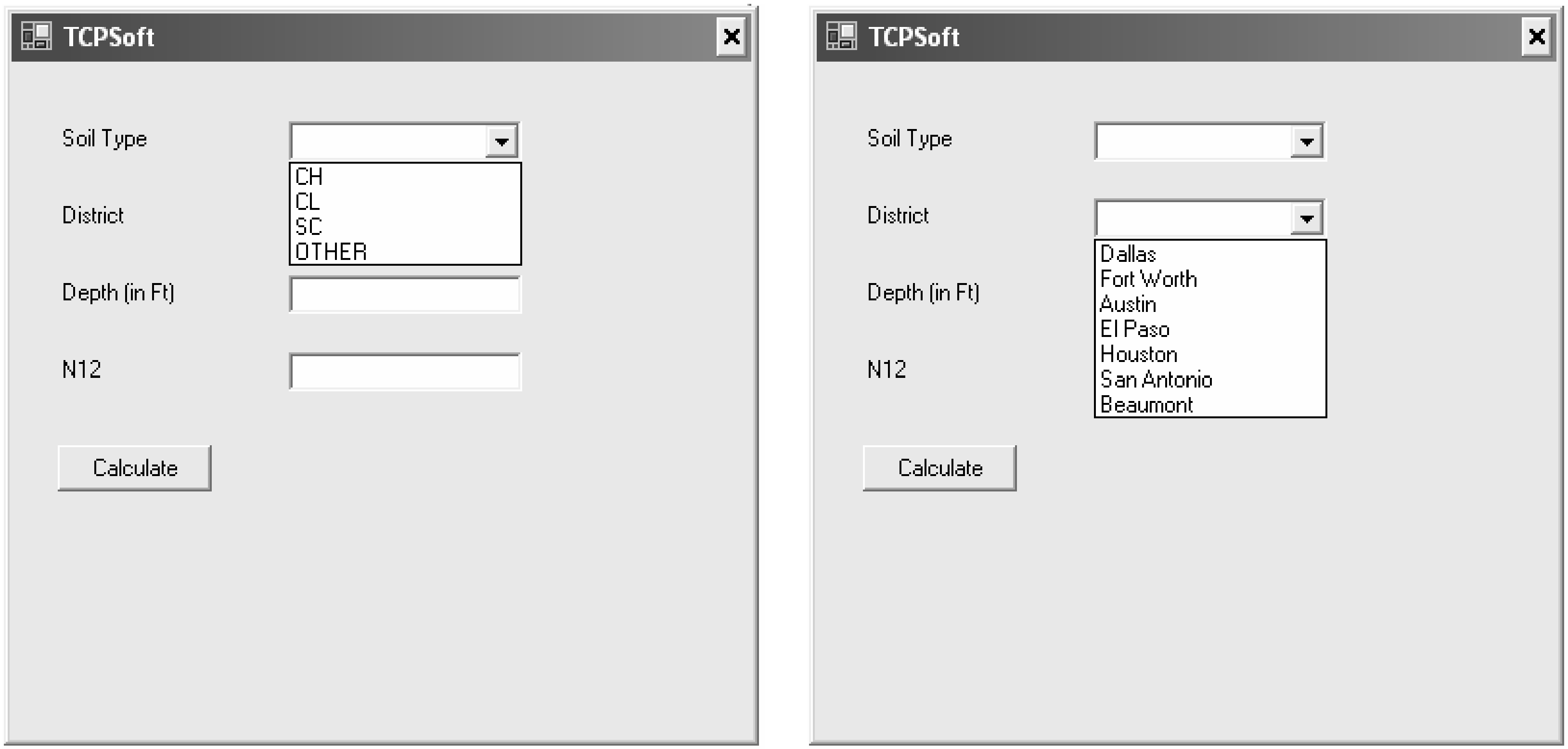


Figure 6.6 Typical Screens Showing the Scroll Down Menus to Select Soil Type and District in TCPSoft Software

6.5 Examples

The following two examples illustrate the procedure for using the software and interpret results from TCPSoft for different input conditions.

6.5.1 Example 1

In this example, “CL” is selected as the soil type and “Dallas” is selected as the district: these are used as two of the input parameters. From the TCP test results, N12 value and corresponding depth of testing are input as 14 and 12 respectively. Details of the data input screen for Example 1 are listed in Table 6.4. Once the input conditions are entered, the user clicks on the “Calculate” button provided on the input screen.

Table 6.4 Details of Data Input for Example 1

INPUT PARAMETERS	INPUT OPTIONS
SOIL TYPE	CL
DISTRICT	Dallas
DEPTH (ft.)	10
N12	14

Once the input conditions are defined by the user, the program processes the request from the user. Accordingly, the program uses the Formula form in the database which stores all the correlations. The conditions to select the exact correlation to be used for the given input conditions are also included in the

Formula form. After finding the exact correlation to be used for the given input, the software chooses the following correlation to predict the undrained shear strength.

$$C_{P,\,N} = -136.60 + (15.10 \times N12) - (3.27 \times Depth)$$

The undrained shear strength is predicted and displayed on the output screen as shown in Figure 6.7.

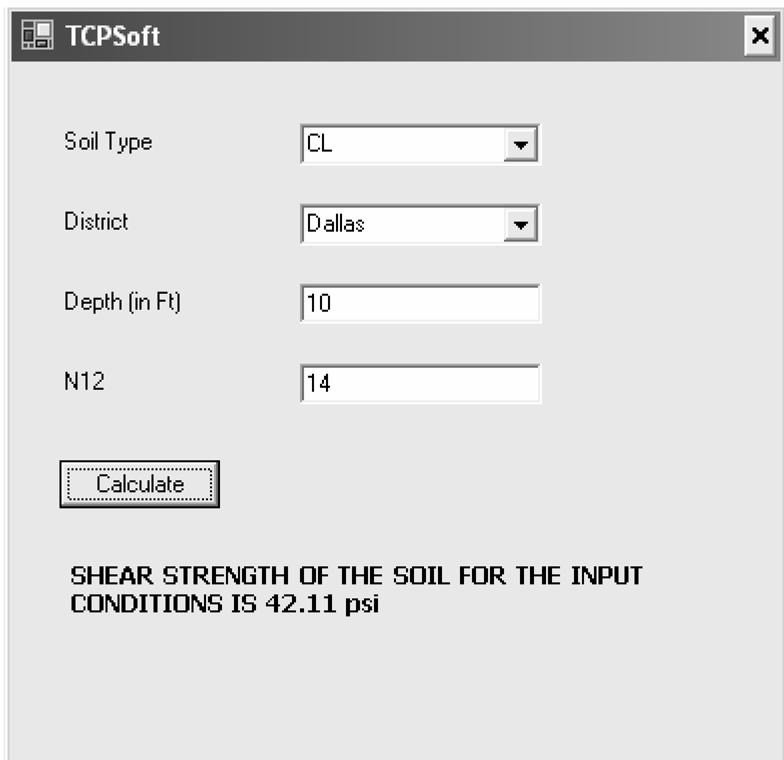


Figure 6.7 Example 1: Typical Output Screen with Input Conditions for which Correlations were Available in TCPSoft Software

6.5.2 Example 2

In this example, two of the input parameters are used when “SC” is selected as the soil type and “Dallas” is selected as the district. From the TCP test results, the N12 value and the corresponding depth of testing are inputted as 14 and 12 respectively. The details of the data input screen for Example 2 are listed in Table 6.5. Once the input conditions are entered, the user clicks on the “Calculate” button provided on the input screen.

Table 6.5 Details of Data Input for Example 2

INPUT PARAMETERS	**INPUT OPTIONS**
SOIL TYPE	SC
DISTRICT	Dallas
DEPTH (ft.)	10
N12	14

The program uses the Formula form in the database which stores the correlations and the different conditions for which a particular correlation is to be used. Since no correlation is available for the given input conditions, the following output screen, as shown in Figure 6.8, is displayed for the user.

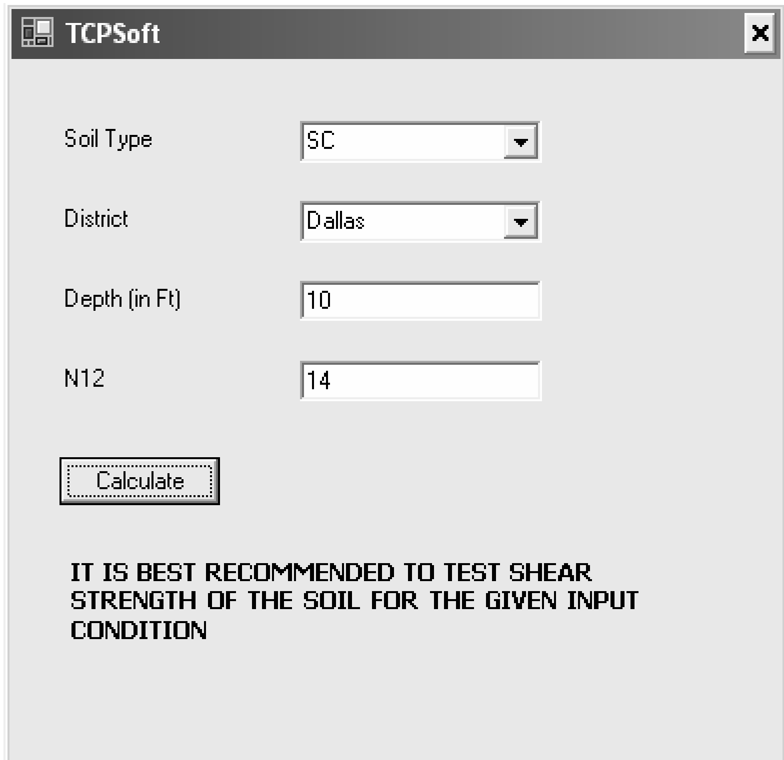


Figure 6.8 Example 2: Typical Output Screen with Input Conditions for which Correlations were NOT Available in TCPSoft Software

6.6 Summary

In this chapter, the development and features of TCPSoft and the database used in the present software are discussed. The salient features and future development capabilities of software are also mentioned. Two examples are presented to illustrate the applications TCPSoft. These examples illustrate the user-friendly nature of the developed software. Reliabilities in predictions would have to be established with independent verification with more TCP data other than those used in the present research. This will enhance the confidence in users and practitioners to use the correlations and software for routine use.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

The objectives of this thesis research were accomplished. A soil database for Dallas and Forth Worth districts containing various geotechnical in situ TCP and strength tests carried out for TxDOT projects over the last 10 years has been created. A software "EXTRACT" was also developed to extract data currently stored in boring logs on Wincore 3.0 files and compile these results in Microsoft excel files. The visual basic code for implementing them as macros in Microsoft excel is presented in Appendix E.

An attempt was first made to classify soils into fine grained USCS symbols using TCP test results. Four different approaches were attempted in this analysis. The existing TxDOT correlations to predict undrained shear strength via TCP N-values was then evaluated. Improved and localized correlations were then developed between TCP test results and undrained shear strength test data of Dallas and Fort Worth districts. Predictions from three developed model correlations were evaluated by comparing them with measured test results. The correlations that provided reasonable to good predictions are recommended for future use. Recommendations are based on the coefficient of determination and standard errors of the estimate, two statistical parameters. Software "TCPSoft" was finally developed to predict undrained shear strength using the recommended TCP based correlations.

The following presents summary and major conclusions of the present thesis research. These are:

1. Software "EXTRACT" was developed and this could be used to regenerate and reproduce TxDOT boring logs in excel format database files. This could expedite, simplify and structure the process of developing the soil database.
2. All four statistical approaches to analyze the data for possible soil classification proved ineffective. In all these approaches, little or no significant difference in TCP test results was noted for the clayey soil types. This implies that the use of TCP test results to classify soils is not deemed practical.
3. Several factors including depth of soil, geological history, type of soil influenced TCP N values and related shear strength parameters including undrained shear strength. Hence, for a given soil type, the undrained shear strength is difficult to predict based on a single parameter type correlation, such as N12 based correlation.
4. Model 1 correlations for undrained shear strength predictions yielded very low coefficient of determination (R^2) values of 0.001 and 0.32 for CL and CH soils, respectively. The same model showed similar low R^2 value of 0.11 for broadly classified clayey soils of Fort Worth district. Poor

correlations are attributed to lack of accounting of an important parameter, depth in the original correlations.

