Correlation of Texas Cone Penetrometer Test Values and Shear Strength of Texas Soils: Technical Report

TxDOT Project Report No. 0-4862-1
Final Report

Texas Department of Transportation
and
Federal Highway Administration

by
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16. Abstract

This report discusses the correlation of Texas Cone Penetrometer (TCP) test values and shear strength of Texas soils. Data collected over the past decade by the Texas Department of Transportation (TxDOT) from several parts of Texas were used to verify the current correlation between TCP blow count and the undrained shear strengths of clays with higher (CH) and low liquid limits (CL), sandy clay (SC) and Other soils. Over 4000 sets of data were used to verify the current TxDOT relationships for the entire state of Texas and three TxDOT districts from where most of the data were collected. Limited field studies were performed to verify the current TxDOT relationship with CH and CL soils. Based on the data available and statistical analyses, linear and nonlinear relationships between undrained shear strength of soil and TCP blow count have been developed. The statistical parameters including the probability distribution functions (PDF) for the undrained shear strength (S_u) and TCP blow count (N_{TCP}) based on the type of soil were determined. Analyses showed that the current TxDOT design relationships overestimated the undrained shear strength (S_u) and TCP blow count (N_{TCP}) was dependent on the depth for all types of soils investigated. The depth dependency also varied from location to location. The undrained shear strength versus TCP blow count relationships developed were also influenced by the locations.

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ENGINEERING DISCLAIMER

PREFACE

In Texas, the Texas Cone Penetrometer (TCP) test is conducted during foundation exploration. Since the TCP test is routinely carried out and required for investigation of foundation materials encountered during geotechnical exploration for TxDOT projects, a large amount of data from this test are available.

Correlations based on the test values could be very useful to engineers to determine the undrained shear strength of the soil and limited research was done in the mid 1970s to correlate the TCP blow count (N_{TCP}) to the undrained shear strength of soil (S_u). These studies were performed in the upper Gulf Coast region with limited number of data. Hence, in order to verify the current correlations for soils from different regions of Texas, a research study was initiated at three universities: The University of Houston, Lamar University and The University of Texas at Arlington.

The main objective of this study was to verify the current design relationship used by TxDOT to determine the undrained shear strength of soil from TCP blow count and, if necessary, develop correlations based on the data collected.

In this study, Texas was divided into three sectors to collect the data and the data were collected from TxDOT projects over the past decade (1994 - 2004) and analyzed. Over 4000 sets of data were collected on CH, CL, SC and Other soil types and used in the analyzes. Collected data were verified with the current TxDOT relationships for each soil type for the entire state and for a few TxDOT districts with large amounts of data. Data were statistically analyzed for each blow count. Linear and nonlinear relationships between TCP blow count and undrained shear strength have been developed. Depth effect (influenced by geology and active zone) on blow count and shear strength was investigated.

This report summarizes the verification of the current TxDOT design relationships and developed new relationships between the undrained shear strength of various soils and TCP blow count based on the data collected by TxDOT.

ABSTRACT

Since the Texas Cone Penetrometer (TCP) tests are routinely performed during any foundation exploration for the Texas Department of Transportation (TxDOT), a large amount of data has been collected over the past decades. Correlations based on the blow counts and soil types are currently used to determine the undrained shear strength of the soils. Limited research was done in the mid 1970s to correlate the TCP blow counts to the undrained shear strength of soil, especially for soil in the Upper Gulf Coast region.

In this study, data collected over the past decade by TxDOT were used to verify the current correlations between the TCP blow count and the undrained shear strengths of CH, CL, SC and Other soils. Over 4000 sets of data were used to verify the current TxDOT relationships and the data were collected from four TxDOT districts. Limited field studies were performed to verify the current TxDOT relationship with CH and CL soils.

Analysis of the data showed that, as compared to other soils, CL soils had better correlation with the current TxDOT Method. Based on the data available and statistical analyses, linear and nonlinear relationships between the undrained shear strength of soil and the TCP blow count have been developed. The statistical parameters including the probability distribution functions (PDF) for the undrained shear strength (S_u) and TCP blow count (N_{TCP}) based on the type of soils were determined. Based on the analysis of data for every TCP blow count (N_{TCP}), the predominant probability distribution function (PDF) for S_u was lognormal. Analysis of the data also showed that the depth affected the TCP blow count. Validation analysis with about 1% of the data (about 50 data sets) collected from this study showed that the TxDOT relationship over predicted the least amount of data compared to the other relationships investigated in this study.

The study was completed in two years and was a joint effort among researchers at University of Houston, University of Texas at Arlington and Lamar University.

SUMMARY

The Texas Cone Penetrometer (TCP) is a sounding test similar to the Standard Penetration Test (SPT) and Cone Penetration Test (CPT) used to determine the in situ soil parameters for foundation design. In the case of the TCP test, the potential energy resulting from the hammer impact is similar to the SPT test. The cone shape and apex angle of the TCP are similar to the CPT but the diameter is larger. Therefore, it can be stated that the TCP is a hybrid of the SPT and the CPT, and can be used in all types of soils. The TCP test is a standardized test procedure currently used by the Texas Department of Transportation (TxDOT) for geotechnical studies to indirectly estimate the in situ undrained shear strength of soils (TxDOT Geotechnical Manual, 2000).

The objective of this project was to verify the current design relationship used by TxDOT to determine the undrained shear strength of soil from TCP blow count and to develop correlations with high level of confidence based on the data collected. The parameters investigated were soil types, depth and locations. The objectives were achieved by collecting data from TxDOT projects over the past decade (1994 - 2004) by three universities—The University of Houston, Lamar University and University of Texas at Arlington—together with limited field study and laboratory tests on the soil samples collected for the field. Over 4,000 data sets (TCP blow count (N_{TCP}) and undrained shear strength (S_u) were collected from 3,987 bore holes from past TxDOT projects. The cumulative length of the bore holes was 177,298 ft. Of the over 4,000 data sets, 2,100 data sets were identified as CH soils, 1,852 data sets were identified as CL soils, 29 data sets were identified as SC soils, and 42 data sets were identified as Other soils.

Collected data were compared to the current TxDOT S_u versus N_{TCP} relationship for each soil type and analyzed based on statistical methods and theoretical concepts in this study. Also, limited tests were done to validate the data. The relationship between N_1 and N_2 was also investigated based on the soil type. A total of three approaches were used to develop new correlations between S_u versus N_{TCP} . The first attempt was to investigate directly the S_u versus N_{TCP} relationship, the second was to consider the

average strength ($\bar{S}_u$) for each TCP blow count ($\bar{N}_{TCP}$), and in the final attempt depth effect on the mean N_{TCP} ($\bar{N}_{TCP}$) and mean S_u ($\bar{S}_u$) was considered.

All the analyses were based on soil type. For the CH soil, based on 2100 data sets, the undrained shear strength (S_u) varied from 0.45 to 88.75 psi with a mean of 16.8 psi. The coefficient of variation (COV) was 67%, which was the highest for the soils investigated in this study. The probability distribution function (PDF) for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 2 to 100 with a mean of 31. The COV was 70%, which was the highest for the soils investigated in this study. The PDF for the TCP blow count (N_{TCP}) was lognormal. Current TxDOT relationship over predicted 59% of the data for the CH soils. For the CL soil, based on 1852 data set, the undrained shear strength (S_u) varied from 0.96 to 114.6 psi with a mean of 12.9 psi. The COV was 54%, which was the lowest for the soils investigated in this study. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 2 to 100 with a mean of 35. The COV was 58%. The PDF for the TCP blow count (N_{TCP}) was lognormal. For the SC soil, based on 29 data set, the undrained shear strength (S_u) varied from 3.5 to 38.55 psi with a mean of 10.8 psi. The COV was 60%. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 7 to 87 with a mean of 30. The COV was 66%. The PDF for the TCP blow count (N_{TCP}) was Weibull. For the other soil, based on 42 data set, the undrained shear strength (S_u) varied from 1.4 to 69.3 psi with a mean of 16.8 psi. The COV was 66%. The PDF for the undrained shear strength (S_u) was Weibull. The TCP blow count (N_{TCP}) varied from 10 to 93 with a mean of 45. The COV was 45%, which was the lowest for the soils investigated in this study. The PDF for the TCP blow count (N_{TCP}) was normal.

Based on the analyses of raw data and average values, linear and nonlinear relationships were developed from three attempts. Analyses showed that the current TxDOT design relationships overestimated the undrained shear strength (S_u) and TCP blow count (N_{TCP})depended on the depth for all the types of soils investigated. The depth dependency also varied from location to location. The undrained shear strength versus TCP blow count relationships developed were also influenced by the locations.

RESEARCH STATEMENT

This research project was to verify the current correlations used by TxDOT to determine the undrained shear strength of soils using the Texas Cone Penetrometer blow counts. Over 4000 data sets collected over the past decade were used in this study. Based on this study, the current TCP correlation better predicted the undrained shear strength of CL soils compared to the other soils.

This report will serve as a guidance document for TxDOT engineers on using the Texas Cone Penetrometer blow count to better predict the shear strength of soils in Texas using the correlations developed in this study. Also, local correlations have been developed for a few areas.

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CHAPTER 1. INTRODUCTION

1.1 Introduction

For site investigation, in situ tests are increasingly used to determine soil properties for geotechnical analysis and design. The penetration resistances are used to classify and characterize subsoils. Based on the problem, substantial data can be obtained economically and in much shorter time using in situ devices, such as the standard penetration test (SPT), cone penetration test (CPT), dilatometer, pressure meter and field vane shear (Bowles, 2002; Jimiolkowski, 1985; Kulhawy et al. 1983; and 1990).

The Texas Department of Transportation is currently using the Texas Cone Penetrometer (TCP) test, which is a sounding test similar to the SPT and CPT for determining the soil parameters in situ. In the case of the TCP test, the driving method is similar to SPT, and the shape of cone is similar to the CPT cone, but the diameter is larger than the CPT. Hence, it can be interpreted that the TCP is a hybrid of SPT and CPT. One advantage of the TCP test is that it can be used in both soil and rock.

In all foundation design, it is necessary to know the shear strength of soil. When it is not feasible to measure the necessary soil strength parameters directly, estimates will have to be made from other available data, such as in situ tests (Kulhawy and Mayne, 1990). Numerous correlations between in situ tests such as Cone Penetration testing (CPT) and the Standard Penetration Test (SPT) and soil shear strength parameters have been developed (Kulhawy and Mayne, 1990). Also, the Texas cone penetrometer test and its 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 tests.

In the case of TCP, limited research was performed in 1974 and 1977 to develop the correlations between N_{TCP}-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, with a small amount of data and empirical analysis. These correlations are currently used by TxDOT for geotechnical design of foundations, embankments and retaining walls. Hence the applicability of these correlations for soils in other regions in Texas must be verified and there is a need to continuously update the existing correlations with more recent test data. Hence, in order to verify the current correlations for soils from different regions of Texas, a research study was undertaken at three universities: The University of Houston, Lamar University and University of Texas at Arlington.

1.2 Research Objectives

The objective of this research study was to develop equations, with high level of confidence to predict the undrained shear strength (s_u) for soils in Texas based on TCP blow count.

The objective was achieved in Six PHASES as follows.

Phase 1: Literature Review: Reports and papers on TCP were critically reviewed and analyzed. Since the SPT and CPT have similarity to TCP, relevant information on the SPT and CPT were collected and analyzed.

Phase 2: Collection of Data: Since TCP is used all around Texas, a large amount of data was available with TxDOT. Hence the state of Texas was divided into three sectors to collect the data and the data were saved on a single server.

Phase 3: Database Analysis and Plan for Field Study: Data were analyzed based on theoretical concepts and using statistical methods. Current TxDOT correlations between TCP and undrained shear strength of soil were verified and new relationships were developed.

Phase 4: Field Study and Laboratory Tests: A limited amount of control tests were performed to determine the repeatability of the TCP in various Texas soils. Also, laboratory tests were performed on undisturbed samples to verify the current TxDOT undrained shear strength correlations with high quality data.

Phase 5: Verification of Correlations: Current TxDOT relationships for CH, CL, SC and Other Soils were verified and linear and nonlinear relationships have been developed.

Phase 6: Final Report: All the information collected during this study was compiled into the final report.

This study was a joint effort between the University of Houston, University of Texas at Arlington and Lamar University. Each University collected data from a different region in Texas.

1.3 Organization

This report has been organized into six chapters. In Chapter 2, literature review related the current study has been summarized. Other in situ methods used to characterize the soils have been compared to the TCP method. In Chapter 3, collected data have been summarized and verified with the current TxDOT relationships for CH, CL, SC and Other Soils with data from the entire state and a few TxDOT districts. Variation of N_1 (blow counts / first 6 inches) and N_2 (blow counts / second 6 inches) for various soil types was investigated. In Chapter 4, data have been statistically analyzed for each blow count. Linear and nonlinear relationships between TCP blow count and mean undrained shear strength have been developed and the data were verified with the current TxDOT method. Depth effect (influenced by geology and active zone) on the TCP blow count and shear strength was investigated in Chapter 5. Conclusions and recommendations are summarized in Chapter 6.

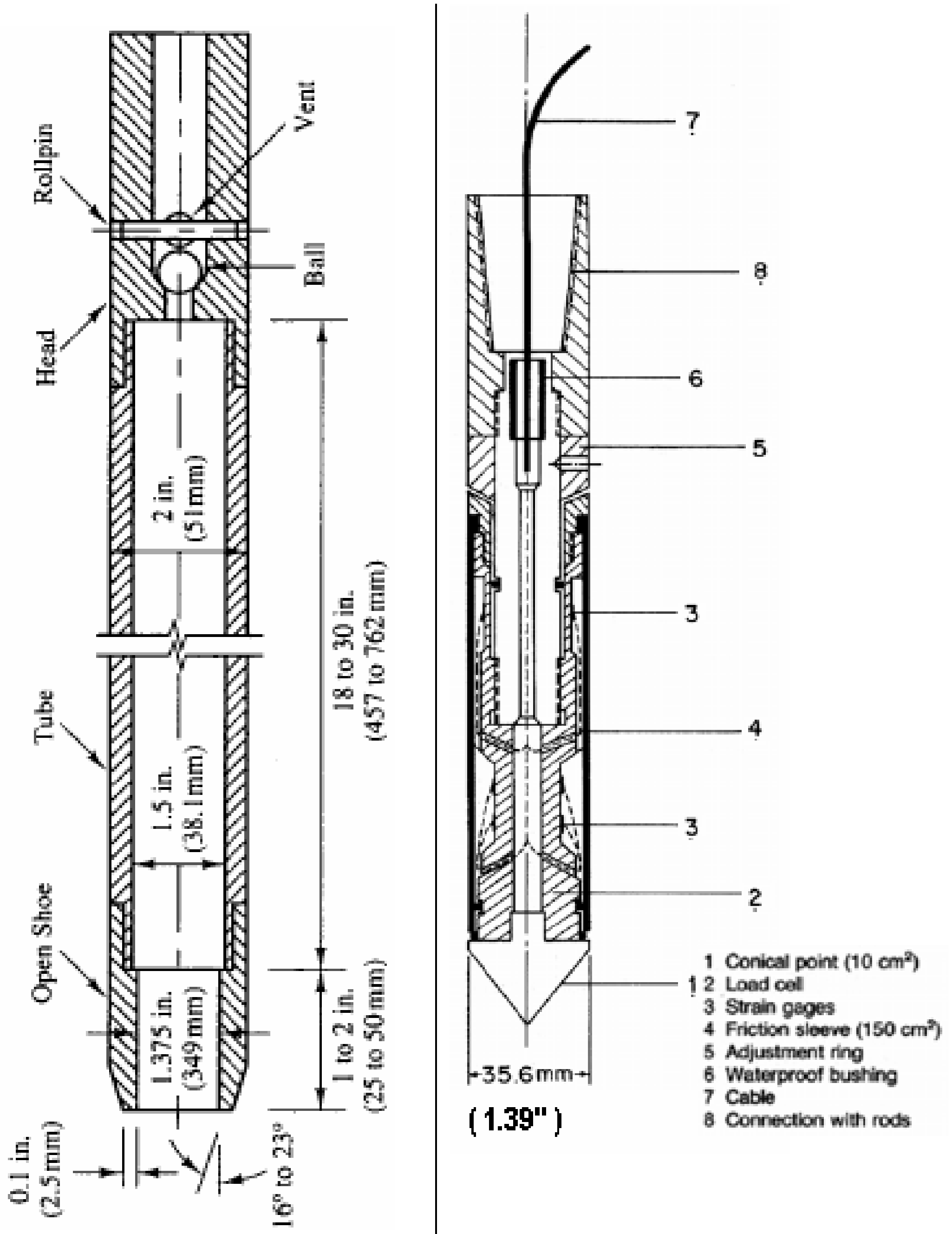
CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

Probing with rods through weak ground to locate a firmer stratum has been practiced since 1917 (Meigh, 1987). Soil sounding or probing consists of forcing a rod into the soil and observing the resistance to penetration. According to Hvorslev (1949), the oldest and simplest form of soil sounding consisted of driving a rod into the ground by repeated blows of a hammer, where the number of blows (N) required per foot penetration of the rod was used as an index of penetration resistance and was correlated to the foundation response parameters. The numerical value of the correlation not only depended 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).

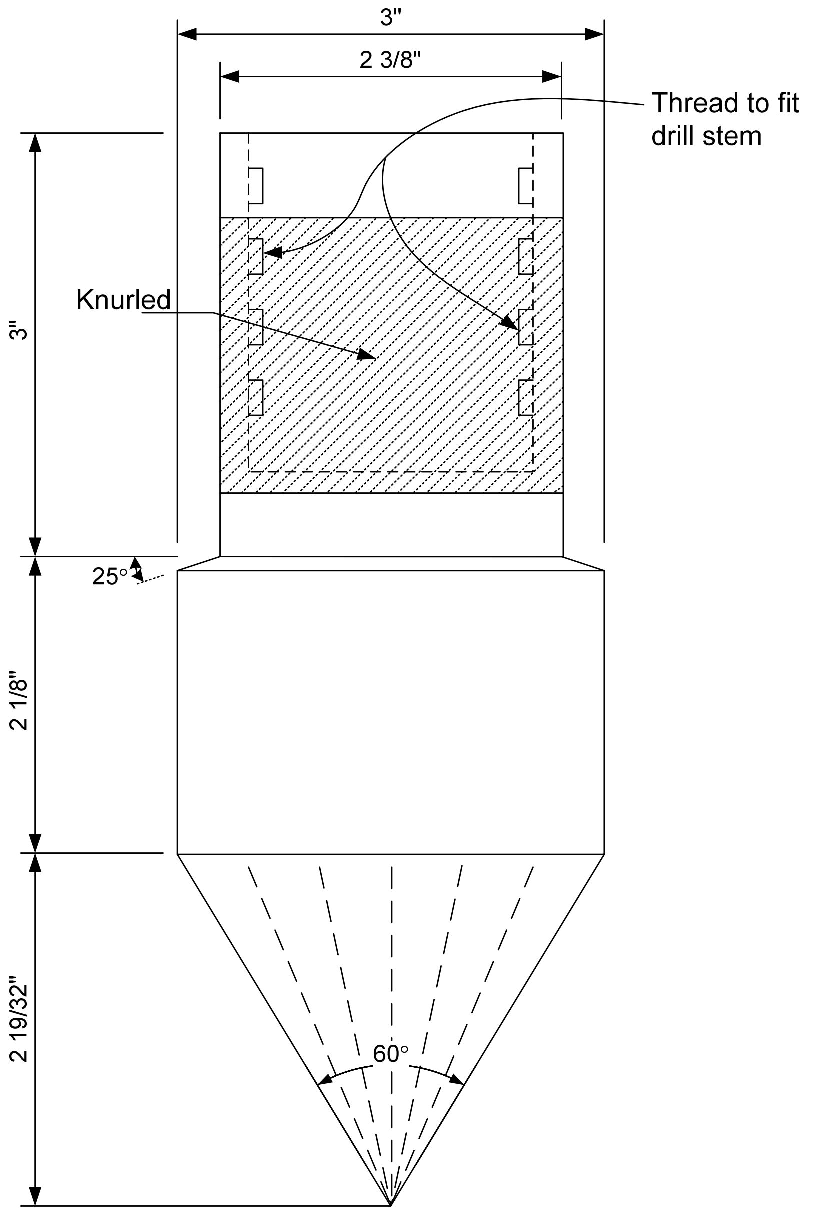
Use of the penetrometer evolved because of the need to acquire data from the subsurface soils which were not obtainable by any other means (Hamoudi et al., 1974). Considerable savings in time and cost are achieved by using in situ devices such as the standard penetration test (SPT), cone penetration test (CPT), dilatometer, pressuremeter, and field vane shear depending on the type of project (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 are inexpensive but the information collected can be hampered by numerous sources of errors that occur during the test including equipment variability and poor correlations. Infrequent sampling in between dynamic penetrometer tests can also lead to sample disturbance.



(a) SPT (from ASTM D 1586)	(b) CPT (from ASTM D 5778)

Figure 2.1 Comparisons of Penetrometers (a) SPT, (b) CPT and (c) TCP



Note : Driving point is manufactured from **AISI 4142 steel**. Point is heated in an electric oven for 1 hour at 1550° - 1600°F. Point is plunged point first into approximately 25 gal. of tempering oil and moved continuously until adequately cooled.

(c) TCP (from Tex-132-E)

Figure 2.1 Comparison of Penetrometers (a) SPT, (b) CPT and (c) TCP – Continued

On the other hand, static cone penetrometers provide relatively accurate test results and enhanced test repeatability. Static penetrometers provide continuous data.

However, they have been limited by their economic viability and their limitations in the ranges of soil resistance that can be measured using them (Fritton, 1990; Vyn and Raimbault, 1993).

2.2 Penetrometers

In the United States, the most commonly used penetration devices for soil related applications are the standard penetration test and the cone penetration test. One of the in situ tools commonly used for this process in the state of Texas by the Texas Department of Transportation is the Texas cone penetrometer.

The SPT originated in about 1927, has been in use for some 80 years. It is being used worldwide and is currently the most popular and economical means to obtain subsurface information. It is estimated that 85 to 90 % of conventional design in North America is made using the SPT (Bowles, 2002; Marcuson, 1977; Mayne, 1984 and 1991; and Meyerhof, 1956). The method has been standardized as an ASTM D1586 since 1958 with periodic revisions to date.

The CPT is now widely used in lieu of the SPT, particularly in soft clays, soft silts and in fine to medium sand deposits (Jimiolkowski, 1985; Kulhawy, 1990; and Mayne, 1984). The test is not well adopted to gravel deposits or to stiff/hard cohesive deposits. This test has been standardized by ASTM as D 5778. The test consists of pushing a 35.6 mm diameter standard cone into the ground at a rate of 10 to 20 mm/s and recording the resistance. Because of the complexity of soil behavior, empirical correlations are used extensively in evaluating soil parameters (Orchant et al., 1988; Robertson and Campanella, 1983; and Schmertmann, 1975).

2.2.1 Standard Penetration Test (SPT)

The standard penetration test was developed around 1927, and is the most widely used dynamic penetration test in the United States. Since 1958, the SPT has been standardized (ASTM method 1586 with periodic updates, Figure 2.1 (a)). SPT is an economical means to obtain subsurface information. The test involves driving a 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 gave a reasonable, if not somewhat conservative, estimate of the allowable bearing capacity of fine sands. The results of the SPT can usually be correlated 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 of soil, ϕ', which has been widely used in foundation design procedures dealing with sands. Also, several researchers have 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). The energy/blow in the SPT is similar to what is used for TCP. SPT and TCP use 12 inch penetration to determine the blow count in soils. The refusal conditions used for SPT are the same as for TCP.

2.2.2 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) (Figure 2.1 (b)). The cone penetration test is used in lieu of the SPT in 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 5778.

While the cone angle is 60˚ for both TCP and CPT, the diameter of the cone in TCP was double that of CPT. Similar to CPT, no sample is recovered during the TCP test. Unlike CPT, soil sampling can be done in between TCP tests.

2.2.3 Texas Cone Penetrometer (TCP)

The Texas Cone Penetrometer is commonly used in site investigations by the Texas Department of Transportation (Figure 2.1 (c) and Figure 2.2). The TCP test involves driving a hardened conical point into soil and hard rock by dropping a 170 lb (77 kg) hammer a height of 2 feet (0.6 m) (Tex-132-E). From the soil test, a penetration resistance or blow count (N_{TCP}) is obtained which equals the number of blows of the hammer for the first 6 inches (150 mm) and the second 6 inches (150 mm) of penetration.

The relationship developed by Touma and Reese (1969) between SPT and TCP in cohesive and cohesionless soils is summarized in Tables 2.1 and 2.2. The N values of SPT and TCP at different soil density classifications are also summarized in these two tables.

Table 2.1 Existing Correlations between SPT and TCP for Cohesionless Soils (Touma and Reese (1969))

Soil Classification	N_{SPT}	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 2.2 Existing Correlations between SPT and TCP for Cohesive Soils (Touma and Reese (1969))

Soil Classification	N_{SPT}	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	$N_{SPT} = 0.7\ N_{TCP}$

2.2.3.1 History and Development of TCP

According to the Geotechnical Manual (2000), TCP was developed by the bridge foundation group in the bridge division with the help of several other divisions in TxDOT. 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 1940s. The first use of TCP dates back to 1949 and the 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).

2.2.3.2 TCP Equipment and Testing Procedure

The TCP test (Tex-132-E) is a standardized test procedure by TxDOT. The apparatus is shown in Figures 2.1 (c) and 2.2 and the equipment needed to run the TCP test is as follows:

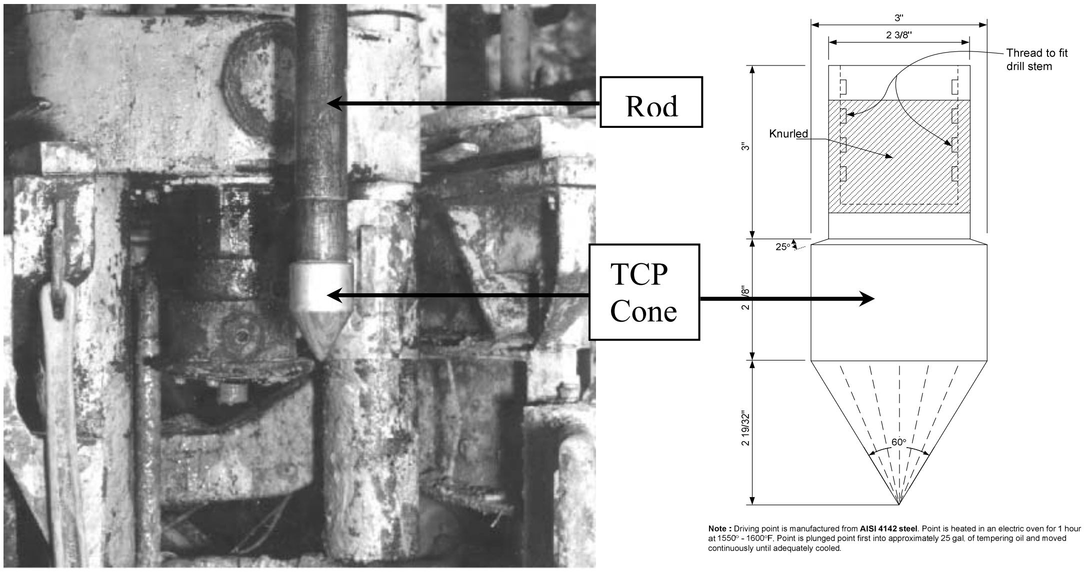
a. Hammer, 170 ± 2 lb with a 24 ± 0.5 in. drop

b. Drill stem, sufficient to accomplish boring to the desired depth

c. Anvil, threaded to fit the drill stem, and slotted to accept the hammer

d. TCP Cone (Conical driving point), 3 in. in diameter with a 2.50 in. long point.

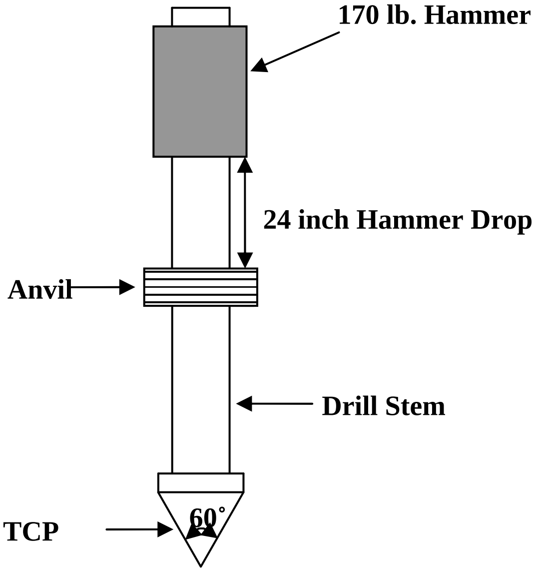
The driving point is to be manufactured from AISI 4142 steel. The point is to be heated in an electric oven for 1 hour at 1550 to 1600 degrees Fahrenheit. Point is plunged into approximately 25 gallons of tempering oil and moved continuously until adequately cooled (Geotechnical Manual, 2000).



Note : Driving point is manufactured from **AISI 4142 steel**. Point is heated in an electric oven for 1 hour at 1550° - 1600°F. Point is plunged point first into approximately 25 gal. of tempering oil and moved continuously until adequately cooled.

(a) Actual view
(TxDOT Geotechnical Manual, 2000)

(b) Texas Cone Schematic



(c) Details of the Texas Cone Penetrometer (Not to Scale)

Figure 2.2 Texas Cone Penetrometer (TCP)

(a) Fully Automatic **(b) Automatic Trip**

Figure 2.3 TCP Hammers (TxDOT Geotechnical Manual, 2000)

The test consists of dropping a 170 lb hammer to drive the 3 inch diameter penetrometer cone attached to the stem. The penetrometer cone (Figure 2.2 (b)) is first driven for 12 inches or 12 blows, whichever comes first and is seated in soil. 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.

2.3 TCP and Shear Strength

Shear strength is one of the most important engineering properties of soils that is needed for designs of foundation of earth structure (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.

TxDOT presently uses the triaxial test to determine the undrained shear strength of soils for its design purposes. 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 the soil shear strength at bridge sites (Geotechnical Manual, 2000).

2.4 Review of Past Research on TCP

TCP tests are routinely performed since they are required for investigation of foundation materials encountered during foundation exploration for TxDOT projects. Limited research was done during 1974 to 1977 to correlate N_{TCP} -values to shear strength parameters. These studies were performed especially in the upper gulf coast region. The research objectives and results of these studies along with references are summarized in Table 2.3.

Based on past research, TxDOT presently uses the design chart shown in Figure 2.4 and the same is summarized as equations in Table 2.4 to predict the shear strength of soils using N_{TCP} -values. 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 (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 N_{TCP} values and soil shear strength could result in significant financial savings in the design and construction of earth structures built by TxDOT (Kim et al., 2007; Vipulanandan et al., 2007b). 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 2.3 Research Findings of the 1977 Research Report and Current Correlations

Objectives	Research Findings	Current Correlations
To develop an improved correlation between the N_{TCP} - value from TCP test and: 1. the unconsolidated – undrained shear strength of cohesive soils 2. drained shear strength of cohesionless soil (Duderstadt, F.J., Coyle, H.M., Bartoskewitz, R.E.)	$S_u = 0.067\ N_{TCP}$ (Homogeneous CH Soils)	$S_u = N_{TCP}/25$ $= 0.04\ N_{TCP}$ (CH Soils)
	$S_u = 0.054\ N_{TCP}$ (Silty CL Soils) $S_u = 0.053\ N_{TCP}$ (Sandy CL Soils)	$S_u = N_{TCP}/30$ $= 0.033\ N_{TCP}$ (CL Soils)
	-	$S_u = N_{TCP}/35$ $= 0.029\ N_{TCP}$ (SC Soils)
	$S_u = 0.021\ N_{TCP}$ (SP, SM, and SP-SM soils)	$S_u = N_{TCP}/40$ $= 0.025\ N_{TCP}$ (OTHER Soils)
	Where: S_u = Undrained Shear Strength (tsf) N_{TCP} = TCP blow count	

Table 2.4 Design Table to Predict Shear Strength for Foundation Design Using N_{TCP} - values (Geotechnical Manual, 2000)

Soil Type	Constants – C	Design Shear Strength (0.5 × Su) = N_{TCP}/C (tsf)	Undrained Shear Strength (Su) = 2× (N_{TCP}/C) (tsf)	Undrained Shear Strength (Su) =2×(N_{TCP}/C)×13.888 (psi)
CH	50	$N_{TCP}/50$	$N_{TCP}/25$	$0.556\times N_{TCP}$
CL	60	$N_{TCP}/60$	$N_{TCP}/30$	$0.463\times N_{TCP}$
SC	70	$N_{TCP}/70$	$N_{TCP}/35$	$0.397\times N_{TCP}$
OTHER	80	$N_{TCP}/80$	$N_{TCP}/40$	$0.347\times N_{TCP}$

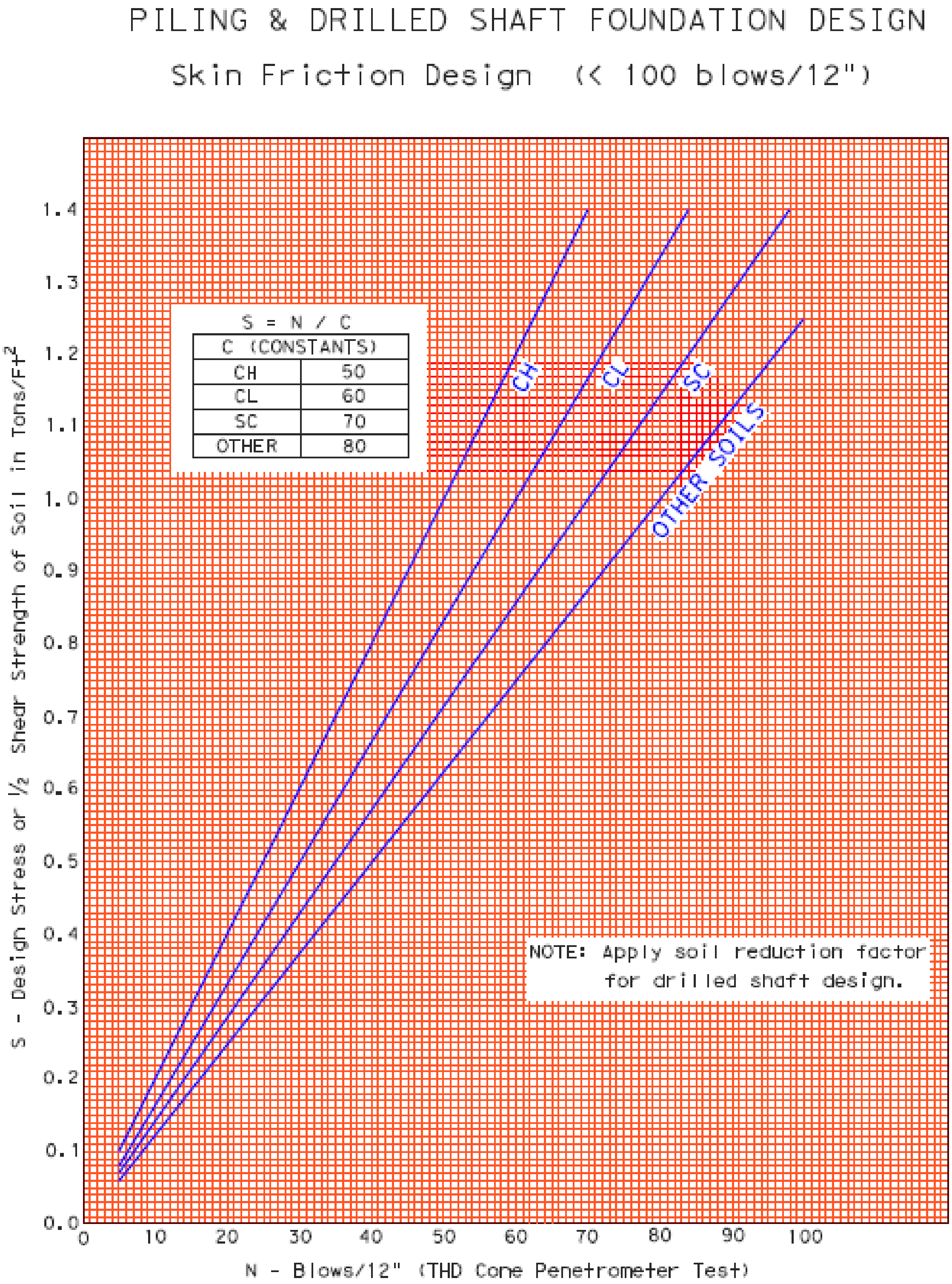


Figure 2.4 Design Chart to Predict Shear Strength for Foundation Design Using - values; Presently Used by TxDOT (Geotechnical Manual, 2000)

2.5 Texas Geology

From northwest to southeast across the state of Texas, the geology varies drastically (Figure 2.5). Predominantly, the North-West part of Texas is Quaternary and Tertiary periods of Cenozoic era which formed ~10000 years to ~58 million years ago. The central part of Texas is more of Cretaceous period of Mesozoic era. From northwest to southeast up to the central part of Texas, the formation is mainly of Ochean Series (formed ~245 million years ago) to Missourian series (formed ~320 million years ago) of Paleozoic series (formed ~245 million years to ~570 million years ago). Few parts of Central Texas are formed during Paleozoic Undivided (~570 million years ago). From Central Texas to South East Texas toward the Gulf of Mexico, the geologic formation is mainly of Navarro Taylor groups to Fredericksburg and L. Washita Groups (~66 million years to ~144 million years ago) of Cretaceous period of Mesozoic era. The formation near the gulf coast is the most recent of all formations (~2 million years to ~58 million years ago) (Vipulanandan et al., 2007b). The formations predominant from South East to North West are in order of Alluvium, Quaternary undivided, Beaumont formation, Lissie formation, Willis formation, Fleming and Oakville formation, Catahoula formation and Claiborne group (or Yegua Formation) of Cenozoic era.

2.5.1 Houston-Beaumont Area

The geology of the Houston and Beaumont area is complex due to cyclic deposition of sedimentary facies (Vipulanandan et al., 2007b). Sediments of the Gulf Coast were mainly deposited in the coastal plains of the Gulf of Mexico Basin. These sediments were deposited under a fluvial-deltaic to shallow-marine environments during the Miocene to the Pleistocene periods. Repeated sea-level changes with mainly deltaic deposit and natural basin subsidence produced discontinuous beds of sand, silt, clay, and gravel. Six major sediment dispersal systems that were the source of large deltas distributed sediments from erosion of the Laramide uplift along the central and southern Rockies and Sierra Madre Oriental (Galloway et al., 2000; Galloway, 2005; Vipulanandan et al., 2007b). The coastal plain is underlain by a massive thickness of sediments that form a homocline sloping gently towards the Gulf of Mexico. Several major rivers flow nearly perpendicular to the Gulf of Mexico. These rivers include the Sabine, Trinity, Colorado, Guadalupe, Brazos, San Antonio, and Rio Grande. The Houston-Galveston areas would have been mainly influenced by the Brazos, Trinity and San Jacinto rivers (Chowdhury et al., 2006).

The depositional environment of the Pleistocene-aged sediments is consistent with the erosional and sedimentary cycles associated with periods of glaciations and coincident sea-level variations. Coastal terrace deposits and a fining upward sequence are typical of glacial cycling (Hosman, 1996). The Lissie and Beaumont formations are the two dominant subdivisions of the Pleistocene system in the Houston-Galveston area. These fluvial-deltaic sediments have been identified in the subsurface in Harris, Galveston, Chambers, and Brazoria counties (Kreitler et al., 1977).

The Lissie Formation is unconformably contained between the Goliad Sand and the overlying Beaumont Clay. The Lissie Formation crops out in a band parallel to the coast and is about 30 miles wide from the Sabine River to the Rio Grande. The sediments of the Lissie Formation in the outcrop are partly continental deposits laid down on flood plains and partly as delta sands, silts, and mud at the mouth of rivers (Sellards et al., 1932).

The Beaumont clay is contained between the underlying Lissie Formation and overlying Holocene-aged stream deposits and windblown sands (Weeks, 1937). The Beaumont sediments were deposited largely by rivers in the form of natural levees and deltas that coalesced as river mouths shifted along the coast and, to a lesser extent, by marine and lagoonal water in the bays and embayments between stream ridges and delta banks (Sellards et al., 1932). The Holocene-aged alluvial systems in the Texas Gulf Coast are local in scale.

The Houston and Beaumont area geology is influenced by the Beaumont and Lissie formations with the soft soils deposited during the Pleistocene period under conditions of changing sea levels. The clay is essentially a late coastal plain formed by the deposition of sediments from the ancient rivers along the coast. As the river mouths shifted, so did the levees and deltas formed by them. These inter delta areas were then buried beneath deltaic sediments (Vipulanandan et al. 2007b). The resulting formation is one of deltaic deposition interbedded in places with marine and lagoon beds. The Beaumont coastal plain formation stretches from the Mississippi Delta to the Tamaulipas Range in Northeastern Mexico (Ganstine, 1971).

The Beaumont formation itself is generally composed of clay. Although in the Central Gulf Coast the percentage of clay might be in the range of 30% to 90%. The clay is bluish gray, yellowish gray, pinkish gray, purple, and shades of red. In most places it contains calcareous nodules and some fragments of more or less decomposed wood. All of these clays are characterized by the high silica, and low lime content, and highly plastic. In general, the Beaumont clay formation consists of poorly bedded, plastic clay interbedded with silt and sand lentils, and has some more or less continuous layers of sand. The Beaumont clays have been oxidized and desiccated during the Wisconsin glacial stage when sea levels were more than 400 feet (120 m) lower than at present. The clay in general is an over consolidated clay (Ganstine, 1971). Finally, with the recession of the late Wisconsin glaciers, the sea level returned to its present level, leaving both formations preconsolidated through desiccation. The rate of deposit was between 2500-30,000 mm/1000 years (Vipulanandan et al., 2007 (a) & (b)).

2.5.2 Dallas-Forth Worth Area

The formation of Dallas can be accounted to Navarro and Taylor groups which formed during Cretaceous period of Mesozoic era about 66 million years ago whereas Fort Worth was also formed during Cretaceous period of Mesozoic era but the difference is it belongs to Austin, Eagle Ford, Woodbine, and U. Washita Groups. Dallas, and its surrounding area, are mostly flat and lie at an elevation ranging from 450 to 550 feet (137 to 168 m). The western edge of the Austin chalk formation, a limestone escarpment, rises 200 feet (61 m) and runs roughly north-south through Dallas County. The uplift is particularly noticeable in the neighborhood of Oak Cliff and the adjacent cities of Cockrell Hill, Cedar Hill, Grand Prairie, and Irving. Marked variations in terrain are also found in cities immediately to the west in Tarrant County surrounding Fort Worth.

The Trinity River is a major Texas waterway that passes from the city of Irving into west Dallas, where it is paralleled by Interstate 35E along the Stemmons Corridor, then flows alongside western and southern downtown, and ultimately between south Dallas and Pleasant Grove, paralleled by Interstate 45, where it exits into unincorporated Dallas County and heads southeast to Houston. The river is flanked on both sides with a 50 feet (15 m) earthen levee to keep the city from flooding (Spearing, 1991).

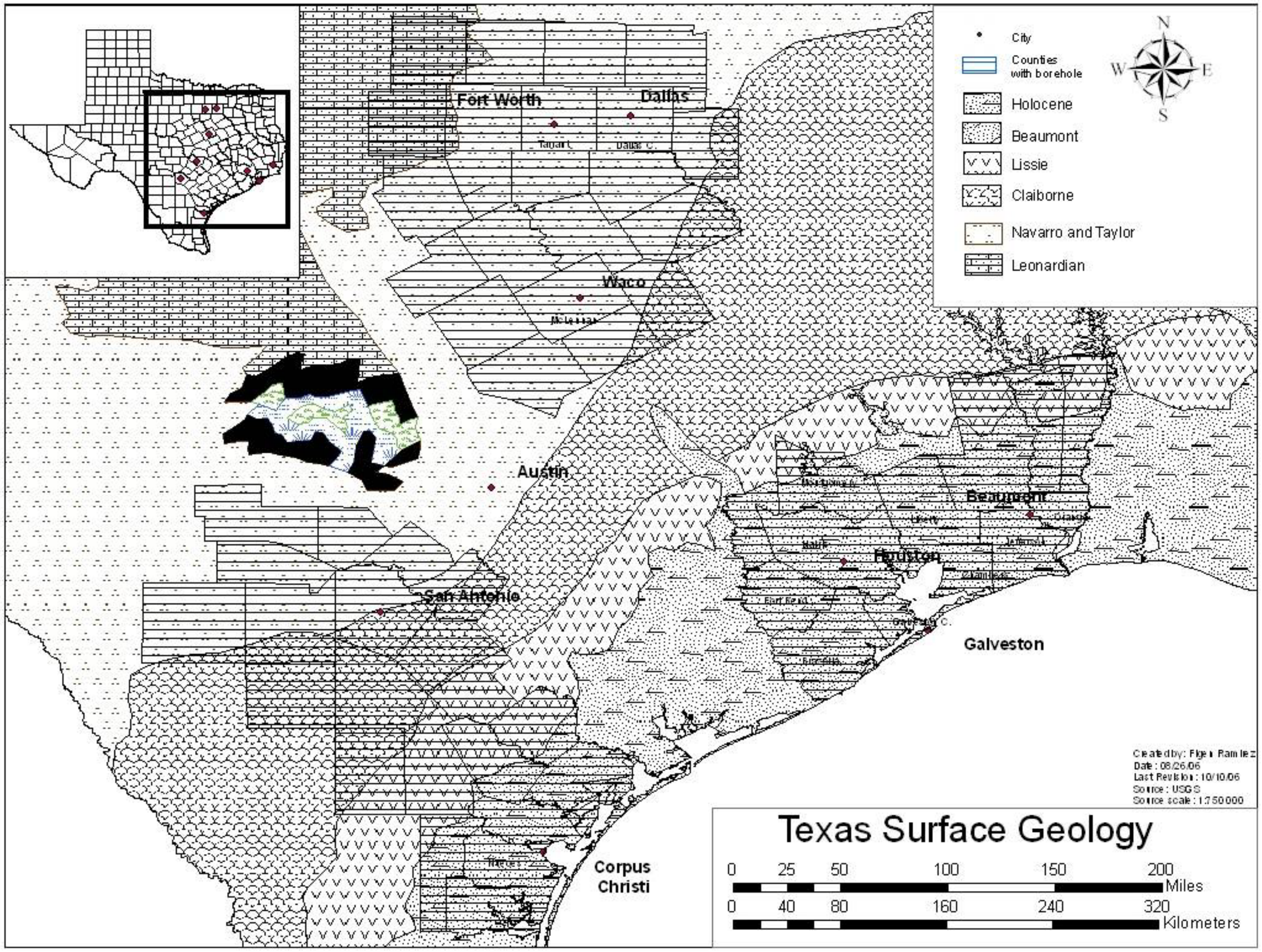


Figure 2.5 Texas Surface Geology

2.6 Summary

Based on the literature review the following conclusions are advanced:

1. Energy per blow used in the SPT is similar to the TCP. Diameter of the TCP Cone is double the size of the CPT Cone. Similar to the CPT, no sample is recovered during the TCP test. Unlike the CPT, soil sampling can be done in between the TCP tests.
2. Studies done on the TCP in the mid 1970s developed correlations between TCP blow count and the undrained shear strength of soils. The data for the study were obtained from the upper Gulf Coast region.
3. The geology of Texas soils varies substantially. The soil deposits in the Gulf Coast region are mainly deltaic and large variations in the properties are observed.

CHAPTER 3. DATA COLLECTION AND ANALYSIS

3.1 Database System

Data collected from various locations in Texas were digitally stored for easy processing and developing correlations for each TxDOT project with a CSJ designation. The data were stored in five Tables as shown in Figure 3.1.

3.1.1 Soil Database Management System (SDBMS)

Microsoft's Access® database system consists of Tables, Queries, Forms, Reports, and Data Access Pages. Tables store data in rows and columns. All databases contain one or more Tables. Queries retrieve and process data. They can combine data from different Tables, update data, and perform calculations on the data. Forms control data entry and data views. They provide visual cues that make data easier to process.

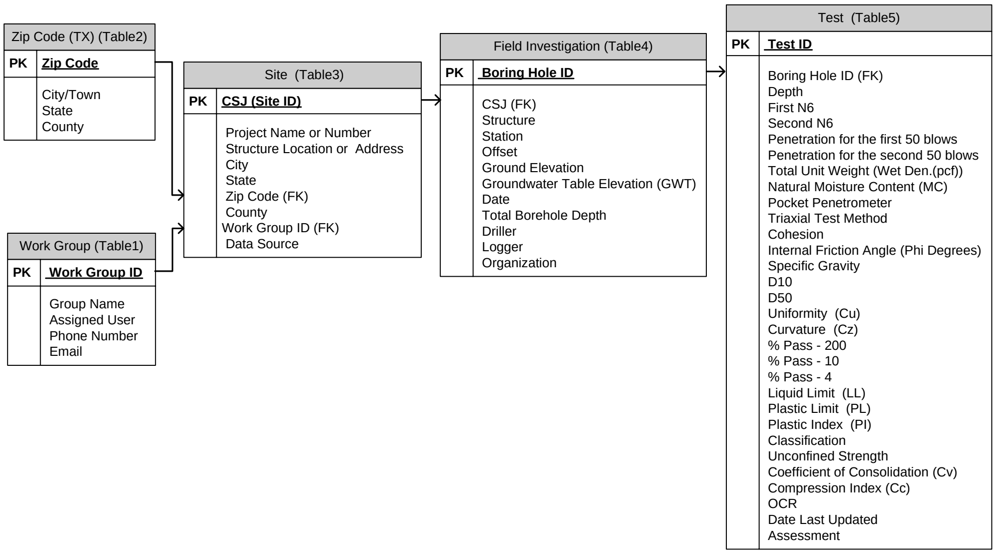


Figure 3.1 Structure of the Data Model for SDBMS

Five Tables in five different worksheets were used for storing information collected from the TxDOT districts. Each of the five Tables was assigned a Primary key (PK) such as Work Group ID (Table 1), Zip Code (Table 2), CSJ (Table 3), Boring Hole ID (Table 4) and Test ID (Table 5). This key was used to identify information carried over to the next Table. Each Primary key (PK) was converted into a Foreign key (FK) in the later Tables. For example, Boring Hole ID was the Primary key (PK) in Table 4. In Table 5, Boring Hole ID was the Foreign key (FK). Thus information corresponding to a boring hole in Table 4 was linked to the information in Table 5 by the analogous Boring Hole ID. Similarly, information from all five Tables were linked and provided 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 are described in Tables 3.1 through 3.5.

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

Table 1 of Database – Work Group		
Name	**Definition**	**Example**
Work Group ID (PK)	An ID for each work group	UH
Group Name	A Individual Name for each work group	University of Houston
Assigned User	An assigned name for each work group	Vipu
Phone Number	Phone number of the work group	713-743-4278
Email	Email address of the work group	cvipulanandan@uh.edu

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

Table 2 of Database – Zip Code		
Name	**Definition**	**Example**
Zip Code (PK)	Zip Code of the work site	77024
City/Town	City/Town of the work site	Houston
State	State of the work site	TX
County	County of the work site	Harris

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

Table 3 of Database – Site Information		
Name	**Definition**	**Example (Fig. 3.2)**
CSJ (Site ID) (PK)	An ID number of the work site. The first four digits designate the Control number, the next two digits specify the Section number, and the last three digits represent the Job number	0271-07-244 (1)
Project Name or Number	A common name or number of the work site	99-230G-02
Structure Location or Address	Physical address of the work site	I-10, Section 2 (2)
City or District	City of the work site	Houston (3)
State	State of the work site	TX
Zip Code (FK)	Zip Code of the work site	77024
County	County of the work site	Harris (4)
Work Group ID (FK)	ID of the work group collecting the data	UH
Data Source	Source of the data	TxDOT

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

Table 4 of Database – Field Test		
Name	**Definition**	**Example (Fig. 3.2)**
Boring Hole ID (PK)	An ID number of the boring hole	BR2-01 (5)
CSJ (Site ID) (FK)	The boring hole must be related to a work site represented by CSJ	0271-07-244 (1)
Station	Station	1865+38.60 (6)
Offset (ft)	Offset	-91.94 (7)
Ground Elevation (ft)	Ground of the boring hole at the depth datum. Elevations are positive upward, measured from the elevation datum	64.5 (8)
Groundwater Table Elevation (GWT) (ft)	Groundwater Table elevation	N/A (9)
Date	Date of the drilling job	9/25/2000 (10)
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	75 (11)
Driller	Name of the Driller	Masa (12)
Logger	Name of the Logger	MG (13)
Organization	Name of Organization performing the job	HVJ (14)

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

Table 5 of Database – Test		
Name	**Definition**	**Example (Fig. 3.2)**
Test ID (PK)	An ID number of the work group for the Test Table (Example: UTA01, UH01, LAR01)	UH000629
Boring Hole ID (FK)	An ID number of the boring hole	BR2-01 (5)
Depth (ft)	The measured depth to the sample where the test was performed at each boring hole	5 (15)
Classification	The soil classification used to describe the layer	CL (16)
First N6 or N_1	The number of blows required for the TCP to penetrate the first 6 inches	17 (17)
Second N6 or N_2	The number of blows required for the TCP to penetrate the second 6 inches	17 (18)
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	4 (19)
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	0 (20)
Pocket penetrometer	Pocket penetrometer readings	4.5 (21)
Triaxial test method	The type of triaxial test performed	ASTM
Lateral pressure (psi)	Lateral pressure from the triaxial test	0 (22)
Deviator stress (psi)	Deviator stress from the triaxial test	117.2 (23)
Specific gravity	Specific gravity measured	N/A
D10	Grain diameter corresponding to 10 percent passing	N/A
D50	Grain diameter corresponding to 50 percent passing	N/A
Uniformity Coefficient (Cu)	A coefficient describing the degree of uniformity of the grain size distribution. This coefficient is defined as (D60)/(D10)	N/A

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

Coefficient of Curvature (C_c)	A coefficient describing the degree of curvature of the grain size distribution. This coefficient is defined as $(D30)^2$ / ((D60)*(D10))	N/A
% Pass No. 200 Sieve	The percentage of fines by weight passing the No. 200 sieve	20 (24)
% Pass No. 10 Sieve	The percentage of fines by weight passing the No.10 sieve	N/A
% Pass No. 4 Sieve	The percentage of fines by weight passing the No. 4 sieve	N/A
Natural Moisture Content (MC)	The in situ moisture content of the soil generally expressed in percent	10 (25)
Liquid Limit (LL)	The water content of the soil at the arbitrary boundary between the semi-liquid and plastic states generally expressed in percent	32 (26)
Plastic Limit (PL)	The water content of the soil at the arbitrary boundary between the plastic and semi-solid states generally expressed in percent (LL-PI)	15
Plasticity Index (PI)	Plasticity index is Liquid Limit-Plastic Limit	17 (27)
Total Unit Weight (Wet Density) (pcf)	Total unit weight	131 (28)
Compression Index (Cc)	Compression index (Cc) from the consolidation test	N/A
Coefficient of Consolidation (Cv)	Coefficient of consolidation (Cv) from the consolidation test	N/A
OCR	Over consolidation ratio (OCR) from the consolidation test	N/A
Date Last Updated	The date of the last update of data in the Table	10/18/2004
Assessment	An assessment of information relevant to the lab test	N/A

3.1.2 Data Collected

Based on the recommendations of the TxDOT project committee, data for the past 10 years starting from 1994 to 2004 were collected for this study (Figure 3.3). To expedite the research, three universities were involved in collecting the data required for this study. The state of Texas was divided into three sectors. The following research teams were responsible for collecting data from each sector:

University of Houston (UH) team – Central and south central Texas (Contacted districts : Houston, Waco, Corpus Christi, and San Antonio Districts)

Lamar University (LU) team – East Texas (Contacted district : Beaumont District)

The University of Texas at Arlington (UTA) team – North and west Texas (Contacted districts : Dallas, Fort Worth and Austin Districts)

The data were collected on four soil types and their basic properties are summarized in Table 3.6. The data were then manually entered into the database created using Microsoft Access. The data available on Wincore files were extracted by the software developed by UTA during this study. Details of the data collected (TCP blow count (N_{TCP}) and undrained shear strength (S_u) for each soil type) by University of Houston, Lamar University, and University of Texas at Arlington are summarized in Table 3.7.

Other than basic or simple identification of soil types, classification of soils into various Universals Soil Classification System (USCS) symbols including CL or CH required additional laboratory tests including the Atterberg limits test. An attempt was first made to group N_{TCP} and S_u values into four major soil classification categories.

Table 3.6 Typical Soil Properties of Clay (TxDOT Geotechnical Manual, 2000)

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

Table 3.7 Details on Data Collected from various Districts

District		***Available Data Set***				***Total Data (ft)***	***Total Bore Holes***
		CH	**CL**	**SC**	**Others**		
Total		**2,100**	**1,852**	**29**	**42**	**177,298**	**3,987**
U of Houston	Houston	1,726	1,762	29	42	60,029	1,070
	Waco	22	13	0	0	944	24
	Corpus Christi	0	0	0	0	320	4
	San Antonio	0	0	0	0	2,300	57
Lamar U	Beaumont	341	26	0	0	10,997	398
Uof Texas at Arlington	Dallas	11	51	0	0	73,999	1,757
	Fort Worth	0	0	0	0	28,709	677

Total Soil Data Collected

Table 3.7 summarizes the total amount of data collected from various TxDOT districts. Over 4,000 data sets (TCP blow count (N_{TCP}) and undrained shear strength (S_u))

were collected from 3,987 bore holes. The cumulation length of the bore holes was 177,298 ft. Of the over 4,000 data sets, 2,100 data sets were identified as CH soils, 1,852 data sets were identified as CL soils, 29 data sets were identified as SC soils, and 42 data sets were identified as Other soils. The amount of data sets from the Houston District was 88 % of Total Soil Data sets.

Local Soil Data Collected by University of Houston

A total of 3,594 data sets (TCP blow count (N_{TCP}) and undrained shear strength (S_u)) were collected from 1,155 bore holes by the University of Houston. The cumulation length of the bore holes from the districts was 63,593 ft. Of the 3,594 data sets, 1,748 data sets were identified as CH soils, 1,775 data sets were identified as CL soils, 29 data sets were identified as SC soils, and 42 data sets were identified as Other soils.

Local Soil Data Collected from Lamar University

A total of 367 data sets (TCP blow count (N_{TCP}) and undrained shear strength (S_u)) were collected from 398 bore holes by Lamar University. The cumulation length of the bore holes from the districts was 10,997 ft. Of the 367 data sets, 341 data sets were identified as CH soils and 26 data sets were identified as CL soils. There were no available data sets for SC and Other soils.

Local Soil Data Collected from University of Texas at Arlington

A total of 62 data sets (TCP blow count (N_{TCP}) and undrained shear strength (S_u)) were collected from 2,437 bore holes by University of Texas at Arlington. The cumulation length of the bore holes from the districts was 102,708 ft. Of the 62 data sets, 11 data sets were identified as CH soils and 51 data sets were identified as CL soils. There were no available data sets for SC and Other soils.

3.1.3 TCP and Shear Strength Data

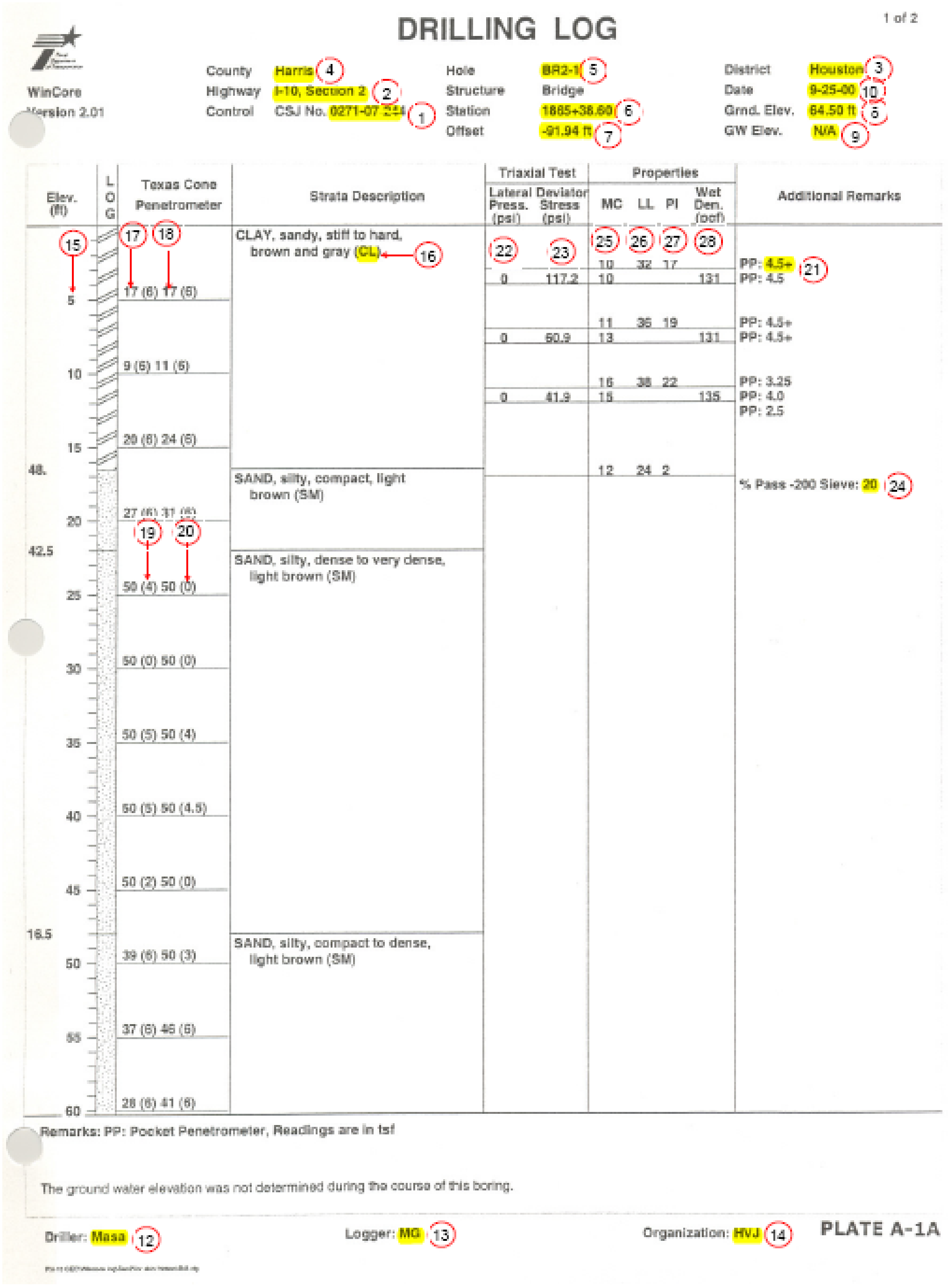
Geotechnical engineers consider shear strength as one of the most important engineering properties of soils (Schmertmann, 1975). The load-carrying capacity of soils is usually dependent on the shear strength of soil. Hence this strength parameter is used in both foundation and geotechnical designs. In the laboratory, the shear strength of soils can be determined by various methods including triaxial, direct shear and the unconfined compression test (UCS) test method. Laboratory testing is conducted on undisturbed samples obtained during subsoil 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 triaxial test method to determine undrained shear strength of soils in the laboratory conditions. However, during routine subsurface investigations, laboratory tests for determining the soil shear strength are often unrealistic, expensive and time consuming. 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.

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 uses empirical correlations to predict strength properties of soils. This test is typically conducted by 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. A typical drilling log is shown in Figure 3.2.

It must be noted that the undrained shear strength was paired with the closest TCP value within the same soil layer.



DRILLING LOG

1 of 2

WinCore
Version 2.01

County Harris ④
Highway I-10, Section 2 ②
Control CSJ No. 0271-07 244 ①

Hole BR2-1 ⑤
Structure Bridge
Station 1885+38.60 ⑥
Offset -91.94 ft ⑦

District Houston ③
Date 9-25-00 ⑩
Grnd. Elev. 64.50 ft ⑧
GW Elev. N/A ⑨

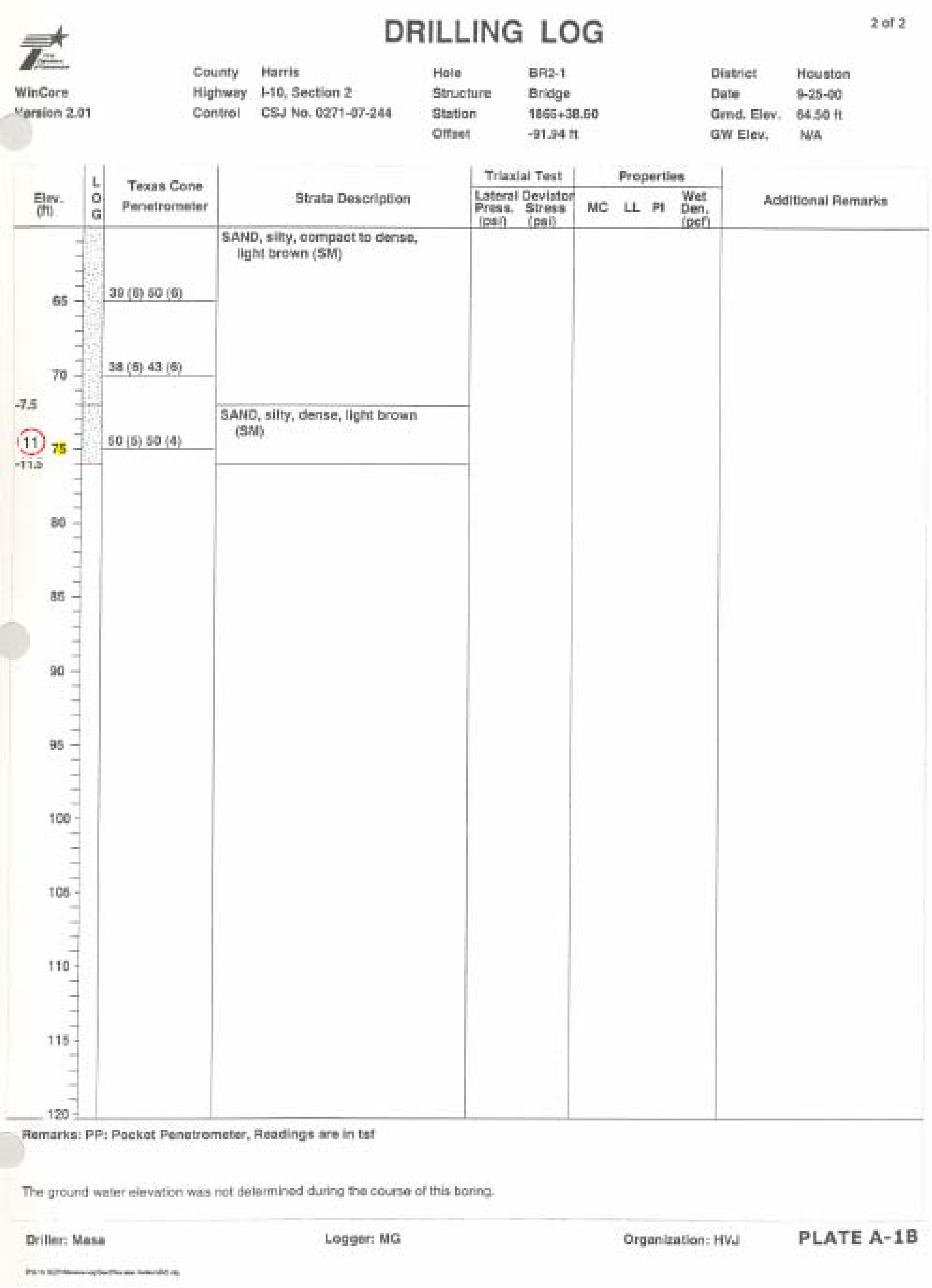
Elev. (ft)	LOG	Texas Cone Penetrometer	Strata Description	Triaxial Test: Lateral Press. (psi)	Triaxial Test: Deviator Stress (psi)	Properties: MC	Properties: LL	Properties: PI	Properties: Wet Den. (pcf)	Additional Remarks
⑮		⑰ ⑱	CLAY, sandy, stiff to hard, brown and gray (CL) ⑯	㉒	㉓	㉕	㉖	㉗	㉘	
						10	32	17		PP: 4.5+ ㉑
				0	117.2	10			131	PP: 4.5
5		17 (6) 17 (6)								
						11	36	19		PP: 4.5+
				0	60.9	13			131	PP: 4.5+
10		9 (6) 11 (6)								
						16	38	22		PP: 3.25
				0	41.9	15			135	PP: 4.0
										PP: 2.5
15		20 (6) 24 (6)								
48.			SAND, silty, compact, light brown (SM)			12	24	2		% Pass -200 Sieve: 20 ㉔
20		27 (6) 31 (6)								
42.5		⑲ ⑳	SAND, silty, dense to very dense, light brown (SM)							
25		50 (4) 50 (0)								
30		50 (0) 50 (0)								
35		50 (5) 50 (4)								
40		50 (5) 50 (4.5)								
45		50 (2) 50 (0)								
16.5			SAND, silty, compact to dense, light brown (SM)							
50		39 (6) 50 (3)								
55		37 (6) 46 (6)								
60		28 (6) 41 (6)								

Remarks: PP: Pocket Penetrometer, Readings are in tsf

The ground water elevation was not determined during the course of this boring.

Driller: Masa ⑫ Logger: MG ⑬ Organization: HVJ ⑭ PLATE A-1A

Figure 3.2 Typical Drilling Log



DRILLING LOG

2 of 2

WinCore
Version 2.01

County	Harris	Hole	BR2-1	District	Houston
Highway	I-10, Section 2	Structure	Bridge	Date	9-25-00
Control	CSJ No. 0271-07-244	Station	1865+38.60	Grnd. Elev.	64.50 ft
		Offset	-91.94 ft	GW Elev.	N/A

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
			SAND, silty, compact to dense, light brown (SM)							
65		39 (6) 50 (6)								
70		38 (5) 43 (6)								
-7.5			SAND, silty, dense, light brown (SM)							
⑪ 75 -11.5		50 (5) 50 (4)								
80										
85										
90										
95										
100										
105										
110										
115										
120										

Remarks: PP: Pocket Penetrometer, Readings are in tsf

The ground water elevation was not determined during the course of this boring.

Driller: Masa　Logger: MG　Organization: HVJ　**PLATE A-1B**

Figure 3.2 Typical Drilling Log - Continued

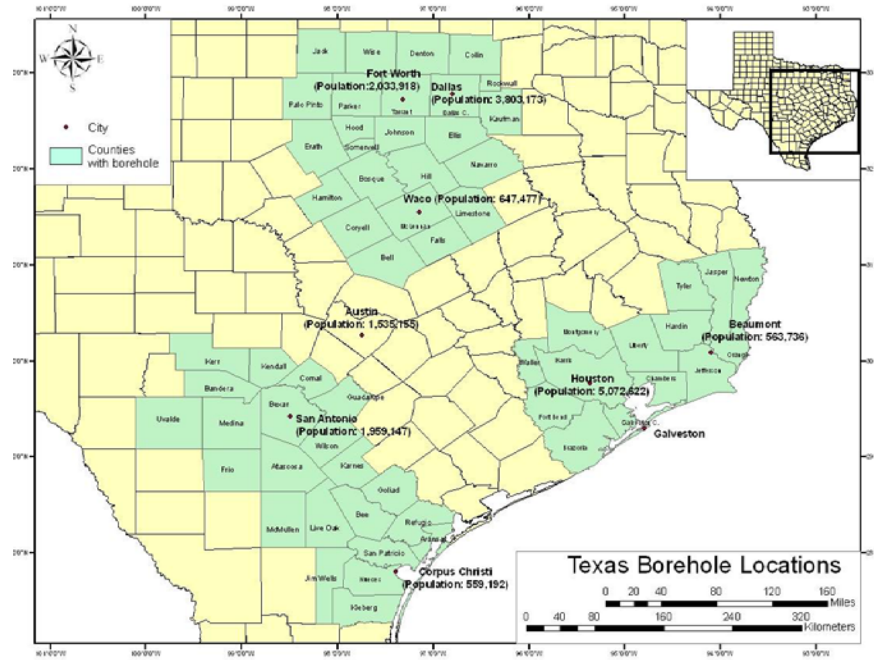


Figure 3.3 Texas Borehole Locations

3.2 Data Correlation

The main focus of this study was to investigate the relationship between N_{TCP} and S_u and verify the current relationship used by TxDOT.

The undrained shear strength of soil (S_u) is influenced by the geology, overconsolidation ratio (OCR), type of soil, moisture content and vertical stress at in situ conditions and can be represented as follows:

S_u = f (Geology, OCR, Type of Soil, Moisture Content (MC), In Situ vertical Stress (σ_v))

The N_{TCP} will be influenced by S_u, hammer efficiency, modulus and depth and can be represented as follow:

N_{TCP} = g (S_u , Hammer Efficiency, Modulus, Depth)

The data were used to validate the current TxDOT relationship and, if necessary, develop linear and nonlinear relationship to best fit the data.

This study focused on three Models as follows:

Model-1 : Current TxDOT design relationship (TxDOT Line, Figure 2.4)

Model-2 : Linear regression analysis line based on bearing capacity relationship

Model-3 : Nonlinear regression analysis – Best fit relationship

Model-1 : This is the current relationship used by TxDOT. Once the soil is classified as CH, CL, SC, Others, the following relationship can be used to determine the undrained shear strength (S_u) of soils (TxDOT Geotechnical Manual, 2000):

For CH Soils

$$S_u = 2\left({}^{N_{TCP}}\!/_{50} \right) tsf = {}^{N_{TCP}}\!/_{25}\, tsf = (0.555) \cdot N_{TCP}\ psi \text{ ---------------------------------------(3.1)}$$

For CL Soils

$$S_u = 2\left({}^{N_{TCP}}\!/_{60} \right) tsf = {}^{N_{TCP}}\!/_{30}\, tsf = (0.463) \cdot N_{TCP}\ psi \text{ ---------------------------------------(3.2)}$$

For SC Soils

$$S_u = 2\left({}^{N_{TCP}}\!/_{70} \right) tsf = {}^{N_{TCP}}\!/_{35}\, tsf = (0.397) \cdot N_{TCP}\ psi \text{ ---------------------------------------(3.3)}$$

For OTHER Soils

$$S_u = 2\left({}^{N_{TCP}}\!/_{80} \right) tsf = {}^{N_{TCP}}\!/_{40}\, tsf = (0.347) \cdot N_{TCP}\ psi \text{ ---------------------------------------(3.4)}$$

In these linear relationships, it is assumed that all the factors that influence S_u of soils will directly influence N_{TCP}.

Model-2 : The ultimate bearing capacity (q_{ult}) formula for deep foundations is as follow (Das, 2004):

$$q_{ult} = cN_c + qN_q \qquad \text{------------------------------------(3.5)}$$

Where N_c *and* N_q are called the bearing capacity factors and q is the overburden pressure (unit weight x height $(= \gamma h)$). Since, during driving undrained condition in the clay is assumed and hence $\phi = 0$, $c = S_u\ (> 0)$ and $N_q = 1$. The ultimate capacity (Figure 3.4 is the Point Bearing Relationship, TxDOT Geotechnical Manual (2000)) for CH, CL, SC, and Other soils can be estimated as follows:

For CH Soils

$$q_{ult} = 2 * Pb = 2\left(N_{TCP}/19.5\right) tsf = N_{TCP}/9.75\, tsf = 1.4245 \cdot N_{TCP}\ psi\ (for < 100\, blows/ft) \text{------}(3.6)$$

For CL Soils

$$q_{ult} = 2 * Pb = 2\left(N_{TCP}/16.6\right) tsf = N_{TCP}/8.3\, tsf = 1.6733 \cdot N_{TCP}\ psi\ (for < 100\, blows/ft) \text{-----}(3.7)$$

For SC Soils

$$q_{ult} = 2 * Pb = 2\left(N_{TCP}/16.3\right) tsf = N_{TCP}/8.15\, tsf = 1.7041 \cdot N_{TCP}\ psi\ (for < 100\, blows/ft) \text{----}(3.8)$$

For OTHER Soils

$$q_{ult} = 2 * Pb = 2\left(N_{TCP}/18.6\right) tsf = N_{TCP}/9.3\, tsf = 1.4934 \cdot N_{TCP}\ psi\ (for < 100\, blows/ft) \text{-----}(3.9)$$

Hence, $q_{ult} = \beta \cdot N_{TCP}$ ------------------------------------(3.10)

Substituting Equations (3.6) through (3.10) into Equation (3.5), will result in the relationship for S_u:

For CH Soils

$$S_u = \frac{1.4245}{N_c} N_{TCP} - \alpha \cdot q(h)\ psi \text{ ----------------------------}(3.11)$$

For CL Soils

$$S_u = \frac{1.6733}{N_c} N_{TCP} - \alpha \cdot q(h)\ psi \text{ ----------------------------}(3.12)$$

For SC Soils

$$S_u = \frac{1.7041}{N_c} N_{TCP} - \alpha \cdot q(h)\ psi \text{ ----------------------------}(3.13)$$

For OTHER Soils

$$S_u = \frac{1.4934}{N_c} N_{TCP} - \alpha \cdot q(h)\ psi \qquad \text{----------------------------(3.14)}$$

Hence, $$S_u = \frac{\beta}{N_c} N_{TCP} - \alpha \cdot q(h)\ psi \qquad \text{----------------------------(3.15)}$$

Based on the S_u relationships, when $S_u = 0$, $N_{TCP} = {}^{\alpha}\!/_{\beta} \cdot q(h) \cdot N_c$. Hence, it is possible to have TCP blow count, even when the undrained shear strength of soil is zero.

Equations (3.11) through (3.15) can be simplified by assuming $\alpha = 0$, neglecting the depth effect, the relationships will be similar to Model-1 and will be as follows:

For CH Soils

$$S_u = \frac{1.4245}{N_c} N_{TCP}\ \ psi \qquad \text{------------------------------------(3.16)}$$

For CL Soils

$$S_u = \frac{1.6733}{N_c} N_{TCP}\ \ psi \qquad \text{------------------------------------(3.17)}$$

For SC Soils

$$S_u = \frac{1.7041}{N_c} N_{TCP}\ \ psi \qquad \text{------------------------------------(3.18)}$$

For OTHER Soils

$$S_u = \frac{1.4934}{N_c} N_{TCP}\ \ psi \qquad \text{------------------------------------(3.19)}$$

Using Equations (3.16) through (3.19) and available data N_c will be determined for various soil types.

Model-3: A nonlinear is proposed to relate the S_u to N_{TCP} as follows:

$$S_u = m \cdot (N_{TCP})^n \qquad \text{------------------------------------(3.20)}$$

Parameters m and n will be determined from least square fit of the data. These three Models are used to predict the S_u from N_{TCP} for various soils in Texas.