5. Model 2 correlations developed with combined N12 values and depth data also yielded low R^2 values for CL and CH soils of Dallas district and clayey soils of Fort Worth district. This indicates that though depth effects were accounted for, the correlations still yielded low R^2 values. This is due to a wider variation of N12 and depth data of the present database, which will be difficult to simulate with a simple statistical regression model. This warranted the need to separate correlations to predict the undrained shear strength based on N12 values and depth parameters. This was attempted in model 3 correlations.
6. Model 3 correlations developed for CL soils of Dallas district provided moderate to high R^2 values ranging from 0.66 to 0.94, indicating a better correlation obtained. The R^2 values of correlations for CH soils of Dallas district were 0.72 and 0.98, again indicating that these are better correlations. For Fort Worth district soils, the R^2 values of the two correlations for different depth and N12 zones were 0.84 and 0.81, respectively. The high R^2 values suggest these are statistically better correlations developed in the present thesis research.
7. Localized correlations, overall, have proven to produce better results than the broader and more generalized correlations currently used by TxDOT.

This is attributed to overconsolidation nature of the present expansive clays found in Dallas and Fort Worth regions.

8. The "TCPSoft" program developed using Visual Basic. This software provides a simple approach to interpret shear strength of clays using N12 and depth parameters as input parameters. This software can also be used to make modifications to the newly developed correlations and also incorporate new correlations developed for other soils.

7.2 Recommendations for Future Research

Based on the present research, the following recommendations are suggested for future studies:

1. Although correlations developed in the present research methodology have shown promising results, more field testing and evaluations are needed for further validation and refinement of the new correlations.
2. Since TCP tests are normally conducted on a routine basis by TxDOT, the "EXTRACT" software could be used to augment the existing database containing information pertaining to TCP test data of different TxDOT districts. This database could be used to validate and modify the existing correlation. Such usage will lead to more economical and less conservative designs in geotechnical practice.
3. Artificial neural networks and theoretical bearing capacity based models to predict undrained shear strength properties should be attempted.