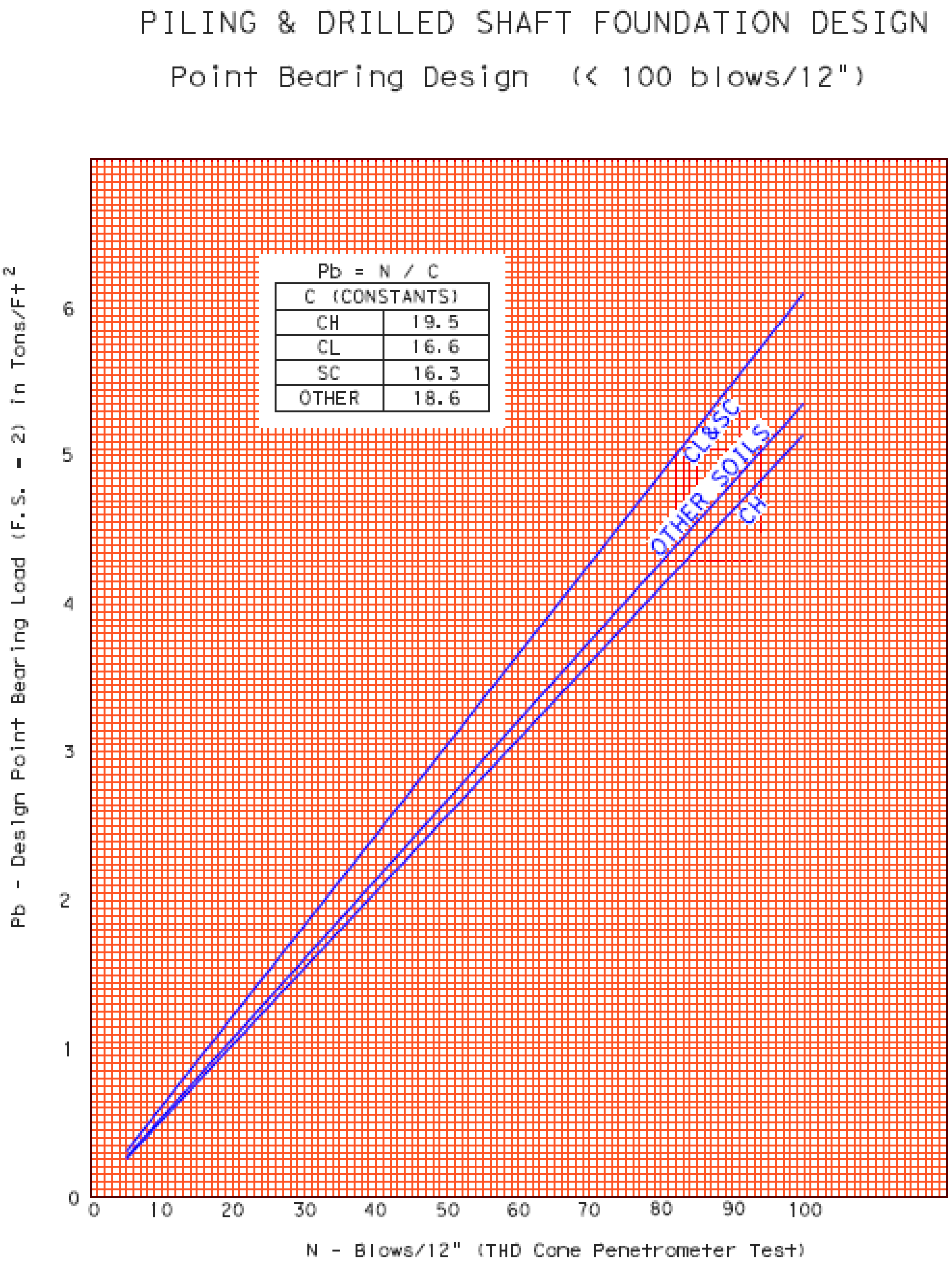


Figure 3.4 Point Bearing Relationship; Presently Used by TxDOT (TxDOT Geotechnical Manual, 2000)

3.2.1 Total Soil Data Analysis

In the present analyses, data collected for various soil types were used to verify Model-1 (Current TxDOT relationship). Also Model-2 and Model-3 were used to predict the strength. Table 3.7 summarizes the number of data sets used for total and local soil analyses.

CH Soil

A total of 2100 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.5. Current TxDOT relationship (Model-1) over predicted 59 % of the undrained shear strength data, and had the highest standard error of 11.40 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.331 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{42} tsf \qquad \text{----------------------------(3.21)}$$

Where, $N_c = 4.305$.

Hence the slope (β / N_c) of the relationship was 40 % lower than the current TxDOT relationship. Model-2 over predicted 28 % of the data, and had a standard error of 7.67.

Model-3 relationship for the data is as follow:

$$Su = 4.041 \cdot (N_{TCP})^{0.355} \ psi = 0.291 \cdot (N_{TCP})^{0.355} \ tsf \qquad \text{-----------------------------(3.22)}$$

Model-3 over predicted 58 % of the data (percentage of data below the curve), and had the lowest standard error of 6.02.

The Model parameters are summarized in Table 3.8.

CL Soil

A total of 1852 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.6. Current TxDOT relationship (Model-1) over predicted 48 % of the undrained shear strength data, and had the highest standard error of 13.32 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.386 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{36} tsf \qquad \text{----------------------------(3.23)}$$

Where, $N_c = 4.333$.

Hence the slope (β / N_c) of the relationship was 17 % lower than the current TxDOT relationship. Model-2 over predicted 38 % of the data, and had a standard error of 12.95.

Model-3 relationship for the data is as follow:

$$S_u = 8.162 \cdot (N_{TCP})^{0.213} \ psi = 0.588 \cdot (N_{TCP})^{0.213} \ tsf \qquad \text{----------------------------(3.24)}$$

Model-3 over predicted 60 % of the data (percentage of data below the curve), and had the lowest standard error of 11.02.

The Model parameters are summarized in Table 3.8.

SC Soil

Total of 29 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.7. Current TxDOT relationship (Model-1) over predicted 41 % of the undrained shear strength data, and had the highest standard error of 10.16 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.252 \cdot N_{TCP} = \frac{1.704}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{55} tsf \qquad \text{----------------------------(3.25)}$$

Where, $N_c = 6.762$.

Hence the slope (β / N_c) of the relationship was 37 % lower than the current TxDOT relationship. Model-2 over predicted 31 % of the data, and had a standard error of 8.74.

Model-3 relationship for the data is as follow:

$$S_u = 9.048 \cdot (N_{TCP})^{0.055} \ psi = 0.652 \cdot (N_{TCP})^{0.055} \ tsf \qquad \text{----------------------------(3.26)}$$

Model-3 over predicted 62 % of the data (percentage of data below the curve), and had the lowest standard error of 6.34.

The Model parameters are summarized in Table 3.8.

Other Soils

A total of 42 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.8. Current TxDOT relationship (Model-1) over predicted 48 % of the undrained shear strength data, and had the highest standard error of 13.36 compared to Model-2.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.308 \cdot N_{TCP} = \frac{1.493}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{45} tsf \qquad \text{---------------------------(3.27)}$$

Where, $N_c = 4.847$.

Hence the slope (β / N_c) of the relationship was 11 % lower than the current TxDOT relationship. Model-2 over predicted 36 % of the data, and had a standard error of 13.22. The Model parameters are summarized in Table 3.8.

In the Figure 3.5, it can be seen that the Model 2 (Linear Line) correlation for CH type soil slope of relationship was significantly lower than the Model 1 (TxDOT design relationship) to predict the undrained shear strength. Therefore, it can be interpreted that the current geotechnical manual method over predicted the shear strength for CH soils from all the districts, implying that the measured shear strength was lower than the one predicted by the current TxDOT method (Model-1). Moreover, the best fit trend lines showed a very poor coefficient of determination (R^2) value. 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 was the undrained shear strength and independent variable X is the N_{TCP} values from TCP tests. A low value of R^2 implies that the correlation was very poor at best. This very low value is explained by the large variability of undrained shear strength values used in the correlation development.

3.2.2 Local Soil Data Analysis for Houston District

In this research, a large amount of data sets for N_{TCP} and S_u were collected from the Houston TxDOT district. Table 3.7 presents the total number of data sets used for analyses in the Houston District. The analyses results for SC and Other soils were similar to the Total Soil Data results.

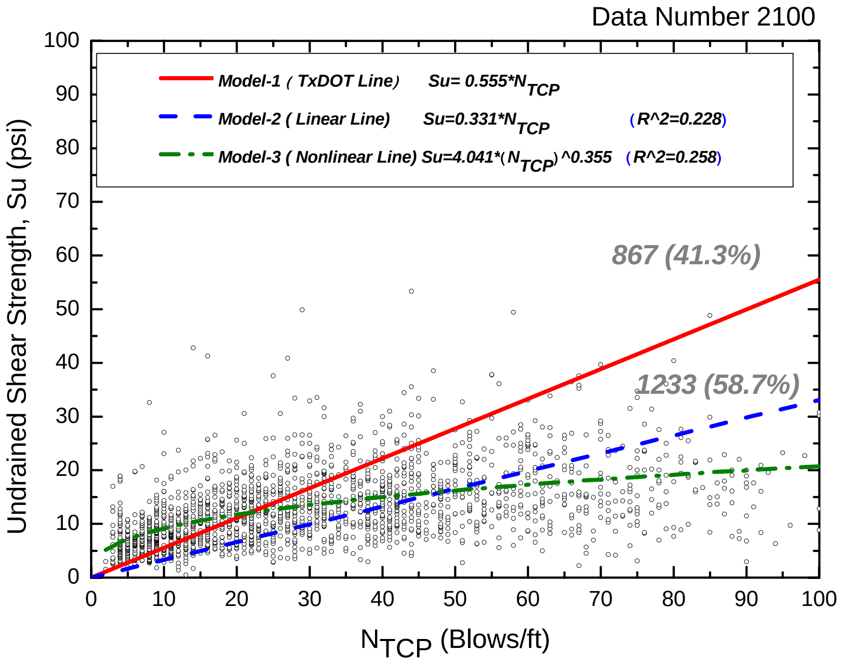


Figure 3.5 Correlation Between S_u and N_{TCP} for CH Soils (Total Soil Data)

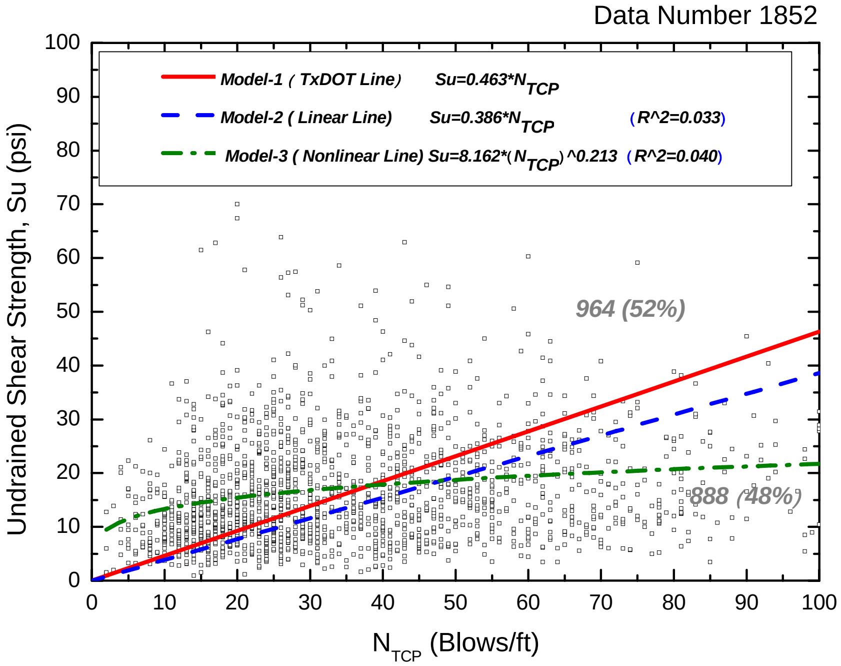


Figure 3.6 Correlation Between S_u and N_{TCP} for CL Soils (Total Soil Data)

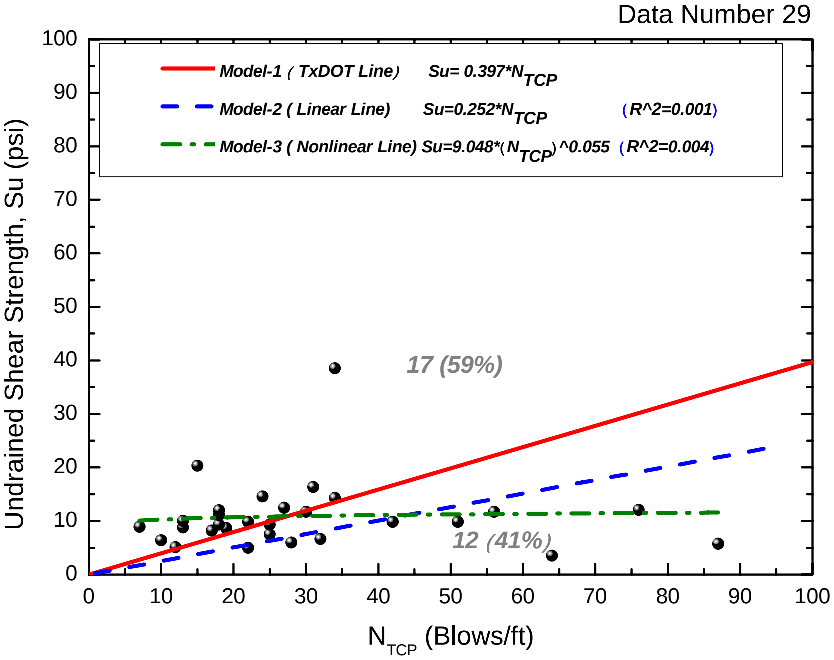


Figure 3.7 Correlation Between S_u and N_{TCP} for SC Soils (Total Soil Data)

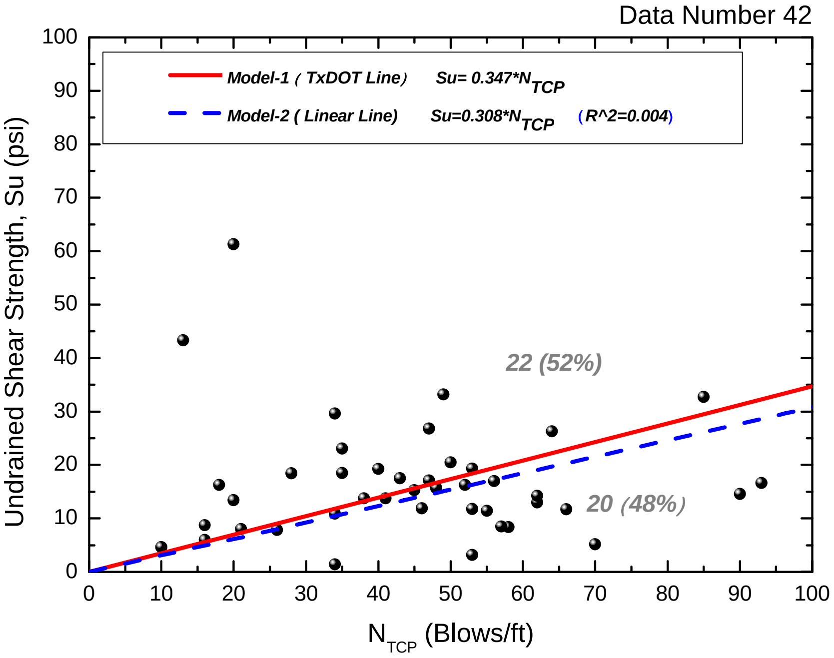


Figure 3.8 Correlation Between S_u and N_{TCP} for Other Soils (Total Soil Data)

Table 3.8 Model Comparisons for Total Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-3	Model-1	Model-2	Model-3
Constants of Linear Eqn	0.555	0.331		0.463	0.386	
Constants of Nonlinear Eqn (m / n)			4.041 / 0.355			8.162 / 0.213
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	4.305		3.613	4.333	
Slope Difference (%)	40			17		
Total Data Set	2100			1852		
Standard Error	11.40	7.67	6.02	13.32	12.95	11.02
Amount of Data Set Over Predicted	1233	594	1211	888	706	1113
Percentage of Data Set Over Predicted (%)	59	28	58	48	38	60

	SC Soil			Other Soil	
	Model-1	Model-2	Model-3	Model-1	Model-2
Constants of Linear Eqn	0.397	0.252		0.347	0.308
Constants of Nonlinear Eqn (m / n)			9.048 / 0.055		
β for Model-2	1.704			1.493	
Nc for Model-1 & 2	4.292	6.762		4.303	4.847
Slope Difference (%)	37			11	
Total Data Set	29			42	
Standard Error	10.16	8.74	6.34	13.36	13.22
Amount of Data Set Over Predicted	12	9	18	20	15
Percentage of Data Set Over Predicted (%)	41	31	62	48	36

CH Soil

A total of 1726 data sets were used to investigate the s_u versus N_{TCP} relationship shown in Figure 3.9. Current TxDOT relationship (Model-1) over predicted 67 % of the undrained shear strength data, and had the highest standard error of 12.34 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.322 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{43} tsf \qquad \text{----------------------------(3.28)}$$

Where, $N_c = 4.424$.

Hence the slope (β / N_c) of the relationship was 42 % lower than the current TxDOT relationship. Model-2 over predicted 32 % of the data, and had a standard error of 7.75.

Model-3 relationship for the data is as follows:

$$S_u = 4.534 \cdot (N_{TCP})^{0.322} \ psi = 0.327 \cdot (N_{TCP})^{0.322} \ tsf \qquad \text{----------------------------(3.29)}$$

Model-3 over predicted 55 % of the data (percentage of data below the curve), and had the lowest standard error of 6.12.

The Model parameters are summarized in Table 3.9.

CL Soil

Total of 1762 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.10. Current TxDOT relationship (Model-1) over predicted 48 % of the undrained shear strength data, and had the highest standard error of 13.35 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.384 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{36} tsf \qquad \text{----------------------------(3.30)}$$

Where, $N_c = 4.357$.

Hence the slope (β/N_c) of the relationship was 17 % lower than the current TxDOT relationship. Model-2 over predicted 38 % of the data, and had a standard error of 12.96.

Model-3 relationship for the data is as follows:

$$S_u = 8.316 \cdot (N_{TCP})^{0.208}\ psi = 0.599 \cdot (N_{TCP})^{0.208}\ tsf \qquad \text{----------------------------(3.31)}$$

Model-3 over predicted 60 % of the data (percentage of data below the curve), and had the lowest standard error of 11.

The Model parameters are summarized in Table 3.9.

In Figure 3.9, it can be seen that the Model 2 (Linear Line) correlation for CH type soil slope of relationship was significantly lower than the Model 1 (TxDOT design relationship) to predict the undrained shear strength. Therefore, it can be interpreted that the current geotechnical manual line over predicted the shear strength for CH soils from Houston District. Moreover, the linear fit trend lines showed a very poor coefficient of determination (R^2) value.

Table 3.9 Model Comparisons for Houston Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-3	Model-1	Model-2	Model-3
Constants of Linear Eqn	0.555	0.322		0.463	0.384	
Constants of Nonlinear Eqn (m / n)			4.534 / 0.322			8.316 / 0.208
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	4.424		3.613	4.357	
Slope Difference (%)	42			17		
Total Data Set	1726			1762		
Standard Error	12.34	7.75	6.12	13.35	12.96	11
Amount of Data Set Over Predicted	1156	548	944	853	670	1057
Percentage of Data Set Over Predicted (%)	67	32	55	48	38	60

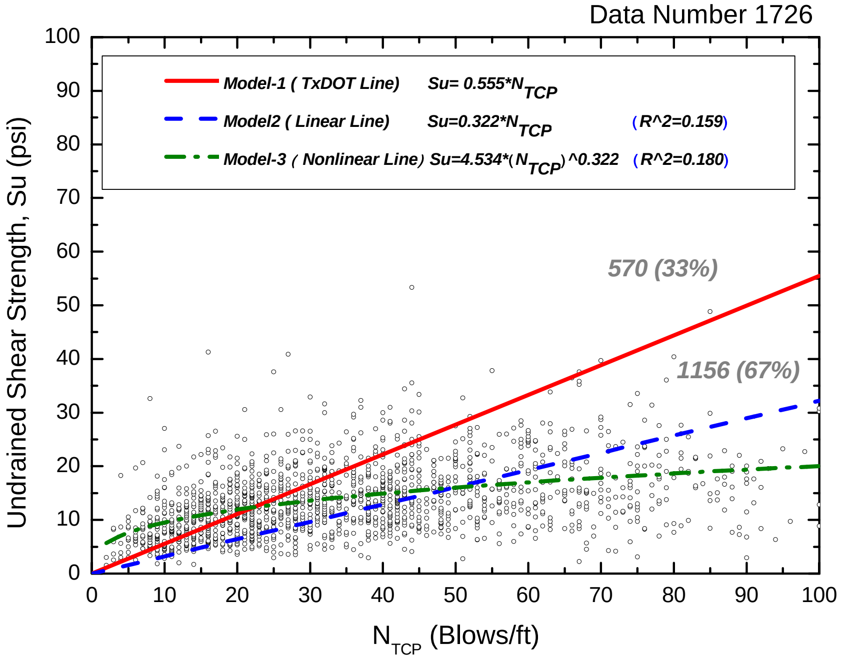


Figure 3.9 Correlation Between S_u and N_{TCP} for CH Soils (Houston Soil Data)

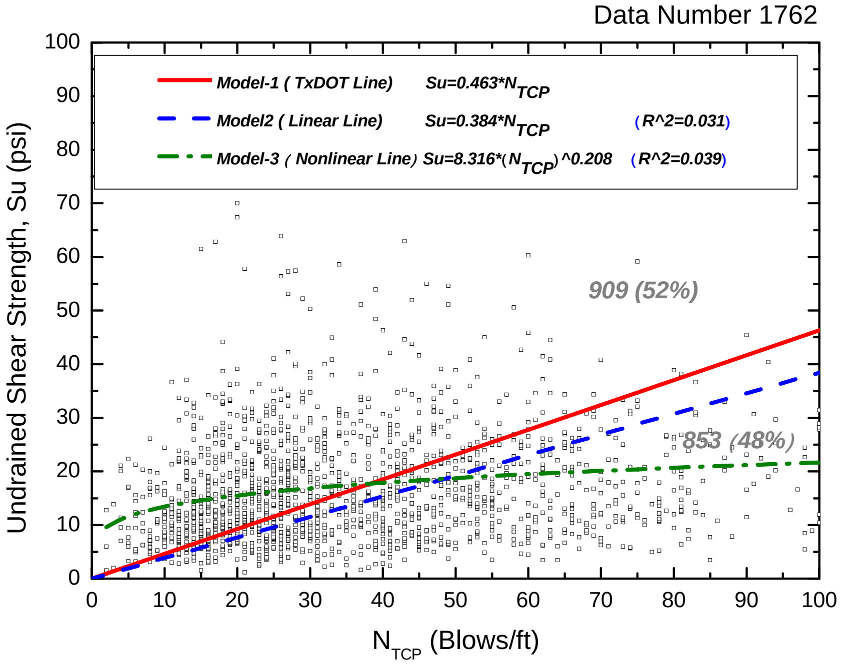


Figure 3.10 Correlation Between S_u and N_{TCP} for CL Soils (Houston Soil Data)

3.2.3 Local Soil Data Analysis for Beaumont District

In this research, a large amount of data set for N_{TCP} and S_u were collected from the TxDOT Beaumont District. Table 3.7 presents the total number of data sets used for analyses in the Beaumont District.

CH Soil

A total of 341 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.11. Current TxDOT relationship (Model-1) over predicted 19 % of the undrained shear strength data, and had the highest standard error of 4.84 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.671 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{21} tsf \qquad \text{----------------------------(3.32)}$$

Where, $N_c = 2.123$.

Hence the slope (β / N_c) of the relationship was 21 % higher than the current TxDOT relationship. Model-2 over predicted 30 % of the data, and had a standard error of 4.69.

Model-3 relationship for the data is as follows:

$$S_u = 4.037 \cdot (N_{TCP})^{0.305} \ psi = 0.291 \cdot (N_{TCP})^{0.305} \ tsf \qquad \text{----------------------------(3.33)}$$

Model-3 over predicted 57 % of the data (percentage of data below the curve), and had the lowest standard error of 3.53.

The Model parameters are summarized in Table 3.10.

CL Soil

A total of 26 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.12. Current TxDOT relationship (Model-1) over predicted 46 % of the undrained shear strength data, and had the highest standard error of 8.06 compared to Model-2.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.283 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{49} tsf \qquad \text{---------------------------(3.34)}$$

Where, $N_c = 5.912$.

Hence the slope (β / N_c) of the relationship was 39 % lower than the current TxDOT relationship. Model-2 over predicted 31 % of the data, and had a standard error of 6.385.

The Model parameters are summarized in Table 3.10.

In Figure 3.12, it can be seen that the Model 2 (Linear Line) correlation for CL type soil slope of relationship was significantly lower than the Model 1 (TxDOT design relationship) to predict the undrained shear strength. Therefore, it can be interpreted that the current geotechnical manual line over predicted the shear strength for CL soils from the Beaumont District. Moreover, the linear fit trend lines showed a very poor coefficient of determination (R^2) value.

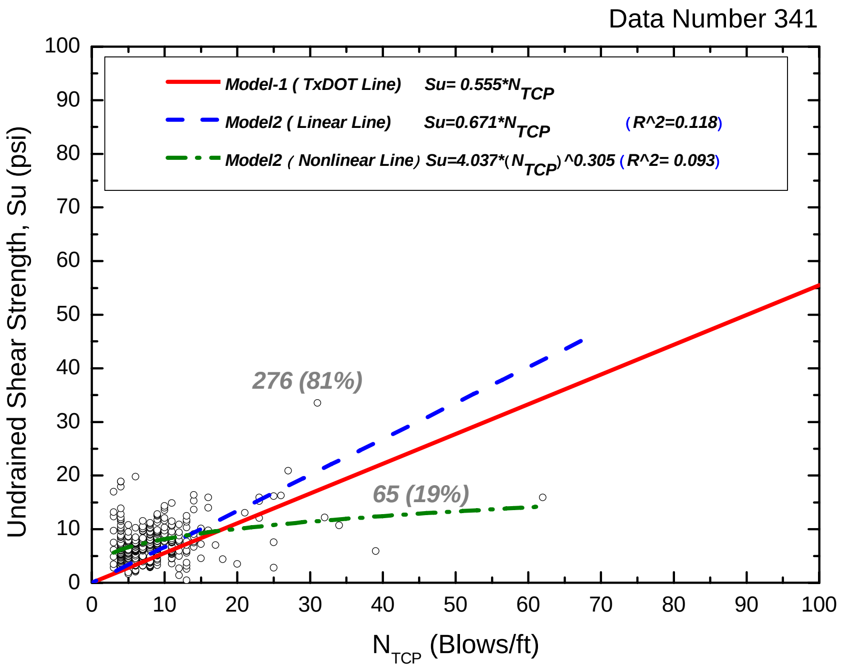


Figure 3.11 Correlation Between S_u and N_{TCP} for CH Soils (Beaumont Soil Data)

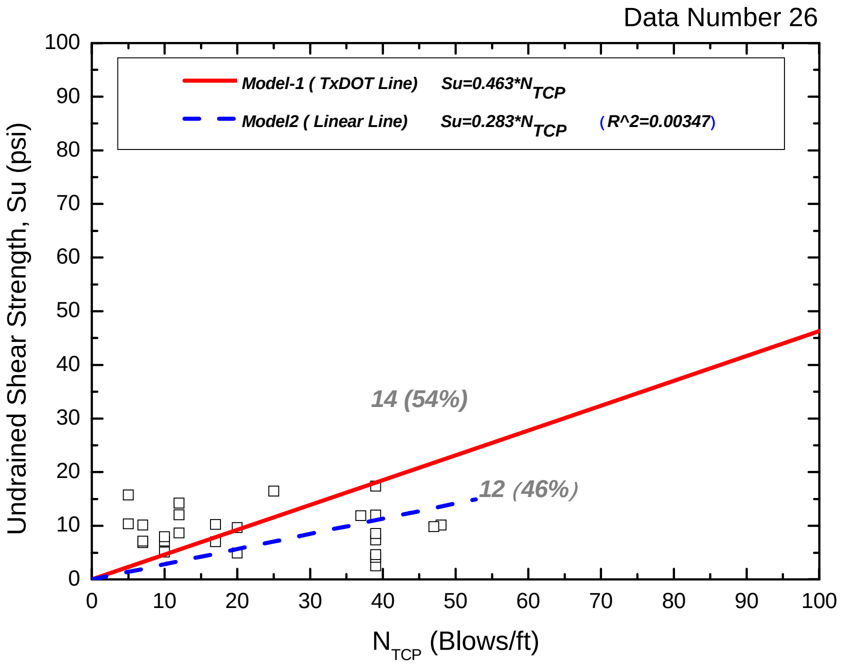


Figure 3.12 Correlation Between S_u and N_{TCP} for CL Soils (Beaumont Soil Data)

Table 3.10 Model Comparisons for Beaumont Soil Data

	CH Soil			CL Soil	
	Model-1	Model-2	Model-3	Model-1	Model-2
Constants of Linear Eqn	0.555	0.671		0.463	0.283
Constants of Nonlinear Eqn (m / n)			4.037 / 0.305		
β for Model-2	1.425			1.673	
Nc for Model-1 & 2	2.567	2.123		3.613	5.912
Slope Difference (%)	21			39	
Total Data Set	341			26	
Standard Error	4.84	4.69	3.53	8.06	6.39
Amount of Data Set Over Predicted	65	101	193	12	8
Percentage of Data Set Over Predicted (%)	19	30	57	46	31

3.2.4 Local Soil Data Analysis for Dallas-Fort Worth District

In this research, a small amount of data set for N_{TCP} and S_u were collected from the TxDOT Dallas-Fort Worth District. Table 3.7 presents the total number of data sets used for analyses in the Dallas-Fort Worth District.

CH Soil

A total of 11 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.13. Current TxDOT relationship (Model-1) over predicted 9 % of the undrained shear strength data, and had the highest standard error of 16.72 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.937 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{15} tsf \qquad \text{---------------------------(3.35)}$$

Where, $N_c = 1.520$.

Hence the slope (β / N_c) of the relationship was 69 % higher than the current TxDOT relationship. Model-2 over predicted 36 % of the data, and had a standard error of 13.08.

Model-3 relationship for the data is as follow:

$$S_u = 4.225 \cdot (N_{TCP})^{0.574}\ psi = 0.304 \cdot (N_{TCP})^{0.574}\ tsf \qquad \text{----------------------------(3.36)}$$

Model-3 over predicted 64 % of the data (percentage of data below the curve), and had the lowest standard error of 11.78.

The Model parameters are summarized in Table 3.11.

CL Soil

A total of 51 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.14. Current TxDOT relationship (Model-1) over predicted 22 % of the undrained shear strength data, and had the highest standard error of 22.71 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.949 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{15} tsf \qquad \text{---------------------------(3.37)}$$

Where, $N_c = 1.763$.

Hence the slope (β / N_c) of the relationship was 105 % higher than the current TxDOT relationship. Model-2 over predicted 55 % of the data, and had a standard error of 20.17.

Model-3 relationship for the data is as follows:

$$S_u = 12.717 \cdot (N_{TCP})^{0.195}\ psi = 0.916 \cdot (N_{TCP})^{0.195}\ tsf \qquad \text{----------------------------(3.38)}$$

Model-3 over predicted 67 % of the data (percentage of data below the curve), and had the lowest standard error of 18.15.

The Model parameters are summarized in Table 3.11.

In Figures 3.13 and 3.14, it can be seen that the Model 2 (Linear Line) correlation for CH and CL type soil slope of relationship was significantly higher than the Model 1 (TxDOT design relationship) to predict the undrained shear strength. Therefore, it can be interpreted that the current geotechnical manual line underestimated the shear strength for CH and CL soils in the Dallas-Fort Worth District.

Table 3.11 Model Comparisons for Dallas-Fort Worth Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-3	Model-1	Model-2	Model-3
Constants of Linear Eqn	0.555	0.937		0.463	0.949	
Constants of Nonlinear Eqn (m / n)			4.225 / 0.574			12.717 / 0.195
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	1.520		3.613	1.763	
Slope Difference (%)	69			105		
Total Data Set	11			51		
Standard Error	16.72	13.08	11.78	22.71	20.17	18.15
Amount of Data Set Over Predicted	1	4	7	11	28	34
Percentage of Data Set Over Predicted (%)	9	36	64	22	55	67

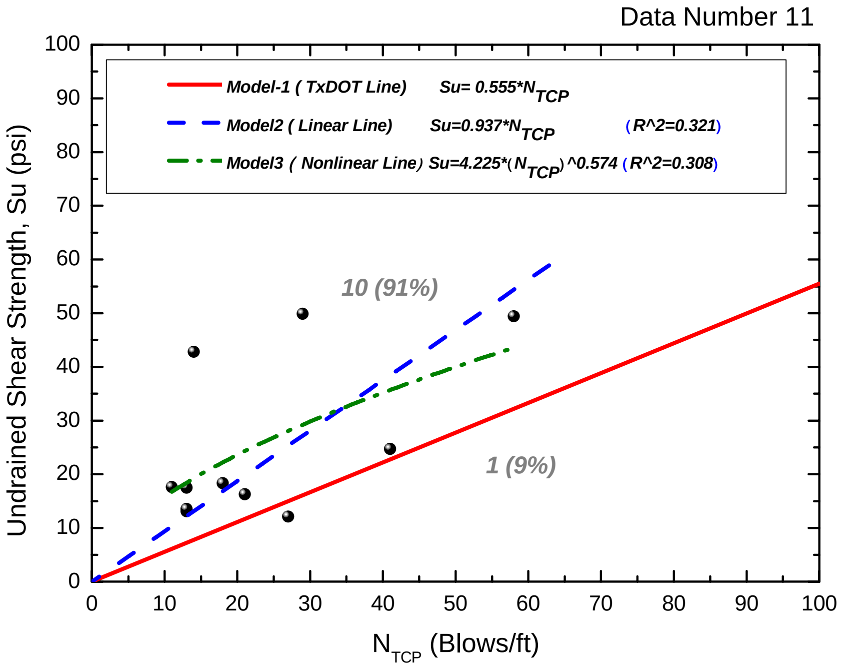


Figure 3.13 Correlation Between S_u and N_{TCP} for CH Soils (Dallas and Fort Worth Soil Data)

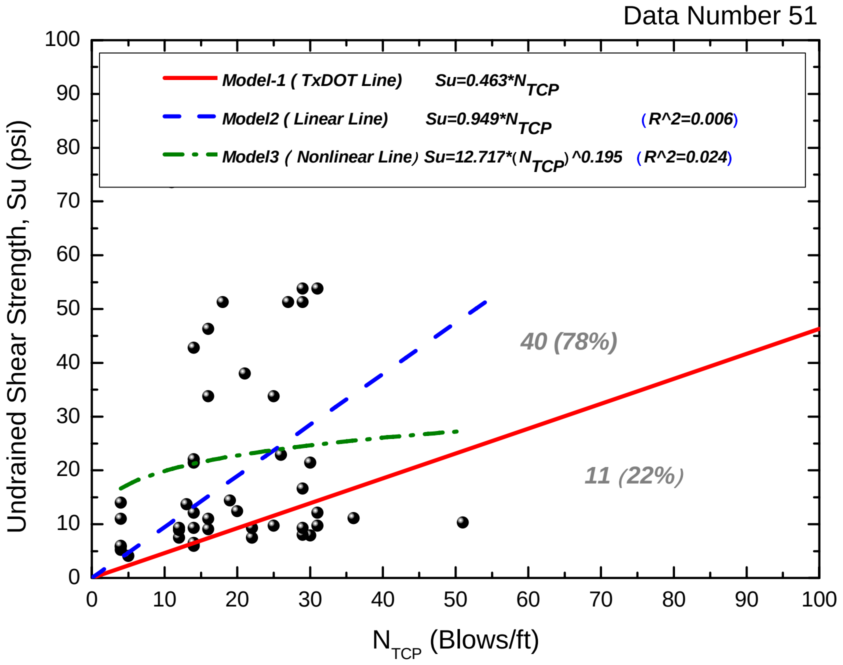


Figure 3.14 Correlation Between S_u and N_{TCP} for CL Soils (Dallas and Fort Worth Soil Data)

3.3 Comparison of Correlations

The linear relationships developed for various locations are compared to the TxDOT relationship (Model-1) also referred to as Case-B. Case-A and Case-C represent higher and lower slopes (β / N_c), respectively, than Case-B.

Table 3.12 Trend Observed in Various Locations

	Houston	Waco	Dallas - Fort Worth	Beaumont	
				US-69	I-10
CL	B &C	B	A&B	B&C	No Data
CH	B &C	B	A&B	B	A&B

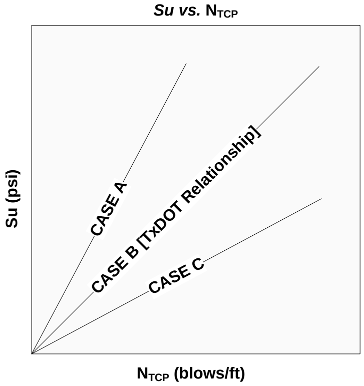


Figure 3.15 Possible Trends Observed

The trend observed shows that locations (hence geology) affected the N_{TCP} versus S_u correlation. Hence, statistical methods will be used to develop new relationships in Chapters 4 and 5.

3.4 Validation

Additional tests were performed to validate the data collected and compare it to the current and other relationships developed in this study.

3.4.1 Houston District

In the Houston area 42 samples were collected and unconfined, undrained compression tests were performed in the UH laboratory.

CL Soil

A total of 42 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.16. Current TxDOT relationship (Model-1) over predicted 24 % of the undrained shear strength data, and had the highest standard error of 11.84 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.553 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{25} tsf \quad \text{----------------------------(3.39)}$$

Where, $N_c = 3.025$.

Hence the slope (β / N_c) of the relationship was 19 % higher than the current TxDOT relationship. Model-2 over predicted 40 % of the data, and had a standard error of 11.42.

Model-3 relationship for the data is as follows:

$$S_u = 3.868 \cdot (N_{TCP})^{0.478} \ psi = 0.279 \cdot (N_{TCP})^{0.478} \ tsf \quad \text{----------------------------(3.40)}$$

Model-3 over predicted 64 % of the data (percentage of data below the curve), and had the lowest standard error of 10.5.

The Model parameters are summarized in Table 3.13.

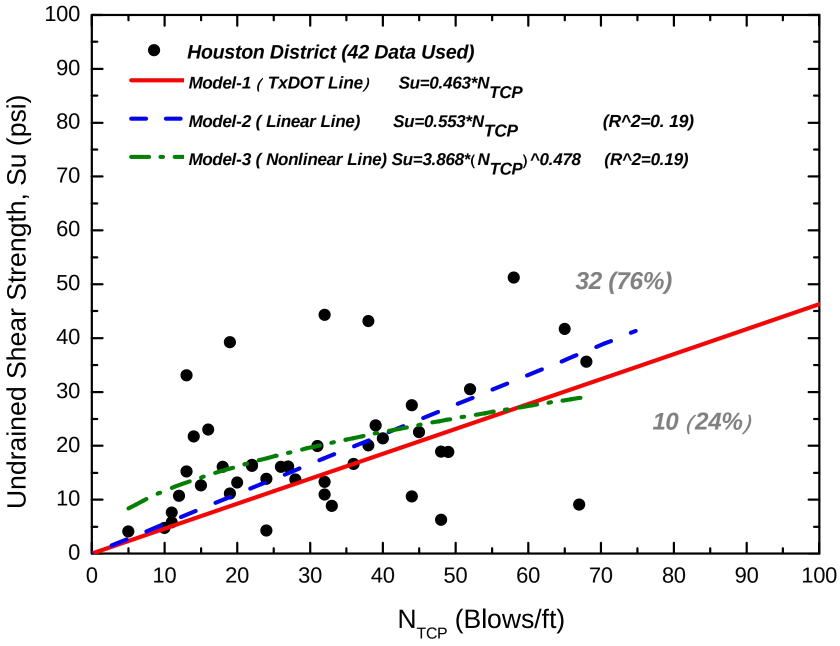


Figure 3.16 Data Validation (Houston District-CL Soil)

Table 3.13 Model Comparisons for Data Validation (Houston District-CL Soil)

	CL Soil		
	Model-1	Model-2	Model-3
Constants of Linear Eqn	0.463	0.553	
Constants of Nonlinear Eqn (m / n)			3.868 / 0.478
β for Model-2	1.673		
Nc for Model-1 & 2	3.613	3.025	
Slope Difference (%)	19		
Total Data Set	42		
Standard Error	11.84	11.42	10.5
Amount of Data Set Over Predicted	10	17	27
Percentage of Data Set Over Predicted (%)	24	40	64

3.4.2 Dallas-Fort Worth District

In the Dallas area, 15 samples were collected and unconfined, undrained compression tests were performed in the UTA laboratory.

CH Soil

A total of 8 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.17. Current TxDOT relationship (Model-1) did not over predict any of the undrained shear strength data but had the highest standard error of 33.74 compared to Model-2 and Model-3.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 4.105 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP} \; psi = \frac{N_{TCP}}{3} tsf \qquad \text{---------------------------}(3.41)$$

Where, $N_c = 0.347$.

Hence the slope (β / N_c)of the relationship was 640 % higher than the current TxDOT relationship. Model-2 over predicted 50 % of the data, and had a standard error of 13.

Model-3 relationship for the data is as follows:

$$S_u = 12.915 \cdot (N_{TCP})^{0.482} \; psi = 0.930 \cdot (N_{TCP})^{0.482} \; tsf \qquad \text{----------------------------}(3.42)$$

Model-3 over predicted 50 % of the data (percentage of data below the curve), and had the lowest standard error of 12.15.

The Model parameters are summarized in Table 3.14.

CL Soil

A total of 7 data sets were used to investigate the S_u versus N_{TCP} relationship shown in Figure 3.18. Current TxDOT relationship (Model-1) over predicted 14 % of the undrained shear strength data, and had the highest standard error of 19.01 compared to Model-2.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$S_u = 0.706 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP} \ psi = \frac{N_{TCP}}{20} tsf \qquad \text{----------------------------(3.43)}$$

Where, $N_c = 2.370$.

Hence the slope (β / N_c) of the relationship was 52 % higher than the current TxDOT relationship. Model-2 over predicted 29 % of the data, and had a standard error of 17.38.

All Model parameters for the two soils are summarized in Table 3.14.

Table 3.14 Model Comparisons for Dallas Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-3	Model-1	Model-2	Model-3
Constants of Linear Eqn	0.555	0.937		0.463	0.949	
Constants of Nonlinear Eqn (m / n)			4.225 / 0.574			12.717 / 0.195
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	1.520		3.613	1.763	
Slope Difference (%)	69			105		
Total Data Set	11			51		
Standard Error	16.72	13.08	11.78	22.71	20.17	18.15
Amount of Data Set Over Predicted	1	4	7	11	28	34
Percentage of Data Set Over Predicted (%)	9	36	64	22	55	67

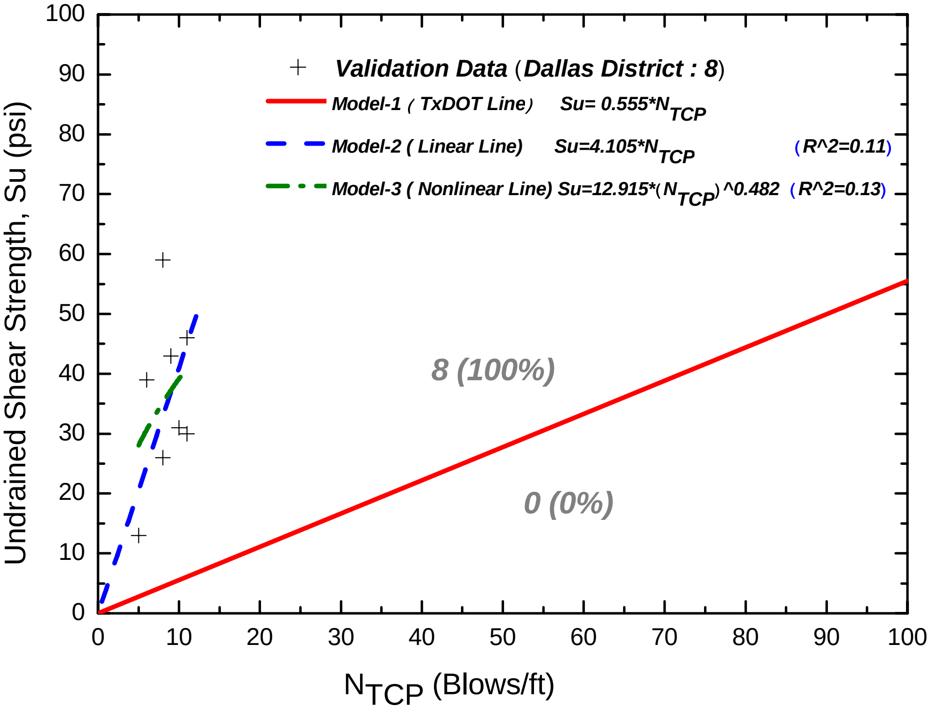


Figure 3.17 Data Validation (Dallas District-CH Soil)

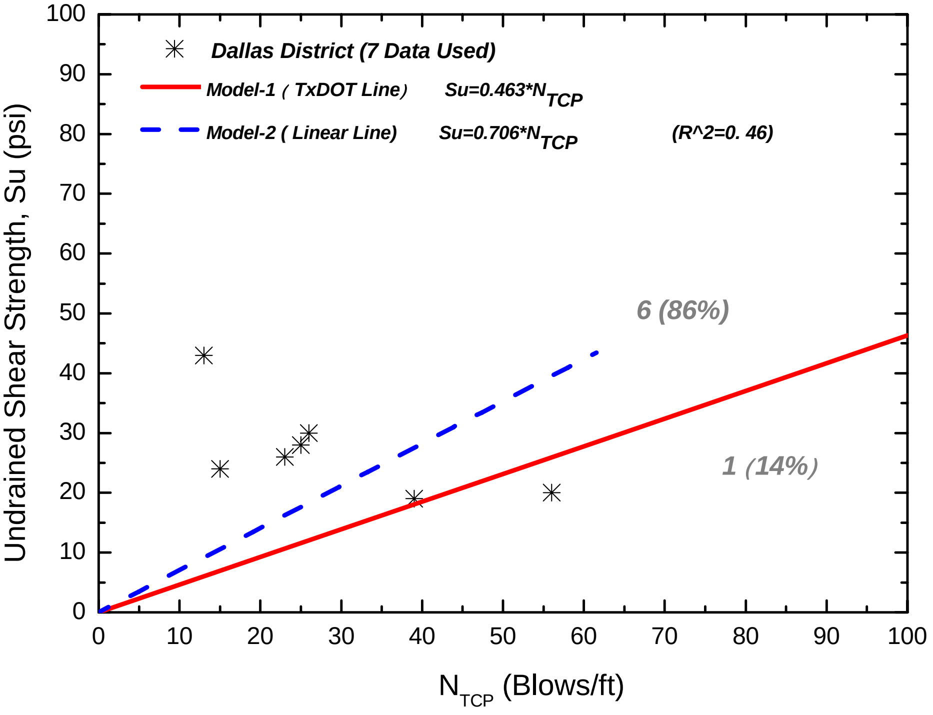


Figure 3.18 Data Validation (Dallas District-CL Soil)

3.5 Relationships between N_1 and N_2

During the TCP test, N_1 (the number of blows for the first 6 inches of penetration) and N_2 (the number of blows for the second 6 inches of penetration) are recorded separately. According to the TxDOT Geotechnical Manual (2000), 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 N_1 and N_2 is generally about the same. Based on the data collected, this statement will be further investigated and quantified by investigating the best fit linear relationship between N_1 and N_2.

3.5.1 Total Soil Data Analysis

The relationship between N_1 and N_2 was investigated using the following relationship.

$$N_2 = p \cdot N_1 \qquad \text{---------------------------(3.44)}$$

CH Soil

A total of 2100 data sets were used and the parameter p was 1.121 with a R^2 of 0.886 (Table 3.15 and Figure 3.19). Hence N_2 was 12% higher than N_1.

CL Soil

A total of 1852 data sets were used and the parameter p was 1.122 with a R^2 of 0.819 (Table 3.15 and Figure 3.20). Hence N_2 was 12% higher than N_1.

SC Soil

A total of 29 data sets were used and the parameter p was 1.083 with a R^2 of 0.753 (Table 3.15 and Figure 3.21). Hence N_2 was 8.3% higher than N_1.

A total of 29 data sets were used and the parameter p was 1.083 with a R^2 of 0.753 (Table 3.15 and Figure 3.21). Hence N_2 was 8.3% higher than N_1.

OTHER Soils

A total of 42 data sets were used and the parameter p was 1.103 with a R^2 of 0.569 (Table 3.15 and Figure 3.22). Hence N_2 was 10% higher than N_1.

It should be noted from Table 3.15 that there is no significant difference in the parameter p for CH, CL, SC and Other soils.

Table 3.15 Summary for Best Fit Linear Lines – Total Districts

Soil Type	p	R^2	Number of Data
CH	1.121	0.886	2100
CL	1.122	0.819	1852
SC	1.083	0.753	29
OTHERS	1.103	0.569	42

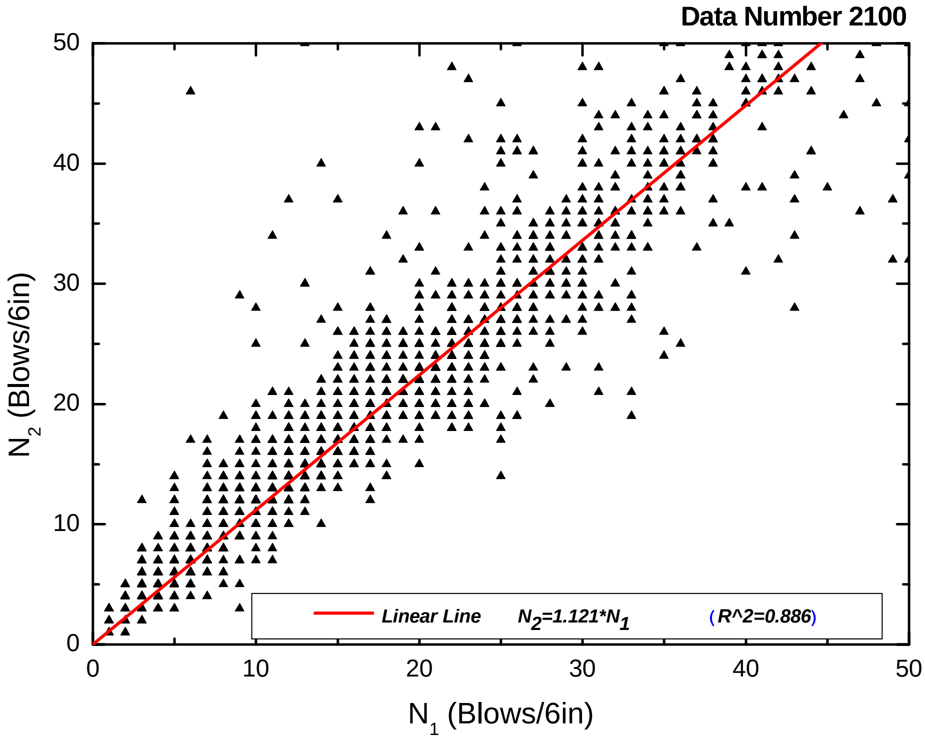


Figure 3.19 Correlation Between N_1 and N_2 for Total CH Soils

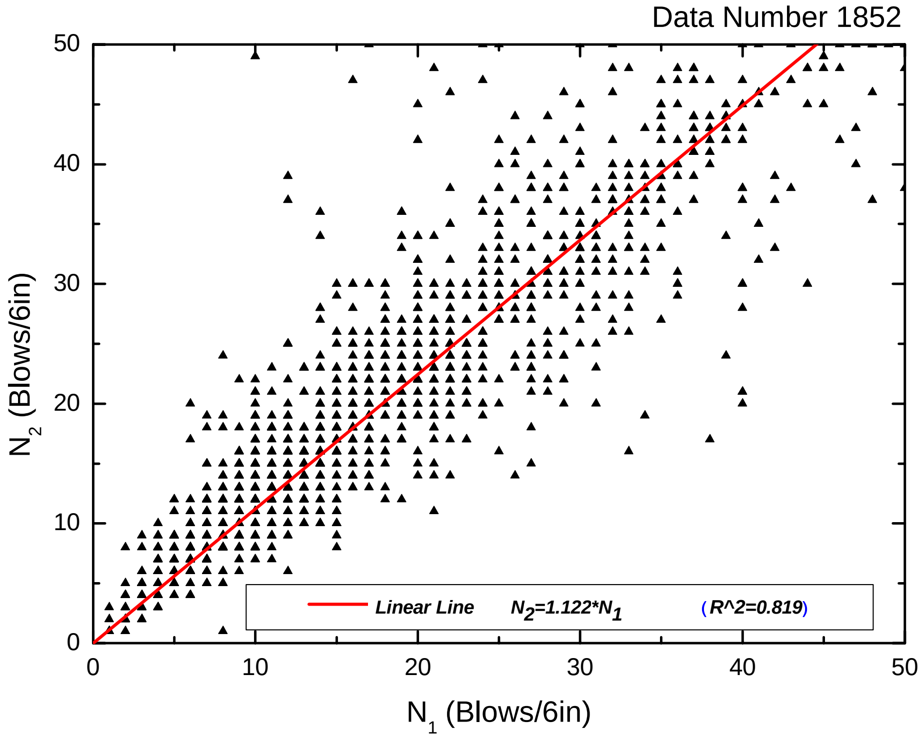


Figure 3.20 Correlation Between N_1 and N_2 for Total CL Soils

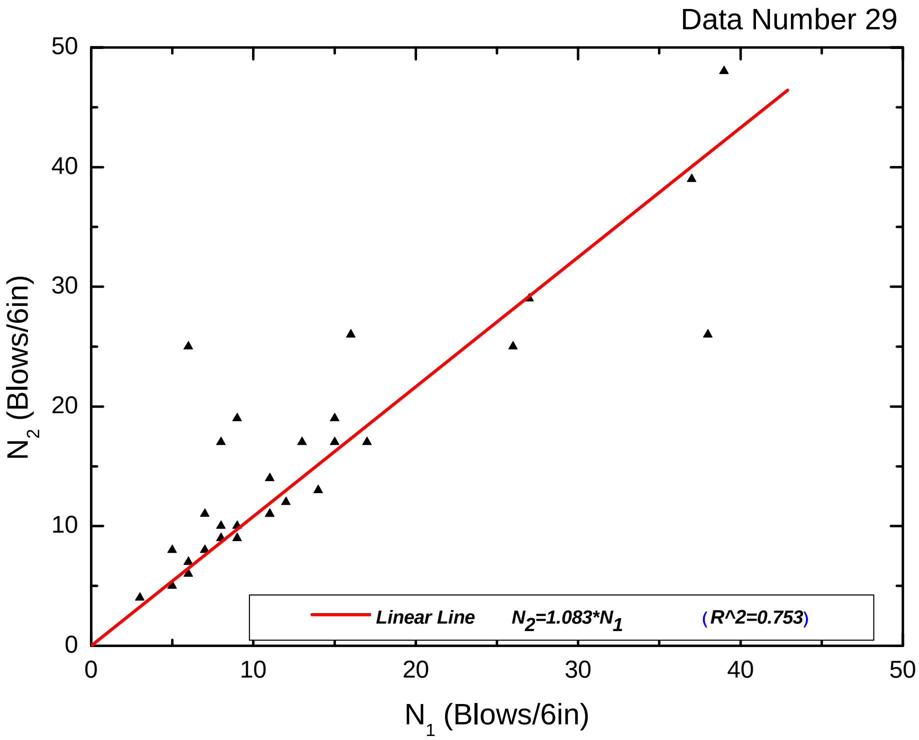


Figure 3.21 Correlation Between N_1 and N_2 for Total SC Soils

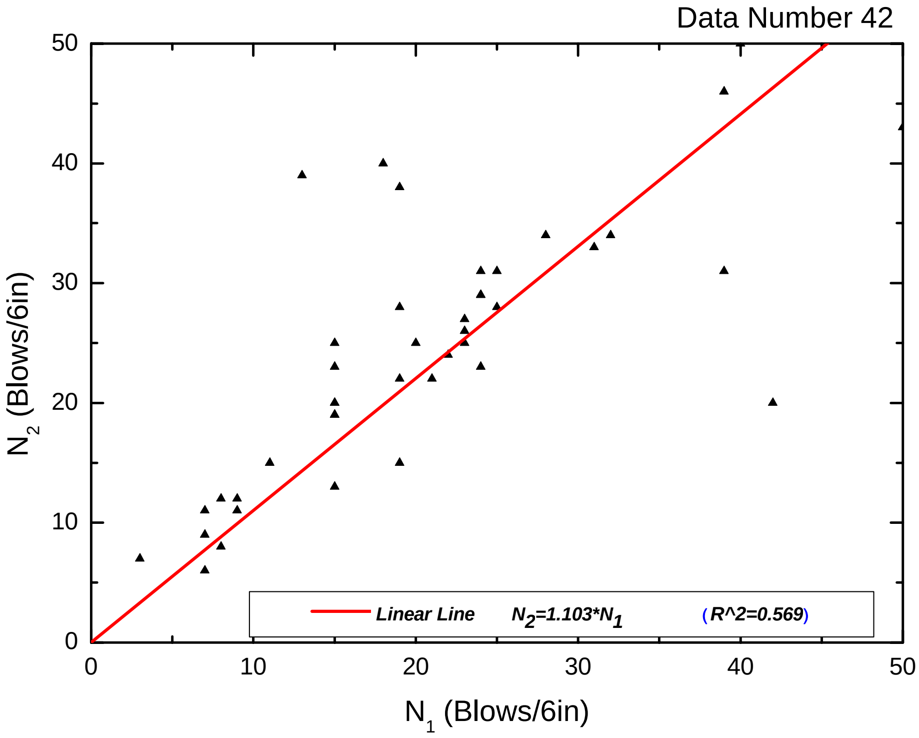


Figure 3.22 Correlation Between N_1 and N_2 for Total OTHER Soils

3.5.2 Local Data Analysis for Houston District

The results of best fit linear trend lines for each soil type in the Houston District are shown in Figures 3.23 and 3.24, and summarized in Table 3.16.

CH Soil

A total of 1726 data sets were used and the parameter p was 1.121 with a R^2 of 0.859 (Table 3.16 and Figure 3.23). Hence N_2 was 12% higher than N_1.

CL Soil

A total of 1762 data sets were used and the parameter p was 1.120 with a R^2 of 0.821 (Table 3.16 and Figure 3.24). Hence N_2 was 12% higher than N_1.

Table 3.16 Summary for Best Fit Linear Lines – Houston District

Soil Type	**p**	**R^2**	**Number of Data**
CH	1.121	0.859	1726
CL	1.120	0.821	1762

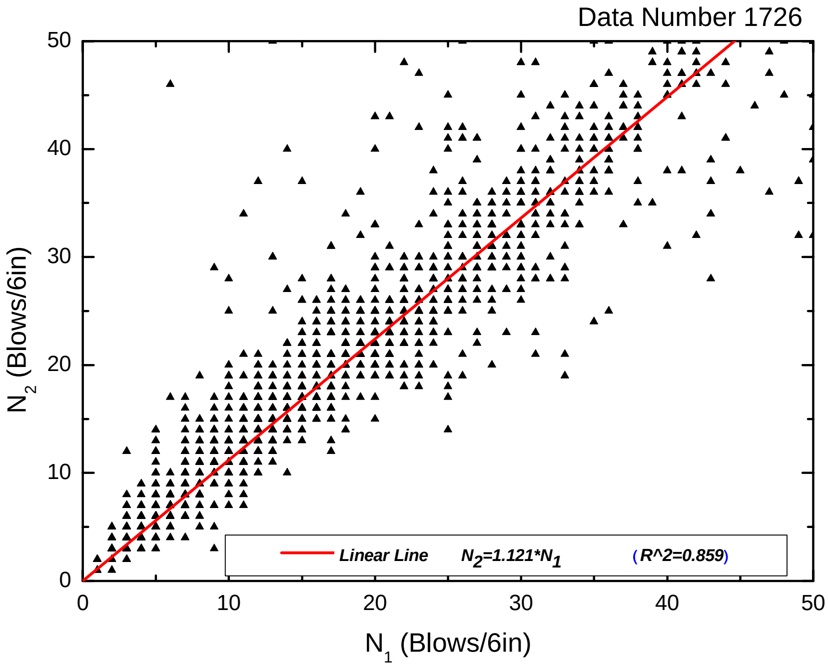


Figure 3.23 Correlation Between N_1 and N_2 for Houston CH Soils

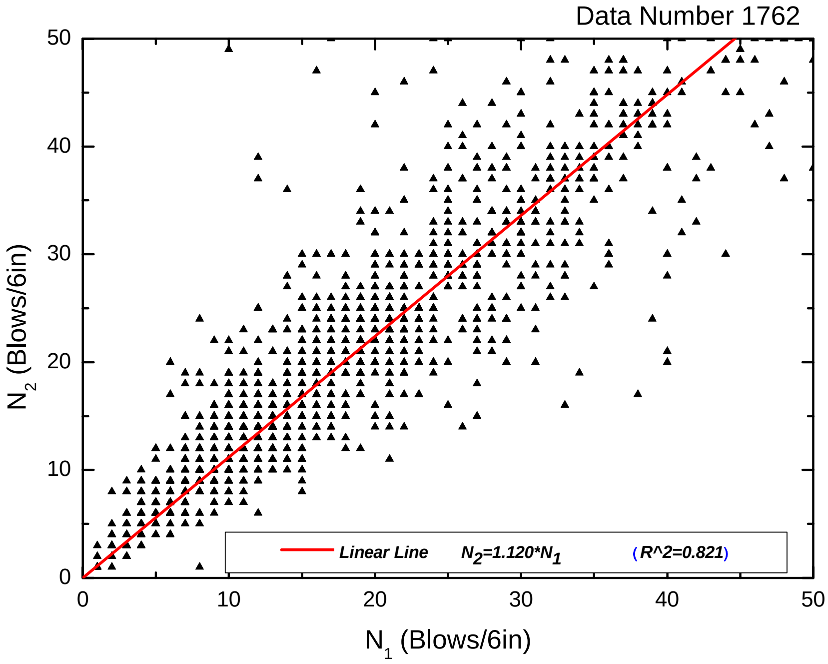


Figure 3.24 Correlation Between N_1 and N_2 for Houston CL Soils

3.5.3 Local Data Analysis for Beaumont District

The results of best fit linear trend lines for each soil type in the Beaumont District are shown in Figures 3.25 and 3.26, and summarized in Table 3.17.

CH Soil

A total of 341 data sets were used and the parameter p was 1.204 with a R^2 of 0.845 (Table 3.17 and Figure 3.25). Hence N_2 was 20% higher than N_1.

CL Soil

A total of 36 data sets were used and the parameter p was 1.355 with a R^2 of 0.887 (Table 3.17 and Figure 3.26). Hence N_2 was 36% higher than N_1.

Table 3.17 Summary for Best Fit Linear Lines – Beaumont District

Soil Type	Equation	R^2	Number of Data
CH	$N_2 = 1.204 \times N_1$	0.845	341
CL	$N_2 = 1.355 \times N_1$	0.887	36

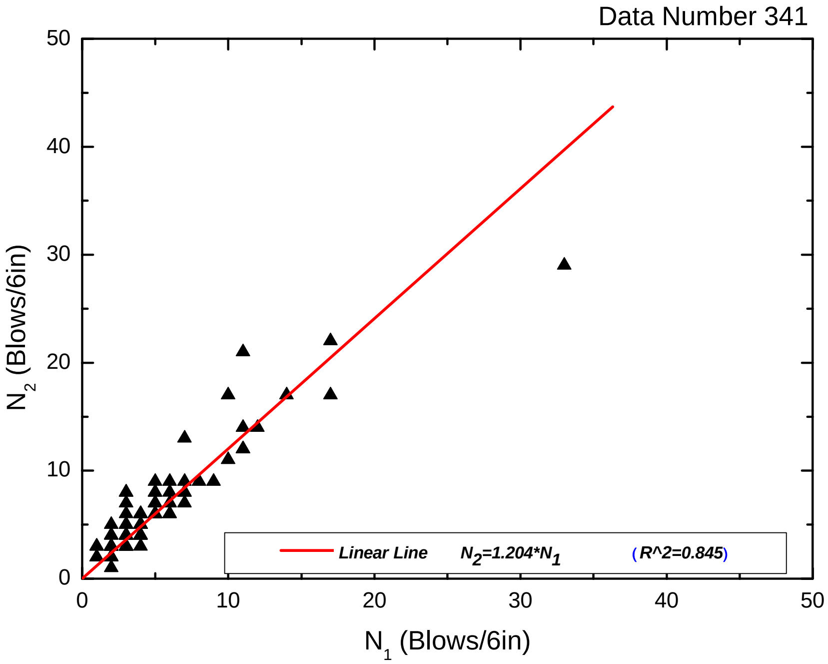


Figure 3.25 Correlation Between N_1 and N_2 for Beaumont CH Soils

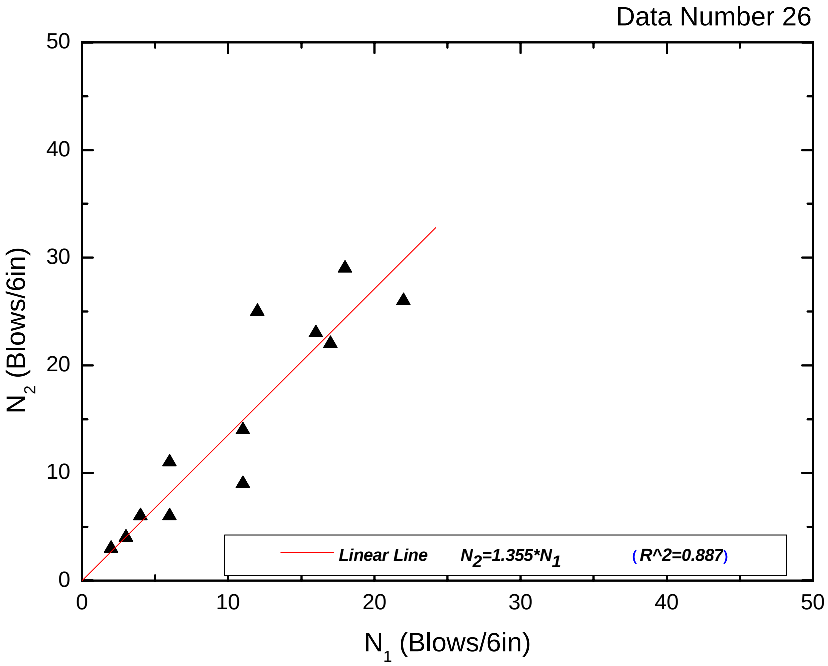


Figure 3.26 Correlation Between N_1 and N_2 for Beaumont CL Soils

3.5.4 Local Data Analysis for Dallas-Fort Worth District

The results of best fit linear trend lines for each soil type in the Dallas-Fort Worth District are shown in Figures 3.27 and 3.28, and summarized in Table 3.18.

CH Soil

A total of 11 data sets were used and the parameter p was 1.068 with a R^2 of 0.944 (Table 3.18 and Figure 3.27). Hence N_2 was 6.8% higher than N_1.

CL Soil

A total of 51 data sets were used and the parameter p was 1.152 with a R^2 of 0.743 (Table 3.18 and Figure 3.28). Hence N_2 was 15% higher than N_1.

Table 3.18 Summary for Best Fit Linear Lines – Dallas-Fort Worth District

Soil Type	Equation	R^2	Number of Data
CH	$N_2 = 1.068 \times N_1$	0.944	11
CL	$N_2 = 1.152 \times N_1$	0.743	51

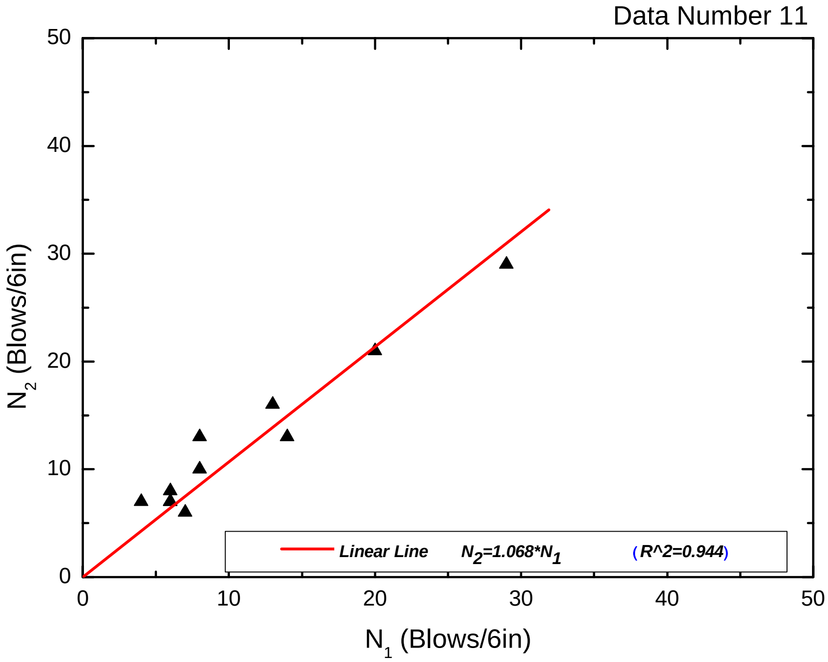


Figure 3.27 Correlation Between N_1 and N_2 for Dallas-Fort Worth CH Soils

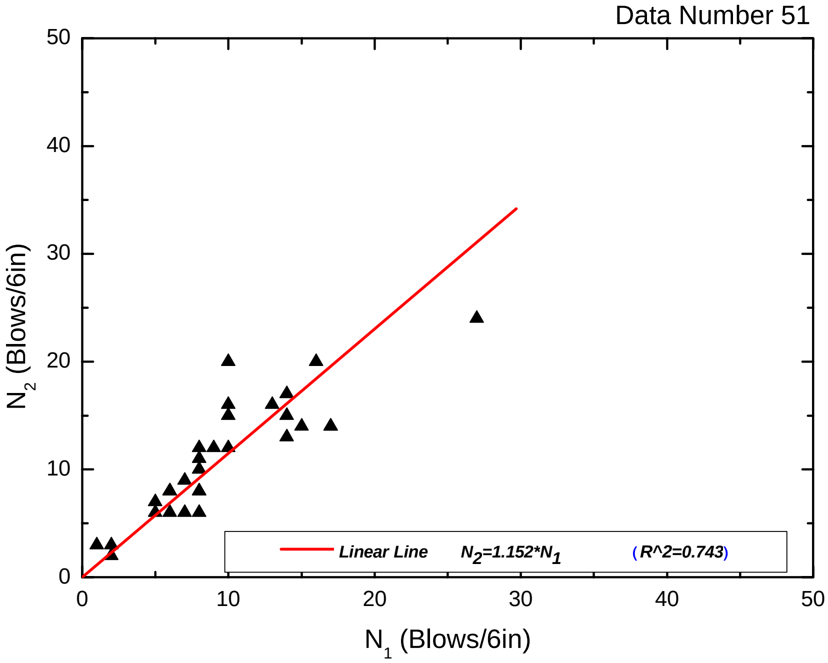


Figure 3.28 Correlation Between N_1 and N_2 for Dallas-Fort Worth CL Soils

3.6 Summary

A total of 4023 data were collected from the 3987 bore holes from various parts of Texas and analyzed and compared to the current TxDOT S_u versus N_{TCP} relationship. Also, limited tests were done to validate the data. The relationship between N_1 and N_2 was also investigated.

Based on the analyses of the data the following can be concluded for each type of soil.

1. **CH Soils:**

   Current TxDOT relationship over predicted 59% of the data (Total of 2100 data). The linear relationship between TCP blow count and undrained shear strength of soil varied with the location. The blow count N_2 was 12% higher than N_1 based on the total CH soil data. Model study results are as follows:

Model-1:		
	$S_u = 2\left(N_{TCP} \big/ 50 \right) tsf = N_{TCP} \big/ 25\, tsf = (0.555) \cdot N_{TCP}\ psi$	
Model-2 :		
Texas	$S_u = 0.331 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{42} tsf$	Where, $N_c = 4.305$
Houston District	$S_u = 0.322 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{43} tsf$	Where, $N_c = 4.424$
Beaumont District	$S_u = 0.671 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{21} tsf$	Where, $N_c = 2.123$
Dallas-Fort Worth District	$S_u = 0.937 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{15} tsf$	Where, $N_c = 1.520$
Data Validation (Dallas-Fort Worth District)	$S_u = 4.105 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{3} tsf$	Where, $N_c = 0.347$

Model-3:	
Texas	$S_u = 4.041 \cdot (N_{TCP})^{0.355}\ psi = 0.291 \cdot (N_{TCP})^{0.355}\ tsf$
Houston District	$S_u = 4.534 \cdot (N_{TCP})^{0.322}\ psi = 0.327 \cdot (N_{TCP})^{0.322}\ tsf$
Beaumont District	$S_u = 4.037 \cdot (N_{TCP})^{0.305}\ psi = 0.291 \cdot (N_{TCP})^{0.305}\ tsf$
Dallas-Fort Worth District	$S_u = 4.225 \cdot (N_{TCP})^{0.574}\ psi = 0.304 \cdot (N_{TCP})^{0.574}\ tsf$
Data Validation (Dallas-Fort Worth District)	$S_u = 12.915 \cdot (N_{TCP})^{0.482}\ psi = 0.930 \cdot (N_{TCP})^{0.482}\ tsf$

2. CL Soils:

Current TxDOT relationship over predicted 48% of the data (Total of 1852 data). The linear relationship between TCP blow count and undrained shear strength of soil varied with the location. The blow count N_2 was 12% higher than N_1 based on the total CL soil data. Model study results are as follows:

Model-1:		
	$S_u = 2\left(N_{TCP}/60\right) tsf = N_{TCP}/30\ tsf = (0.463) \cdot N_{TCP}\ psi$	
Model-2 :		
Texas	$S_u = 0.386 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{36} tsf$	Where, $N_c = 4.333$
Houston District	$S_u = 0.384 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{36} tsf$	Where, $N_c = 4.357$
Beaumont District	$S_u = 0.283 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{49} tsf$	Where, $N_c = 5.912$
Dallas-Fort Worth District	$S_u = 0.949 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{15} tsf$	Where, $N_c = 1.763$
Data Validation (Houston District)	$S_u = 0.553 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{25} tsf$	Where, $N_c = 3.025$

Data Validation (Dallas-Fort Worth District)	$S_u = 0.706 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{20} tsf$	Where, $N_c = 2.370$
Model-3:		
Texas	$S_u = 8.162 \cdot (N_{TCP})^{0.213}\ psi = 0.588 \cdot (N_{TCP})^{0.213}\ tsf$	
Houston District	$S_u = 8.316 \cdot (N_{TCP})^{0.208}\ psi = 0.599 \cdot (N_{TCP})^{0.208}\ tsf$	
Dallas-Fort Worth District	$S_u = 12.717 \cdot (N_{TCP})^{0.195}\ psi = 0.916 \cdot (N_{TCP})^{0.195}\ tsf$	
Data Validation (Houston District)	$S_u = 3.868 \cdot (N_{TCP})^{0.478}\ psi = 0.279 \cdot (N_{TCP})^{0.478}\ tsf$	

3. SC Soils:

Current TxDOT relationship over predicted 41% of the data (Total of 29 data). The blow count N_2 was 8.3% higher than N_1 based on the total SC soil data. Model study results are as follows:

Model-1:		
	$S_u = 2\left({}^{N_{TCP}}\!/_{70}\right) tsf = {}^{N_{TCP}}\!/_{35}\, tsf = (0.397)\cdot N_{TCP}\ psi$	
Model-2 :		
Texas	$S_u = 0.252 \cdot N_{TCP} = \frac{1.704}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{55} tsf$	Where, $N_c = 6.762$
Model-3:		
Texas	$S_u = 9.048 \cdot (N_{TCP})^{0.055}\ psi = 0.652 \cdot (N_{TCP})^{0.055}\ tsf$	

4. OTHER Soils:

Current TxDOT relationship over predicted 48% of the data (Total of 42 data). The blow count N_2 was 10% higher than N_1 based on the total CH soil data. Model study results are as follows:

Model-1:		
	$S_u = 2\left({}^{N_{TCP}}\!/_{80} \right) tsf = {}^{N_{TCP}}\!/_{40}\ tsf = \left(0.347\right)\cdot N_{TCP}\ psi$	
Model-2 :		
Texas	$S_u = 0.308 \cdot N_{TCP} = \dfrac{1.493}{N_c} N_{TCP}\ psi = \dfrac{N_{TCP}}{45} tsf$	Where, $N_c = 4.847$

The correlations developed through Model study are verified with new set of field and laboratory test data for validation.

CHAPTER 4. STATISTICAL ANALYSIS

Statistics in its broadest sense is the methodology of analyzing groups of data to better interpret the trends and relationships in a quantifiable manner. The statistical quantities used in this report are range, mean, standard deviation, variance, coefficient of variation (COV), and probability distribution function (PDF).

Range

The range of the data is the difference between the highest value and lowest value observed. The range can be used when quick measure of variability is required.

Mean

The mean is the arithmetic average. It is the sum of the values of the variable divided by the number of data points.

$$\overline{X} = \frac{\sum x}{N} \quad \text{---} \; (4.1)$$

Where $\overline{X}$ = mean

$\sum x$ = the sum of the values of the variable x

N = number of the data points

Standard Deviation

The standard deviation is a measure of how much a group of data tends to scatter from the mean of the value.

$$\text{Standard deviation } (\sigma) = \sqrt{\frac{\sum (x - \overline{X})^2}{N}} \quad \text{--} (4.2)$$

Where $\overline{X}$ = mean

x = observed value of data point

N = number of the data points

Variance

The variance is the square of the standard deviation (σ^2). It has limited use in basic statistics, but because it is always a positive value, it has been used in many higher statistical analyses (Ganstine, 1971).

Coefficient of Variation (COV)

The Coefficient of Variation (COV) is the ratio of standard deviation to mean ($\frac{\sigma}{\overline{\overline{X}}}$) and is expressed in percentage. The COV has a wide range of applications in statistical analysis. This definition was proposed in 1895 by K. Pearson (Pearson, 1965).

Probability Distribution Functions (PDF)

Probability distribution function is the best curve fit to the histogram. It represents the best distribution function of the histogram developed from the data. Histogram shows the relationship between the value of the data observed (or class frequency distribution of the data) and the number of times that value (or range of values) was observed. The values are usually separated into group of intervals. A best curve is fitted using a known probability density function to represent the distribution of the data. The probability distribution functions considered here are uniform distribution, normal distribution, lognormal distribution and Weibull distribution.

The analysis only includes data with N_{TCP} values up to 100 blows (N_{TCP} =1 to 100). For all 100 intervals from 1 to 100, the mean ($\bar{S}u$) and two standard deviations of the undrained shear strength ($\sigma_{\bar{S}u}$) for each N_{TCP} class interval were determined and analyzed for total and local districts (Houston, Beaumont and Dallas-Fort Worth) for CH, CL, SC and other soil. For the analyses based on N_{TCP} category, three models explained in the previous chapter were used to predict the observed trends.

4.1 Total Soil Data Analysis

The database SDBMS has 2100 data set (pair of N_{TCP} and S_u), 1852 data set, 29 data set and 42 data set of CH, CL, SC and Other soil, respectively. Statistical analyses of various parameters such as TCP blow count for first 6-inch penetration (N_1), TCP blow count for second 6-inch penetration (N_2) and TCP blow count for 1 foot or 12 inches (N_{TCP}) and the undrained shear strength (S_u) of CH and CL were summarized in Table 4.1 and SC and OTHER soils in Table 4.2, respectively. The statistics provided were range, mean, standard deviation, variance, COV, number of data and PDF.

4.1.1 Total CH Soil

Blow Count N_1 (first 6-inches):

The N_1 varied from 1 to 50 with a mean of 14, standard deviation of 10.3, variance of 107.7, and COV of 72%. The CH soil and SC soil had the highest COV among all the soil types for N_1. The COV of 72% for N_1 was comparable to N_2, N_{TCP} and S_u for the CH soil (about 70%). The probability distribution function for N_1

was lognormal based on 2100 data and the results of the analyses are summarized in Table 4.1.

Blow Count N_2 (second 6-inch):

The N_2 varied from 1 to 50 with a mean of 17, standard deviation of 11.4 variance of 131.3, and COV of 69% and the results of the analyses are summarized in Table 4.1. The CH soil had the highest COV among all the soil types for N_2. The COV of 69% for N_2 was comparable to N_1, N_{TCP} and S_u for the CH soil (about 70%). The probability distribution function for N_2 was lognormal based on 2100 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 2 to 100 with a mean of 31, standard deviation of 21.4 variance of 461.5. COV of 70% and the results of the analyses are summarized in Table 4.1. The CH soil had the highest COV among all the soil types for N_{TCP}. The COV of 70% for S_u was comparable to N_1, N_2 and S_u for the CH soil (about 70%). The probability distribution function for N_{TCP} was lognormal based on 2100 data as shown in Figure 4.1.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 0.45 to 83.75 psi with a mean of 16.8 psi, standard deviation of 11.2 psi, variance of 126.5 psi, COV of 67% and the results of the analyses are summarized in Table 4.1. The CH soil and OTHER soil had the highest COV among all the soil types for S_u. The COV of 67% for S_u was comparable to N_1, N_2, and N_{TCP} for the CH soil (about 70%). The probability distribution function for S_u was lognormal based on 2100 data as shown in Figure 4.1.

4.1.2 Total CL Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 1 to 50 with a mean of 16, standard deviation of 9.8, variance of 97.1, and COV of 61%. The CL soil and OTHER soil had the lowest COV among all the soil types for N_1. The COV of 61% for N_1 was comparable to N_2, N_{TCP} and S_u for the CL soil (about 60%). The probability distribution function for N_1 was lognormal based on 1852 data and the results of the analyses are summarized in Table 4.1.

Blow Count N_2 (second 6-inch):

The N_2 varied from 1 to 50 with a mean of 19, standard deviation of 10.9, variance of 120.5, COV of 59% and the results of the analyses are summarized in Table 4.1. The COV of 59% for N_2 was comparable to N_1, N_{TCP} and S_u for the CL soil (about 60%). The probability distribution function for N_2 was lognormal based on 1852 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 2 to 100 with a mean of 35, standard deviation of 20.3, variance of 413.3 COV of 58% and the results of the analyses are summarized in Table 4.1. The COV of 58% for N_{TCP} was comparable to N_1, N_2 and S_u for the CL soil (about

60%). The probability distribution function for N_{TCP} was lognormal based on 1852 data as shown in Figure 4.1.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 1 to 114.6 psi with a mean of 12.8 psi, standard deviation of 7.0 psi, variance of 48.8 psi, COV of 54% and the results of the analyses are summarized in Table 4.1. The CL soil had the lowest COV among all the soil types for S_u. The distribution of S_u was lognormal based on 1852 data as shown in Figure 4.1.