APPENDIX A

WINCORE SOFTWARE INPUT SCREENS

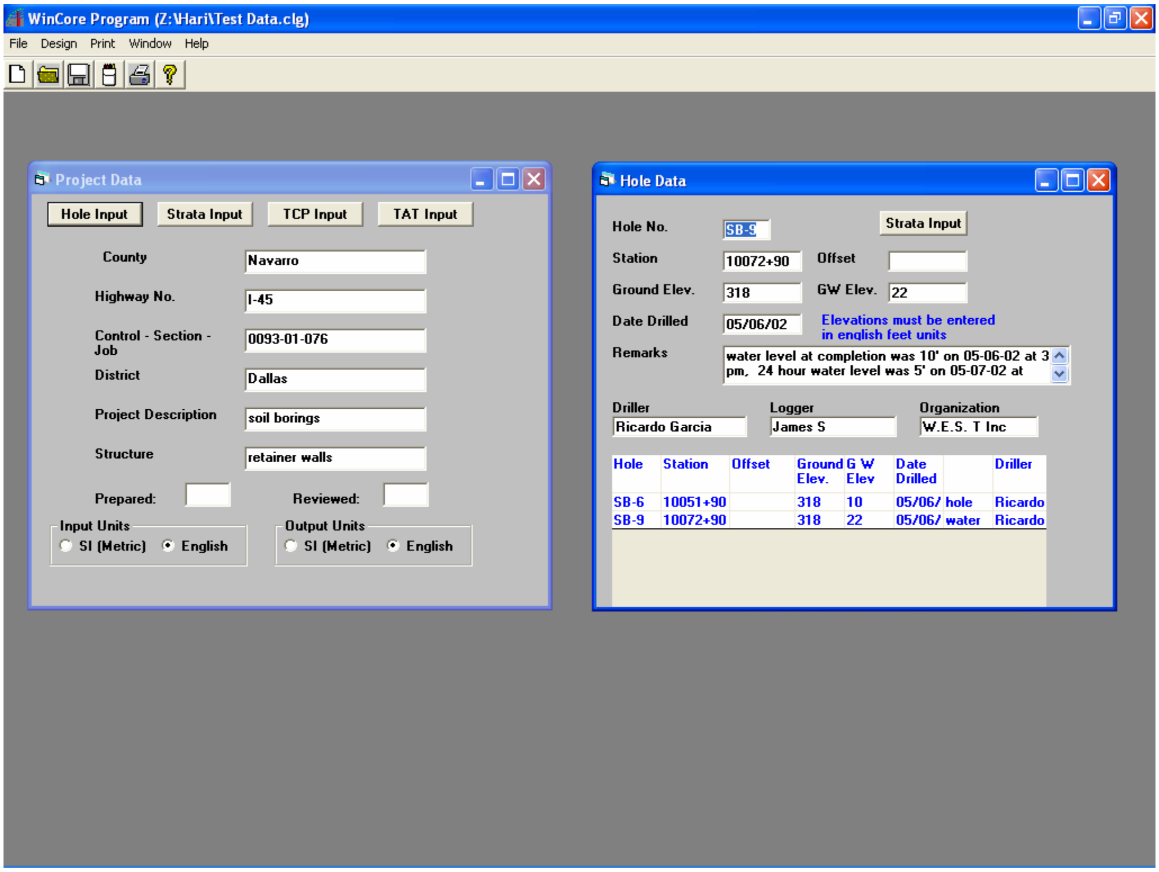


Figure A.1 Typical Wincore 3.0 Screen Showing Project Data and Borehole Data

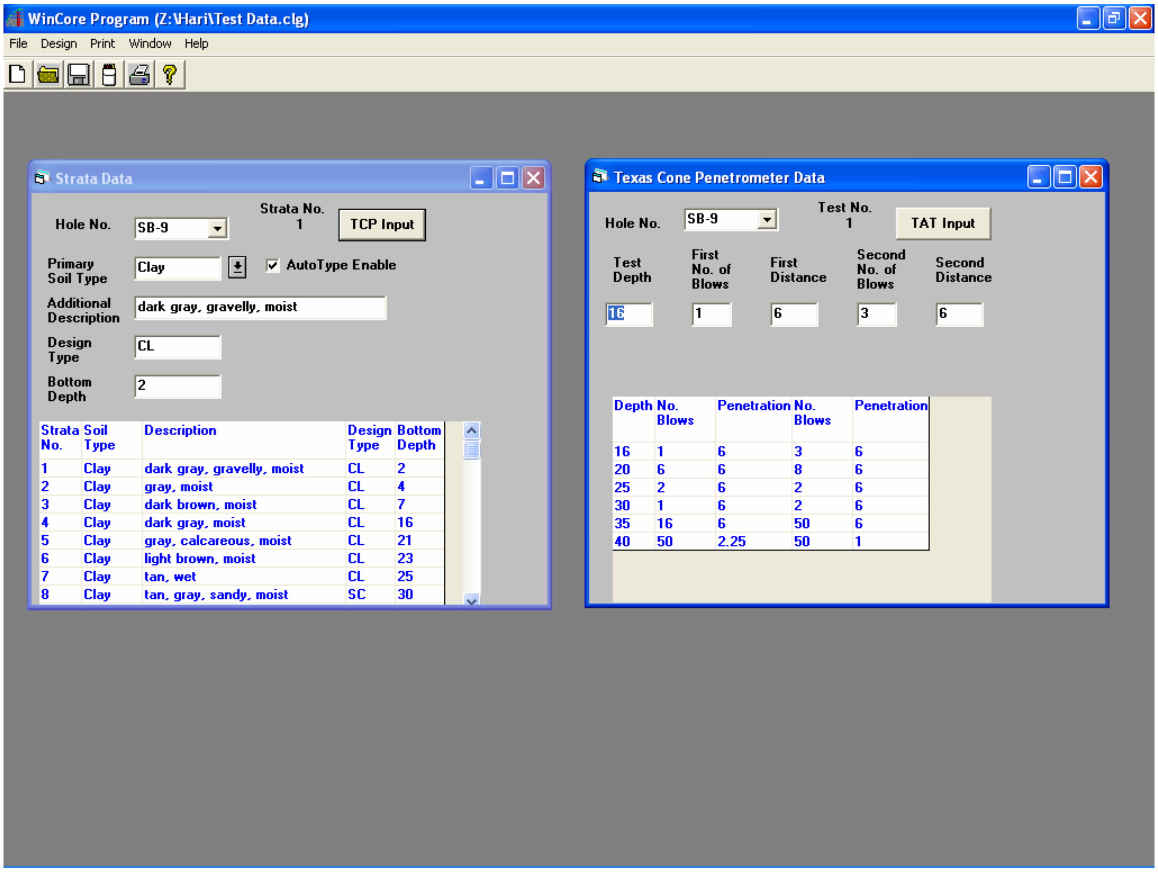


Figure A.2 Typical Wincore 3.0 Screen Showing Strata Data and TCP Data

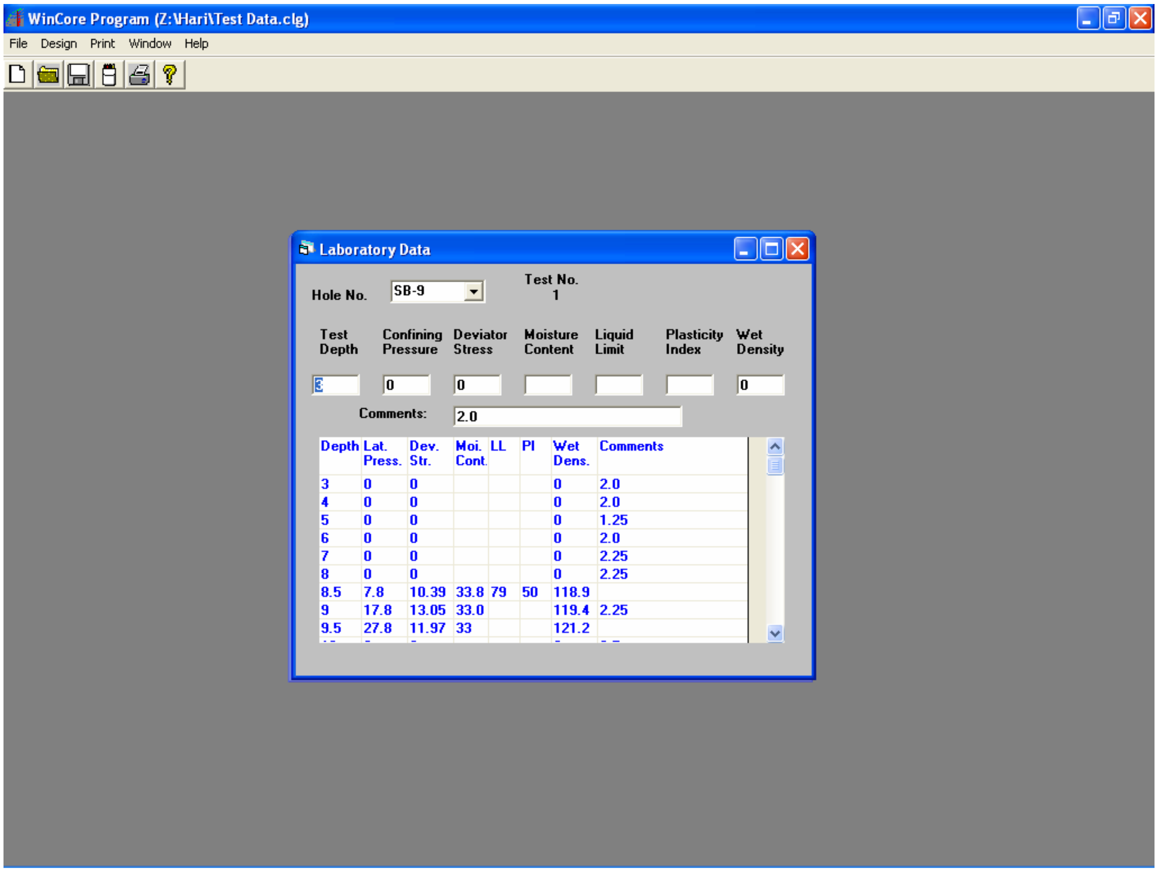


Figure A.3 Typical Wincore 3.0 Screen Showing Laboratory Data

APPENDIX B

TYPICAL SCREENS SHOWING OUTPUT OF EXTRACT SOFTWARE

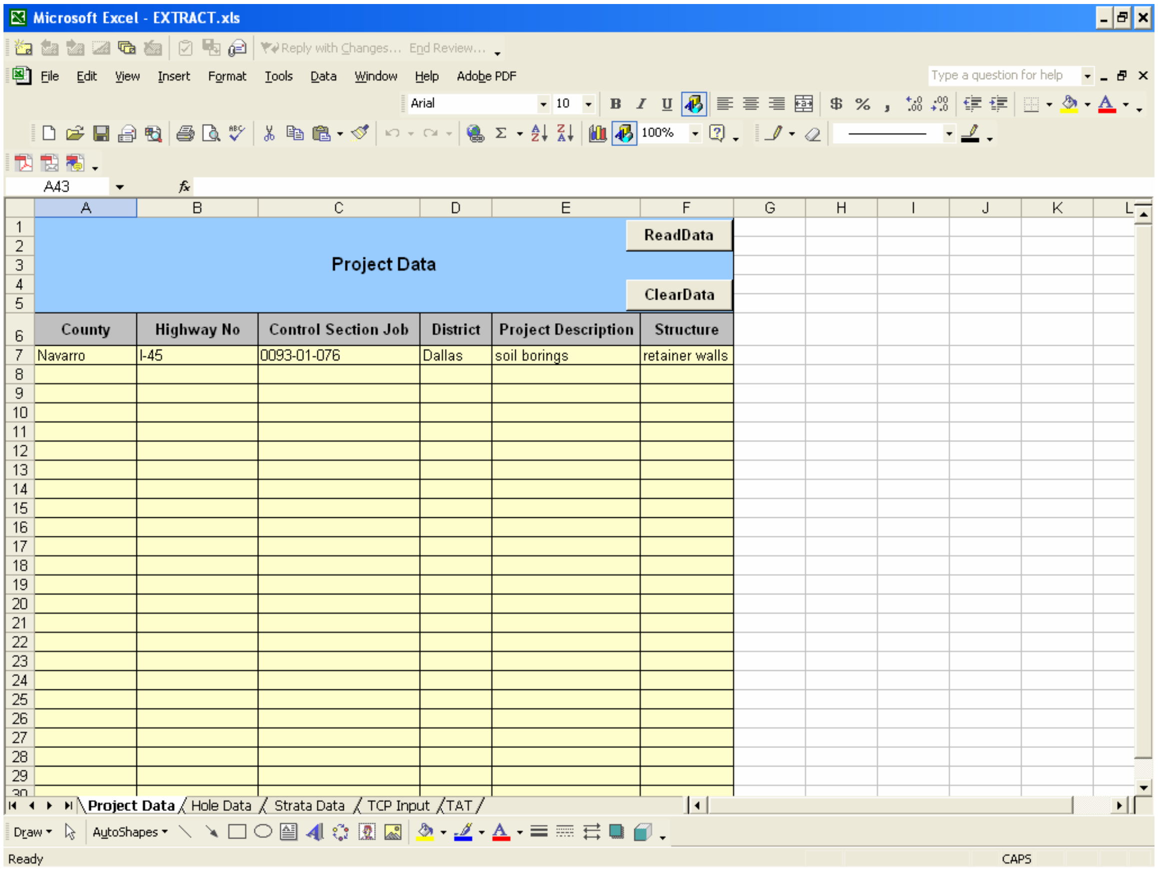


Figure B.1 Typical EXTRACT Software Screen Showing Project Data

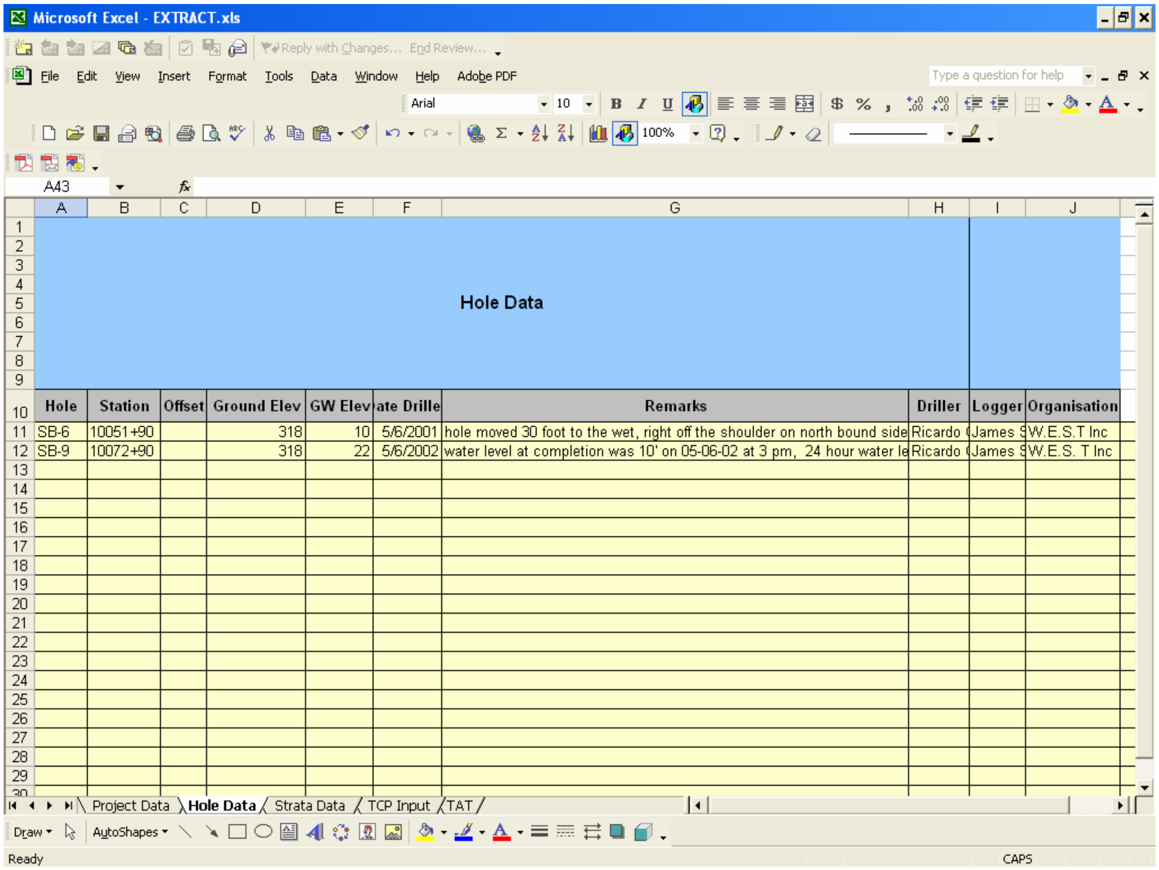
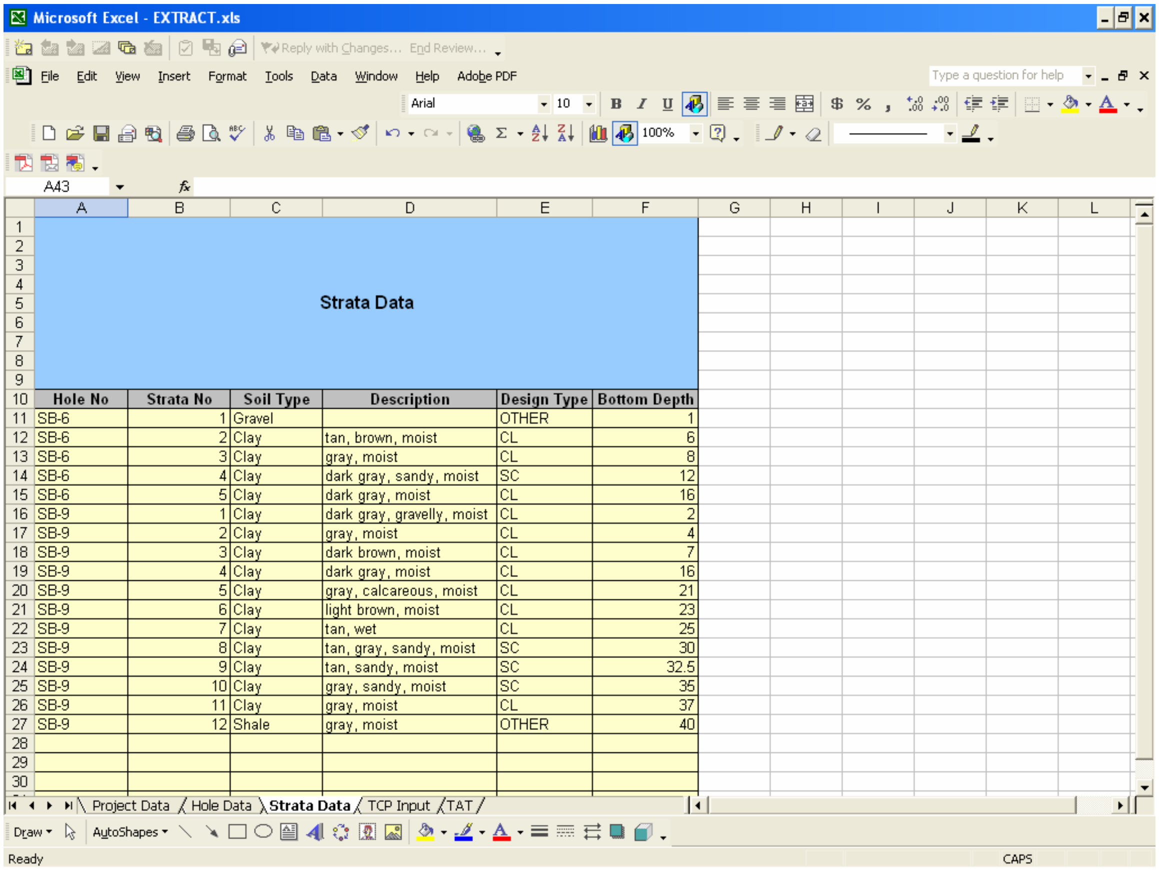


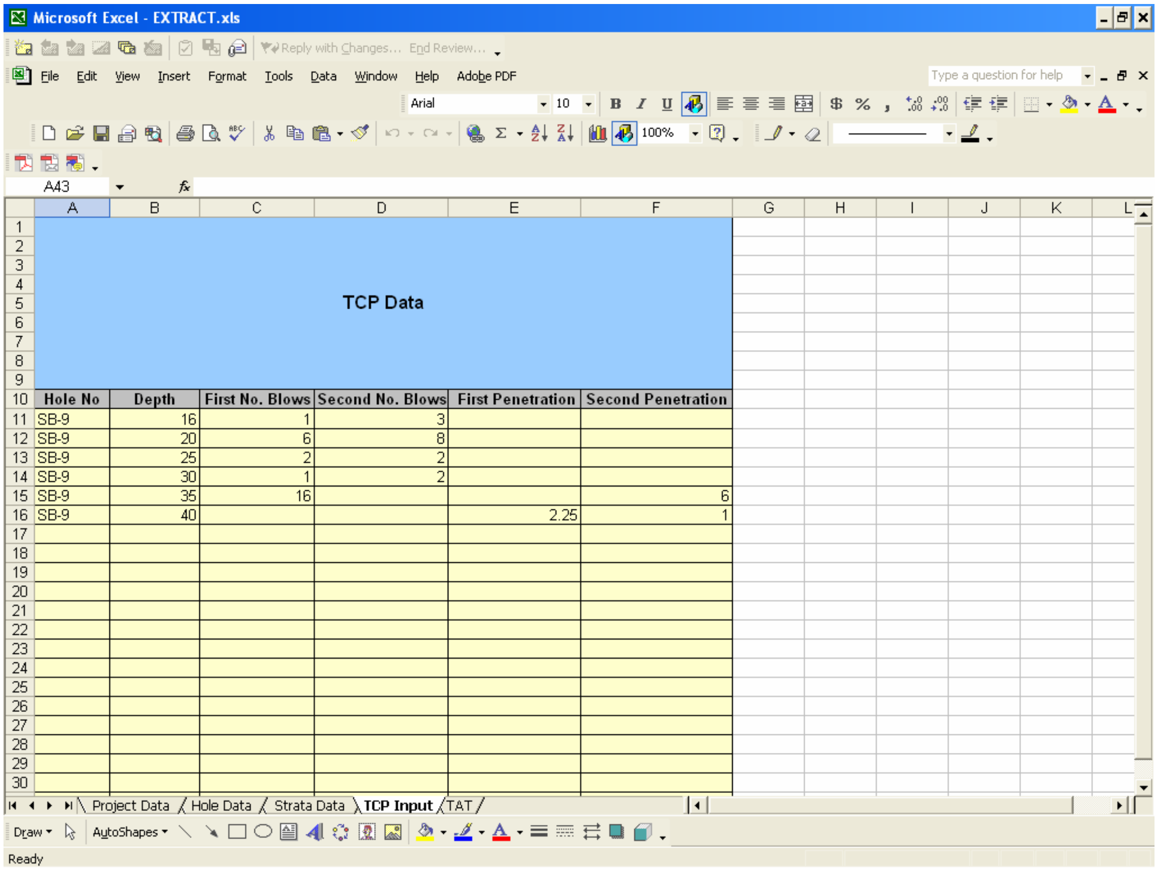
Figure B.2 Typical EXTRACT Software Screen Showing Borehole Data