4.1.3 Total SC Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 3 to 39 with a mean of 14, standard deviation of 10.1, variance of 101.6, and COV of 73%. The CH soil and SC soil had the highest COV among all the soil types for N_1. The COV of 73% for N_1 was comparable to N_2, N_{TCP} and S_u for the CH soil (about 70%). The probability distribution function for N_1 was lognormal based on 29 data and the results of the analyses are summarized in Table 4.2.

Table 4.1 Summary of the Total CH and CL Soil Data

Type of soil	N_1 (Blows/6 in)	N_2 (Blows/6 in)	N_{TCP} (Blows/ft)	S_u (psi)
CH Soil (Data Set= 2100)				
Range	1-50	1-50	2-100	0.45-83.75
Mean	14	17	31	16.8
Standard Deviation	10.3	11.4	21.4	11.2
Var	107.0	131.3	461.5	126.5
COV (%)	72	69	70	67
Number of Data	2100	2100	2100	2100
Probability Density Function (PDF)	Lognormal	Lognormal	Lognormal	Lognormal
CL Soil (Data Set= 1852)				
Range	1-50	1-50	2-100	1-114.6
Mean	16	19	35	12.8
Standard Deviation	9.8	10.9	20.3	7.0
Var	97.1	120.5	413.3	48.8
COV (%)	61	59	58	54
Number of Data	1852	1852	1852	1852
Probability Density Function (PDF)	Lognormal	Lognormal	Lognormal	Lognormal

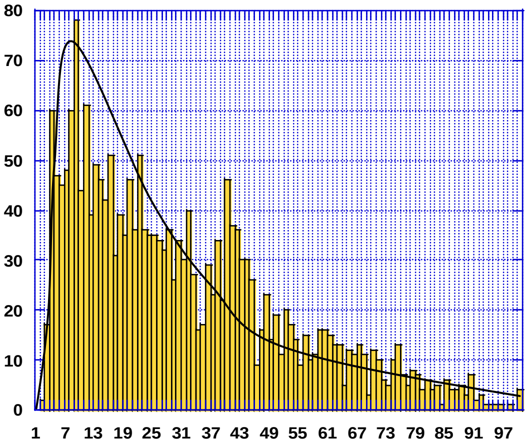
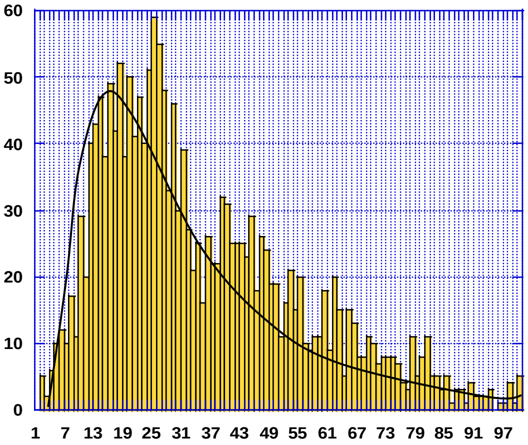
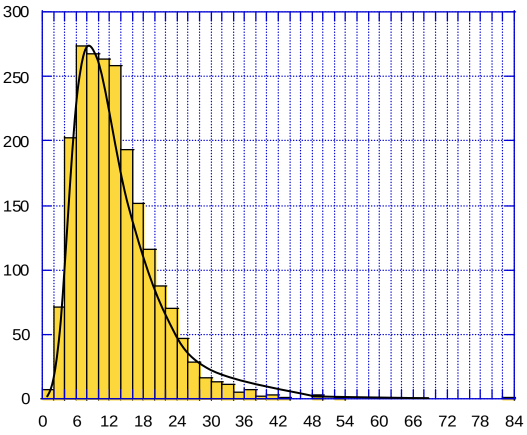
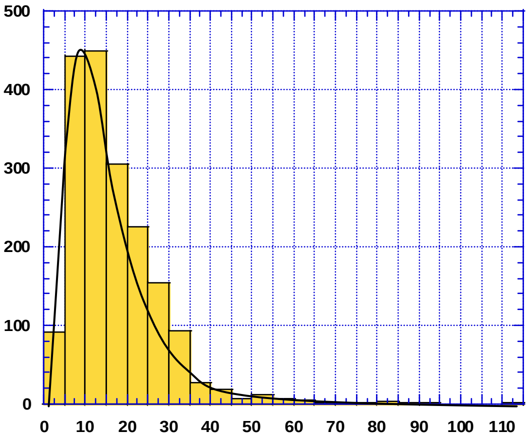
	CH	**CL**
N_{TCP}		
	(a) Lognormal	**(b) Lognormal**
S_u *psi*		
	(c) Lognormal	**(d) Lognormal**

Figure 4.1 Probability Distribution Functions for N_{TCP} and S_u of Total CH and CL Soil Data (a) N_{TCP} for CH Soil (b) N_{TCP} for CL Soil (c) S_u (psi) for CH Soil and (d) S_u (psi) for CL Soils

Blow Count N_2 (second 6-inch):

The N_2 varied from 4 to 48 with a mean of 16, standard deviation of 10.3, variance of 105.4, COV of 63% and the results of the analyses are summarized in Table 4.2. The SC soil had the highest COV among all the soil types for N_2. The COV of 63% for N_2 was comparable to N_1, N_{TCP} and S_u for the SC soil (about 70%). The probability distribution function for N_2 was Weibull based on 29 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 7 to 87 with a mean of 30, standard deviation of 19.7, variance of 386.6, COV of 66% and the results of the analyses are summarized in Table 4.2. The SC soil and CH soil had the highest COV among all the soil types for N_{TCP}. The COV of 70% for N_{TCP} was comparable to N_1, N_2 and S_u for the CH soil (about 70%). The distribution function for N_{TCP} was Weibull based on 29 data as shown in Figure 4.2.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 3.5 to 38.55 psi with a mean of 10.8 psi, standard deviation of 6.5 psi, variance of 41.7 psi, coefficient of variation (COV) of 60% and the analysis was summarized in Table 4.2. The SC soil and CL soil had the lowest COV among all the soil types for S_u. The distribution of S_u was lognormal based on 29 data as shown in Figure 4.2.

4.1.4 Total OTHER Soils

Blow Count N_1 (first 6-inch):

The N_1 varied from 3 to 50 with a mean of 20, standard deviation of 10.6, variance of 112.4, COV of 52%. The CL soil and OTHER soil had the least COV among all the soil types for N_1. The COV of 52% for N_1 was comparable to N_2, N_{TCP} and S_u for the OTHER soil (about 50%). The probability distribution of N_1 was Weibull based on 42 data and the results of the analysis are summarized in Table 4.2.

Blow Count N_2 (second 6-inch):

The N_2 varied from 6 to 50 with a mean of 24, standard deviation of 10.8, variance of 117.8, and COV of 45%. The CL soil and OTHER soil had the lowest COV among all the soil types for N_2. The COV of 45% for N_2 was comparable to N_1, N_{TCP} and S_u for OTHER soil (about 50%). The probability distribution function for N_2 was normal based on 42 data and the results of the analyses are summarized in Table 4.2.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 10 to 93 with a mean of 45, standard deviation of 20.1, variance of 403.9, COV of 45% and the result of the analyses was summarized in Table 4.2. The CL soil and OTHER soil had the lowest COV among all the soil types for N_{TCP}. The COV of 45% for N_2 was comparable to N_1, N_{TCP} and S_u for the OTHER soil (about 50%). The probability distribution function for N_{TCP} was normal based on 42 data as shown in Figure 4.2.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 1.4 to 69.3 psi with a mean of 16.8 psi, standard deviation of 11.1 psi, variance of 122.4 psi, COV of 66% and the results of the analyses are summarized in Table 4.2. The CH soil and OTHER soil had the highest COV among all the soil types for S_u. The COV of 66% for S_u was comparable to N_1, N_2, and N_{TCP} for the CH soil (about 50%).The distribution of S_u was Weibull based on 42 data as shown in Figure 4.2.

4.2 Local Soil Data Analysis

4.2.1. Houston District

The database SDBMS has 1726 data set (pair of N_{TCP} and S_u), 1762 data set, 29 data set and 42 data set of CH, CL, SC and other soil, respectively. Statistical analyses of various parameters such as TCP blow count for first 6-inch penetration (N_1), TCP blow count for second 6-inch penetration (N_2)TCP blow count for 1 foot or 12 in (N_{TCP}) and Undrained Shear Strength (S_u) of Houston CH and CL soil are summarized in Table 4.3. The statistics provided were range, mean, standard deviation, variance, COV, number of data and probability distribution function.

Table 4.2 Summary of the Total SC and OTHER Soil Data

Type of soil	N_1 **(Blows/6 in)**	N_2 **(Blows/ 6 in)**	N_{TCP} **(Blows/ft)**	S_u **(psi)**
SC Soil (Data Set=29)				
Range	3-39	4-48	7-87	3.5-38.55
Mean	14	16	30	10.8
Standard Deviation	10.1	10.3	19.7	6.5
Var	101.6	105.4	386.6	41.7
COV (%)	73	63	66	60
Number of Data	29	29	29	29
Probability Density Function (PDF)	Lognormal	Weibull	Weibull	Lognormal
Other Soil (Data Set= 42)				
Range	3-50	6-50	10-93	1.4-69.3
Mean	20	24	45	16.8
Standard Deviation	10.6	10.8	20.1	11.1
Var	112.4	117.8	403.9	122.4
COV (%)	52	45	45	66
Number of Data	42	42	42	42
Probability Density Function (PDF)	Weibull	Normal	Normal	Weibull

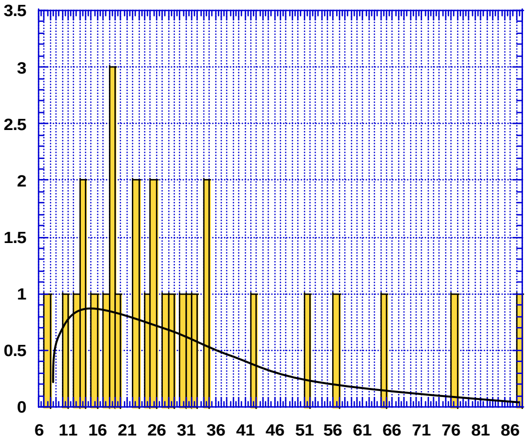
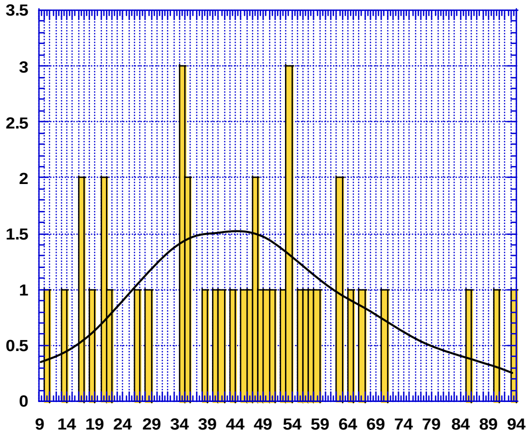
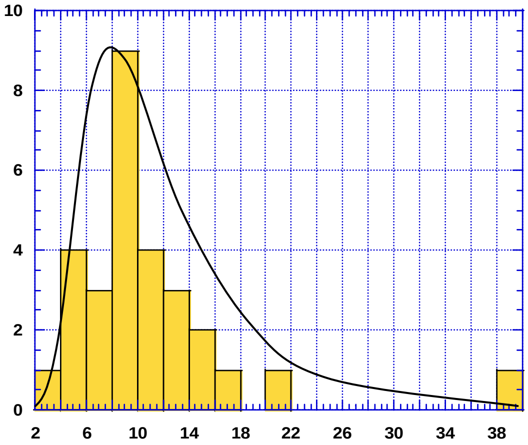
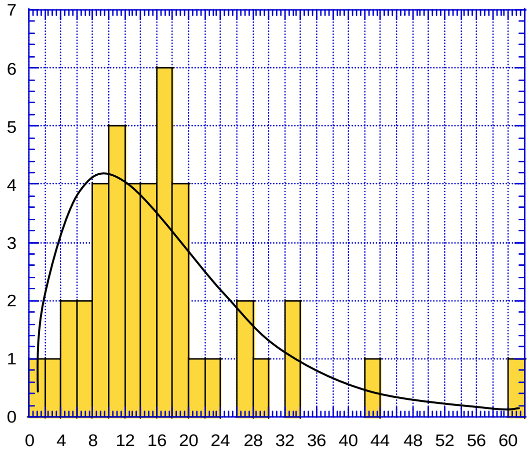
	SC	OTHERS
N_{TCP}		
	(a) Weibull	**(b) Normal**
S_u (psi)		
	(c) Lognormal	**(d) Weibull**

Figure 4.2 Probability Distribution Functions for N_{TCP} and S_u of Total SC and OTHER Soil Data (a) N_{TCP} for SC Soil (b) N_{TCP} for OTHER Soil (c) S_u for SC Soil and (d) S_u for OTHER Soils

(a) Houston CH Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 1 to 50 with a mean of 16, standard deviation of 10.1, variance of 101.9, and COV of 62%. The CH soil and SC soil had the highest COV among all the soil types for N_1. The COV of 62% for N_1 was comparable to N_2 and N_{TCP} except S_u for the CH soil (about 60%). The probability distribution function for N_1 was lognormal based on 1726 data and the results of the analyses are summarized in Table 4.3.

Blow Count N_2 (second 6-inch):

The N_2 varied from 1 to 50 with a mean of 19, standard deviation of 11.2, variance of 124.5, COV of 59% and the results of the analyses are summarized in Table 4.3. The CH soil and the SC soil had the highest COV among all the soil types for N_2. The COV of 59% for N_2 was comparable to N_1 and N_{TCP} except S_u for the CH soil (about 60%). The probability distribution function for N_2 was lognormal (1726 data).

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 2 to 100 with a mean of 35, standard deviation of 20.9, variance of 435.1, COV of 59% and the results of the analyses are summarized in Table 4.3. The CH soil and the SC soil had the highest COV among all the soil types for N_{TCP}. The COV of 59% for N_{TCP} was comparable to N_1 and N_2 except S_u for the CH soil (about 60%). The distribution of N_{TCP} was lognormal based on 1726 data.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 1.5 to 83.75 psi with a mean of 13.7 psi, standard deviation of 6.8 psi, variance of 45.7 psi, COV of 49% and the results of the analyses are summarized in Table 4.3. The CH soil had the lowest COV among all the soil types for S_u. The distribution of S_u was lognormal based on 1726 data.

(b) Houston CL Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 1 to 50 with a mean of 16, standard deviation of 9.9, variance of 98.3, and COV of 61%. The CH soil and CL soil had the same COV among all the soil types for N_1. The COV of 61% for N_1 was comparable to N_2 and N_{TCP} except S_u for the CL soil (about 60%). The probability distribution function for N_1 was lognormal based on 1762 data and the results of the analyses are summarized in Table 4.3.

Blow Count N_2 (second 6-inch):

The N_2 varied from 1 to 50 with a mean of 19, standard deviation of 11.0, variance of 121.9, COV of 58% and the results of the analyses are summarized in Table 4.3. The CL soil had the same COV among all the soil types for N_2. The COV of 58% for N_2 was comparable to N_1 and N_{TCP} except S_u for the CL soil (about 60%). The probability distribution function for N_2 was lognormal based on 1762 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 2 to 100 with a mean of 35, standard deviation of 20.5, variance of 418.5, coefficient of variation (COV) of 58% and the results of the analyses are summarized in Table 4.3. The CH soil and the CL soil had the same COV among all the soil types for N_{TCP}. The COV of 58% for N_{TCP} was comparable to N_1 and N_2 except S_u for the CL soil (about 60%). The distribution of N_{TCP} was lognormal based on 1762 data.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 1 to 114.6 psi with a mean of 16.8 psi, standard deviation of 11.2 psi, variance of 125.9 psi, COV of 66% and the results of the analyses are summarized in Table 4.3. The CL soil had the lowest COV among all the soil types for S_u. The probability distribution function for S_u was lognormal based on 1762 data.

(c) Houston SC and OTHER Soils

The database SDBMS has total data for SC and Other soil which was collected only from the Houston District. The analysis for Houston SC and Other soils is not presented here because the Total SC and OTHER soils are the same as Houston SC and OTHER soils.

4.2.2 Beaumont District

The database SDBMS has 341 data set (pair of N_{TCP} and S_u), and 26 data set of CH, and CL soil, respectively. Statistical analyses of various parameters such as TCP blow count for the first 6-inch penetration (N_1), TCP blow count for second 6-inch penetration (N_2) and TCP blow count for 1 foot or 12 in (N_{TCP}) and Undrained Shear Strength (S_u) of Beaumont CH and CL soil are summarized in Table 4.4. The statistics provided were Range, Mean, Standard Deviation, Variance, Coefficient of Variation (COV), number of data and Probability distribution function (PDF).

(a) Beaumont CH Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 1 to 33 with a mean of 4, standard deviation of 2.8, variance of 7.7, and COV of 72%. The CH soil had a higher COV than CL soil for N_1. The COV of 72% for N_1 was comparable to N_2 and N_{TCP} except S_u for the CH soil (about 70%). The probability distribution function for N_1 was lognormal based on 341 data and the results of the analyses are summarized in Table 4.4.

Table 4.3 Summary of the Houston CH and CL Soil Data

Type of soil	N_1 (Blows/6 in)	N_2 (Blows/6 in)	N_{TCP} (Blows/ft)	S_u (psi)
CH Soil (Data Set= 1726)				
Range	1-50	1-50	2-100	1.5-83.75
Mean	16	19	35	13.7
Standard Deviation	10.1	11.2	20.9	6.8
Var	101.9	124.5	435.1	45.7
COV (%)	62	59	59	49
Number of Data	1726	1726	1726	1726
Probability Density Function (PDF)	Lognormal	Lognormal	Lognormal	Lognormal
CL Soil (Data Set= 1762)				
Range	1-50	1-50	2-100	1-114.6
Mean	16	19	35	16.9
Standard Deviation	9.9	11.0	20.5	11.2
Var	98.3	121.9	418.5	125.9
COV (%)	61	58	58	66
Number of Data	1762	1762	1762	1762
Probability Density Function (PDF)	Lognormal	Lognormal	Lognormal	Lognormal

Blow Count N_2 (second 6-inch):

The N_2 varied from 1 to 29 with a mean of 5, standard deviation of 3.2, variance of 10.0, COV of 64% and the results of the analyses are summarized in Table 4.4. The CH soil had a lower COV than CL soil for N_2. The COV of 64% for N_2 was comparable to N_1 and N_{TCP} except S_u for the CH soil (about 70%). The probability distribution function for N_2 was lognormal based on 341 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 2 to 62 with a mean of 9, standard deviation of 5.8, variance of 33.7, COV of 66% and the results of the analyses are summarized in Table 4.4. The CH soil had a higher COV than CL soil for N_{TCP}. The COV of 66% for N_{TCP} was comparable to N_1 and N_2 except S_u for the CH soil (about 70%). The distribution of N_{TCP} was lognormal based on 341 data.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 0.45 to 33.5 psi with a mean of 7.6 psi, standard deviation of 3.7 psi, variance of 13.8 psi, COV of 49% and the results of the analyses are summarized in Table 4.4. The CH soil had a higher COV than CL soil for S_u. The COV of 49% for S_u was the lowest comparable to N_1 and N_2 and N_{TCP} for the CH soil. The distribution of S_u was lognormal based on 341 data.

(b) Beaumont CL Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 1 to 50 with a mean of 10, standard deviation of 6.2, variance of 38.7, and COV of 63%. The CH soil had a higher COV than CL soil for N_1. The COV of 63% for N_1 was comparable to N_2 and N_{TCP} except S_u for the CH soil (about 65%). The probability distribution function for N_1 was lognormal based on 26 data and the results of the analyses are summarized in Table 4.4.

Blow Count N_2 (second 6-inch):

The N_2 varied from 1 to 50 with a mean of 13, standard deviation of 8.9, variance of 79.5, COV of 67% and the results of the analyses are summarized in Table 4.4. The CH soil had a lower COV than CL soil for N_2. The COV of 67% for N_2 was comparable to N_1 and N_{TCP} except S_u for the CH soil (about 70%). The probability distribution function for N_2 was lognormal based on 26 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 2 to 100 with a mean of 23, standard deviation of 14.9, variance of 222.7, COV of 65% and the results of the analyses are summarized in Table 4.4. The CH soil had a higher COV than CL soil for N_{TCP}. The COV of 65% for N_{TCP} was comparable to N_1 and N_2 except S_u for the CH soil (about 70%). The distribution of N_{TCP} was Weibull based on 26 data.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 1 to 114.6 psi with a mean of 9.3 psi, standard deviation of 3.8 psi, variance of 14.7 psi, COV of 41% and the results of the analyses are summarized in Table 4.4. The CL soil had a lower COV than CH soil for S_u. The COV of 41% for S_u was the lowest comparable to N_1 and N_2 and N_{TCP} for the CH soil. The distribution of S_u was Weibull based on 26 data.

4.2.3 Dallas-Fort Worth district

The database SDBMS has 11 data set (pair of N_{TCP} and S_u), 51 data set of CH, and CL soil, respectively. Statistical analyses of various parameters such as TCP blow count for first 6-inch penetration (N_1), TCP blow count for second 6-inch penetration (N_2), TCP blow count for 1 foot or 12 in (N_{TCP}) and Undrained Shear Strength (S_u) of Dallas-Fort Worth CH and CL soil are summarized in Table 4.5. The statistics provided were range, mean, standard deviation, variance, COV, number of data and PDF.

(a) Dallas-Fort Worth CH Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 4 to 29 with a mean of 11, standard deviation of 7.6, variance of 57.6, and COV of 69%. The CH soil had a higher COV than CL soil for N_1. The COV of 69% for N_1 was comparable to N_2, N_{TCP} and S_u for the CH soil (about 60%). The probability distribution function for N_1 was lognormal based on 11 data and the results of the analyses are summarized in Table 4.5.

Blow Count N_2 (second 6-inch):

The N_2 varied from 6 to 29 with a mean of 12, standard deviation of 7.2, variance of 51.7, COV of 58% and the results of the analyses are summarized in Table 4.5. The CH soil had a higher COV than CL soil for N_2. The COV of 58% for N_2 was comparable to N_1, N_{TCP} and S_u for the CH soil (about 60%). The probability distribution function for N_2 was lognormal based on 11 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 11 to 58 with a mean of 23, standard deviation of 14.7, variance of 215.3, COV of 63% and the results of the analyses are summarized in Table 4.5. The CH soil had a higher COV than CL soil for N_{TCP}. The COV of 63% for N_{TCP} was comparable to N_1, N_2 and S_u for the CH soil (about 60%). The distribution of N_{TCP} was lognormal based on 11 data.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 12.1 to 41.9 psi with a mean of 25.0 psi, standard deviation of 14.8 psi, variance of 220.5 psi, COV of 59% and the results of the analyses are summarized in Table 4.5. The CH soil had a lower COV than CL soil for S_u. The COV of 59% for S_u was lowest comparable to N_1 and N_{TCP} for the CH soil. The distribution of S_u was lognormal based on 11 data.

(b) Dallas-Fort Worth CL Soil

Blow Count N_1 (first 6-inch):

The N_1 varied from 1 to 27 with a mean of 9, standard deviation of 4.8, variance of 23.2, COV of 55% and the results of the analyses are summarized in Table 4.5. The CL soil had a lower COV than CH soil for N_1. The COV of 55% for N_1 was comparable to N_2, N_{TCP} and S_u for the CL soil (about 60%). The probability distribution function for N_1 was normal based on 11 data and the results of the analyses are summarized in Table 4.5.

Blow Count N_2 (second 6-inch):

The N_2 varied from 2 to 24 with a mean of 11, standard deviation of 5.1, variance of 26.5, coefficient of variation (COV) of 49% and the results of the analyses are summarized in Table 4.5. The CH soil had lower COV than CL soil for N_2. The COV of 49% for N_2 was lower than N_1, N_{TCP} and S_u for the CH soil (about 60%). The probability distribution function for N_2 was normal based on 51 data.

Blow Count N_{TCP} (12-inch):

The N_{TCP} varied from 4 to 51 with a mean of 19, standard deviation of 9.6, variance of 92.4, coefficient of variation (COV) of 50% and the results of the analyses are summarized in Table 4.5. The CH soil had lower COV than CH soil for N_{TCP}. The

COV of 50% for N_{TCP} was lower than N_1, N_2 and S_u for the CH soil (about 60%). The distribution of N_{TCP} was normal based on 11 data.

Undrained Shear Strength (S_u):

The undrained shear strength varied from 4.1 to 73.6 psi with a mean of 22.0 psi, standard deviation of 18.5 psi, variance of 343.9 psi, coefficient of variation (COV) of 84% and the results of the analyses are summarized in Table 4.5. The CH soil had the lower COV than CL soil for S_u. The COV of 84% for S_u was the highest comparable to N_1 and N_{TCP} for the CH soil. The distribution of S_u was lognormal based on 51 data.

4.3 Mean Undrained Shear Strength ($\bar{S}_u$) Analysis

The mean undrained shear strength ($\bar{S}_u$) for each soil type was determined for every blow count and $\bar{S}_u$ versus N_{TCP} relationships were developed.

4.3.1 Total Data Analysis

TCP Blow count (N_{TCP}) versus Mean Undrained Shear Strength ($\bar{S}_u$)

(a) <u>CH Soils</u>: A total of 97 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{25}$ in tsf) over predicted 80% of mean undrained shear strength data. Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.25N_{TCP} = \frac{1.425}{N_c}N_{TCP}\,psi = \frac{N_{TCP}}{55}tsf \text{ ; where } N_C = 5.698 \text{ ---------------------- (4.3)}$$

Table 4.4 Summary of the Beaumont CH and CL Soil Data

Type of soil	N_1 (Blows/6 in)	N_2 (Blows/6 in)	N_{TCP} (Blows/ft)	S_u (psi)
CH Soil (Data Set= 341)				
Range	1-33	1-29	2-62	0.45-33.5
Mean	4	5	9	7.6
Standard Deviation	2.8	3.2	5.8	3.7
Var	7.7	10.0	33.7	13.8
COV (%)	72	64	66	49
Number of Data	341	341	341	341
Probability Density Function (PDF)	Lognormal	Lognormal	Lognormal	Lognormal
CL Soil (Data Set= 26)				
Range	1-50	1-50	2-100	1-114.6
Mean	10	13	23	9.3
Standard Deviation	6.2	8.9	14.9	3.8
Var	38.7	79.5	222.7	14.7
COV (%)	63	67	65	41
Number of Data	26	26	26	26
Probability Density Function (PDF)	Lognormal	Lognormal	Weibull	Weibull

Table 4.5 Summary of the Dallas-Fort Worth CH and CL Soil Data

Type of soil	N_1 (Blows/6 in)	N_2 (Blows/6 in)	N_{TCP} (Blows/ft)	S_u (psi)
CH Soil (Data Set= 11)				
Range	4-29	6-29	11-58	12.1-41.9
Mean	11	12	23	25.0
Standard Deviation	7.6	7.2	14.7	14.8
Var	57.6	51.7	215.3	220.5
COV (%)	69	58	63	59
Number of Data	11	11	11	11
Probability Density Function (PDF)	Lognormal	Lognormal	Lognormal	Lognormal
CL Soil (Data Set= 51)				
Range	1-27	2-24	4-51	4.1-73.6
Mean	9	11	19	22.0
Standard Deviation	4.8	5.1	9.6	18.5
Var	23.2	26.5	92.4	343.9
COV (%)	55	49	50	84
Number of Data	51	51	51	51
Probability Density Function (PDF)	Normal	Normal	Normal	Lognormal

The slope of this relationship was 57% lower than the current TxDOT relationship ($\frac{N_{TCP}}{25}$ in tsf). Model-2 ($\frac{N_{TCP}}{55}$ in tsf) over predicted 27% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$$\bar{S}_u = 4.84(N_{TCP})^{0.3}\, psi \quad = \quad 0.35\,(N_{TCP})^{0.3}\, tsf \qquad \text{------------------ (4.4)}$$

Model-3 over predicted 47% of the data (below the curve).

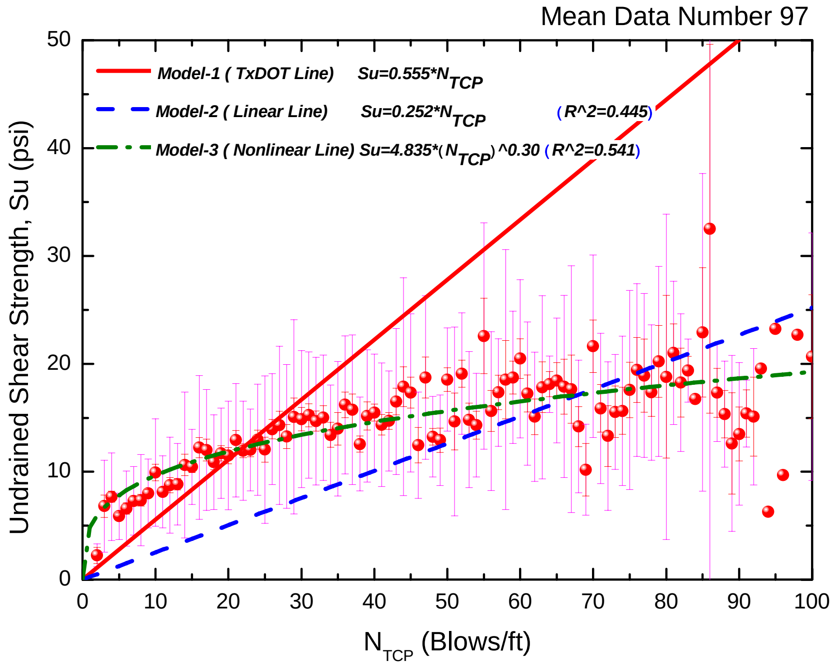


Figure 4.3 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} for CH Soil

(b) **<u>CL Soils</u>**: A total of 98 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{30}$ in tsf) over predicted 60% of mean undrained shear strength data.

Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$\bar{S}_u = 0.31 N_{TCP} = \frac{1.673}{N_c} N_{TCP}\, psi = \frac{N_{TCP}}{45}\, tsf$; where $N_C = 5.355$ --------------------- (4.5)

The slope of this relationship was 34% lower than the current TxDOT relationship ($\frac{N_{TCP}}{30}$ in tsf). Model-2 ($\frac{N_{TCP}}{45}$ in tsf) over predicted 34% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$\bar{S}_u = 6.51 (N_{TCP})^{0.28}\, psi = 0.47\, (N_{TCP})^{0.28}\, tsf$ ------------------------- (4.6)

Model-3 over predicted 57% of the data (below the curve).

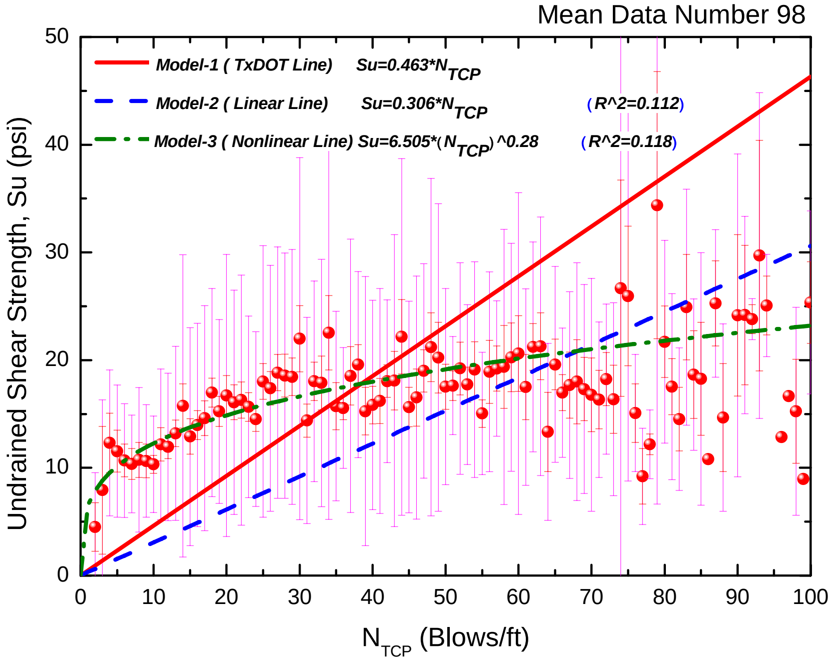


Figure 4.4 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} for CL Soil

(c) **SC Soils**: Total of 23 data (mean) was used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{35}$ in tsf) over predicted 48% of mean undrained shear strength data.

Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.22 N_{TCP} = \frac{1.704}{N_c} N_{TCP}\, psi = \frac{N_{TCP}}{63} tsf \text{ ; where } N_C = 5.355 \text{ -------------------- (4.7)}$$

The slope of this relationship was 44% lower than the current TxDOT relationship ($\frac{N_{TCP}}{35}$ in tsf). Model-2 ($\frac{N_{TCP}}{63}$ in tsf) over predicted 30% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$$\bar{S}_u = 5.23 (N_{TCP})^{0.23}\, psi = 0.38\, (N_{TCP})^{0.23}\, tsf \qquad \text{-------------------------- (4.8)}$$

Model-3 over predicted 65% of the data (below the curve).

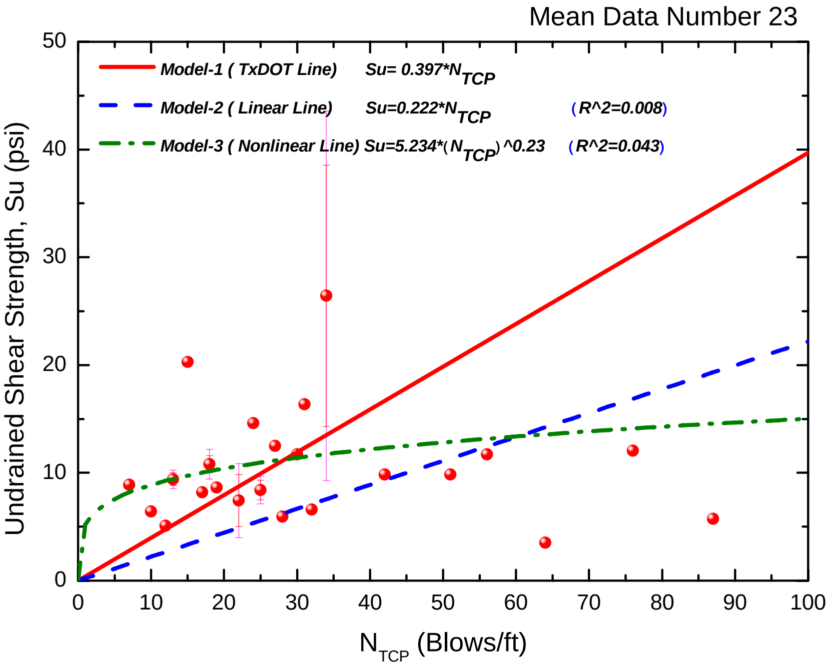


Figure 4.5 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} for SC Soil

(d) **OTHER Soils**: A total of 33 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.30 N_{TCP} = \frac{1.493}{N_c} N_{TCP}\, psi = \frac{N_{TCP}}{46} tsf \text{ ; where } N_C = 4.928 \text{ -------------------- (4.9)}$$

The slope of this relationship was 14% lower than the current TxDOT relationship (Model-1: $\frac{N_{TCP}}{40}$ in tsf). Model-1 ($\frac{N_{TCP}}{40}$ in tsf) over predicted 49% of the data.

Model-2 ($\frac{N_{TCP}}{46}$ in tsf) over predicted 30% (below the curve) of the data. From both models, Model-2 better predicts $\bar{S}_u$ versus N_{TCP} relationship.

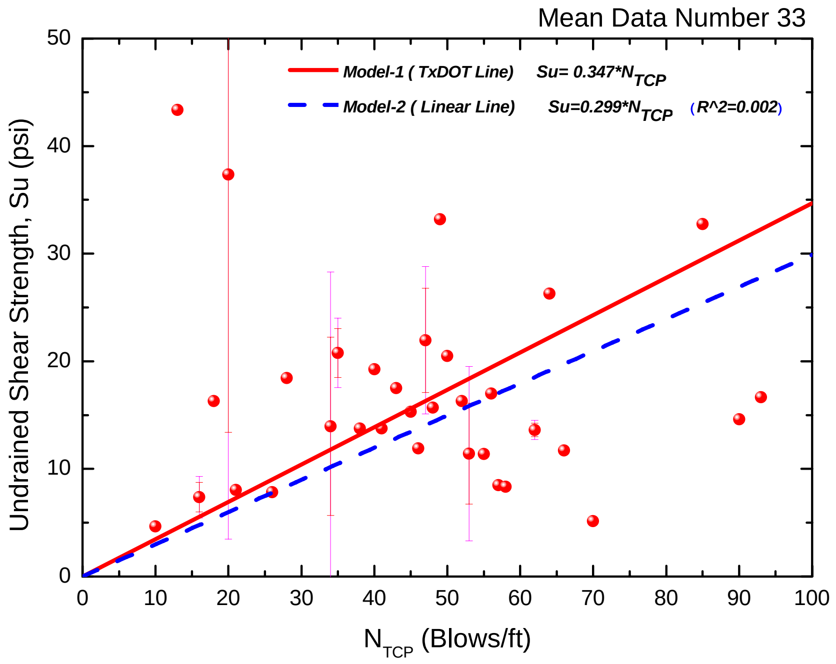


Figure 4.6 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} for OTHER Soils

4.3.2 Local Data Analysis (Houston District):

TCP Blow count (N_{TCP}) versus Mean Undrained Shear Strength ($\bar{S}_u$)

(a) <u>CH Soils</u>: A total of 97 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{25}$ in tsf) over predicted 80% of the mean undrained shear strength data.

Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$\bar{S}_u = 0.23 N_{TCP} = \frac{1.425}{N_C} N_{TCP}\, psi = \frac{N_{TCP}}{60} tsf$; where $N_C = 6.125$ ------------------- (4.10)

The slope of this relationship was 59% lower than the current TxDOT relationship ($\frac{N_{TCP}}{25}$ in tsf). Model-2 ($\frac{N_{TCP}}{60}$ in tsf) over predicted 20% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$\bar{S}_u = 4.91 (N_{TCP})^{0.29}\, psi = 0.35\, (N_{TCP})^{0.29}\, tsf$ ------------------------ (4.11)

Model-3 over predicted 50% of the data (below the curve).

(b) <u>CL Soils</u>: A total of 98 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{30}$ in tsf) over predicted 60% of the mean undrained shear strength data.

Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$\bar{S}_u = 0.31 N_{TCP} = \frac{N_{TCP}}{3.2}\, psi = \frac{N_{TCP}}{45} tsf$; where $N_C = 5.355$ ----------------------- (4.12)

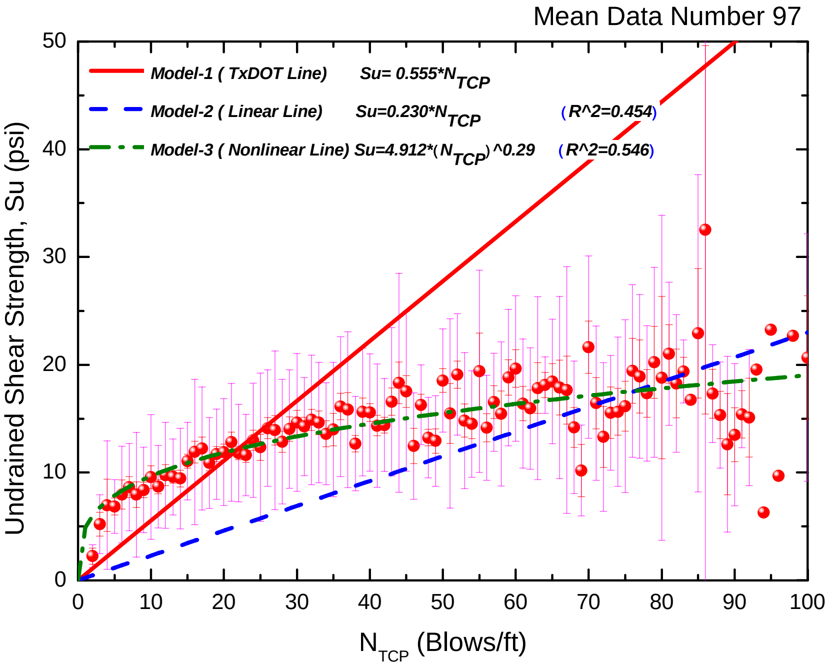


Figure 4.7 Variation of Mean Undrained Shear Strength ($\bar{S}_u$)with N_{TCP} for Houston CH Soils

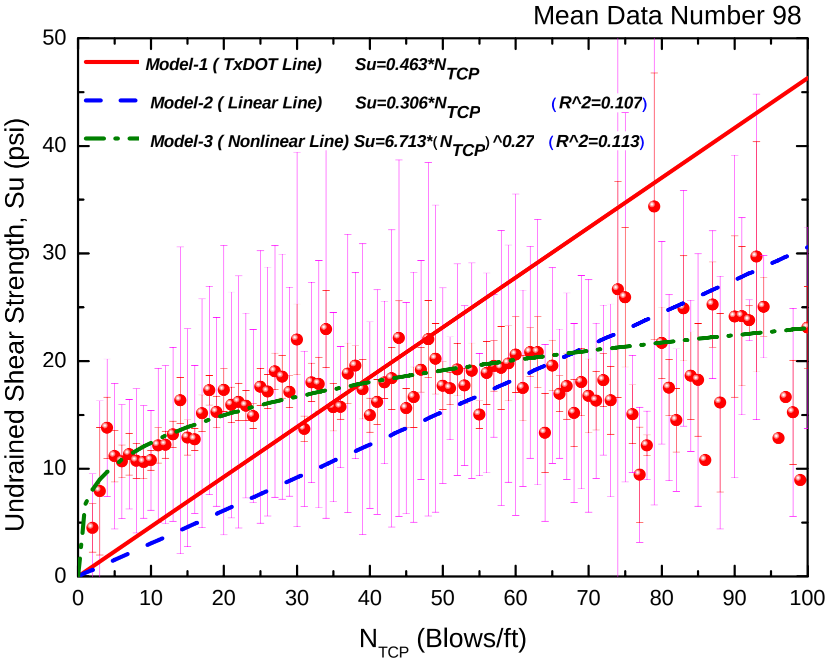


Figure 4.8 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} for Houston CL Soils

The slope of this relationship was 34% lower than the current TxDOT relationship ($\frac{N_{TCP}}{30}$ in tsf). Model-2 ($\frac{N_{TCP}}{45}$ in tsf) over predicted 34% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$$\bar{S}_u = 6.71(N_{TCP})^{0.27}\, psi = 0.48\,(N_{TCP})^{0.27}\, tsf \qquad \text{----------------------- (4.13)}$$

Model-3 over predicted 57% of the data (below the curve).

4.3.3 Local Data Analysis (Beaumont district)

TCP Blow count (N_{TCP}) versus Mean Undrained Shear Strength ($\bar{S}_u$)

(a) **<u>CH Soils</u>**: A total of 27 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{25}$ in tsf) over predicted 37% of the mean undrained shear strength data.

Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.44 N_{TCP} = \frac{1.425}{N_C} N_{TCP}\, psi = \frac{N_{TCP}}{32} tsf \text{ ; where } N_C = 3.278 \text{ ------------------- (4.14)}$$

The slope of this relationship was 20% lower than the current TxDOT relationship ($\frac{N_{TCP}}{25}$ in tsf). Model-2 ($\frac{N_{TCP}}{32}$ in tsf) over predicted 30% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$$\bar{S}_u = 4.84(N_{TCP})^{0.3}\, psi = 0.35\,(N_{TCP})^{0.3}\, tsf \qquad \text{----------------------- (4.15)}$$

Model-3 over predicted 63% of the data (below the curve).

(b) CL Soils: A total of 11 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.30N_{TCP} = \frac{1.673}{N_C} N_{TCP}\, psi = \frac{N_{TCP}}{46} tsf \text{ ; where } N_C = 5.522 \text{ ------------------- } (4.16)$$

The slope of this relationship was 35% lower than the current TxDOT relationship ($\frac{N_{TCP}}{30}$ in tsf). Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{30}$ in tsf) over predicted 45% (below the curve) of the data.

Model-2 ($\frac{N_{TCP}}{46}$ in tsf) over predicted 5% (below the curve) of the data. From both models, Model-2 better predicts $\bar{S}_u$ versus N_{TCP} relationship.

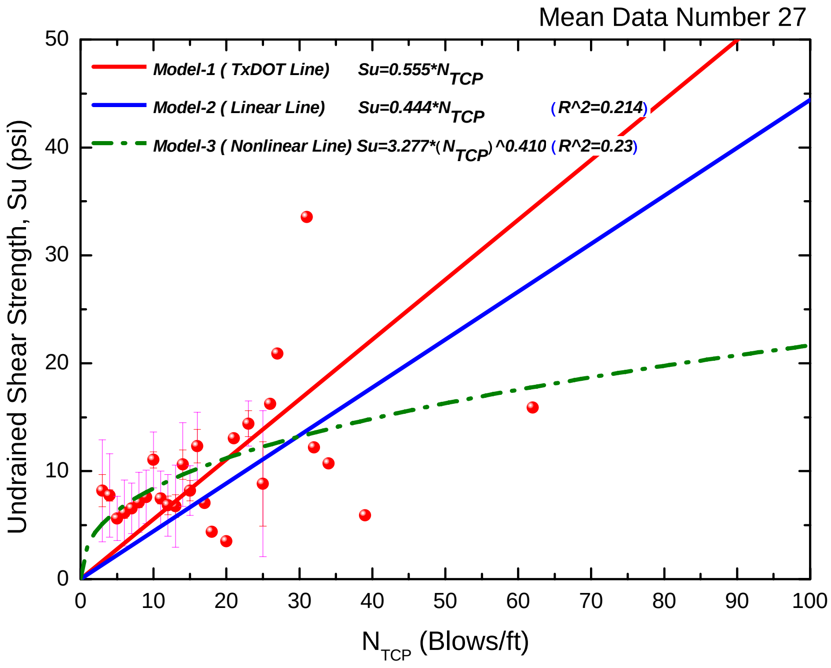


Figure 4.9 Variation of Mean Undrained Shear Strength ($\bar{S}_u$)with N_{TCP} for Beaumont CH Soils

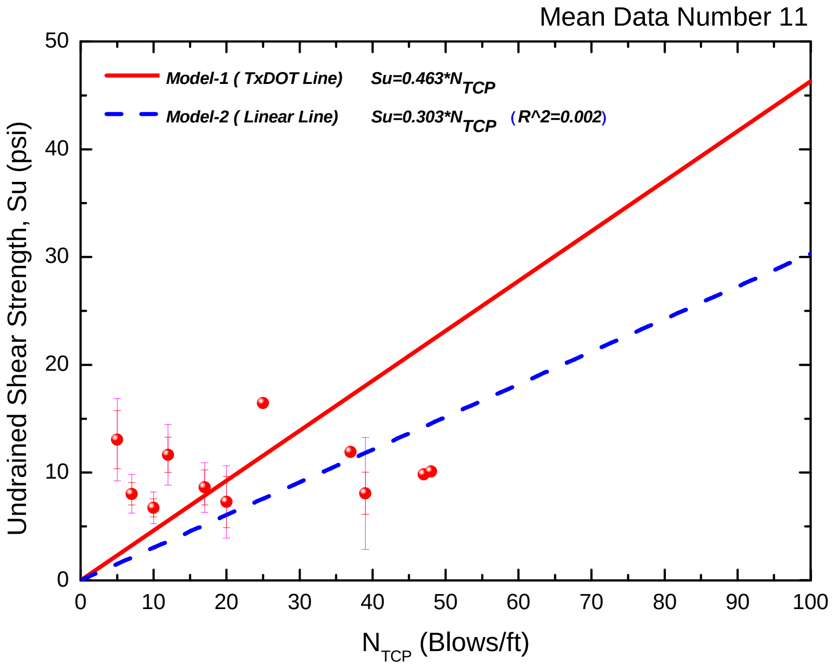


Figure 4.10 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} intervals for Beaumont CL Soil

4.3.4 Local Data Analysis (Dallas-Fort Worth District)

TCP Blow Count (N_{TCP}) versus Mean Undrained Shear Strength ($\bar{S}_u$)

(a) <u>CH Soils</u>: A total of 9 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP} relationship. Current TxDOT relationship (Model-1: $\frac{N_{TCP}}{25}$ in tsf) under predicted 95% of the mean undrained shear strength data.

Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.93 N_{TCP} = \frac{1.425}{N_C} N_{TCP}\, psi = \frac{N_{TCP}}{15} tsf$$; where $N_C = 1.567$ ------------------- (4.17)

The slope of this relationship was 40% higher than the current TxDOT relationship ($\frac{N_{TCP}}{25}$ in tsf). Model-2 ($\frac{N_{TCP}}{15}$ in tsf) over predicted 44% (below the curve) of the data.

Model-3 relationship for the data is as follows

$\bar{S}_u = 5.45(N_{TCP})^{0.51}\, psi = 0.39\,(N_{TCP})^{0.51}\, tsf$ ---------------------- (4.18)

Model-3 over predicted 67% of the data (below the curve).

(b) <u>CL Soils</u>: A total of 20 data (mean) were used to investigate $\bar{S}_u$ versus N_{TCP}. Current TxDOT relationship ($\frac{N_{TCP}}{30}$ in tsf) under predicted 85% of mean undrained shear strength data. Model-2 (least squares fit for linear relationship) for this set of data is as follows:

$\bar{S}_u = 0.84 N_{TCP} = \frac{1.673}{N_C} N_{TCP}\, psi = \frac{N_{TCP}}{16} tsf$; where $N_C = 2.008$ ------------------ (4.19)

The slope of this relationship was 45% higher than the current TxDOT relationship ($\frac{N_{TCP}}{30}$ in tsf). Model-2 ($\frac{N_{TCP}}{16}$ in tsf) over predicted 45% (below the curve) of the data.

Model-3 relationship for the data is as follows:

$\bar{S}_u = 18.72(N_{TCP})^{0.07}\, psi = 1.35\,(N_{TCP})^{0.07}\, tsf$ ------------------------ (4.20)

Model-3 over predicted 65% of the data (below the curve).

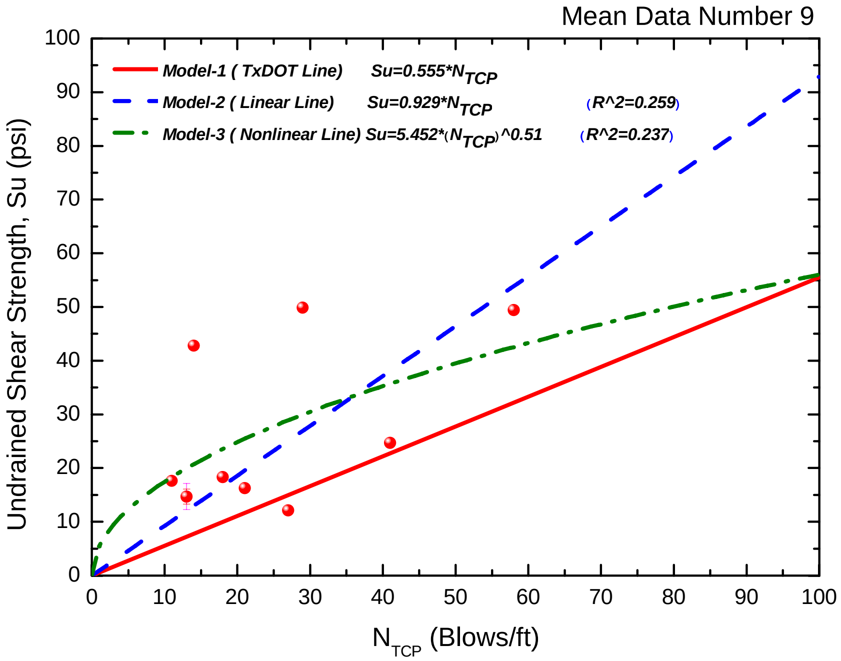


Figure 4.11 Variation of Mean Undrained Shear Strength ($\bar{S}_u$) with N_{TCP} intervals for Dallas-Fort Worth CH Soil

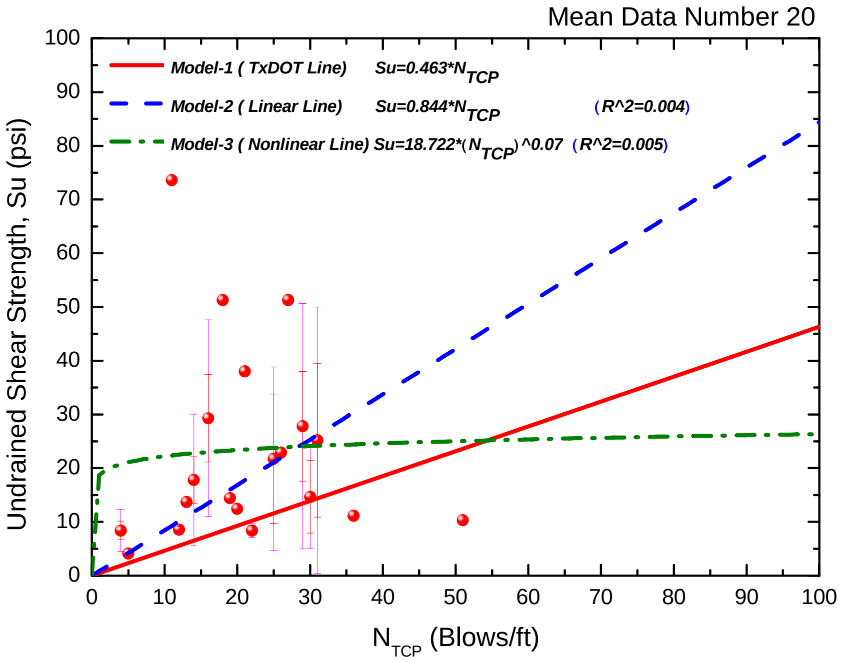


Figure 4.12 Variation of Mean Undrained Shear Strength ($\bar{S}_u$)with N_{TCP} intervals for Dallas-Fort Worth CL Soil

4.4 Summary

A total of the 4023 data, collected from four TxDOT districts in Texas, were used to determine statistical measures such as range, mean, standard deviation, variance, coefficient of variation (COV), and probability distribution function (PDF) of undrained shear strength for CH, CL, SC and OTHER soil types. Also, relation between mean undrained shear strength ($\bar{S}_u$) and N_{TCP} was investigated. A total of 513 $\bar{S}_u$ data were used for analyses. Relationships for total and local districts have been developed. Based on the analyses, the following can be concluded for total data.

1. **CH Soil:**

   Based on the 2100 data set, the undrained shear strength (S_u) varied from 0.45 to 88.75 psi with a mean of 16.8 psi. The COV was 67%, which was the highest for the soils investigated in this study. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 2 to 100 with a mean of 31. The COV was 70%, which was the highest for the soils investigated in this study. The PDF for the TCP blow count (N_{TCP}) was lognormal.

   Current TxDOT relationship or Model-1($\frac{N_{TCP}}{25}$ in tsf) over predicted 80% of the 97 mean undrained shear strength ($\bar{S}_u$) data on CH soil. Linear and Nonlinear relationships have been developed to relate the mean undrained shear strength ($\bar{S}_u$) to N_{TCP} and the relationships are as follows:

Linear relations (Model-2)

$$\bar{S}_u = 0.25 N_{TCP} = \frac{1.425}{N_c} N_{TCP}\, psi = \frac{N_{TCP}}{55} tsf \text{ ; where } N_C = 5.698$$

Model-2 over predicted 27% of the 97 data on mean undrained shear strength ($\bar{S}_u$).

Nonlinear relation (Model-3)

$$\bar{S}_u = 4.84 (N_{TCP})^{0.3}\, psi \quad = \quad 0.35\,(N_{TCP})^{0.3}\, tsf$$

Model-3 over predicted 47% of the 97 data on mean undrained shear strength ($\bar{S}_u$).

2. CL Soil:

Based on the 1852 data set, the undrained shear strength (S_u) varied from 0.96 to 114.6 psi with a mean of 12.9 psi. The COV was 54%, which was the lowest for the soils investigated in this study. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 2 to 100 with a mean of 35. The COV was 58%. The PDF for the TCP blow count (N_{TCP}) was lognormal.

Current TxDOT relationship or Model-1 ($\frac{N_{TCP}}{30}$ in tsf) over predicted 60% of the 98 mean undrained shear strength ($\bar{S}_u$) data on CL soil. Linear and Nonlinear relationships have been developed to relate the mean undrained shear strength ($\bar{S}_u$) to N_{TCP} and the relationships are as follows:

Linear relation (Model-2)

$$\bar{S}_u = 0.31 N_{TCP} = \frac{1.673}{N_c} N_{TCP}\, psi = \frac{N_{TCP}}{45} tsf \text{ ; where } N_C = 5.355$$

Model-2 over predicted 34% of the 98 data on mean undrained shear strength ($\bar{S}_u$).

Nonlinear relation (Model-3)

$$\bar{S}_u = 6.51(N_{TCP})^{0.28}\,psi = 0.47\,(N_{TCP})^{0.28}\,tsf$$

Model-3 over predicted 57% of the 98 mean data on undrained shear strength ($\bar{S}_u$).

3. SC Soil:

Based on the 29 data set, the undrained shear strength (S_u) varied from 3.5 to 38.55 psi with a mean of 10.8 psi. The COV was 60%. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 7 to 87 with a mean of 30. The COV was 66%. The PDF for the TCP blow count (N_{TCP}) was Weibull.

Current TxDOT relationship or Model-1 ($\frac{N_{TCP}}{35}$ in tsf) over predicted 48% of the 23 mean undrained shear strength ($\bar{S}_u$) data on SC soil. Linear and Nonlinear relationships have been developed to relate the mean undrained shear strength ($\bar{S}_u$) to N_{TCP} and the relationships are as follows:

Linear relation (Model-2)

$$\bar{S}_u = 0.22N_{TCP} = \frac{1.704}{N_c} N_{TCP}\,psi = \frac{N_{TCP}}{63}\,tsf \text{ ; where } N_C = 5.355$$

Model-2 over predicted 30% of the 23 data on mean undrained shear strength ($\bar{S}_u$).

Nonlinear relation (Model-3)

$$\bar{S}_u = 5.23(N_{TCP})^{0.23}\,psi = 0.38\,(N_{TCP})^{0.23}\,tsf$$

Model-3 over predicted 65% of the 23 data on mean undrained shear strength ($\bar{S}_u$).

4. OTHER Soil:

Based on the 42 data set, the undrained shear strength (S_u) varied from 1.4 to 69.3 psi with a mean of 16.8 psi. The COV was 66%. The PDF for the undrained shear strength (S_u) was Weibull. The TCP blow count (N_{TCP}) varied from 10 to 93 with a mean of 45. The COV was 45%, which was the lowest for the soils investigated in this study. The PDF for the TCP blow count (N_{TCP}) was normal.

Current TxDOT relationship or Model-1 ($\frac{N_{TCP}}{40}$ in tsf) over predicted 49% of the 33 mean undrained shear strength ($\bar{S}_u$) data on OTHER soil. Linear and Nonlinear relationships have been developed to relate the mean undrained shear strength ($\bar{S}_u$) to N_{TCP} and the relationship is as follows:

Linear relation (Model-2)

$$\bar{S}_u = 0.30 N_{TCP} = \frac{1.493}{N_c} N_{TCP}\, psi = \frac{N_{TCP}}{46} tsf \text{ ; where } N_C = 4.928$$

Model-2 over predicted 30% of the 33 data on mean undrained shear strength ($\bar{S}_u$).

CHAPTER 5. DEPTH EFFECT ANALYSES

The variation of 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 variation. Hence, the use of generalized correlations to predict soil properties like the shear strength for soils of all geologic formations is not always possible and 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 this study, a third approach was used to develop new correlations considering depth effect on N_{TCP} and S_u for total and local soil data.

The data set of N_{TCP} and S_u at 5 ft. intervals up to 75 ft. were collected for these analyses. At 5 ft. intervals, the mean and two standard deviation values of the N_{TCP} and S_u for all the types of soils were determined. The variations of the mean N_{TCP} ($\overline{N}_{TCP}$) and mean S_u ($\overline{S}_u$) with depth were compared with the nine possible CASES (Figure 5.1) to verify the current TxDOT design relationship and to investigate how the depth affects both the N_{TCP} and S_u. The relationships between mean N_{TCP} ($\overline{N}_{TCP}$) and mean S_u ($\overline{S}_u$) are investigated using three Models as follows:

Model-1 : TxDOT design relationship (TxDOT line)

Model-2 : Linear relationship based on best least-square fit line (Mean Values)

Model-4 : Depth Effect on N_{TCP} and S_u

(Note that Model-3, which is the nonlinear relationship, is not considered.)

5.1 Factors Affecting Resistance to Penetration, N_{TCP}

The relationship between the undrained shear strength (S_u) and resistance to penetration (N_{TCP}) is not well understood because of the fact that number variable can influence the results. Hence, it was necessary to investigate an important factor, the depth effect on S_u and N_{TCP} .

The ease with which the cone penetrates the subsoil is represented by the magnitude of the N_{TCP} 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).

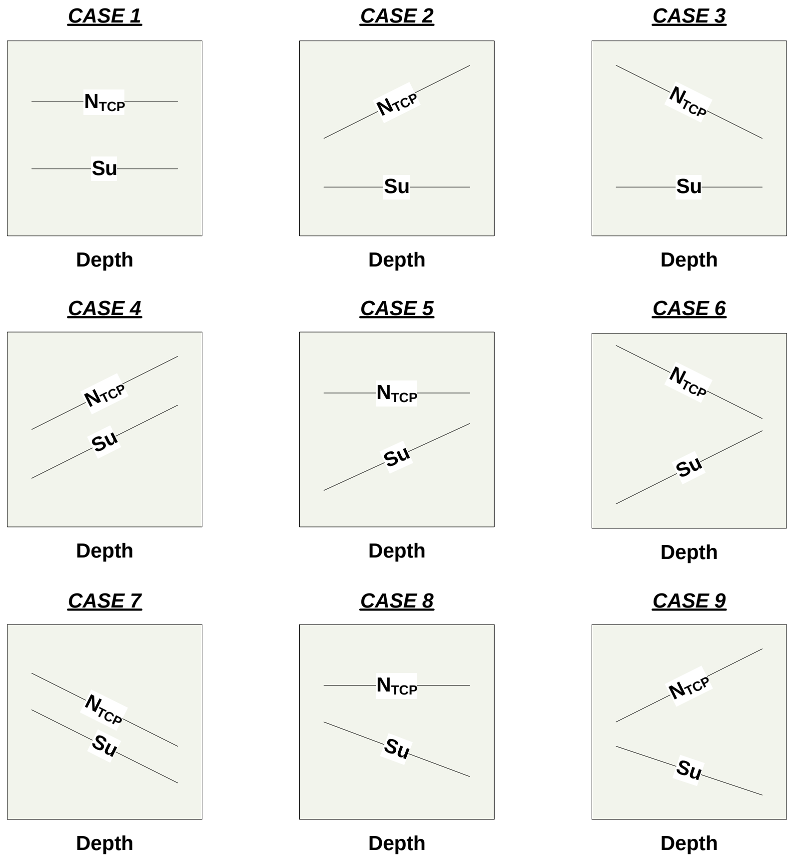
In impervious and saturated cohesive soils below the water table, the resistance to penetration of the cone is mostly attributed to its skin friction and resistance of pore water (Sanglerat, 1972). Desai (1970) and Sengupta and Aggarwal (1966) reported that the friction was appreciable in loose sands and all types of clay soils as well as those in stratified deposits. The diameter of the cone used by Desai (1970) and Sengupta and Aggarwal (1966) was either equal to or smaller than the drill rod that was attached to the cone. The TCP cone is larger in diameter than the drill rod to which it is attached (Hamoudi et al., 1974). This can be shown in Figures 2.2, 2.3 and 2.5. 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_{TCP}-values obtained from TCP for depth and soil type effects. Further, the factors which affect the N_{TCP} value are obviously interrelated, and it is difficult, if not impossible, to isolate a single, most important factor (Hamoudi et al., 1974).

5.2 Depth Effect

The N_{TCP} and S_u either will or will not depend on the depth. Based on this concept, it is possible to have nine CASES to represent the depth effect as shown in Figure 5.1. For example, in CASES 1, 2 and 3, S_u was independent to depth N_{TCP} had varying trends. In CASES 4, 5 and 6, S_u increased with depth. In CASES 7, 8 and 9, S_u decreased with depth. In addition, the current TxDOT design relationship can be explained by only if CASE 1 trends are observed or in special conditions in CASES 4 and 7. Other CASES address that existing TxDOT design relationships currently used by TxDOT to predict the shear strength are not valid.

The variations of $\overline{N}_{TCP}$ and $\overline{S}_u$ with depth will be compared to the nine CASES and verify the current TxDOT design relationship (Model-1).



CASES	Parameters				Remarks
	a	b	c	d	
CASE 1	$a = 0$	$b > 0$	$c = 0$	$d > 0$	Model-1
CASE 2	$a = 0$	$b > 0$	$c > 0$	$d > 0$	Observed for Texas Soil
CASE 3	$a = 0$	$b > 0$	$c < 0$	$d > 0$	Not Observed for Texas Soil
CASE 4	$a > 0$	$b > 0$	$c > 0$	$d > 0$	When $a/b = c/d$ Model-1
CASE 5	$a > 0$	$b > 0$	$c = 0$	$d > 0$	Not Observed for Texas Soil
CASE 6	$a > 0$	$b > 0$	$c < 0$	$d > 0$	Not Observed for Texas Soil
CASE 7	$a < 0$	$b > 0$	$c < 0$	$d > 0$	When $a/b = c/d$ Model-1
CASE 8	$a < 0$	$b > 0$	$c = 0$	$d > 0$	Not Observed for Texas Soil
CASE 9	$a < 0$	$b > 0$	$c > 0$	$d > 0$	Observed for Texas Soil

Figure 5.1 Nine Possible CASES for Depth Effect

5.3 Model-4

The variations of mean N_{TCP} ($\overline{N}_{TCP}$) and mean S_u ($\overline{S}_u$) with depth (Z) can be represented by a linear relationship with depth (Z) as follows :

$$\overline{S}_u = a \cdot Z + b \qquad \text{--------------------------------------(5.1)}$$

$$\overline{N}_{TCP} = c \cdot Z + d \qquad \text{--------------------------------------(5.2)}$$

Equations (5.1) and (5.2) explain the depth effect on the $\overline{N}_{TCP}$ and $\overline{S}_u$. By eliminating Z from Equations (5.1) and (5.2), Equation (5.3) will be generated.

$$\frac{\overline{S}_u - b}{a} = \frac{\overline{N}_{TCP} - d}{c} \qquad \text{--------------------------------------(5.3)}$$

Finally, Equation (5.3) can be rewritten depth effect (linear dependency) as follows:

$$\overline{S}_u = \frac{a}{c} \cdot \overline{N}_{TCP} + (b - \frac{a}{c} \cdot d) \qquad \text{--------------------------------------(5.4)}$$

Where,

$\overline{S}_u$: Mean of undrained shear strength (psi)

$\overline{N}_{TCP}$: Mean of TCP blow counts (blows/ft)

Z : Depth in feet

When $\frac{a}{b} = \frac{c}{d}$, Model-4 becomes Model-1 (TxDOT design relationship) and Model-2. Additionally, the possible nine CASE combinations can be explained by Model-4.

5.4 Total Soil Data Analysis

The mean, two standard deviation values and standard error of the mean of the N_{TCP} and S_u for the Total CH, CL, SC and OTHER soils were determined and plotted against the depth in Figures 5.2, 5.4, 5.6 and 5.8, respectively. $\overline{N}_{TCP}$ showed greater dependence on depth than $\overline{S}_u$. Where standard error of the mean (SEM) is calculated by dividing the standard deviation by the square root of the sample size. The SEM is used to calculate confidence intervals for the mean.

Also, new arranged relationships between mean of N_{TCP} and mean of S_u at 5 ft. interval depth selected are presented in Figures 5.3, 5.5, 5.7 and 5.9 for the Total CH, CL, SC and OTHER soils, respectively. The new relationships between $\overline{N}_{TCP}$ and $\overline{S}_u$ are compared with three Models (Model-1, Model-2 and Model-4).

The total number of data sets used for $\overline{N}_{TCP}$ and $\overline{S}_u$, and all statistical analysis results are summarized in Tables 5.1, 5.2 and 5.3. Additionally, all three Model parameters are summarized in Table 5.4. Depth analyses were done at 5 ft intervals.

5.4.1 CH Soil

Mean Strength ($\overline{S}_u$) vs. Depth

The minimum S_u varied from 1 to 6 psi with depth. The maximum S_u fluctuated from 28 to 84 psi. As shown in Figure 5.2, mean S_u ($\overline{S}_u$) varied from 9 to 18 psi and increased with depth (5 ft to 65 ft (a>0)). The COV varied from 38 % to 74 % and tended to reduce with depth. The PDF for S_u was represented by lognormal, Weibull and normal distributions and there was no clear trend with depth. The relationship is as follows:

$$\overline{S}_u = 0.112 \cdot Z + 9.586 \qquad \text{-------------------------------------(5.5)}$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 2 to 20 with depth. The maximum N_{TCP} fluctuated from 70 to 100. As shown in Figure 5.2, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 12 to 51 and increased with depth (5 ft to 70 ft (a>0)). The COV varied from 37 % to 87 % and tended to reduce with depth. The dominant PDFs were lognormal and Weibull distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.527 \cdot Z + 15.888 \qquad \text{-------------------------------------(5.6)}$$

The trends showed that CH soils in Texas can be represented by CASE 4.

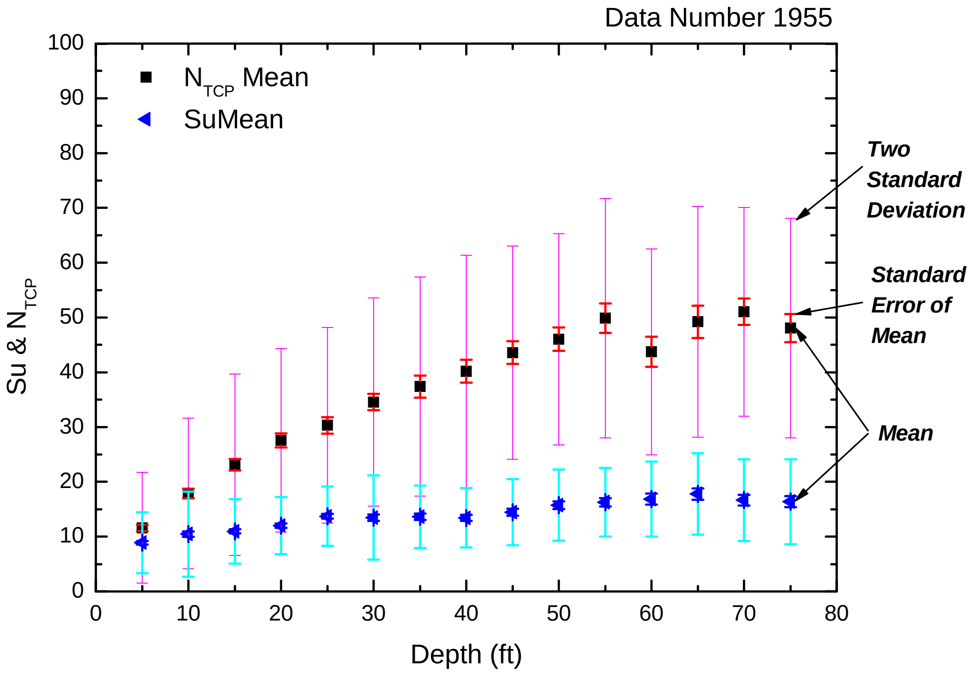


Figure 5.2 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with depth for All (Total) the CH Soils

Table 5.1 Statistical Analysis Summary –Total CH Soil (Depth in ft.)

Total CH Soil																
Depth		*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*55*	*60*	*65*	*70*	*75*
N_{TCP}	Range	2-70	3-85	2-85	4-90	7-83	7-86	7-89	11-100	6-92	20-92	14-100	19-98	14-91	15-94	17-95
	Mean	12	18	23	28	30	35	37	40	44	46	50	44	49	51	48
	Standard Deviation	10	14	17	17	18	19	20	21	19	19	22	19	21	19	20
	Var	102	188	275	280	319	361	399	449	379	371	476	353	442	363	401
	COV (%)	87	77	72	61	59	55	53	53	45	42	44	43	43	37	42
	Number of Data	304	260	255	172	142	166	98	102	90	81	65	46	51	62	61
	PDF	LN	LN	LN	W	W	W	W	W	W	W	LN	W	W	W	N
S_u	Range	2-40	2-53	1-40	2-28	3-38	3-84	1-29	3-29	3-38	3-37	2-31	4-36	5-38	4-41	6-39
	Mean	9	10	11	12	14	13	14	13	14	16	16	17	18	17	16
	Standard Deviation	6	8	6	5	5	8	6	5	6	7	6	7	7	7	8
	Var	31	61	35	27	29	59	33	29	36	42	39	47	55	55	61
	COV (%)	62	74	54	43	40	57	42	40	42	41	38	41	42	45	48
	Number of Data	304	260	255	172	142	166	98	102	90	81	65	46	51	62	61
	PDF	LN	LN	W	W	LN	W	W	W	W	W	W	N	N	W	W

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

Mean Strength ($\overline{S}_u$) vs. Mean TCP Blow Count ($\overline{N}_{TCP}$)

A total of 15 mean data sets (Depth from 5 ft to 75 ft) were used to investigate the $\overline{S}_u$ versus $\overline{N}_{TCP}$ relationship shown in Figure 5.3. Current TxDOT relationship (Model-1) over predicted 87 % of the mean strength data, and had the highest standard error of 7.77 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\overline{S}_u = 0.363 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP} \ psi = \frac{\overline{N}_{TCP}}{38} \ tsf \qquad \text{----------------------------}(5.7)$$

Where, $N_c = 3.924$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 35 % lower than the current TxDOT relationship. Model-2 over predicted 47 % of the mean data, and had a standard error of 2.15.

Model-4 relationship for the data is as follows:

$$\overline{S}_u = 0.212 \cdot \overline{N}_{TCP} + 6.219 \ psi = 0.015 \cdot \overline{N}_{TCP} + 0.448 \ tsf \ \text{---------------------------}(5.8)$$

Model-4 over predicted 67 % of the mean data (percentage of data below the curve), and had the lowest standard error of 0.73.

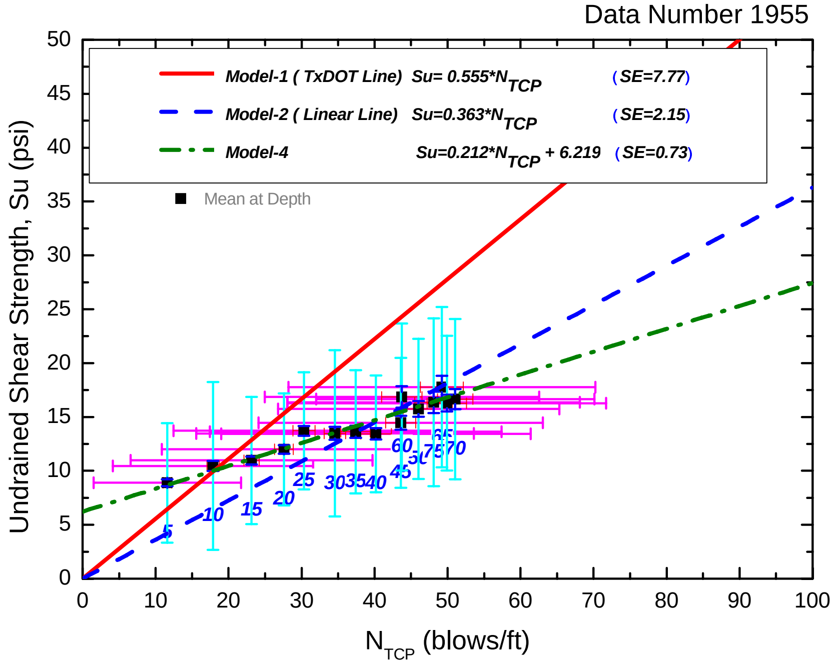


Figure 5.3 Relationship between Mean N_{TCP} and Mean s_u for All the CH Soils

5.4.2 CL Soil

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum s_u varied from 1 to 5 psi with depth. The maximum s_u fluctuated from 31 to 116 psi. As shown in Figure 5.4, mean s_u ($\bar{S}_u$) varied from 14 to 19 psi but was unchanged with depth (15ft to 75ft ($a \approx 0$)). The COV varied from 48 % to 80 % and tended to reduce with depth. The dominant PDFs were lognormal and weibull distribution. The relationship is as follows:

$$\bar{S}_u = 0.001 \cdot Z + 15.383 \qquad \text{-------------------------------------}(5.9)$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 2 to 23 with depth. The maximum N_{TCP} fluctuated from 81 to 100. As shown in Figure 5.4, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 26 to 60 and increased with depth (from 5 ft to 75 ft (a>0)). The COV varied from 33 % to 68 % and tended to reduce with depth. The dominant PDFs were lognormal and Weibull distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.344 \cdot Z + 28.687 \qquad \text{------------------------------------}(5.10)$$

The trends showed that CL soils in Texas can be represented by CASE 2.

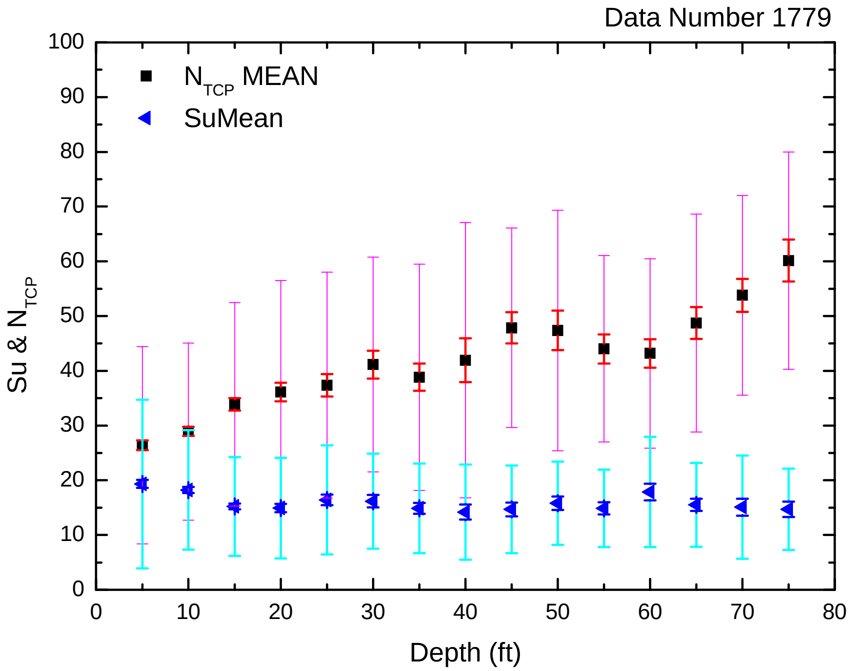


Figure 5.4 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for All (Total) the CL Soils

Table 5.2 Statistical Analysis Summary –Total CL Soil (Depth in ft.)

Total CL Soil																
Depth		*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*55*	*60*	*65*	*70*	*75*
N_{TCP}	Range	2-100	2-93	2-100	5-100	4-81	6-100	8-87	11-92	16-82	14-94	20-81	21-98	13-87	23-100	22-98
	Mean	26	29	34	36	37	41	39	42	48	47	44	43	49	54	60
	Standard Deviation	18	16	19	20	21	20	21	25	18	22	17	17	20	18	20
	Var	325	263	346	415	426	385	427	633	333	483	291	300	397	332	394
	COV (%)	68	56	55	56	55	48	53	60	38	46	39	40	41	34	33
	Number of Data	433	396	265	140	102	59	70	39	42	37	41	44	47	37	27
	PDF	LN	LN	W	W	W	W	W	W	U	W	W	W	N	N	N
S_u	Range	1-116	2-77	1-51	2-64	1-51	3-54	4-33	4-45	2-33	1-32	5-35	4-41	3-33	4-51	5-31
	Mean	19	18	15	15	16	16	15	14	15	16	15	18	16	15	15
	Standard Deviation	15	11	9	9	10	9	8	9	8	8	7	10	8	9	7
	Var	237	119	81	85	100	76	67	75	64	58	50	101	59	89	55
	COV (%)	80	60	59	62	61	54	55	61	55	48	48	56	49	62	50
	Number of Data	433	396	265	140	102	59	70	39	42	37	41	44	47	37	27
	PDF	LN	LN	W	LN	LN	N	LN	W	W	N	W	W	N	W	U

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

Mean Strength ($\overline{S}_u$) vs. Mean TCP Blow Count ($\overline{N}_{TCP}$)

A total of 15 mean data sets (Depth from 5 ft to 75 ft) were used to investigate the $\overline{S}_u$ versus $\overline{N}_{TCP}$ relationship shown in Figure 5.5. Current TxDOT relationship (Model-1) over predicted 87 % of the mean strength data, and had the highest standard error of 6.17 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\overline{S}_u = 0.358 \cdot \overline{N}_{TCP} = \frac{1.673}{N_c} \overline{N}_{TCP} \ psi = \frac{\overline{N}_{TCP}}{39} \ tsf \qquad \text{---------------------------}(5.11)$$

Where, $N_c = 4.673$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 23 % lower than the current TxDOT relationship. Model-2 over predicted 53 % of the data, and had a standard error of 4.23.