Strata Data

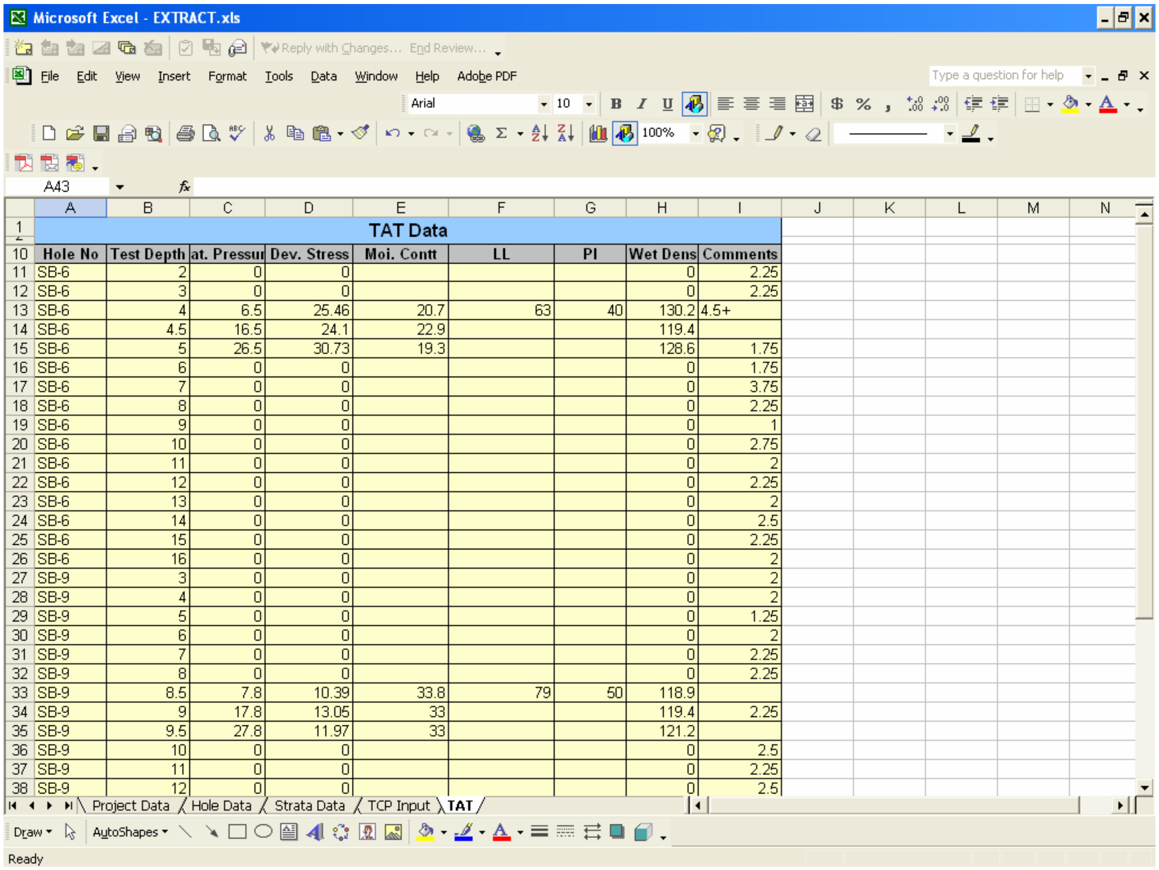
Hole No	Strata No	Soil Type	Description	Design Type	Bottom Depth
SB-6	1	Gravel		OTHER	1
SB-6	2	Clay	tan, brown, moist	CL	6
SB-6	3	Clay	gray, moist	CL	8
SB-6	4	Clay	dark gray, sandy, moist	SC	12
SB-6	5	Clay	dark gray, moist	CL	16
SB-9	1	Clay	dark gray, gravelly, moist	CL	2
SB-9	2	Clay	gray, moist	CL	4
SB-9	3	Clay	dark brown, moist	CL	7
SB-9	4	Clay	dark gray, moist	CL	16
SB-9	5	Clay	gray, calcareous, moist	CL	21
SB-9	6	Clay	light brown, moist	CL	23
SB-9	7	Clay	tan, wet	CL	25
SB-9	8	Clay	tan, gray, sandy, moist	SC	30
SB-9	9	Clay	tan, sandy, moist	SC	32.5
SB-9	10	Clay	gray, sandy, moist	SC	35
SB-9	11	Clay	gray, moist	CL	37
SB-9	12	Shale	gray, moist	OTHER	40

Figure B.3 Typical EXTRACT Software Screen Showing Strata Data



Hole No	Depth	First No. Blows	Second No. Blows	First Penetration	Second Penetration
SB-9	16	1	3		
SB-9	20	6	8		
SB-9	25	2	2		
SB-9	30	1	2		
SB-9	35	16			6
SB-9	40			2.25	1

Figure B.4 Typical EXTRACT Software Screen Showing TCP Data



	A	B	C	D	E	F	G	H	I
1	TAT Data								
10	Hole No	Test Depth	at. Pressur	Dev. Stress	Moi. Contt	LL	PI	Wet Dens	Comments
11	SB-6	2	0	0				0	2.25
12	SB-6	3	0	0				0	2.25
13	SB-6	4	6.5	25.46	20.7	63	40	130.2	4.5+
14	SB-6	4.5	16.5	24.1	22.9			119.4	
15	SB-6	5	26.5	30.73	19.3			128.6	1.75
16	SB-6	6	0	0				0	1.75
17	SB-6	7	0	0				0	3.75
18	SB-6	8	0	0				0	2.25
19	SB-6	9	0	0				0	1
20	SB-6	10	0	0				0	2.75
21	SB-6	11	0	0				0	2
22	SB-6	12	0	0				0	2.25
23	SB-6	13	0	0				0	2
24	SB-6	14	0	0				0	2.5
25	SB-6	15	0	0				0	2.25
26	SB-6	16	0	0				0	2
27	SB-9	3	0	0				0	2
28	SB-9	4	0	0				0	2
29	SB-9	5	0	0				0	1.25
30	SB-9	6	0	0				0	2
31	SB-9	7	0	0				0	2.25
32	SB-9	8	0	0				0	2.25
33	SB-9	8.5	7.8	10.39	33.8	79	50	118.9	
34	SB-9	9	17.8	13.05	33			119.4	2.25
35	SB-9	9.5	27.8	11.97	33			121.2	
36	SB-9	10	0	0				0	2.5
37	SB-9	11	0	0				0	2.25
38	SB-9	12	0	0				0	2.5

Figure B.5 Typical EXTRACT Software Screen Showing Laboratory Data

APPENDIX C

TEMPLATE OF TABLES DEVELOPED FOR DATABASE COMPILATION

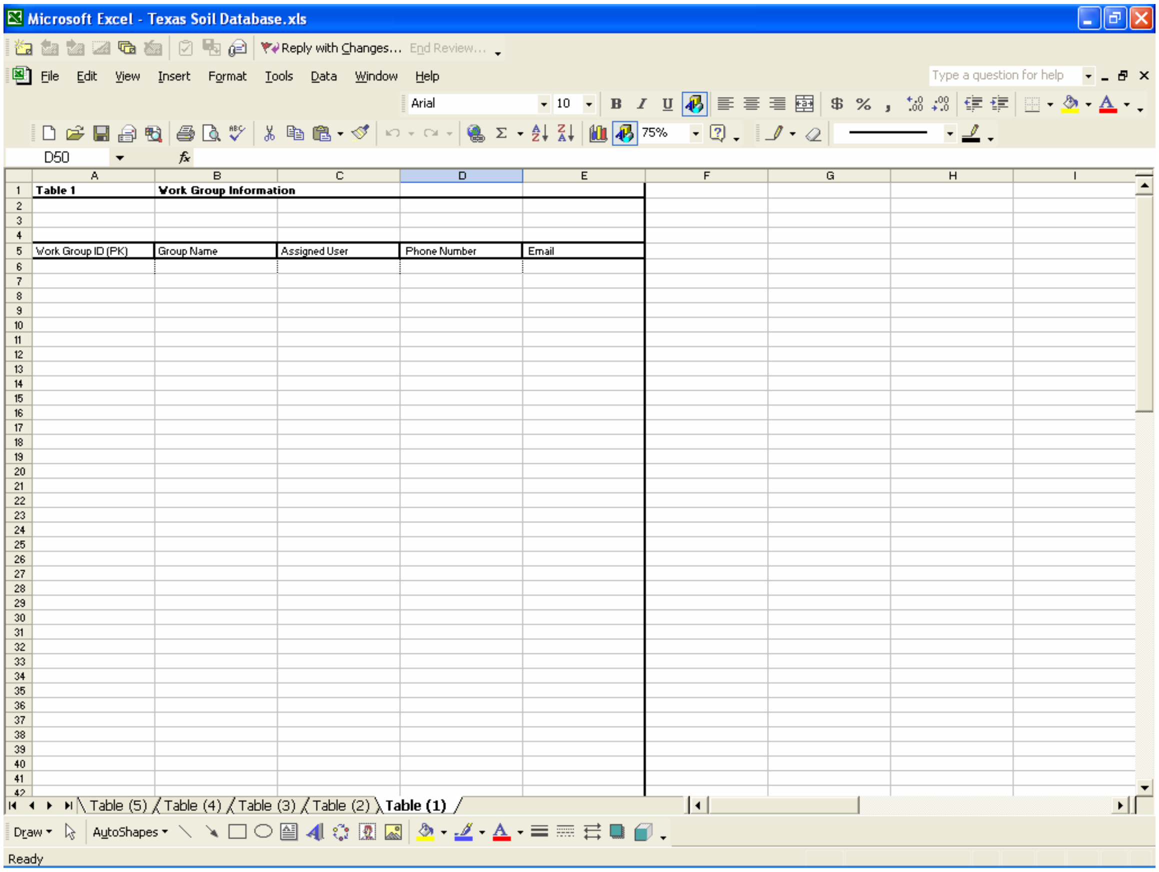


Figure C.1 Template of Table 1 for Database Compilation

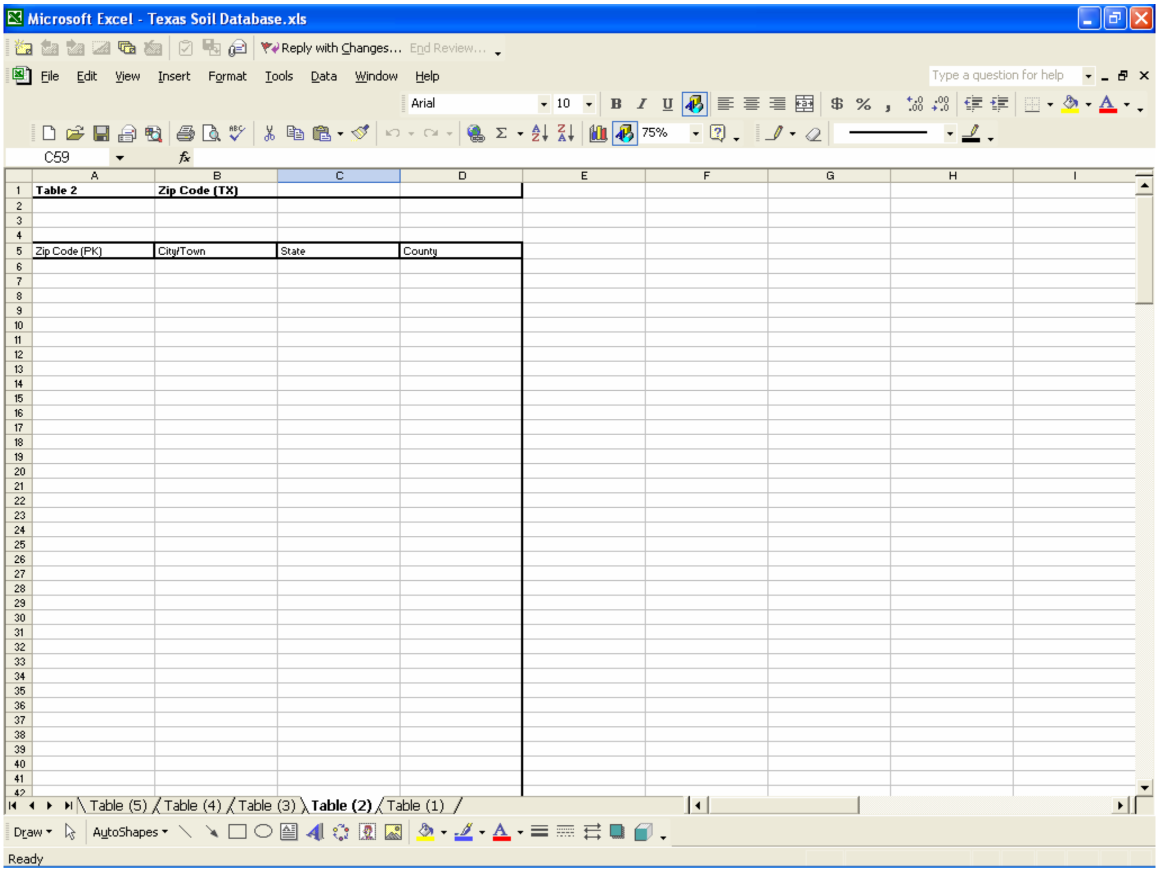


Figure C.2 Template of Table 2 for Database Compilation

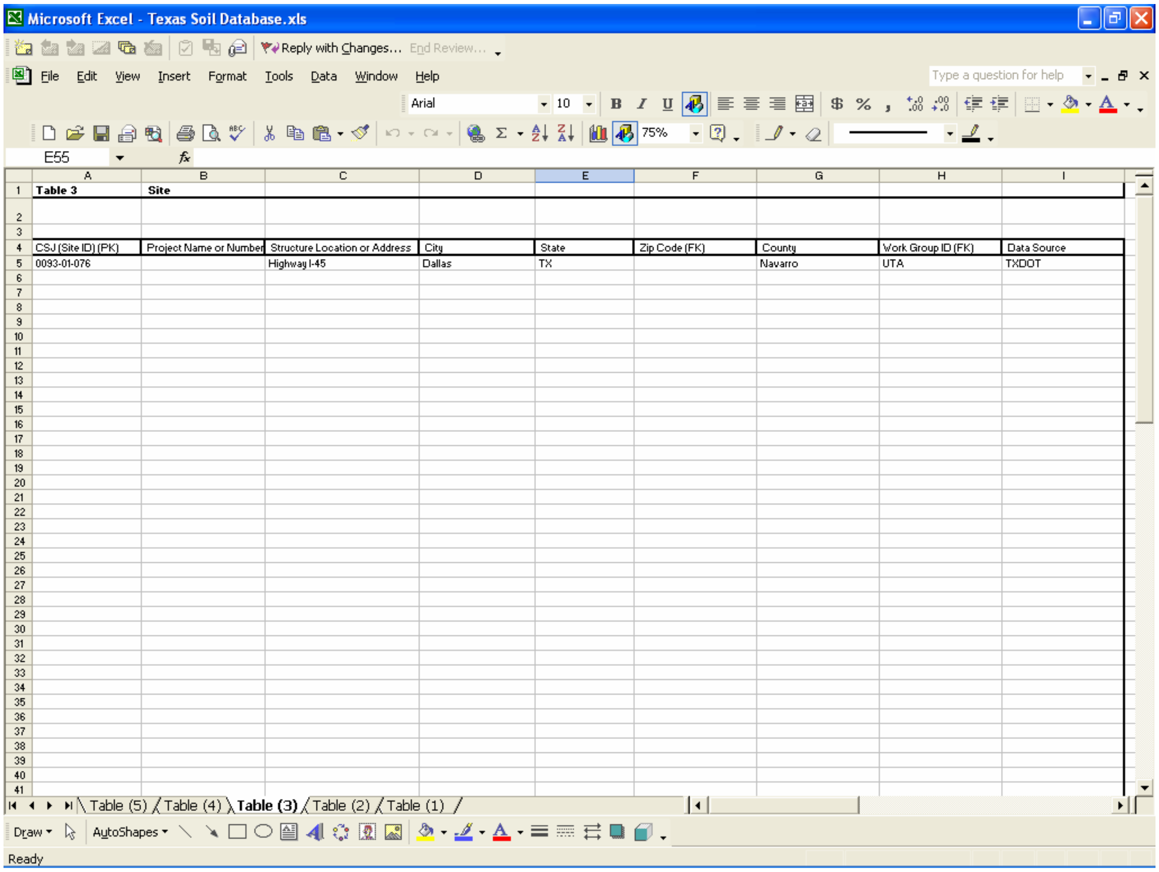


Table 3	Site							
CSJ (Site ID) (PK)	Project Name or Number	Structure Location or Address	City	State	Zip Code (FK)	County	Work Group ID (FK)	Data Source
0093-01-076		Highway I-45	Dallas	TX		Navarro	UTA	TXDOT

Figure C.3 Template of Table 3 for Database Compilation

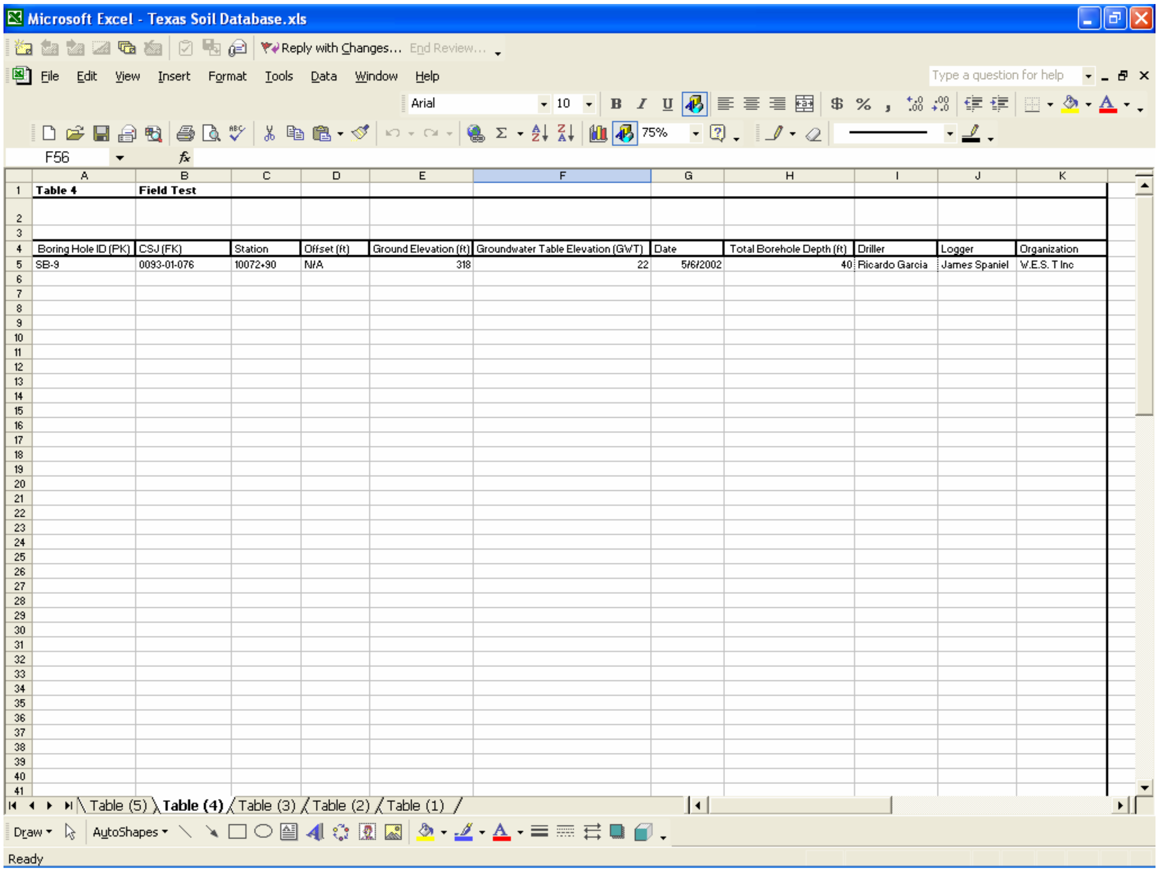


Table 4	Field Test									
Boring Hole ID (PK)	CSJ (FK)	Station	Offset (ft)	Ground Elevation (ft)	Groundwater Table Elevation (GWT)	Date	Total Borehole Depth (ft)	Driller	Logger	Organization
SB-9	0093-01-076	10072+90	N/A	318	22	5/6/2002	40	Ricardo Garcia	James Spaniel	W.E.S. T Inc

Figure C.4 Template of Table 4 for Database Compilation

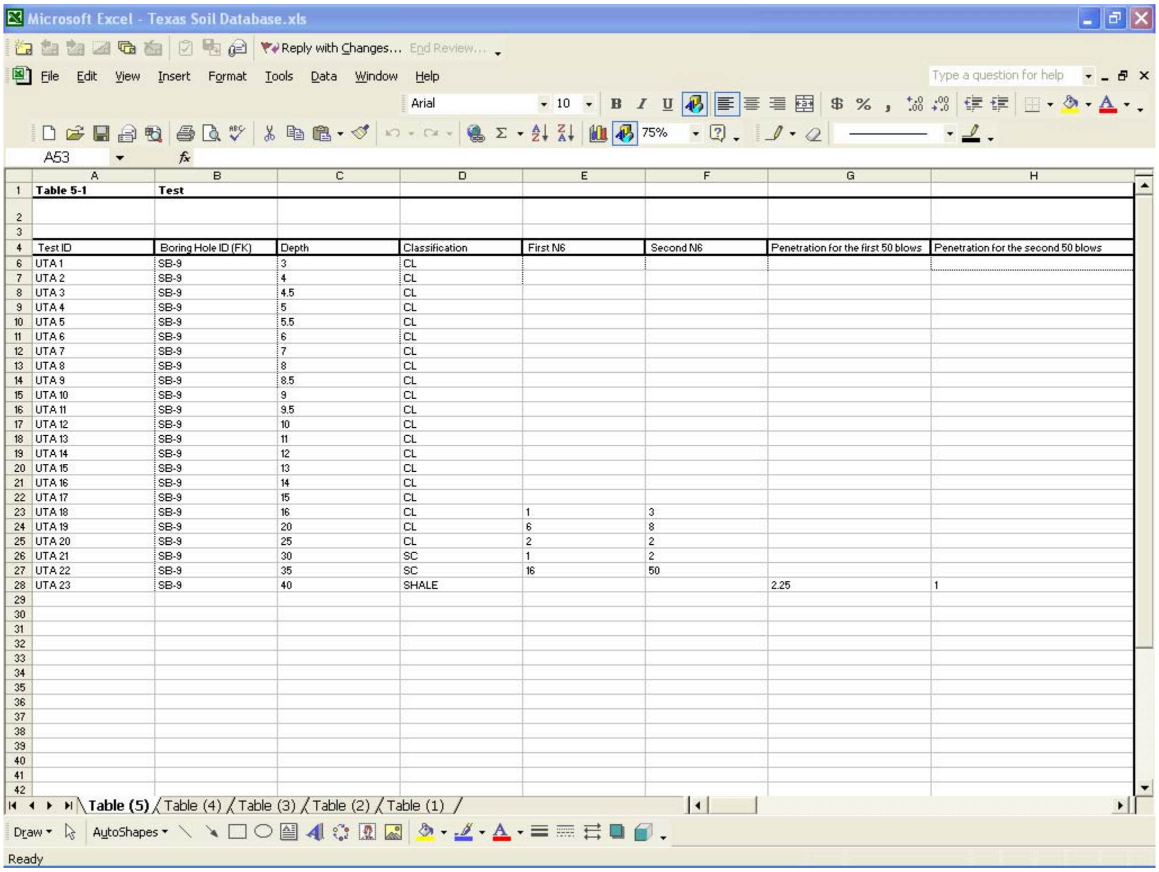


Table 5-1	Test						
Test ID	Boring Hole ID (FK)	Depth	Classification	First N6	Second N6	Penetration for the first 50 blows	Penetration for the second 50 blows
UTA 1	SB-9	3	CL				
UTA 2	SB-9	4	CL				
UTA 3	SB-9	4.5	CL				
UTA 4	SB-9	5	CL				
UTA 5	SB-9	5.5	CL				
UTA 6	SB-9	6	CL				
UTA 7	SB-9	7	CL				
UTA 8	SB-9	8	CL				
UTA 9	SB-9	8.5	CL				
UTA 10	SB-9	9	CL				
UTA 11	SB-9	9.5	CL				
UTA 12	SB-9	10	CL				
UTA 13	SB-9	11	CL				
UTA 14	SB-9	12	CL				
UTA 15	SB-9	13	CL				
UTA 16	SB-9	14	CL				
UTA 17	SB-9	15	CL				
UTA 18	SB-9	16	CL	1	3		
UTA 19	SB-9	20	CL	6	8		
UTA 20	SB-9	25	CL	2	2		
UTA 21	SB-9	30	SC	1	2		
UTA 22	SB-9	35	SC	16	50		
UTA 23	SB-9	40	SHALE			2.25	1