Model-4 relationship for the data is as follows:

$$\overline{S}_u = 0.001 \cdot \overline{N}_{TCP} + 15.342 \ psi = 0.0001 \cdot \overline{N}_{TCP} + 1.105 \ tsf \ \text{----------------------}(5.12)$$

Model-4 over predicted 53 % of the mean data (percentage of data below the curve), and had the lowest standard error of 1.53.

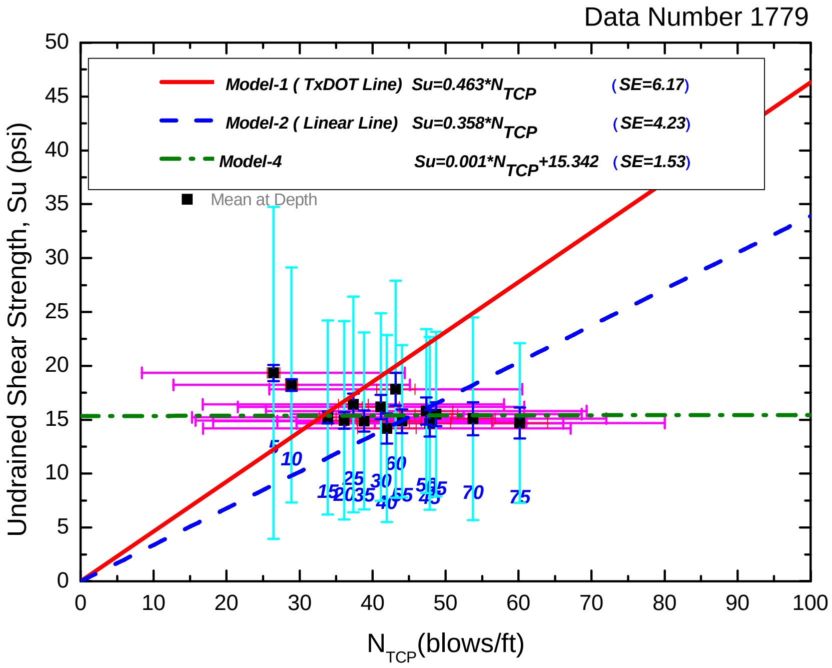


Figure 5.5 Relationship between Mean N_{TCP} and Mean s_u for All the CL Soils

5.4.3 SC Soil

A total of 28 data sets were available and only one data set was available for depths higher than 30 ft. Hence, the statistical analysis was limited to 25 ft depth.

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum s_u varied from 5 to 9 psi with depth. The maximum s_u varied from 10 to 39 psi. As shown in Figure 5.6, mean s_u ($\bar{S}_u$) varied from 8 to 13 psi and decreased with depth (from 5 ft to 25 ft (a<0)). The COV varied from 34 % to 92 %. The PDFs for s_u were represented by lognormal, weibull and uniform distributions and there was no clear trend with depth. The relationship is as follows:

$$\bar{S}_u = -0.232 \cdot Z + 13.760 \qquad \text{-----------------------------------}(5.13)$$

The higher strength at shallower depth could be due to the active zone of about 15 feet in the Houston area.

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 7 to 22 with depth. The maximum N_{TCP} fluctuated from 28 to 56. As shown in Figure 5.6, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 17 to 29, fluctuated and slightly increased with depth. Therefore it is difficult to apply Model-4 to the SC soils. The COV varied from 17 % to 58 % and tended to reduce with depth. The dominant PDFs were Weibull distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.259 \cdot Z + 21.195 \quad \text{------------------------------------(5.14)}$$

The trends showed that SC soils (based on limited data) in Texas can be represented by CASE 9.

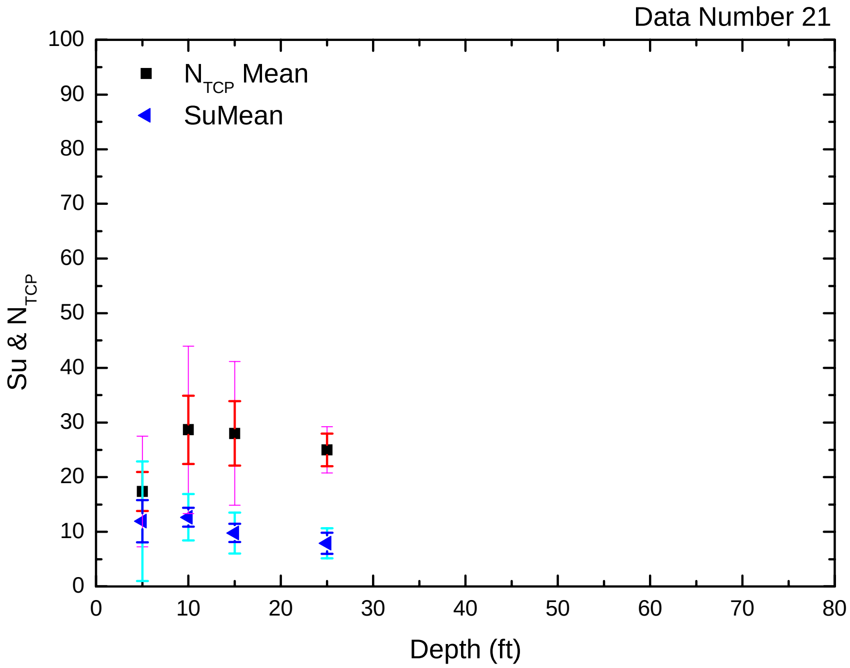


Figure 5.6 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for All (Total) the SC Soils

Table 5.3 Statistical Analysis Summary –Total SC and OTHER Soil (Depth in ft.)

		Total SC Soil											**Total OTHER Soil**											
Depth		*5*	*10*	*15*	*25*	*30*	*35*	*45*	*50*	*55*	*60*	*70*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*55*	*60*	*70*
N_{TCP}	Range	7-34	15-56	18-51	22-28	25	17	31	64	76	87	42	16-57	10-70	20-90	16-55	34-40	47	50-93	46-62	66	53	13	58
	Mean	17	29	28	25	25	17	31	64	76	87	42	32	38	49	39	37	47	72	53	66	53	13	58
	Standard Deviation	10	15	13	4	0	0	0	0	0	0	0	17	20	26	17	4	0	30	6	0	0	0	0
	Var	103	234	173	18	0	0	0	0	0	0	0	290	407	652	291	18	0	925	41	0	0	0	0
	COV (%)	58	53	47	17	0	0	0	0	0	0	0	53	53	52	44	11	0	43	12	0	0	0	0
	Number of Data	8	6	5	2	1	1	1	1	1	1	1	6	6	9	5	2	1	2	5	1	1	1	1
	PDF	W	W	W									W	U	W	U				U				
S_u	Range	5-39	9-20	5-15	6-10	9	8	16	4	12	6	10	1-61	5-33	8-33	3-18	19-30	17	17-21	12-17	12	19	43	8
	Mean	12	13	10	8	9	8	16	4	12	6	10	21	16	16	9	24	17	19	14	12	19	43	8
	Standard Deviation	11	4	4	3	0	0	0	0	0	0	0	22	11	7	6	7	0	3	2	0	0	0	0
	Var	120	18	14	8	0	0	0	0	0	0	0	474	120	49	31	54	0	7	6	0	0	0	0
	COV (%)	92	34	38	35	0	0	0	0	0	0	0	106	67	44	60	30	0	15	17	0	0	0	0
	Number of Data	8	6	5	2	1	1	1	1	1	1	1	6	6	9	5	2	1	2	5	1	1	1	1
	PDF	LN	W	U									W	U	N	W				LN				

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

Mean Strength ($\bar{S}_u$) vs. Mean TCP Blow Count ($\bar{N}_{TCP}$)

A total of 4 mean data sets (Depth from 5 to 25 ft) were used to investigate the $\bar{S}_u$ versus $\bar{N}_{TCP}$ relationship shown in Figure 5.7. Current TxDOT relationship (Model-1) over predicted 50 % of the mean strength data and had the highest standard error of 2.86 compared to Model-2.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.411 \cdot \bar{N}_{TCP} = \frac{1.704}{N_c} \bar{N}_{TCP} \ psi = \frac{\bar{N}_{TCP}}{34} \ tsf \qquad \text{----------------------------(5.15)}$$

Where, $N_c = 4.146$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 4 % higher than the current TxDOT relationship. Model-2 over predicted 50 % of the data, and had a standard error of 2.84.

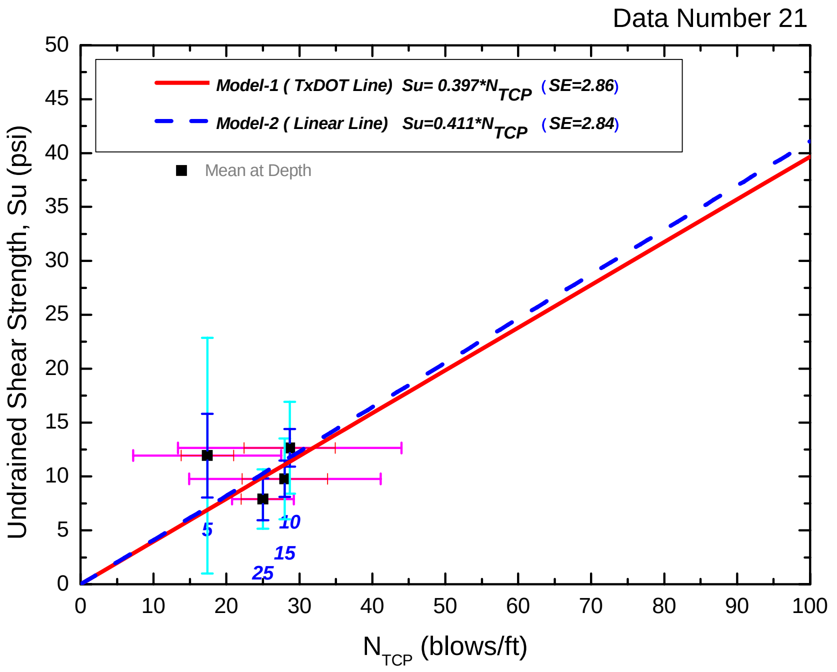


Figure 5.7 Relationship between Mean N_{TCP} and Mean S_u for All the SC Soils

5.4.4 OTHER Soil

A total of 40 data sets were available and only one data set was available for depths higher than 45 ft. Hence, the statistical analysis was limited to 40 ft depth.

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum S_u varied from 1 to 19 psi with depth. The maximum S_u fluctuated from 17 to 61 psi. As shown in Figure 5.8, mean S_u ($\bar{S}_u$) varied from 9 to 24 psi, fluctuated and decreased with depth (a<0). Therefore, it is difficult to apply Model-4 to the OTHER soil. The COV varied from 15 % to 106 % and tended to reduce with depth. The dominant PDFs were Weibull distribution. The relationship is as follows:

$$\bar{S}_u = -0.044 \cdot Z + 17.930 \qquad \text{------------------------------------}(5.16)$$

Mean TCP Blow Count ($\bar{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 10 to 50 with depth. The maximum N_{TCP} fluctuated from 40 to 93. As shown in Figure 5.8, mean N_{TCP} ($\bar{N}_{TCP}$) varied from 32 to 72, fluctuated and increased with depth (c>0). The COV varied from 11 % to 53 % and tended to reduce with depth. The dominant PDFs were uniform and weibull distribution. The relationship is as follows:

$$\bar{N}_{TCP} = 0.762 \cdot Z + 29.362 \qquad \text{------------------------------------}(5.17)$$

The trends showed that Other soils (based on limited data) in Texas can be represented by CASE 9.

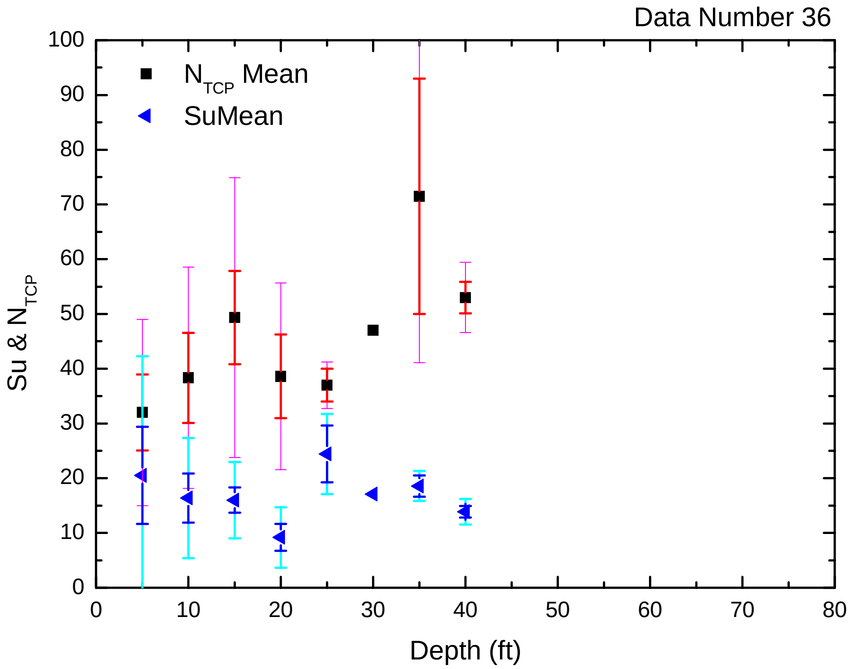


Figure 5.8 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for All (Total) the Other Soils

Mean Strength ($\overline{S}_u$) vs. Mean TCP Blow Count ($\overline{N}_{TCP}$)

A total of 7 mean data sets (Depth from 5 to 40 ft) were used to investigate the $\overline{S}_u$ versus $\overline{N}_{TCP}$ relationship shown in Figure 5.9. Current TxDOT relationship (Model-1) over predicted 57 % of the mean strength data, and had the highest standard error of 6.660 compared to Model-2.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\overline{S}_u = 0.343 \cdot \overline{N}_{TCP} = \frac{1.493}{N_c} \overline{N}_{TCP} \; psi = \frac{\overline{N}_{TCP}}{40} \; tsf \qquad \text{---------------------------}(5.18)$$

Where, $N_c = 4.353$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 1 % lower than the current TxDOT relationship. Model-2 over predicted 57 % of the data and had a standard error of 6.657.

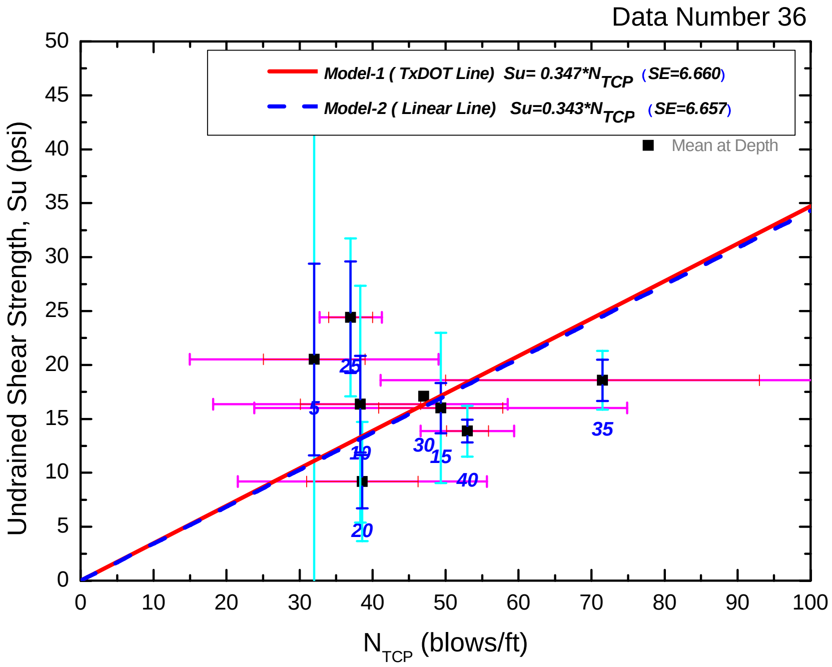


Figure 5.9 Relationship between Mean N_{TCP} and Mean S_u for All the Other Soils

Table 5.4 Model Comparisons for Total Soil Data

	CH Soil			CL Soil			SC Soil		Other Soil	
	Model-1	Model-2	Model-4	Model-1	Model-2	Model-4	Model-1	Model-2	Model-1	Model-2
Constants of Linear Eqn	0.555	0.363		0.463	0.358		0.397	0.411	0.347	0.343
Constants of Model-4 (Slope / Y-Intercept)			0.212 / 6.219			0.001 / 15.342				
β for Model-2	1.425			1.673			1.704		1.493	
Nc for Model-1 & 2	2.567	3.924		3.613	4.673		4.292	4.146	4.303	4.353
Slope Difference (%)	35			23			4		1	
Total Data Set	1995			1779			28		40	
Total Mean Data Set	15			15			4		7	
Standard Error	7.77	2.15	0.73	6.17	4.23	1.53	2.86	2.84	6.66	6.66
Amount of Data Set Over Predicted	13	7	10	13	8	8	2	2	4	4
Percentage of Data Set Over Predicted (%)	87	47	67	87	53	53	50	50	57	57

5.5 Local Data Analysis for Houston District

The mean, two standard deviation values and standard error of the mean of the N_{TCP} and S_u for the Houston CH and CL soils were determined and plotted against the depth in Figures 5.10 and 5.12. $\overline{N}_{TCP}$ showed greater dependence on depth than $\overline{S}_u$.

Also, new arranged relationships between mean of N_{TCP} and mean of S_u at 5 ft. interval depth selected are presented in Figures 5.11 and 5.13 for the Houston CH and CL soils. The new relationships between $\overline{N}_{TCP}$ and $\overline{S}_u$ are compared with three Models (Model-1, Model-2 and Model-4).

Total number of data sets used for $\overline{N}_{TCP}$ and $\overline{S}_u$, and all statistical analysis results are summarized in Tables 5.5 and 5.6. Additionally, all three Model parameters are summarized in Table 5.7. Depth analyses were done at 5 ft intervals.

5.5.1 CH Soil

Mean Strength ($\overline{S}_u$) vs. Depth

The minimum S_u varied from 2 to 6 psi with depth. The maximum S_u fluctuated from 28 to 84 psi. As shown in Figure 5.10, mean S_u ($\overline{S}_u$) varied from 10 to 17 psi and increased with depth (from 5 ft to 70 ft (a>0)). The COV varied from 37 % to 63 % and tended to reduce with depth. The dominant PDFs were lognormal and Weibull distribution. The relationship is as follows:

$$\overline{S}_u = 0.089 \cdot Z + 10.813 \qquad \text{------------------------------------}(5.19)$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 2 to 20 with depth. The maximum N_{TCP} fluctuated from 70 to 100. As shown in Figure 5.10, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 16 to 52 and increased with depth (from 5 ft to 70 ft (a>0)). The COV varied from 36 % to 69 % and tended to reduce with depth. The dominant PDFs were lognormal and weibull distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.462 \cdot Z + 20.411 \qquad \text{-----------------------------------(5.20)}$$

The trends showed that CH soils in Houston can be represented by CASE 4.

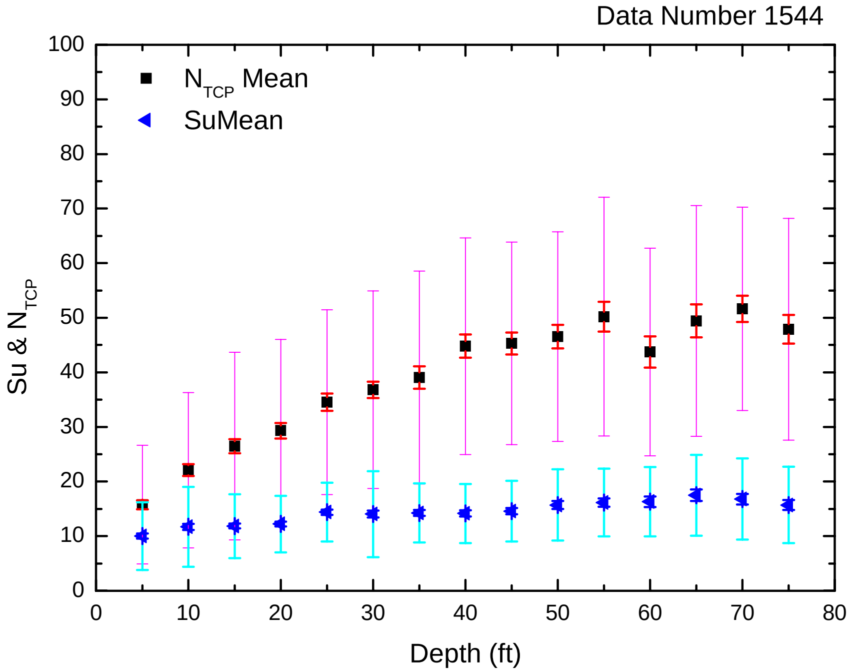


Figure 5.10 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for the Houston CH Soils

Table 5.5 Statistical Analysis Summary –Houston CH Soil (Depth in ft.)

Houston CH Soil																
Depth		*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*55*	*60*	*65*	*70*	*75*
N_{TCP}	Range	2-70	3-85	2-85	4-90	13-83	9-86	8-89	12-100	16-92	20-92	14-100	19-98	14-91	16-94	17-95
	Mean	16	22	26	29	35	37	39	45	45	47	50	44	49	52	48
	Standard Deviation	11	14	17	17	17	18	19	20	19	19	22	19	21	19	20
	Var	118	203	295	280	286	328	380	393	344	369	478	362	447	347	413
	COV (%)	69	64	65	57	49	49	50	44	41	41	44	43	43	36	42
	Number of Data	176	174	175	139	115	147	91	86	85	79	64	44	49	61	59
	PDF	LN	LN	LN	W	W	W	W	W	W	W	LN	W	W	W	N
S_u	Range	3-40	2-53	2-40	2-28	5-38	3-84	5-29	5-29	3-38	3-37	2-31	4-36	5-38	4-41	6-35
	Mean	10	12	12	12	14	14	14	14	15	16	16	16	17	17	16
	Standard Deviation	6	7	6	5	5	8	5	5	6	7	6	6	7	7	7
	Var	39	54	34	27	29	62	29	29	31	43	39	41	55	55	49
	COV (%)	62	63	49	42	37	56	38	38	38	42	39	39	42	44	45
	Number of Data	176	174	175	139	115	147	91	86	85	79	64	44	49	61	59
	PDF	LN	LN	W	W	LN	W	W	W	W	W	W	N	N	W	W

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

Mean Strength ($\overline{S}_u$) vs. Mean TCP Blow Count ($\overline{N}_{TCP}$)

A total of 15 mean data sets (Depth from 5 ft to 75 ft) were used to investigate the $\overline{S}_u$ versus $\overline{N}_{TCP}$ relationship shown in Figure 5.11. Current TxDOT relationship (Model-1) over predicted 93 % of the mean strength data, and had the highest standard error of 8.32 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\overline{S}_u = 0.356 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP} \; psi = \frac{\overline{N}_{TCP}}{39} \; tsf \qquad \text{----------------------------}(5.21)$$

Where, $N_c = 4.001$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 36 % lower than the current TxDOT relationship. Model-2 over predicted 47 % of the mean data, and had a standard error of 2.04.

Model-4 relationship for the data is as follows:

$$\overline{S}_u = 0.193 \cdot \overline{N}_{TCP} + 6.881 \; psi = 0.014 \cdot \overline{N}_{TCP} + 0.495 \; tsf \qquad \text{--------------------------}(5.22)$$

Model-4 over predicted 60 % of the mean data (percentage of data below the curve), and had the lowest standard error of 0.67.

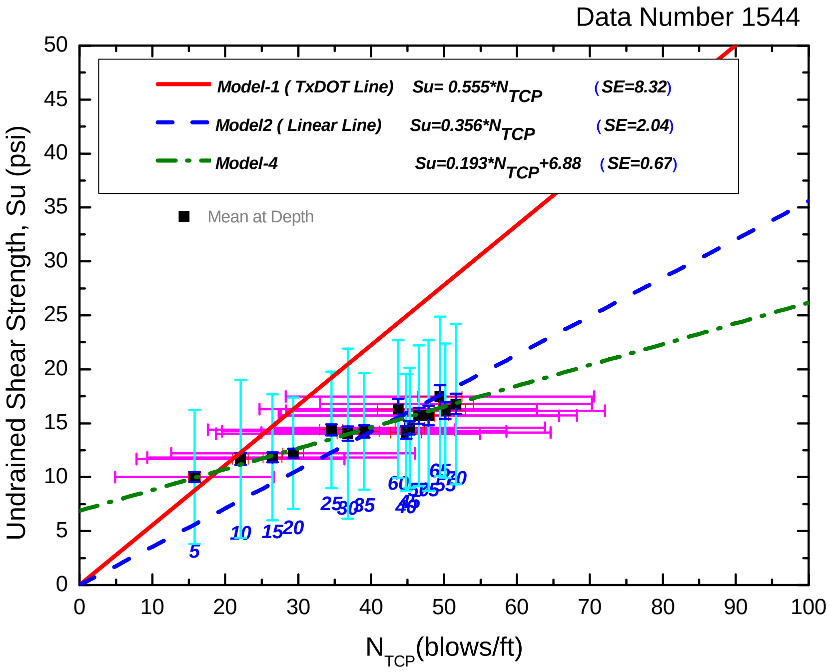


Figure 5.11 Relationship between Mean N_{TCP} and Mean S_u for the Houston CH Soils

5.5.2 CL Soil

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum S_u varied from 1 to 5 psi with depth. The maximum S_u fluctuated from 31 to 115 psi. As shown in Figure 5.12, mean S_u ($\bar{S}_u$) varied from 14 to 19 psi but was unchanged with depth (15ft to 75ft ($a \approx 0$)). The COV varied from 44 % to 79 % and tended to reduce with depth. The dominant PDFs were lognormal and Weibull distribution. The relationship is as follows:

$$\bar{S}_u = 0.004 \cdot Z + 15.219 \qquad \text{-----------------------------------(5.23)}$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 2 to 24 with depth. The maximum N_{TCP} fluctuated from 81 to 100. As shown in Figure 5.12, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 26 to 60 and increased with depth (from 5 ft to 75 ft (a>0)). The COV varied from 32 % to 68 % and tended to reduce with depth. The dominant PDFs were Weibull distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.344 \cdot Z + 29.750 \qquad \text{-----------------------------------(5.24)}$$

The trends showed that CL soils in Houston can be represented by CASE 2.

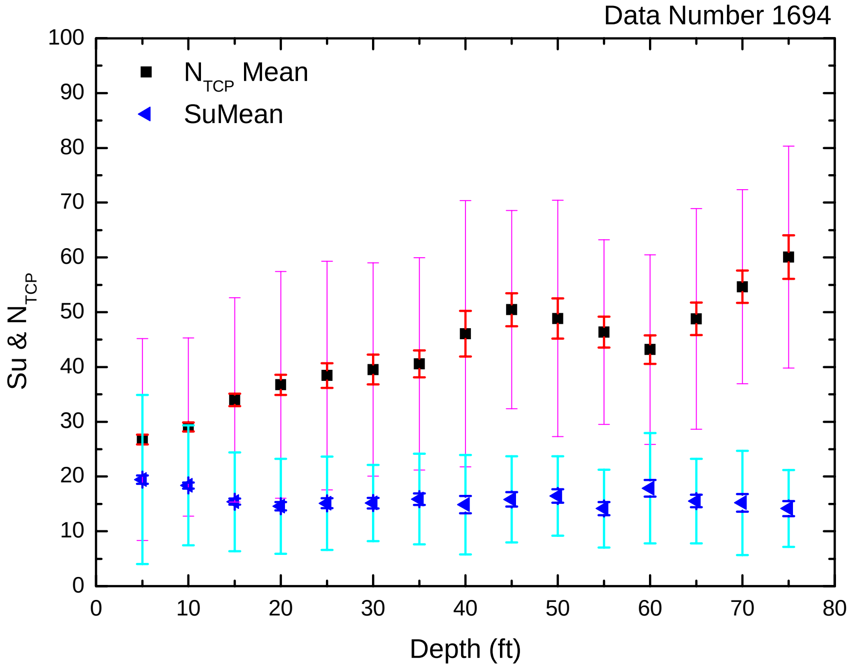


Figure 5.12 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for the Houston CL Soils

Table 5.6 Statistical Analysis Summary –Houston CL Soil (Depth in ft.)

Houston CL Soil																
Depth		*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*55*	*60*	*65*	*70*	*75*
N_{TCP}	Range	2-100	2-93	2-100	5-100	4-81	6-100	8-87	13-92	16-82	15-94	20-81	21-98	13-87	24-100	22-98
	Mean	27	29	34	37	38	40	41	46	50	49	46	43	49	55	60
	Standard Deviation	18	16	19	21	21	19	19	24	18	22	17	17	20	18	20
	Var	340	265	347	429	436	378	375	591	327	466	285	300	405	314	410
	COV (%)	69	56	55	56	54	49	48	53	36	44	36	40	41	32	34
	Number of Data	426	389	259	128	87	51	61	34	36	35	36	44	46	36	26
	PDF	LN	LN	W	W	W	W	W	W	U	W	W	W	N	N	N
S_u	Range	1-115	2-77	1-51	2-64	1-38	3-35	4-33	4-45	2-33	2-32	5-35	4-41	3-33	4-51	5-31
	Mean	19	18	15	15	15	15	16	15	16	16	14	18	16	15	14
	Standard Deviation	15	11	9	9	9	7	8	9	8	7	7	10	8	10	7
	Var	238	120	81	75	72	49	69	83	62	53	50	101	60	91	49
	COV (%)	79	60	59	59	56	46	52	61	50	44	50	56	50	63	49
	Number of Data	426	389	259	128	87	51	61	34	36	35	36	44	46	36	26
	PDF	LN	LN	W	LN	LN	N	LN	W	W	N	W	W	N	W	U

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

Mean Strength ($\bar{S}_u$) vs. Mean TCP Blow Count ($\bar{N}_{TCP}$)

A total of 15 mean data sets (Depth from 5 ft to 75 ft) were used to investigate the $\bar{S}_u$ versus $\bar{N}_{TCP}$ relationship shown in Figure 5.13. Current TxDOT relationship (Model-1) over predicted 87 % of the mean strength data, and had the highest standard error of 6.53 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.350 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP} \ psi = \frac{\bar{N}_{TCP}}{40} \ tsf \qquad \text{----------------------------(5.25)}$$

Where, $N_c = 4.780$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 24 % lower than the current TxDOT relationship. Model-2 over predicted 47 % of the data, and had a standard error of 4.27.

Model-4 relationship for the data is as follows:

$$\bar{S}_u = 0.012 \cdot \bar{N}_{TCP} + 14.873 \ psi = 0.0009 \cdot \bar{N}_{TCP} + 1.071 \ tsf \ \text{--------------------(5.26)}$$

Model-4 over predicted 47 % of the mean data (percentage of data below the curve), and had the lowest standard error of 1.64.

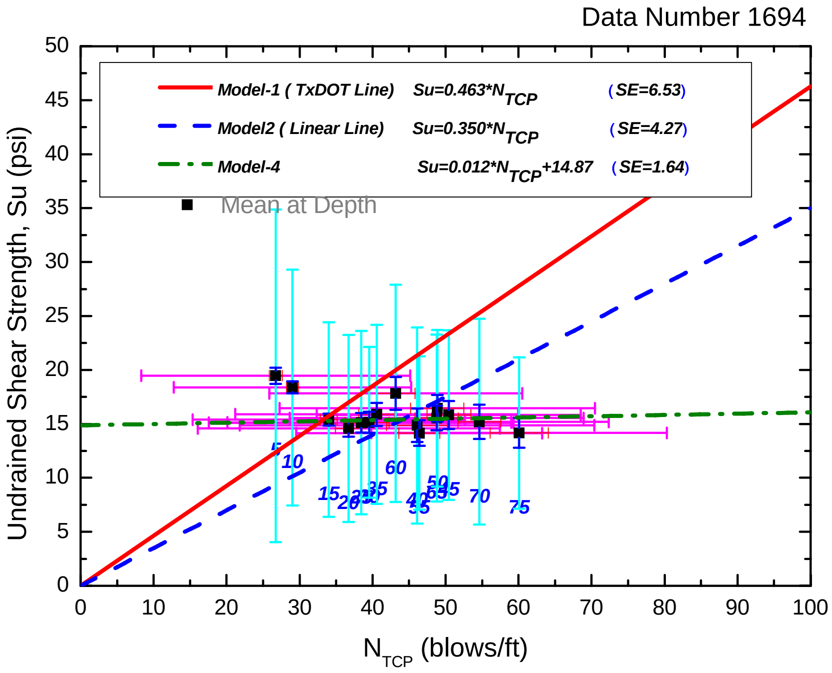


Figure 5.13 Relationship between Mean N_{TCP} and Mean S_u for the Houston CL Soils

Table 5.7 Model Comparisons for Houston Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-4	Model-1	Model-2	Model-4
Constants of Linear Eqn	0.555	0.356		0.463	0.350	
Constants of Model-4 (Slope / Y-Intercept)			0.193 / 6.881			0.012 / 14.873
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	4.001		3.613	4.780	
Slope Difference (%)	36			24		
Total Data Set	1554			1694		
Total Mean Data Set	15			15		
Standard Error	8.32	2.04	0.67	6.53	4.27	1.64
Amount of Data Set Over Predicted	14	7	9	13	7	7
Percentage of Data Set Over Predicted (%)	93	47	60	87	47	47

5.6 Local Data Analysis for Beaumont District

The mean, two standard deviation values and standard error of the mean of the N_{TCP} and S_u for the Beaumont CH and CL soils, respectively, were determined and plotted against the depth in Figures 5.14 and 5.16. $\overline{N}_{TCP}$ showed a similar dependence on depth with $\overline{S}_u$.

Also, new arranged relationships between mean of N_{TCP} and mean of S_u at 5 ft. interval depth selected are presented in Figures 5.15 and 5.17 for the Beaumont CH and CL soils, respectively. The new relationships between $\overline{N}_{TCP}$ and $\overline{S}_u$ are compared with three Models (Model-1, Model-2 and Model-4).

A total number of data sets used for $\overline{N}_{TCP}$ and $\overline{S}_u$, and all statistical analysis results are summarized in Table 5.9. Additionally, all three Model parameters are summarized in Table 5.8. Depth analyses were done at 5 ft intervals.

5.6.1 CH Soil

Mean Strength ($\overline{S}_u$) vs. Depth

The minimum S_u varied from 1 to 5 psi with depth. The maximum S_u fluctuated from 8 to 20 psi. As shown in Figure 5.14, mean S_u ($\overline{S}_u$) varied from 6 to 10 psi but was unchanged with depth (5 ft to 45 ft ($a \approx 0$)). The COV varied from 30 % to 59 %. The PDFs for S_u were represented by lognormal, Weibull and normal distributions and there was no clear trend with depth. The relationship is as follows:

$$\overline{S}_u = 0.017 \cdot Z + 7.422 \qquad \text{------------------------------------(5.27)}$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 3 to 11 with depth. The maximum N_{TCP} fluctuated from 9 to 62. As shown in Figure 5.14, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 5 to 17 and increased with depth (5 ft to 45 ft (a>0)). The COV varied from 18 % to 78 %. The dominant PDFs were normal and lognormal distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.141 \cdot Z + 7.327 \qquad \text{------------------------------------(5.28)}$$

The trends showed that CH soils in Beaumont can be represented by CASE 2.

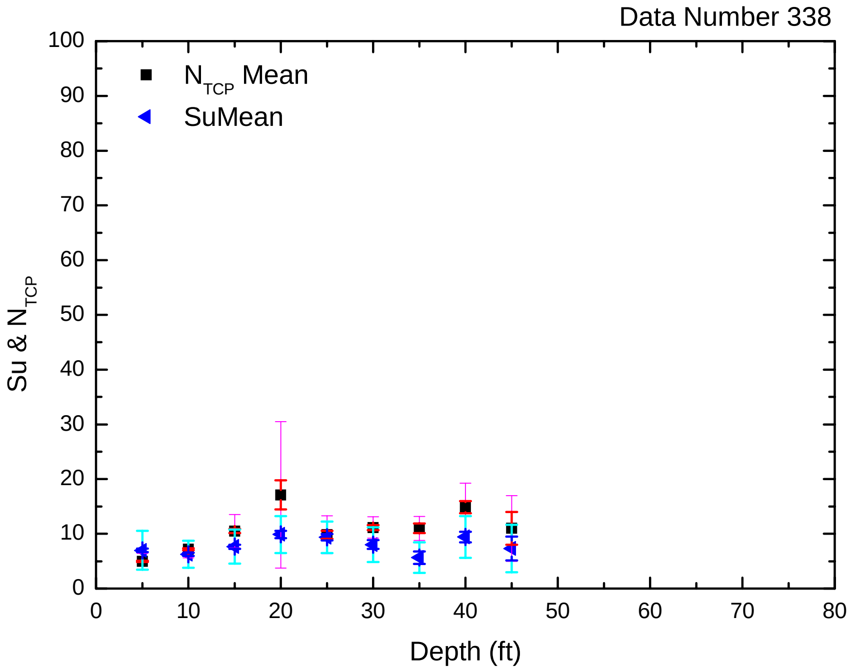


Figure 5.14 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for the Beaumont CH Soils

Mean Strength ($\bar{S}_u$) vs. Mean TCP Blow Count ($\bar{N}_{TCP}$)

A total of 9 mean data sets (Depth from 5 ft to 45 ft) were used to investigate the $\bar{S}_u$ versus $\bar{N}_{TCP}$ relationship shown in Figure 5.15 Current TxDOT relationship (Model-1) over predicted 11 % of the mean strength data, and had the highest standard error of 2.31 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.682 \cdot \bar{N}_{TCP} = \frac{1.425}{N_c} \bar{N}_{TCP} \ psi = \frac{\bar{N}_{TCP}}{20} \ tsf \quad \text{---------------------------(5.29)}$$

Where, $N_c = 2.089$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 23 % higher than the current TxDOT relationship. Model-2 over predicted 44 % of the mean data, and had a standard error of 1.81.

Model-4 relationship for the data is as follows:

$$\bar{S}_u = 0.121 \cdot \bar{N}_{TCP} + 6.539 \ psi = 0.009 \cdot \bar{N}_{TCP} + 0.471 \ tsf \ \text{-------------------------(5.30)}$$

Model-4 over predicted 56 % of the mean data (percentage of data below the curve), and had the lowest standard error of 1.16.

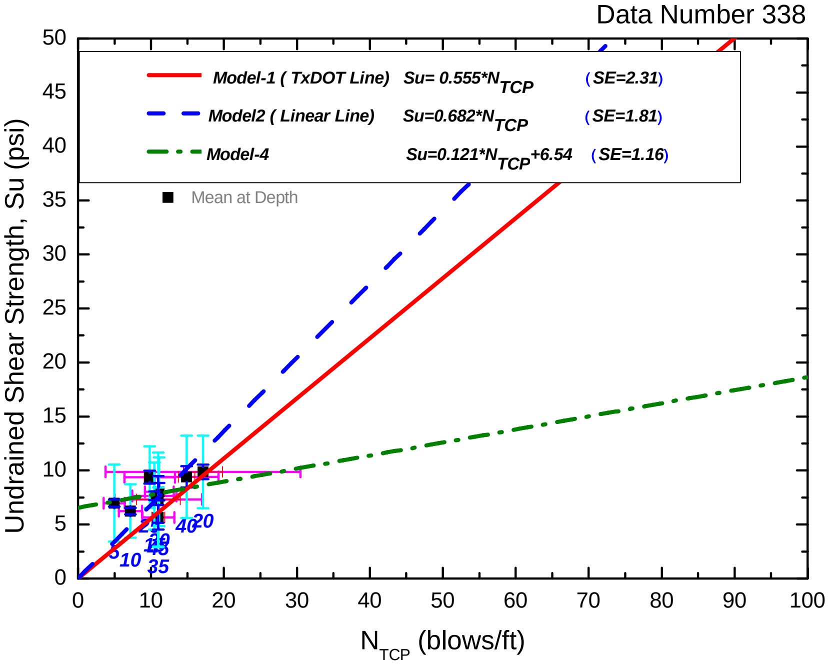


Figure 5.15 Relationship between Mean N_{TCP} and Mean S_u for the Beaumont CH Soils

5.6.2 CL Soil

Since a total of 22 data sets were available, the analysis was limited. In this analysis, statistical analysis results for 5 ft to 45 ft depth were used to interpret.