Figure C.5 Template of Table 5-1 for Database Compilation

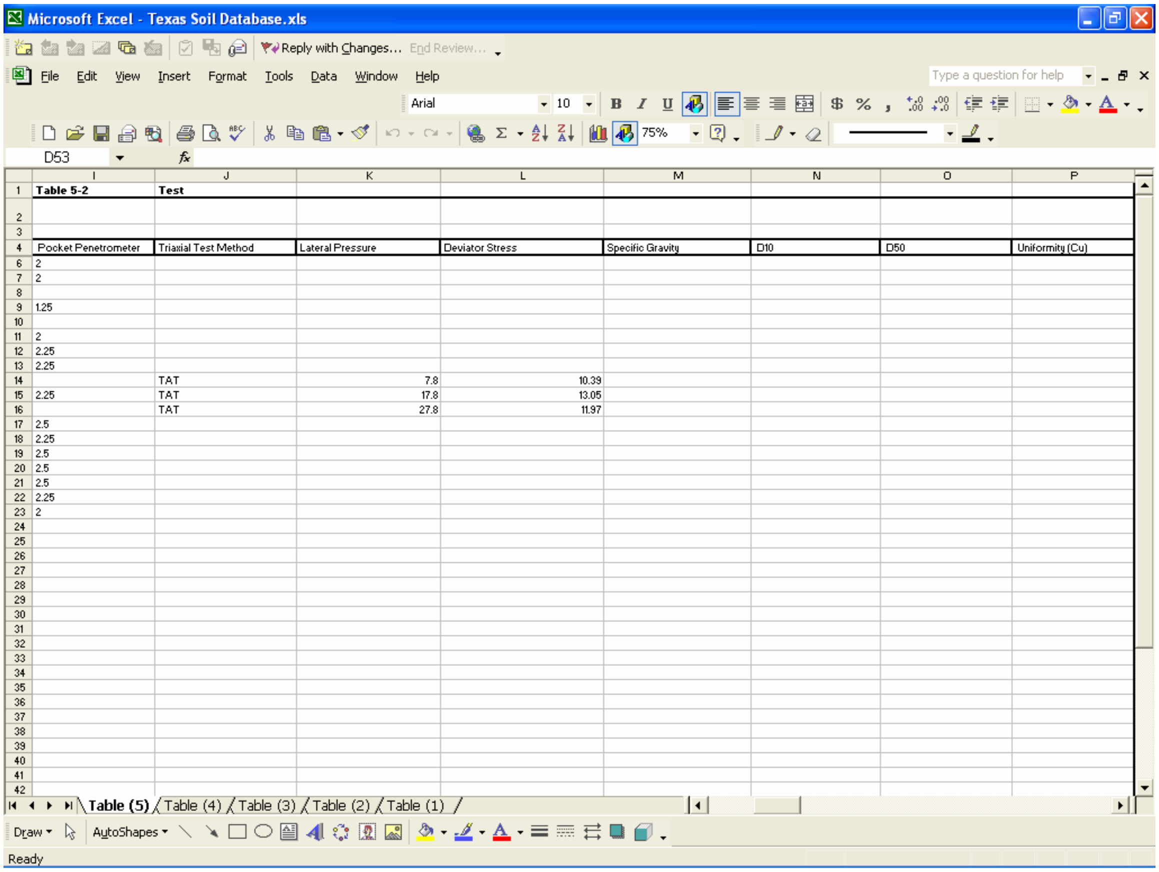


	Table 5-2	Test						
4	Pocket Penetrometer	Triaxial Test Method	Lateral Pressure	Deviator Stress	Specific Gravity	D10	D50	Uniformity (Cu)
6	2							
7	2							
9	1.25							
11	2							
12	2.25							
13	2.25							
14		TAT	7.8	10.39				
15	2.25	TAT	17.8	13.05				
16		TAT	27.8	11.97				
17	2.5							
18	2.25							
19	2.5							
20	2.5							
21	2.5							
22	2.25							
23	2							

Figure C.6 Template of Table 5-2 for Database Compilation

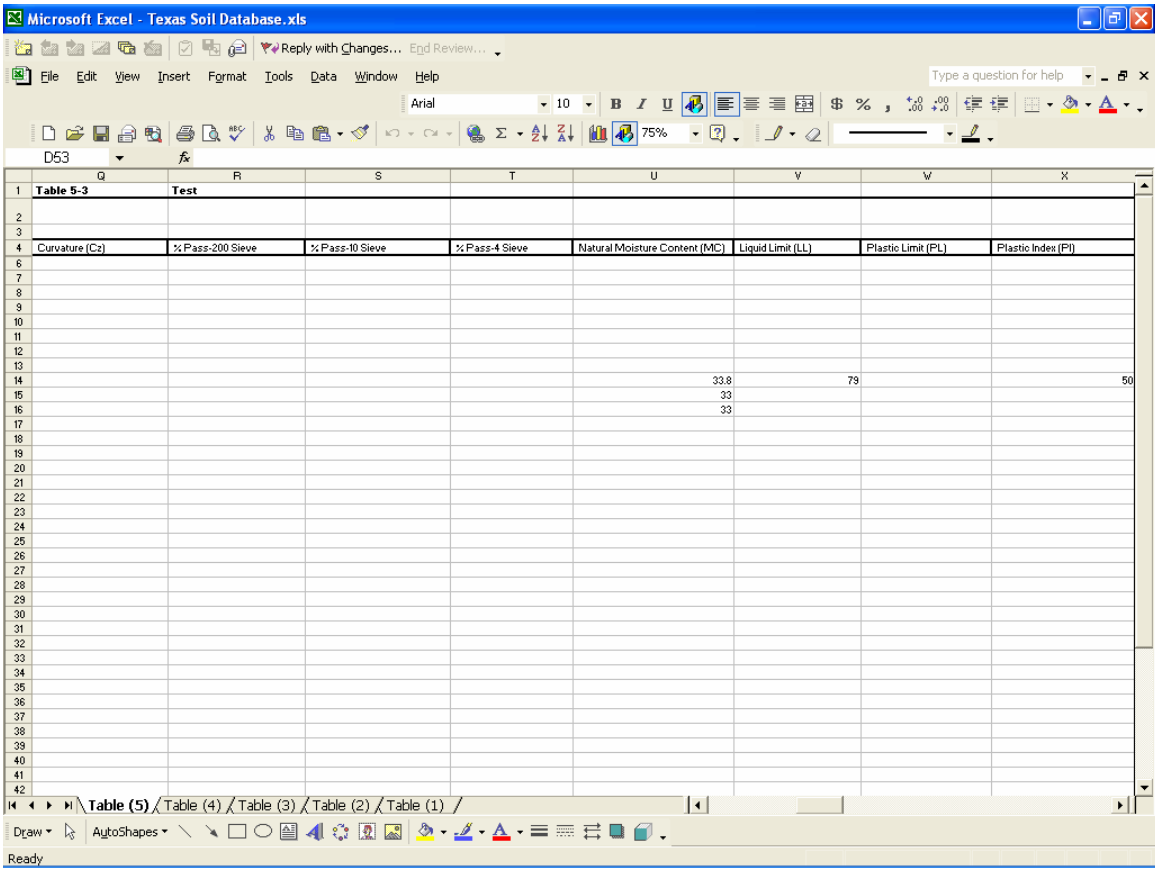


Figure C.7 Template of Table 5-3 for Database Compilation

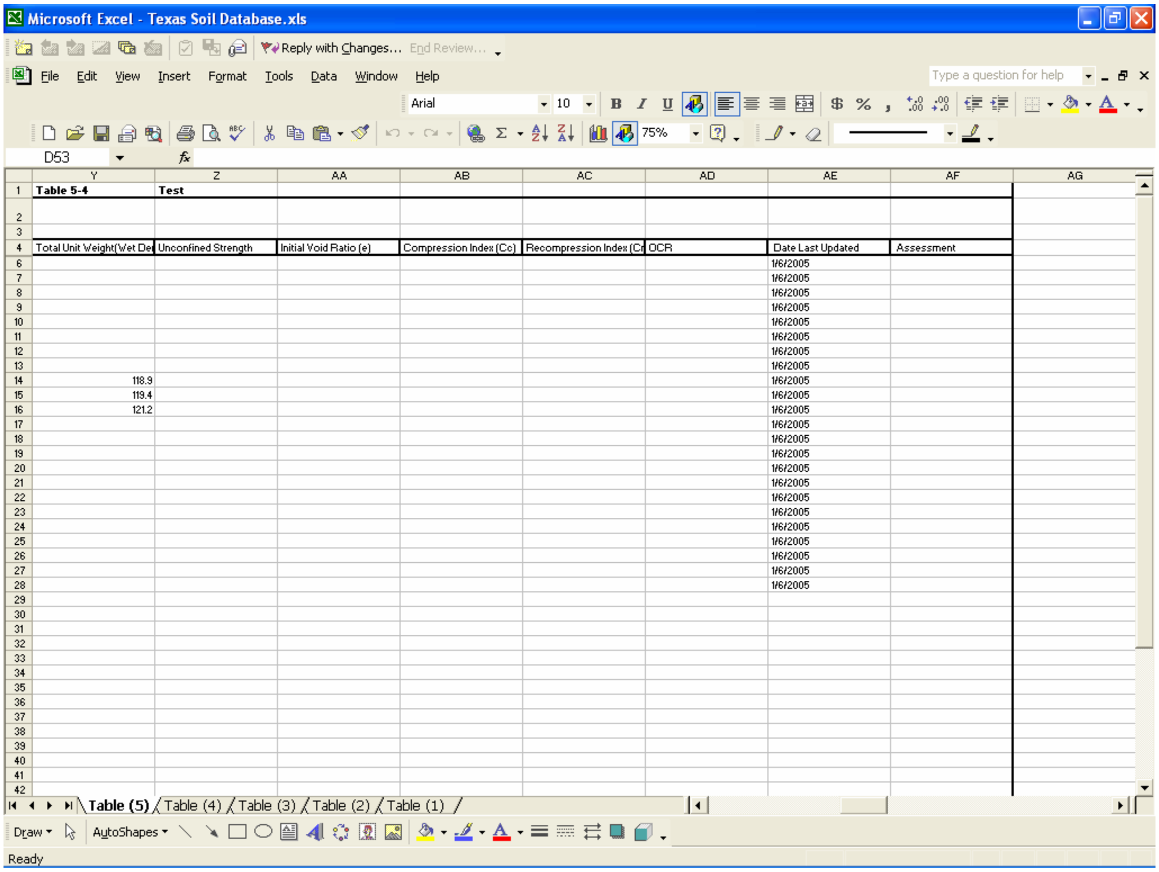


Figure C.8 Template of Table 5-4 for Database Compilation

APPENDIX D

LEGEND FOR GEOLOGY MAP OF DFW

CRETACEOUS

Upper Cretaceous

Kkc — Kemp Clay and Corsicana Marl undivided

Kns — Nacatoch Sand

Knm, Kne, Kmb — Neylandville Marl and Marlbrook Marl

Kpg — Pecan Gap Chalk (?)

Kwc — Wolfe City Sand

Ko — Ozan Formation ("lower Taylor marl")

Kau — Austin Chalk

Kef — Eagle Ford Formation

Kwb — Woodbine Formation

Lower Cretaceous

Kgm — Grayson Marl and Main Street Limestone undivided

Kpw, Kpd, Kwl, Kfd, Kdc

[p] Pawpaw Fm.
[w] Weno Ls
[d] Denton Clay
[f] Fort Worth Ls
[dc] Duck Creek Fm.

Pawpaw Formation, Weno Limestone, Denton Clay, Fort Worth Limestone, and Duck Creek Formation

Kki — Kiamichi Formation

Ked, Kcp, Kgl — Edwards Limestone, Comanche Peak Limestone, and Goodland Limestone

Kwa — Walnut Clay

Kpa — Paluxy Sand

Kgr — Glen Rose Formation

Ktm — Twin Mountains Formation

APPENDIX E

CODE FOR EXTRACT SOFTWARE

```
Type tcp
  Depth As Single
  Pen1 As Integer
  Dim1 As Single
  Pen2 As Integer
  Dim2 As Single
End Type

Type MbePoint
    x As Double
    y As Double
    z As Double
End Type

Type tat
  Depth As Single
  Lat As String
  Dev As String
  Moi As String
  LL As String
  PI As String
  WDen As String
  Comment As String
End Type

Type Strata
  Soil As String
  Desc As String
  Type As String
  Bdepth As Single
End Type

Type hole
  HoleNo As String
  sta As String
  Off As String
  Gelev As String
  Gwelev As String
  Date As String
  Remarks As String
  Driller As String
  Logger As String
  Organ As String
  NoStrata As Integer
```

```
  NoTcp As Integer
  NoTat As Integer
  Stratas(26) As Strata
  TCPs(75) As tcp
  TATs(85) As tat
End Type

Type Parameter
   width   As Single
   lnlength As Integer
   scale   As Single
   metric  As Integer
   patscale As Single
   bothole As Integer
   showunts As Integer
End Type

Type PatternCell
   name        As String
   textJust    As Integer
   height      As Double
   width       As Double
   textOffset  As Double
   labelRatio  As Double
   origin      As MbePoint
   lnlength    As Integer
   metric      As Integer
   scale       As Double
   boring      As String
   sta         As String
   elev        As String
   input       As String
   patscale    As Single
   bothole     As Integer
   showunts    As Integer
End Type

Global Status As Integer, UnitsIn As String, _
UnitsOut As String, Projarray(5) As String, _
NoHoles As Integer, Holes(20) As hole, _
coreinfo As PatternCell, _
HoleNo As Integer, param As Parameter
```

```
Sub ReadData()

Call ClearData
Dim FileName As String
   Dim fileNum   As Integer
   'Dim status    as Integer
   Dim dummy     As String
   Dim Ver       As Single
   Dim stno As Single
   Dim tno As Single
   Dim ttno As Single

stno = 1
tno = 1
ttno = 1

Dim fd As FileDialog
Set fd = Application.FileDialog(msoFileDialogFilePicker)
Dim vrtSelectedItem As Variant
 With fd
  .AllowMultiSelect = False
  .Filters.Clear
  .Filters.Add "All Files[*.*]", "*.*"
  .Filters.Add "Text Files [*.txt]", "*.txt"
  .Filters.Add "Core Log Files [*.clg]", "*.clg"
  .FilterIndex = 3
 If .Show = -1 Then
  For Each vrtSelectedItem In .SelectedItems
              FileName = vrtSelectedItem
  Next vrtSelectedItem
      'The user pressed Cancel.
   Else
     Exit Sub
  End If
   End With

   'Set the object variable to Nothing.
   Set fd = Nothing



Open FileName For Input As #1
```

```
  Input #1, dummy, UnitsIn, UnitsOut   'read units

  Input #1, dummy
  If dummy = "Start Definition" Then
    Ver = 1
  Else
    Ver = 1.5
  End If
  Application.ScreenUpdating = False
'*** input project array
  For I = 0 To 5
    Input #1, Projarray(I)
  Next I
    Sheets("Project Data").Select
    Range("A7").Select
    ActiveCell.FormulaR1C1 = Projarray(0)
    Range("B7").Select
    ActiveCell.FormulaR1C1 = Projarray(1)
    Range("C7").Select
    ActiveCell.FormulaR1C1 = Projarray(2)
    Range("D7").Select
    ActiveCell.FormulaR1C1 = Projarray(3)
    Range("E7").Select
    ActiveCell.FormulaR1C1 = Projarray(4)
    Range("F7").Select
    ActiveCell.FormulaR1C1 = Projarray(5)

'End of Project Data

  Input #1, dummy, NoHoles

For hno = 1 To NoHoles
    Input #1, dummy, Holes(hno).HoleNo, Holes(hno).sta, _
      Holes(hno).Off, Holes(hno).Gelev, Holes(hno).Gwelev, _
      Holes(hno).Date, Holes(hno).Remarks, Holes(hno).Driller, _
      Holes(hno).Logger, Holes(hno).Organ, Holes(hno).NoStrata, _
      Holes(hno).NoTcp, Holes(hno).NoTat

  'Excel Display
    Sheets("Hole Data").Select
    Range("A" & (10 + hno)).Select
    ActiveCell.FormulaR1C1 = Holes(hno).HoleNo
    Range("B" & (10 + hno)).Select
    ActiveCell.FormulaR1C1 = Holes(hno).sta
```

```
  Range("C" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Off
  Range("D" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Gelev
  Range("E" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Gwelev
  Range("F" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Date
  Range("G" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Remarks
  Range("H" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Driller
  Range("I" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Logger
  Range("J" & (10 + hno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Organ

'ExcelDisplay Ends


If Holes(hno).NoStrata > 0 Then
    Input #1, dummy
  For strano = 1 To Holes(hno).NoStrata
    Input #1, Holes(hno).Stratas(strano).Soil, Holes(hno).Stratas(strano).Desc, _
    Holes(hno).Stratas(strano).Type, Holes(hno).Stratas(strano).Bdepth

  Sheets("Strata Data").Select
  Range("A" & (10 + stno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).HoleNo
  Range("B" & (10 + stno)).Select
  ActiveCell.FormulaR1C1 = strano
  Range("C" & (10 + stno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Stratas(strano).Soil
  Range("D" & (10 + stno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Stratas(strano).Desc
  Range("E" & (10 + stno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Stratas(strano).Type
  Range("F" & (10 + stno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).Stratas(strano).Bdepth
  stno = stno + 1

  Next strano
End If
```

```
If Holes(hno).NoTcp > 0 Then
    Input #1, dummy
  For TcpNo = 1 To Holes(hno).NoTcp
    Input #1, Holes(hno).TCPs(TcpNo).Depth, Holes(hno).TCPs(TcpNo).Pen1, _
    Holes(hno).TCPs(TcpNo).Dim1, Holes(hno).TCPs(TcpNo).Pen2, _
    Holes(hno).TCPs(TcpNo).Dim2

  Sheets("TCP Input").Select
  Range("A" & (10 + tno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).HoleNo
  Range("B" & (10 + tno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).TCPs(TcpNo).Depth
  If Holes(hno).TCPs(TcpNo).Pen1 < 50 Then
  Range("C" & (10 + tno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).TCPs(TcpNo).Pen1
  Else
  Range("E" & (10 + tno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).TCPs(TcpNo).Dim1
  End If
  If Holes(hno).TCPs(TcpNo).Pen2 < 50 Then
  Range("D" & (10 + tno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).TCPs(TcpNo).Pen2
  Else
  Range("F" & (10 + tno)).Select
  ActiveCell.FormulaR1C1 = Holes(hno).TCPs(TcpNo).Dim2
  End If
  tno = tno + 1

  Next TcpNo
End If

If Holes(hno).NoTat > 0 Then
    Input #1, dummy
  For TatNo = 1 To Holes(hno).NoTat
  If Ver < 1.5 Then
    Input #1, Holes(hno).TATs(TatNo).Depth, Holes(hno).TATs(TatNo).Lat, _
      Holes(hno).TATs(TatNo).Dev, Holes(hno).TATs(TatNo).Moi, _
      Holes(hno).TATs(TatNo).LL, Holes(hno).TATs(TatNo).PI, _
      Holes(hno).TATs(TatNo).WDen
  End If
  If Ver >= 1.5 Then
    Input #1, Holes(hno).TATs(TatNo).Depth, Holes(hno).TATs(TatNo).Lat, _
      Holes(hno).TATs(TatNo).Dev, Holes(hno).TATs(TatNo).Moi, _
      Holes(hno).TATs(TatNo).LL, Holes(hno).TATs(TatNo).PI, _
```

```
     Holes(hno).TATs(TatNo).WDen, Holes(hno).TATs(TatNo).Comment
   End If

     Sheets("TAT").Select
   Range("A" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).HoleNo
   Range("B" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).Depth
   Range("C" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).Lat
   Range("D" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).Dev
   Range("E" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).Moi
   Range("F" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).LL
   Range("G" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).PI
   Range("H" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).WDen
   Range("I" & (10 + ttno)).Select
   ActiveCell.FormulaR1C1 = Holes(hno).TATs(TatNo).Comment

   ttno = ttno + 1


   Next TatNo
  End If

Next hno

Sheets("Project Data").Select

  Close #1  ' Close file.
  Application.ScreenUpdating = True

  Exit Sub

CantOpen:
   flag = -1


End Sub
```

```
Sub ClearData()

 Application.ScreenUpdating = False
 Sheets("Project Data").Rows("7:10000").ClearContents

 Sheets("Hole Data").Rows("11:10000").ClearContents

 Sheets("Strata Data").Rows("11:10000").ClearContents

 Sheets("TCP Input").Rows("11:10000").ClearContents

 Sheets("TAT").Rows("11:10000").ClearContents

 Sheets("Project Data").Select

Application.ScreenUpdating = True
End Sub
```

APPENDIX F

CODE FOR TCPSoft SOFTWARE

```
Imports System
Imports System.Configuration
Imports System.Collections
Imports System.Data
Imports System.Data.OleDb
Namespace NSTCPSoft
   Public Class InputForm
      Inherits System.Windows.Forms.Form
      Dim ds As DataSet
      'Dim OLEDB_CONN_STRING as String=
ConfigurationSettings.AppSettings["OleDbConnectionString"]
      Dim OLEDB_CONN_STRING As String =
"Provider=Microsoft.Jet.OLEDB.4.0; Data Source=tcpsoft.mdb"
      Dim DBConn As OleDbConnection
      Private Const SQL_DISTRICT_LIST = "select Districtid , Displayname from
tblDistrict where Districtid <> 0"
      Private Const SQL_TYPE_LIST = "select typeid , typedisplayname from
tblSoilType where typeid <>0"

#Region " Windows Form Designer generated code "

      Public Sub New()
         MyBase.New()

         'This call is required by the Windows Form Designer.
         InitializeComponent()

         'Add any initialization after the InitializeComponent() call

      End Sub

      'Form overrides dispose to clean up the component list.
      Protected Overloads Overrides Sub Dispose(ByVal disposing As Boolean)

         If disposing Then
            If Not (components Is Nothing) Then
               components.Dispose()
            End If
         End If
         MyBase.Dispose(disposing)
         Application.Exit()
      End Sub

      'Required by the Windows Form Designer
```

```
    Private components As System.ComponentModel.IContainer

    'NOTE: The following procedure is required by the Windows Form Designer
    'It can be modified using the Windows Form Designer.
    'Do not modify it using the code editor.
    Friend WithEvents lblSoilType As System.Windows.Forms.Label
    Friend WithEvents lblDistrict As System.Windows.Forms.Label
    Friend WithEvents lblDepth As System.Windows.Forms.Label
    Friend WithEvents lblN12 As System.Windows.Forms.Label
    Friend WithEvents cmbSoilType As System.Windows.Forms.ComboBox
    Friend WithEvents cmbDistrict As System.Windows.Forms.ComboBox
    Friend WithEvents txtN12 As System.Windows.Forms.TextBox
    Friend WithEvents txtDepth As System.Windows.Forms.TextBox
    Friend WithEvents btnCalculate As System.Windows.Forms.Button
    Friend WithEvents lblResult As System.Windows.Forms.Label
    <System.Diagnostics.DebuggerStepThrough()> Private Sub
InitializeComponent()
        Me.lblSoilType = New System.Windows.Forms.Label
        Me.lblDistrict = New System.Windows.Forms.Label
        Me.lblDepth = New System.Windows.Forms.Label
        Me.lblN12 = New System.Windows.Forms.Label
        Me.cmbSoilType = New System.Windows.Forms.ComboBox
        Me.cmbDistrict = New System.Windows.Forms.ComboBox
        Me.txtN12 = New System.Windows.Forms.TextBox
        Me.txtDepth = New System.Windows.Forms.TextBox
        Me.btnCalculate = New System.Windows.Forms.Button
        Me.lblResult = New System.Windows.Forms.Label
        Me.SuspendLayout()
        '
        'lblSoilType
        '
        Me.lblSoilType.Location = New System.Drawing.Point(24, 32)
        Me.lblSoilType.Name = "lblSoilType"
        Me.lblSoilType.Size = New System.Drawing.Size(72, 16)
        Me.lblSoilType.TabIndex = 0
        Me.lblSoilType.Text = "Soil Type"
        '
        'lblDistrict
        '
        Me.lblDistrict.Location = New System.Drawing.Point(24, 72)
        Me.lblDistrict.Name = "lblDistrict"
        Me.lblDistrict.Size = New System.Drawing.Size(72, 16)
        Me.lblDistrict.TabIndex = 1
        Me.lblDistrict.Text = "District"
```

```
'
'lblDepth
'
Me.lblDepth.Location = New System.Drawing.Point(24, 112)
Me.lblDepth.Name = "lblDepth"
Me.lblDepth.Size = New System.Drawing.Size(72, 16)
Me.lblDepth.TabIndex = 2
Me.lblDepth.Text = "Depth (in Ft)"
'
'lblN12
'
Me.lblN12.Location = New System.Drawing.Point(24, 152)
Me.lblN12.Name = "lblN12"
Me.lblN12.Size = New System.Drawing.Size(72, 16)
Me.lblN12.TabIndex = 3
Me.lblN12.Text = "N12"
'
'cmbSoilType
'
Me.cmbSoilType.AllowDrop = True
Me.cmbSoilType.Location = New System.Drawing.Point(144, 30)
Me.cmbSoilType.Name = "cmbSoilType"
Me.cmbSoilType.Size = New System.Drawing.Size(121, 21)
Me.cmbSoilType.TabIndex = 1
'
'cmbDistrict
'
Me.cmbDistrict.AllowDrop = True
Me.cmbDistrict.Location = New System.Drawing.Point(144, 70)
Me.cmbDistrict.Name = "cmbDistrict"
Me.cmbDistrict.Size = New System.Drawing.Size(121, 21)
Me.cmbDistrict.TabIndex = 2
'
'txtN12
'
Me.txtN12.Location = New System.Drawing.Point(144, 150)
Me.txtN12.Name = "txtN12"
Me.txtN12.Size = New System.Drawing.Size(121, 20)
Me.txtN12.TabIndex = 4
Me.txtN12.Text = ""
'
'txtDepth
'
Me.txtDepth.Location = New System.Drawing.Point(144, 110)
```

```
        Me.txtDepth.Name = "txtDepth"
        Me.txtDepth.Size = New System.Drawing.Size(121, 20)
        Me.txtDepth.TabIndex = 3
        Me.txtDepth.Text = ""
        '
        'btnCalculate
        '
        Me.btnCalculate.DialogResult =
System.Windows.Forms.DialogResult.Cancel
        Me.btnCalculate.Location = New System.Drawing.Point(24, 198)
        Me.btnCalculate.Name = "btnCalculate"
        Me.btnCalculate.Size = New System.Drawing.Size(80, 24)
        Me.btnCalculate.TabIndex = 5
        Me.btnCalculate.Text = "Calculate"
        '
        'lblResult
        '
        Me.lblResult.Font = New System.Drawing.Font("Tahoma", 9.0!,
System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point, CType(0,
Byte))
        Me.lblResult.Location = New System.Drawing.Point(28, 248)
        Me.lblResult.Name = "lblResult"
        Me.lblResult.Size = New System.Drawing.Size(344, 48)
        Me.lblResult.TabIndex = 10
        '
        'InputForm
        '
        Me.AutoScaleBaseSize = New System.Drawing.Size(5, 13)
        Me.ClientSize = New System.Drawing.Size(384, 357)
        Me.Controls.Add(Me.lblResult)
        Me.Controls.Add(Me.btnCalculate)
        Me.Controls.Add(Me.txtDepth)
        Me.Controls.Add(Me.txtN12)
        Me.Controls.Add(Me.cmbDistrict)
        Me.Controls.Add(Me.cmbSoilType)
        Me.Controls.Add(Me.lblN12)
        Me.Controls.Add(Me.lblDepth)
        Me.Controls.Add(Me.lblDistrict)
        Me.Controls.Add(Me.lblSoilType)
        Me.MaximizeBox = False
        Me.MaximumSize = New System.Drawing.Size(392, 384)
        Me.MinimizeBox = False
        Me.MinimumSize = New System.Drawing.Size(392, 384)
        Me.Name = "InputForm"
```

```
        Me.StartPosition =
System.Windows.Forms.FormStartPosition.CenterScreen
        Me.Text = "TCPSoft"
        Me.ResumeLayout(False)

    End Sub

#End Region

    Public Sub InputForm_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        'public static readonly String OLEDB_CONN_STRING =
ConfigurationSettings.AppSettings["OleDbConnectionString"];
        DBConn = New OleDbConnection(OLEDB_CONN_STRING)
        DBConn.Open()
        Dim cmd As New OleDbCommand(SQL_DISTRICT_LIST, DBConn)
        'Dim assd as Oled
        Dim rdr As OleDbDataReader =
cmd.ExecuteReader(CommandBehavior.CloseConnection)
        While rdr.Read
            'Dim Str As String = rdr.Item(1) 'rdr.GetString(1)
            cmbDistrict.Items.Add(rdr.GetString(1))
            'cmb()
        End While
        rdr.Close()
        DBConn.Open()
        Dim cmd2 As New OleDbCommand(SQL_TYPE_LIST, DBConn)
        rdr = cmd2.ExecuteReader(CommandBehavior.CloseConnection)
        While rdr.Read
            'Dim Str As String = rdr.Item(1) 'rdr.GetString(1)
            cmbSoilType.Items.Add(rdr.GetString(1))
            'cmb()
        End While
        rdr.Close()



    End Sub

    Private Sub txtN12_TextChanged(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles txtN12.TextChanged
        Try

        Catch ex As Exception
```

```
    End Try

End Sub

Private Function ValidateVal() As Boolean
    If (cmbSoilType.SelectedIndex = -1) Then
        MessageBox.Show("Select a Soil Type")
        cmbSoilType.Focus()
        Return False
    End If
    If (cmbDistrict.SelectedIndex = -1) Then
        MessageBox.Show("Select a District")
        cmbDistrict.Focus()
        Return False
    End If


    Try
        Dim temp As Integer = txtDepth.Text
    Catch ex As Exception
        MessageBox.Show("Enter a numeric value for Depth")
        txtDepth.Text = ""
        txtDepth.Focus()
        Return False
    End Try
    Return True
    Try
        Dim temp As Integer = txtN12.Text
        If (temp > 100) Then
            MessageBox.Show("Enter the value of N12 less than 100")
            txtN12.Text = ""
            txtN12.Focus()
            Return False
        End If
    Catch ex As Exception
        MessageBox.Show("Enter a numeric value for N12")
        txtN12.Text = ""
        txtN12.Focus()
        Return False
    End Try

End Function
```

```
    Private Sub btnCalculate_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles btnCalculate.Click
        If Not ValidateVal() Then
            Return
        End If
        'Dim soiltype As Integer = cmbSoilType.SelectedIndex
        'Dim Districtid As Integer = cmbDistrict.SelectedIndex
        Dim soiltype As String = cmbSoilType.SelectedItem
        Dim Districtid As String = cmbDistrict.SelectedItem
        'Dim constantsquery = "select C1, C2, C3 from tblformula where
SoilTypeId=" & soiltype + 1 & " and DistrictId=" & Districtid + 1
        Dim constantsquery = "select C1, C2, C3 from tblformula where
SoilTypeName='" & soiltype & "' and DistrictName='" & Districtid
        constantsquery = constantsquery & "' and Depth1 < " & txtDepth.Text & "
and Depth2>=" & txtDepth.Text
        constantsquery = constantsquery & " and N121 < " & txtN12.Text & " and
N122>=" & txtN12.Text
        Dim C1 As Double, C2 As Double, C3 As Double
        Dim cmd As OleDbCommand = New OleDbCommand(constantsquery,
DBConn)
        DBConn.Open()
        Dim rdr As OleDbDataReader =
cmd.ExecuteReader(CommandBehavior.CloseConnection)
        If rdr.Read Then
            C1 = rdr.GetDouble(0)
            C2 = rdr.GetDouble(1)
            C3 = rdr.GetDouble(2)
            Dim value As Double = C1 + (C2 * txtN12.Text) + (C3 * txtDepth.Text)
            value = (Math.Ceiling(value * 100)) / 100
                            If (value < 0) Then
                  lblResult.Text = "IT IS BEST RECOMMENDED TO TEST
SHEAR STRENGTH OF THE SOIL FOR THE GIVEN INPUT CONDITION"
                            Else
                  lblResult.Text = "SHEAR STRENGTH OF THE SOIL FOR THE
INPUT CONDITIONS IS " & value & " psi"
                            End If
        Else
            lblResult.Text = "IT IS BEST RECOMMENDED TO TEST SHEAR
STRENGTH OF THE SOIL FOR THE GIVEN INPUT CONDITION"

        End If
        rdr.Close()

    End Sub
```

```
        Private Sub lblResult_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles lblResult.Click

        End Sub
    End Class

End Namespace



Namespace NSTCPSoft
    Public Class TCPSoft
        Inherits System.Windows.Forms.Form

#Region " Windows Form Designer generated code "

        Public Sub New()
            MyBase.New()

            'This call is required by the Windows Form Designer.
            InitializeComponent()

            'Add any initialization after the InitializeComponent() call

        End Sub

        'Form overrides dispose to clean up the component list.
        Protected Overloads Overrides Sub Dispose(ByVal disposing As Boolean)
            If disposing Then
                If Not (components Is Nothing) Then
                    components.Dispose()
                End If
            End If
            MyBase.Dispose(disposing)
        End Sub

        'Required by the Windows Form Designer
        Private components As System.ComponentModel.IContainer

        'NOTE: The following procedure is required by the Windows Form Designer
        'It can be modified using the Windows Form Designer.
        'Do not modify it using the code editor.
        Friend WithEvents Timer1 As System.Windows.Forms.Timer
```

```
    Private WithEvents lblDisclaimer As System.Windows.Forms.Label
    Friend WithEvents lblDisclaimerText As System.Windows.Forms.Label
    Friend WithEvents btnOK As System.Windows.Forms.Button
    Friend WithEvents btnCancel As System.Windows.Forms.Button
    <System.Diagnostics.DebuggerStepThrough()> Private Sub
InitializeComponent()
        Me.components = New System.ComponentModel.Container
        Me.Timer1 = New System.Windows.Forms.Timer(Me.components)
        Me.lblDisclaimer = New System.Windows.Forms.Label
        Me.lblDisclaimerText = New System.Windows.Forms.Label
        Me.btnOK = New System.Windows.Forms.Button
        Me.btnCancel = New System.Windows.Forms.Button
        Me.SuspendLayout()
        '
        'Timer1
        '
        Me.Timer1.Interval = 3000
        '
        'lblDisclaimer
        '
        Me.lblDisclaimer.Font = New System.Drawing.Font("Trebuchet MS",
12.0!, System.Drawing.FontStyle.Bold, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.lblDisclaimer.Location = New System.Drawing.Point(120, 16)
        Me.lblDisclaimer.Name = "lblDisclaimer"
        Me.lblDisclaimer.Size = New System.Drawing.Size(96, 24)
        Me.lblDisclaimer.TabIndex = 0
        Me.lblDisclaimer.Text = "DISCLAIMER"
        '
        'lblDisclaimerText
        '
        Me.lblDisclaimerText.Font = New System.Drawing.Font("Trebuchet MS",
9.0!, System.Drawing.FontStyle.Regular, System.Drawing.GraphicsUnit.Point,
CType(0, Byte))
        Me.lblDisclaimerText.Location = New System.Drawing.Point(32, 64)
        Me.lblDisclaimerText.Name = "lblDisclaimerText"
        Me.lblDisclaimerText.Size = New System.Drawing.Size(288, 120)
        Me.lblDisclaimerText.TabIndex = 1
        Me.lblDisclaimerText.Text = "lblDisclaimerText"
        '
        'btnOK
        '
        Me.btnOK.Location = New System.Drawing.Point(48, 208)
        Me.btnOK.Name = "btnOK"
```

```
        Me.btnOK.TabIndex = 2
        Me.btnOK.Text = "OK"
        '
        'btnCancel
        '
        Me.btnCancel.Location = New System.Drawing.Point(216, 208)
        Me.btnCancel.Name = "btnCancel"
        Me.btnCancel.TabIndex = 3
        Me.btnCancel.Text = "Cancel"
        '
        'TCPSoft
        '
        Me.AutoScaleBaseSize = New System.Drawing.Size(5, 13)
        Me.ClientSize = New System.Drawing.Size(344, 264)
        Me.ControlBox = False
        Me.Controls.Add(Me.btnCancel)
        Me.Controls.Add(Me.btnOK)
        Me.Controls.Add(Me.lblDisclaimerText)
        Me.Controls.Add(Me.lblDisclaimer)
        Me.FormBorderStyle = System.Windows.Forms.FormBorderStyle.None
        Me.MaximizeBox = False
        Me.MinimizeBox = False
        Me.Name = "TCPSoft"
        Me.ShowInTaskbar = False
        Me.StartPosition =
System.Windows.Forms.FormStartPosition.CenterScreen
        Me.Text = "TCPSoft"
        Me.ResumeLayout(False)

    End Sub

#End Region
    Private forminput As InputForm
    Private Sub Form1_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        Me.lblDisclaimerText.Text = "The results derived by TCPsoft are intended
for review, "
        Me.lblDisclaimerText.Text = Me.lblDisclaimerText.Text & "interpretation,
and approval by a registered professional engineer."
        Me.lblDisclaimerText.Text = Me.lblDisclaimerText.Text & "The results of
TCPsoft have been tested, but the developer assumes no responsibility for the
validity of the results thus produced."
    End Sub
```

```
    Private Sub Timer1_Tick(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles Timer1.Tick
        'xForm.
        Me.Hide()
        Timer1.Enabled = False
    End Sub

    Private Sub lblDisclaimer_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles lblDisclaimer.Click

    End Sub

    Private Sub btnOK_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles btnOK.Click
        forminput = New InputForm
        Me.Hide()
        forminput.Show()
    End Sub

    Private Sub btnCancel_Click(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles btnCancel.Click
        Application.Exit()

    End Sub
  End Class
End Namespace
```

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