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum S_u varied from 3 to 10 psi with depth. The maximum S_u fluctuated from 7 to 16 psi. As shown in Figure 5.16, mean S_u ($\bar{S}_u$) varied from 5 to 12 psi but was unchanged with depth (15 ft to 45 ft ($a \approx 0$)). The COV varied from 3 % to 44 %. The dominant PDFs were uniform distribution. The relationship is as follows:

$$\bar{S}_u = 0.001 \cdot Z + 9.410 \qquad \text{------------------------------------}(5.31)$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 5 to 39 with depth. The maximum N_{TCP} fluctuated from 7 to 48. As shown in Figure 5.16, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 7 to 39 and increased with depth (5 ft to 45 ft (a>0)). The COV varied from 0 % to 116 %. The dominant PDFs were lognormal distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.138 \cdot Z + 12.922 \qquad \text{------------------------------------}(5.32)$$

The trends showed that CL soils in Beaumont can be represented by CASE 2.

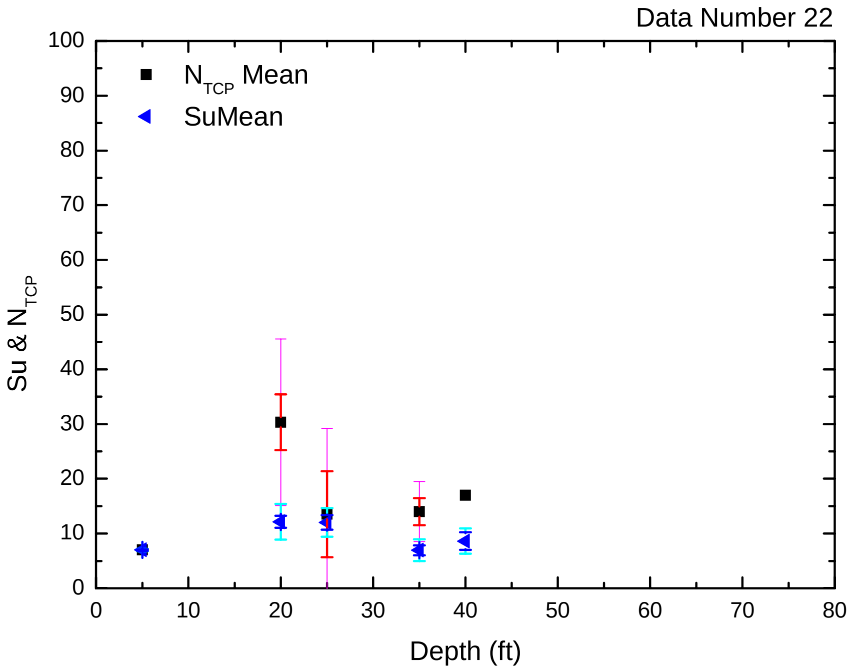


Figure 5.16 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for the Beaumont CL Soils

Mean Strength ($\bar{S}_u$) vs. Mean TCP Blow Count ($\bar{N}_{TCP}$)

Total of 5 mean data sets (Depth from 5 ft to 40 ft) were used to investigate the $\bar{S}_u$ versus $\bar{N}_{TCP}$ relationship shown in Figure 5.17. Current TxDOT relationship (Model-1) over predicted 20 % of the mean strength data, and had the highest standard error of 3.22 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\bar{S}_u = 0.503 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP} \ psi = \frac{\bar{N}_{TCP}}{28} \ tsf \qquad \text{----------------------------}(5.33)$$

Where, $N_c = 3.326$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 9 % higher than the current TxDOT relationship. Model-2 over predicted 40 % of the data, and had a standard error of 3.14.

Model-4 relationship for the data is as follows:

$$\bar{S}_u = 0.007 \cdot \bar{N}_{TCP} + 9.316 \ psi = 0.0005 \cdot \bar{N}_{TCP} + 0.671 \ tsf \ \text{------------------------}(5.34)$$

Model-4 over predicted 60 % of the mean data (percentage of data below the curve), and had the lowest standard error of 2.28.

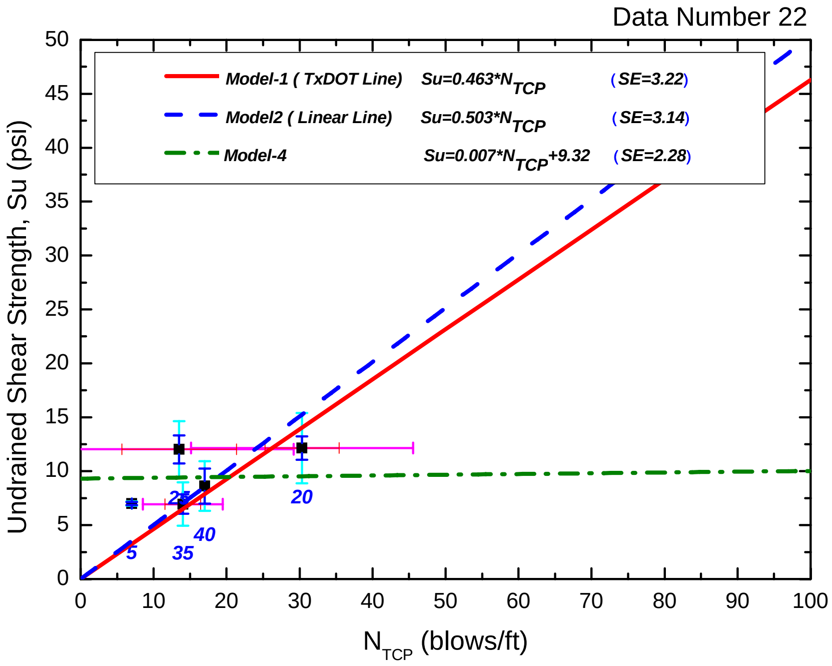


Figure 5.17 Relationship between Mean N_{TCP} and Mean S_u for the Beaumont CL Soils

Table 5.8 Model Comparisons for Beaumont Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-4	Model-1	Model-2	Model-4
Constants of Linear Eqn	0.555	0.682		0.463	0.503	
Constants of Model-4 (Slope / Y-Intercept)			0.121 / 6.539			0.007 / 9.316
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	2.089		3.613	3.326	
Slope Difference (%)	23			9		
Total Data Set	338			22		
Total Mean Data Set	9			5		
Standard Error	2.31	1.81	1.16	3.22	3.14	2.28
Amount of Data Set Over Predicted	1	4	5	1	2	3
Percentage of Data Set Over Predicted (%)	11	44	56	20	40	60

Table 5.9 Statistical Analysis Summary –Beaumont CH&CL Soil (Depth n ft.)

		Beaumont CH Soil												**Beaumont CL Soil**					
Depth		*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*60*	*65*	*5*	*20*	*25*	*35*	*40*	*45*
N_{TCP}	Range	3-9	4-11	4-20	9-62	7-16	7-17	7-13	11-23	6-18	21	32	27	7	12-48	5-37	10-20	17	39
	Mean	5	7	10	17	10	11	11	15	11	21	31	27	7	30	14	14	17	39
	Standard Deviation	1	2	3	13	3	2	2	4	6	0	0	0	0	15	16	5	0	0
	Var	2	3	9	178	12	4	5	19	36	0	0	0	0	232	246	30	0	0
	COV (%)	29	22	29	78	35	18	20	29	55	0	0	0	0	50	116	39	0	0
	Number of Data	116	71	62	25	23	16	6	15	4	1	1	1	2	9	4	5	2	4
	PDF	LN	N	LN	LN	LN	N	N	W	LN					LN	W	LN		U
S_u	Range	2-20	2-15	1-16	3-16	3-16	5-14	1-8	3-16	4-14	13	34	21	6.8-7.1	9-15	10-16	5-10	7-10	3-7
	Mean	7	6	8	10	9	8	6	9	7	13	34	21	7	12	12	7	9	5
	Standard Deviation	4	2	3	3	3	3	3	4	4	0	0	0	0	3	3	2	2	2
	Var	13	6	10	11	8	10	8	15	19	0	0	0	0	11	7	4	5	4
	COV (%)	51	40	41	34	30	39	49	41	59	0	0	0	3	27	22	29	27	44
	Number of Data	116	71	62	25	23	16	6	15	4	1	1	1	2	9	4	5	2	4
	PDF	LN	N	W	W	N	LN	N	LN	W					U	W	U		U

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

5.7 Local Data Analysis for Dallas-Fort Worth District

The mean, two standard deviation values and standard error of the mean of the N_{TCP} and S_u for the Dallas-Fort Worth CH and CL soils were determined and plotted against the depth in Figures 5.18 and 5.20. When compared with other locations, $\bar{S}_u$ showed greater dependence on depth than $\bar{N}_{TCP}$ by contraries.

Also, new arranged relationships between mean of N_{TCP} and mean of S_u at 5 ft. interval depth selected are presented in Figures 5.19 and 5.21 for the Dallas-Fort Worth CH and CL soils. The new relationships between $\bar{N}_{TCP}$ and $\bar{S}_u$ are compared with three Models (Model-1, Model-2 and Model-4).

Total number of data sets used for N_{TCP} and S_u, and all statistical analysis results are summarized in Table 5.11. Additionally, all three Model parameters are summarized in Table 5.10. Depth analyses were done at 5 ft intervals.

5.7.1 CH Soil

Since only a total of 9 data sets were available, the analysis was limited. In this analysis, statistical analysis results for 5 to 10 ft depth were used to interpret. Therefore, it is difficult to develop an accurate Model-4 for the Dallas and Fort Worth districts CH soils.

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum S_u varied from 13 to 16 psi. The maximum S_u varied from 25 to 50 psi. As shown in Figure 5.18, mean S_u ($\bar{S}_u$) varied from 17 to 40 psi and increased with depth (5 ft to 10 ft (a>0)). The COV varied from 27 % to 40 %.. The relationship is as follows:

$$\bar{S}_u = 3.859 \cdot Z \qquad \text{-----------------------------------(5.35)}$$

Mean TCP Blow Count ($\bar{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 11 to 14 with depth. The maximum N_{TCP} fluctuated from 41 to 58. As shown in Figure 5.18, mean N_{TCP} ($\bar{N}_{TCP}$) varied from 18 to 31 and increased with depth (5 ft to 10 ft (a>0)). The COV varied from 63 % to 70 %. The relationship is as follows:

$$\bar{N}_{TCP} = 2.460 \cdot Z + 5.900 \qquad \text{-----------------------------------(5.36)}$$

The trends showed that CH soils in Dallas-Fort Worth can be represented by CASE 4.

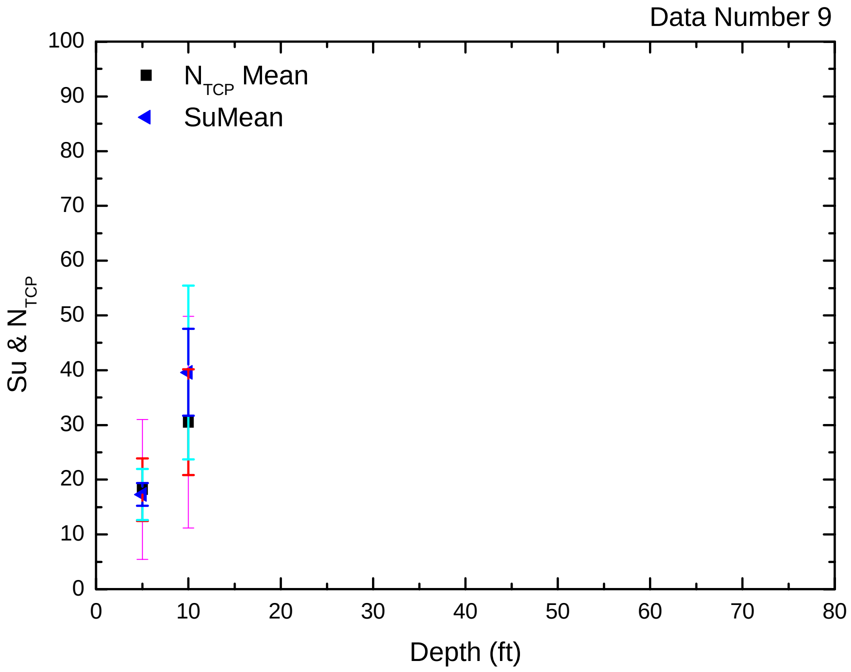


Figure 5.18 Variation of the $\bar{N}_{TCP}$ and $\bar{S}_u$ with Depth for the Dallas & Fort Worth CH Soil

Mean Strength ($\overline{S}_u$) vs. Mean TCP Blow Count ($\overline{N}_{TCP}$)

A total of 2 mean data sets (Depth from 5 ft to 10 ft) were used to investigate the $\overline{S}_u$ versus $\overline{N}_{TCP}$ relationship shown in Figure 5.19. Current TxDOT relationship (Model-1) over predicted 0 % of the mean strength data, and had the highest standard error of 16.80 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\overline{S}_u = 1.207 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP} \ psi = \frac{\overline{N}_{TCP}}{12} \ tsf \qquad \text{----------------------------(5.37)}$$

Where, $N_c = 1.180$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 117 % higher than the current TxDOT relationship. Model-2 over predicted 50 % of the mean data, and had a standard error of 3.86.

Model-4 relationship for the data is as follows:

$$\overline{S}_u = 1.569 \cdot \overline{N}_{TCP} - 9.255 \ psi = 0.113 \cdot \overline{N}_{TCP} - 0.666 \ tsf \ \text{--------------------------(5.38)}$$

Model-4 over predicted 50 % of the mean data (percentage of data below the curve), and had the lowest standard error of 1.59.

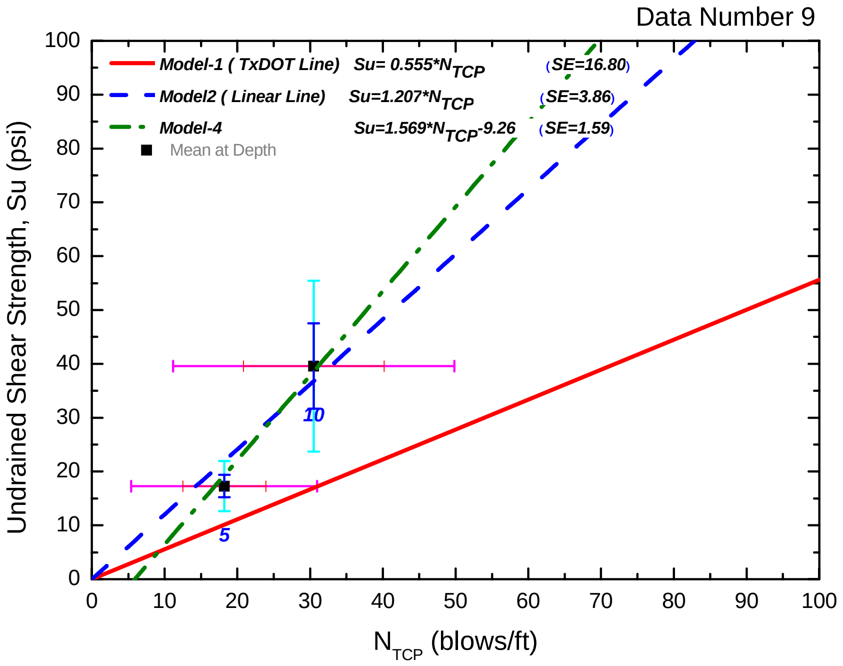


Figure 5.19 Relationship between Mean N_{TCP} and Mean S_u for the Dallas & Fort Worth CH Soils

5.7.2 CL Soil

Mean Strength ($\bar{S}_u$) vs. Depth

The minimum S_u varied from 4 to 10 psi with depth. The maximum S_u fluctuated from 11 to 74 psi. As shown in Figure 5.20, mean S_u ($\bar{S}_u$) varied from 8 to 41 psi and increased with depth (5 ft to 40 ft (a>0)). The COV varied from 31 % to 98 %. The dominant PDFs were lognormal and Weibull distribution. The relationship is as follows:

$$\bar{S}_u = 0.613 \cdot Z + 9.594 \qquad \text{------------------------------------(5.39)}$$

Mean TCP Blow Count ($\overline{N}_{TCP}$) vs. Depth

The minimum N_{TCP} varied from 4 to 31 with depth. The maximum N_{TCP} fluctuated from 12 to 51. As shown in Figure 5.20, mean N_{TCP} ($\overline{N}_{TCP}$) varied from 12 to 31 and increased with depth (5 ft to 40 ft (a>0)). The COV varied from 0 % to 106 %. The dominant PDFs were uniform and Weibull distribution. The relationship is as follows:

$$\overline{N}_{TCP} = 0.150 \cdot Z + 15.286 \qquad \text{------------------------------------(5.40)}$$

The trends showed that CL soils in Dallas-Fort Worth can be represented by CASE 4.

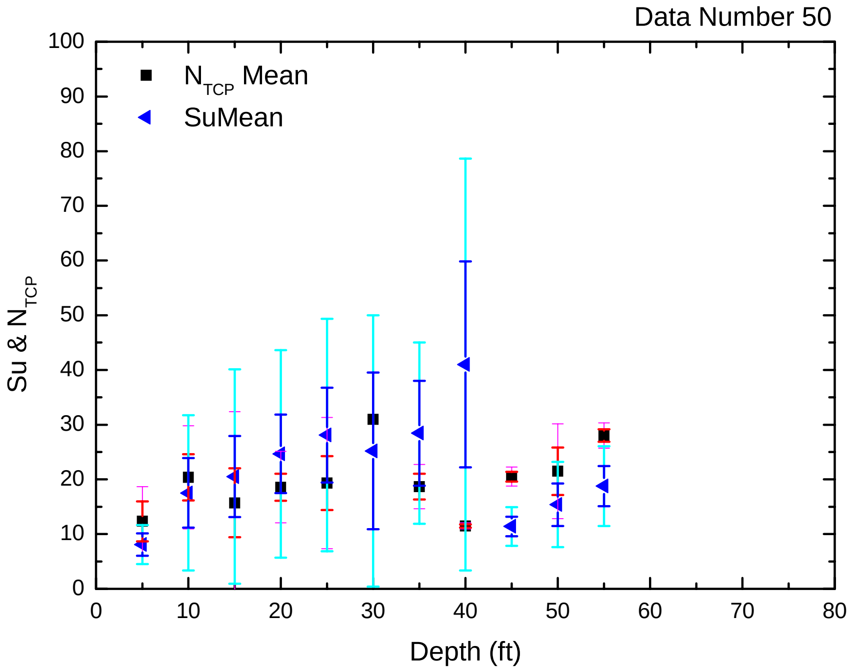


Figure 5.20 Variation of the $\overline{N}_{TCP}$ and $\overline{S}_u$ with Depth for the Dallas & Fort Worth CL Soil

Mean Strength ($\overline{S}_u$) vs. Mean TCP Blow Count ($\overline{N}_{TCP}$)

A total of 11 mean data sets (Depth from 5 ft to 55 ft) were used to investigate the $\overline{S}_u$ versus $\overline{N}_{TCP}$ relationship shown in Figure 5.21. Current TxDOT relationship (Model-1) over predicted 0 % of the mean strength data, and had the highest standard error of 15.72 compared to Model-2 and Model-4.

Model-2 relationship (least square fit for linear relationship) for this set of data is as follows:

$$\overline{S}_u = 1.003 \cdot \overline{N}_{TCP} = \frac{1.673}{N_c} \overline{N}_{TCP}\ psi = \frac{\overline{N}_{TCP}}{14}\ tsf \qquad \text{---------------------------}(5.41)$$

Where, $N_c = 1.668$.

Hence the slope ($\frac{\beta}{N_c}$) of the relationship was 117 % higher than the current TxDOT relationship. Model-2 over predicted 55 % of the data, and had a standard error of 11.15.

Model-4 relationship for the data is as follows:

$$\overline{S}_u = 0.613 \cdot \overline{N}_{TCP} + 9.594\ psi = 0.044 \cdot \overline{N}_{TCP} + 0.691\ tsf \text{ --------------------------}(5.42)$$

Model-4 over predicted 55 % of the mean data (percentage of data below the curve), and had the lowest standard error of 9.802.

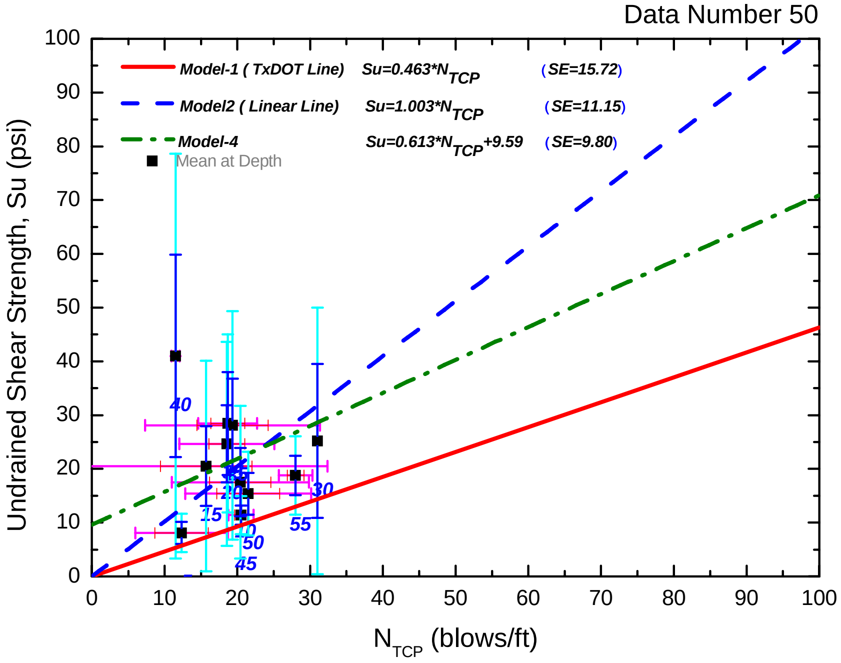
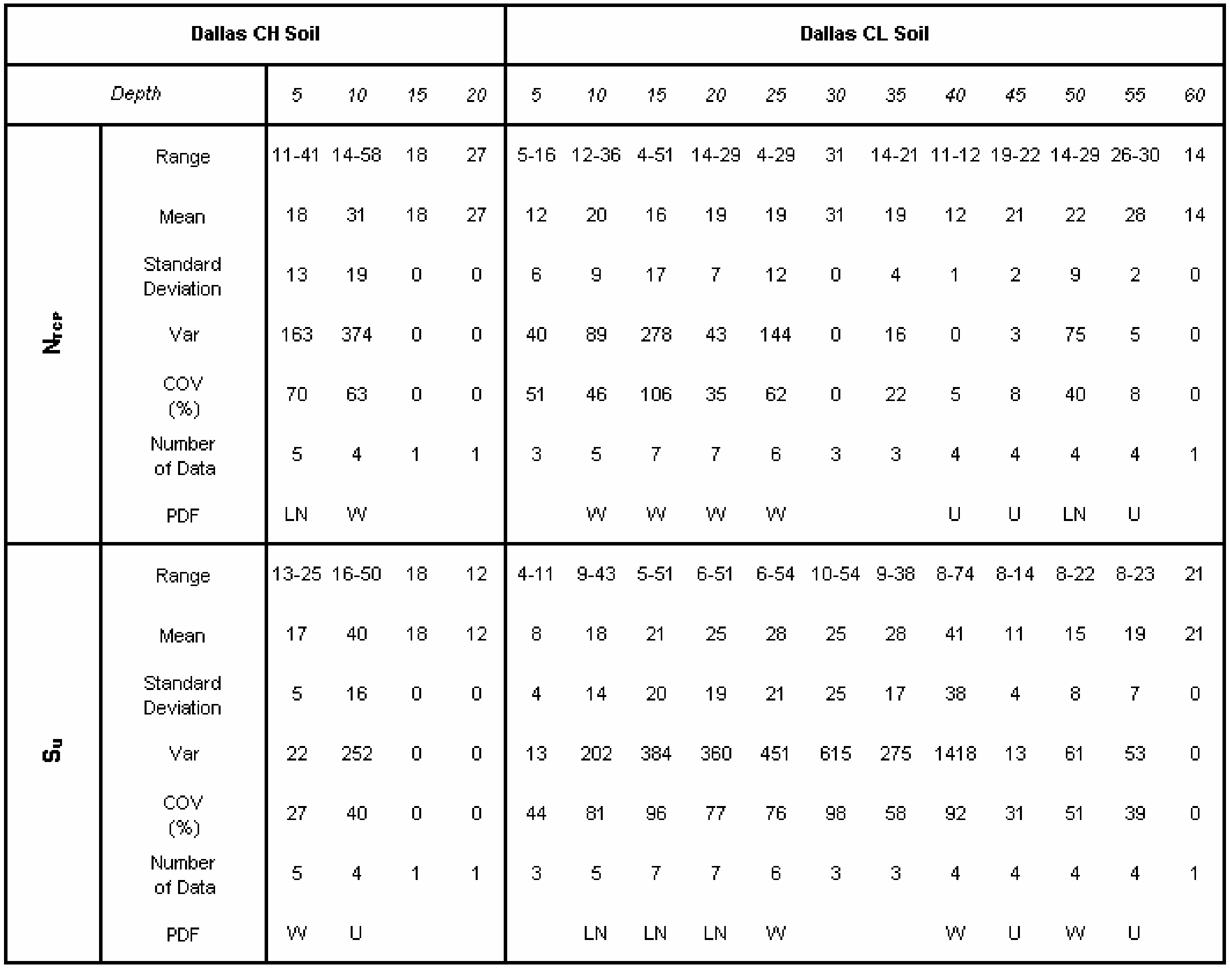


Figure 5.21 Relationship between Mean N_{TCP} and Mean s_u for the Dallas & Fort Worth CL Soils

Table 5.10 Model Comparisons for Dallas & Fort Worth Soil Data

	CH Soil			CL Soil		
	Model-1	Model-2	Model-4	Model-1	Model-2	Model-4
Constants of Linear Eqn	0.555	1.207		0.463	1.003	
Constants of Model-4 (Slope / Y-Intercept)			1.569 / -9.255			0.613 / 9.594
β for Model-2	1.425			1.673		
Nc for Model-1 & 2	2.567	1.180		3.613	1.668	
Slope Difference (%)	117			117		
Total Data Set	9			50		
Total Mean Data Set	2			11		
Standard Error	16.80	3.86	1.59	15.72	11.15	9.802
Amount of Data Set Over Predicted	0	1	1	0	6	6
Percentage of Data Set Over Predicted (%)	0	50	50	0	55	55

Table 5.11 Statistical Analysis Summary –Dallas-Fort Worth CH&CL Soil (Depth in ft.)



		Dallas CH Soil				**Dallas CL Soil**											
Depth		*5*	*10*	*15*	*20*	*5*	*10*	*15*	*20*	*25*	*30*	*35*	*40*	*45*	*50*	*55*	*60*
N_{TCP}	Range	11-41	14-58	18	27	5-16	12-36	4-51	14-29	4-29	31	14-21	11-12	19-22	14-29	26-30	14
	Mean	18	31	18	27	12	20	16	19	19	31	19	12	21	22	28	14
	Standard Deviation	13	19	0	0	6	9	17	7	12	0	4	1	2	9	2	0
	Var	163	374	0	0	40	89	278	43	144	0	16	0	3	75	5	0
	COV (%)	70	63	0	0	51	46	106	35	62	0	22	5	8	40	8	0
	Number of Data	5	4	1	1	3	5	7	7	6	3	3	4	4	4	4	1
	PDF	LN	W				W	W	W	W			U	U	LN	U	
S_u	Range	13-25	16-50	18	12	4-11	9-43	5-51	6-51	6-54	10-54	9-38	8-74	8-14	8-22	8-23	21
	Mean	17	40	18	12	8	18	21	25	28	25	28	41	11	15	19	21
	Standard Deviation	5	16	0	0	4	14	20	19	21	25	17	38	4	8	7	0
	Var	22	252	0	0	13	202	384	360	451	615	275	1418	13	61	53	0
	COV (%)	27	40	0	0	44	81	96	77	76	98	58	92	31	51	39	0
	Number of Data	5	4	1	1	3	5	7	7	6	3	3	4	4	4	4	1
	PDF	W	U				LN	LN	LN	W			W	U	W	U	

*** LN - Lognormal; N - Normal; U - Uniform; W - Weibull**

5.8 Summary

Based on the data collected, the influence of depth (Z) on the mean undrained shear strength ($\bar{S}_u$) and mean TCP blow count ($\bar{N}_{TCP}$) was investigated. The depth affected the N_{TCP} in all the types of soils. CL soils showed the least dependence on depth of the soils investigated.

Based on standard error, Model-4 better predicted the mean undrained shear strength ($\bar{S}_u$) from mean TCP blow count ($\bar{N}_{TCP}$) than Model-1 (TxDOT design relationship) and Model-2.

Based on the depth effect analyses, the following can be concluded.

1. **CH Soils:**

The mean undrained shear strength ($\bar{S}_u$) and mean TCP blow count ($\bar{N}_{TCP}$) increased with depth. $\bar{N}_{TCP}$ showed greater dependency on depth than strength. Model study results are as follows:

Model-4 (Components) :			
Location	Mean S_u (psi)	Mean N_{TCP}	CASES
Texas	$\bar{S}_u = 0.112 \cdot Z + 9.586$	$\bar{N}_{TCP} = 0.527 \cdot Z + 15.888$	CASE 4
Houston District	$\bar{S}_u = 0.089 \cdot Z + 10.813$	$\bar{N}_{TCP} = 0.462 \cdot Z + 20.411$	CASE 4
Beaumont District	$\bar{S}_u = 0.017 \cdot Z + 7.422$	$\bar{N}_{TCP} = 0.141 \cdot Z + 7.327$	CASE 2
Dallas and Fort Worth Districts	$\bar{S}_u = 3.859 \cdot Z$	$\bar{N}_{TCP} = 2.460 \cdot Z + 5.900$	CASE 4
Model-4 (Summary):			
Texas	$\bar{S}_u = 0.212 \cdot \bar{N}_{TCP} + 6.219\ psi = 0.015 \cdot \bar{N}_{TCP} + 0.448\ tsf$		

Houston District	$\overline{S}_u = 0.193 \cdot \overline{N}_{TCP} + 6.881\ psi = 0.014 \cdot \overline{N}_{TCP} + 0.495\ tsf$
Beaumont District	$\overline{S}_u = 0.121 \cdot \overline{N}_{TCP} + 6.539\ psi = 0.009 \cdot \overline{N}_{TCP} + 0.471\ tsf$
Dallas-Fort Worth Districts	$\overline{S}_u = 1.569 \cdot \overline{N}_{TCP} - 9.255\ psi = 0.113 \cdot \overline{N}_{TCP} - 0.666\ tsf$

Model-2 :		
Texas	$\overline{S}_u = 0.363 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP}\ psi = \frac{\overline{N}_{TCP}}{38}\ tsf$	Where, $N_c = 3.924$
Houston District	$\overline{S}_u = 0.356 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP}\ psi = \frac{\overline{N}_{TCP}}{39}\ tsf$	Where, $N_c = 4.001$
Beaumont District	$\overline{S}_u = 0.682 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP}\ psi = \frac{\overline{N}_{TCP}}{20}\ tsf$	Where, $N_c = 2.089$
Dallas-Fort Worth Districts	$\overline{S}_u = 1.207 \cdot \overline{N}_{TCP} = \frac{1.425}{N_c} \overline{N}_{TCP}\ psi = \frac{\overline{N}_{TCP}}{12}\ tsf$	Where**,** $N_c = 1.180$

2. **CL Soils:**

The mean undrained shear strength ($\overline{S}_u$) was independent with depth but mean TCP blow count ($\overline{N}_{TCP}$) increased with depth. $\overline{N}_{TCP}$ showed greater dependency on depth than strength. Model study results are as follows:

Model-4 (Components) :			
Location	Mean S_u	Mean N_{TCP}	CASES
Texas	$\overline{S}_u = 0.001 \cdot Z + 15.383$	$\overline{N}_{TCP} = 0.344 \cdot Z + 28.687$	CASE 2
Houston District	$\overline{S}_u = 0.004 \cdot Z + 15.219$	$\overline{N}_{TCP} = 0.344 \cdot Z + 29.750$	CASE 2
Beaumont District	$\overline{S}_u = 0.001 \cdot Z + 9.410$	$\overline{N}_{TCP} = 0.138 \cdot Z + 12.922$	CASE 2
Dallas-Fort Worth Districts	$\overline{S}_u = 0.613 \cdot Z + 9.594$	$\overline{N}_{TCP} = 0.150 \cdot Z + 15.286$	CASE 4

Model-4 (Summary):	
Texas	$\bar{S}_u = 0.001 \cdot \bar{N}_{TCP} + 15.342\ psi = 0.0001 \cdot \bar{N}_{TCP} + 1.105\ tsf$
Houston District	$\bar{S}_u = 0.012 \cdot \bar{N}_{TCP} + 14.873\ psi = 0.0009 \cdot \bar{N}_{TCP} + 1.071\ tsf$
Beaumont District	$\bar{S}_u = 0.007 \cdot \bar{N}_{TCP} + 9.316\ psi = 0.0005 \cdot \bar{N}_{TCP} + 0.671\ tsf$
Dallas-Fort Worth Districts	$\bar{S}_u = 0.613 \cdot \bar{N}_{TCP} + 9.594\ psi = 0.044 \cdot \bar{N}_{TCP} + 0.691\ tsf$

Model-2 :		
Texas	$\bar{S}_u = 0.358 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{39}\ tsf$	Where, $N_c = 4.673$
Houston District	$\bar{S}_u = 0.350 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{40}\ tsf$	Where, $N_c = 4.780$
Beaumont District	$\bar{S}_u = 0.503 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{28}\ tsf$	Where, $N_c = 3.326$
Dallas-Fort Worth Districts	$\bar{S}_u = 1.003 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{14}\ tsf$	Where**,** $N_c = 1.668$

3. SC Soils:

Although mean TCP blow count ($\bar{N}_{TCP}$) increased with depth, there was no clear trend with depth for the mean undrained shear strength ($\bar{S}_u$). Model study results are as follows:

Model-4 (Components) :			
Location	Mean S_u (psi)	Mean N_{TCP}	CASES
Texas	$\bar{S}_u = -0.232 \cdot Z + 13.760$	$\bar{N}_{TCP} = 0.259 \cdot Z + 21.195$	CASE 9
Model-2 :			
Texas	$\bar{S}_u = 0.411 \cdot \bar{N}_{TCP} = \frac{1.704}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{34}\ tsf$		Where, $N_c = 4.146$

4. OTHER Soils:

The mean undrained shear strength ($\bar{S}_u$) decreased with depth but mean TCP blow count ($\bar{N}_{TCP}$) increased with depth. $\bar{N}_{TCP}$ showed greater dependency on depth than strength. Model study results are as follows:

Model-4 (Components) :			
Location	Mean S_u (psi)	Mean N_{TCP}	CASES
Texas	$\bar{S}_u = -0.044 \cdot Z + 17.930$	$\bar{N}_{TCP} = 0.762 \cdot Z + 29.362$	CASE 9
Model-2 :			
Texas	$\bar{S}_u = 0.343 \cdot \bar{N}_{TCP} = \frac{1.493}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{40}\ tsf$		Where, $N_c = 4.353$

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The main focus of this study was to verify the current design relationship used by TxDOT to determine the undrained shear strength of soil from TCP blow count and to develop correlations based on the data collected by TxDOT. The data for this study were collected from Houston, Beaumont, Dallas and Waco Districts and hence the findings of this study will be directly applicable to these TxDOT districts.

The data were collected from TxDOT projects over the past decade (1994 - 2004) and analyzed. Over 4000 sets of data were collected on CH, CL, SC and Other soils and used.

Based on the analyses, the following can be concluded:

1. **CH Soil**

   Based on the 2100 data set, the undrained shear strength (S_u) varied from 0.45 to 88.75 psi with a mean of 16.8 psi. The COV was 67%, which was the highest for the soils investigated in this study. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 2 to 100 with a mean of 31. The COV was 70%, which was the highest for the soils investigated in this study. The PDF for the TCP blow count (N_{TCP}) was lognormal.

   Based on the analyses of raw data and average values, the following relationships were developed for CH Soils in Texas.

Linear Relationships (Model-2 & Model-4)

(a) Least square fit of the data resulted in the following relationship (Note that the current TxDOT relationship is $S_u = \frac{N_{TCP}}{25}\ tsf$.) (Chapter 3).

$$S_u = 0.331 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{42} tsf \qquad \text{Where, } N_c = 4.305$$

(b) Considering the average strength ($\bar{S}_u$) for each blow count (N_{TCP}), the following relationship was developed (Chapter 4).

$$\bar{S}_u = 0.25 \cdot N_{TCP} = \frac{1.425}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{55} tsf \qquad \text{Where, } N_c = 5.698$$

(c) Taking the depth effect into account with the least square fit through the origin, the following relationship was developed (Chapter 5).

$$\bar{S}_u = 0.363 \cdot \bar{N}_{TCP} = \frac{1.425}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{38}\ tsf \qquad \text{Where, } N_c = 3.924$$

(d) Taking the depth effect into account, the following relationship was developed (Chapter 5).

$$\bar{S}_u = 0.212 \cdot \bar{N}_{TCP} + 6.219\ psi = 0.015 \cdot \bar{N}_{TCP} + 0.448\ tsf$$

Nonlinear Relationships (Model-3)

(e) Nonlinear least square fit of the data resulted in the following relationship (Chapter 3).

$$S_u = 4.041 \cdot (N_{TCP})^{0.355}\ psi = 0.291 \cdot (N_{TCP})^{0.355}\ tsf$$

(f) Considering the average strength ($\bar{S}_u$) for each blow count (N_{TCP}), the following relationship was observed (Chapter 4).

$$\bar{S}_u = 4.84 \cdot (N_{TCP})^{0.3}\ psi \quad = \quad 0.35 \cdot (N_{TCP})^{0.3}\ tsf$$

2. CL Soil

Based on the 1852 data set, the undrained shear strength (S_u) varied from 0.96 to 114.6 psi with a mean of 12.9 psi. The COV was 54%, which was the lowest for the soils investigated in this study. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 2 to 100 with a mean of 35. The COV was 58%. The PDF for the TCP blow count (N_{TCP}) was lognormal.

Based on the analyses of raw data and average values, the following relationships were developed for CL Soils in Texas.

Linear Relationships (Model-2 & Model-4)

(a) Least square fit of the data resulted in the following relationship (Note that the current TxDOT relationship is $S_u = \frac{N_{TCP}}{30}\ tsf$.) (Chapter 3).

$$S_u = 0.386 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{36} tsf \qquad \text{Where, } N_c = 4.333$$

(b) Considering the average strength ($\bar{S}_u$) for each blow count (N_{TCP}), the following relationship was developed (Chapter 4).

$$\bar{S}_u = 0.31 \cdot N_{TCP} = \frac{1.673}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{45} tsf \qquad \text{Where, } N_c = 5.355$$

(c) Taking the depth effect into account with the least square fit through the origin, the following relationship was developed (Chapter 5).

$$\bar{S}_u = 0.358 \cdot \bar{N}_{TCP} = \frac{1.673}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{39}\ tsf \qquad \text{Where, } N_c = 4.673$$

(d) Taking the depth effect into account, the following relationship was developed (Chapter 5).

$$\overline{S}_u = 0.001 \cdot \overline{N}_{TCP} + 15.342 \ psi = 0.0001 \cdot \overline{N}_{TCP} + 1.105 \ tsf$$

Nonlinear Relationships (Model-3)

(e) Nonlinear least square fit of the data resulted in the following relationship (Chapter 3).

$$S_u = 8.162 \cdot (N_{TCP})^{0.213} \ psi = 0.588 \cdot (N_{TCP})^{0.213} \ tsf$$

(f) Considering the average strength ($\overline{S}_u$) for each blow count (N_{TCP}), the following relationship was observed (Chapter 4).

$$\overline{S}_u = 6.51 \cdot (N_{TCP})^{0.28} \ psi = 0.47 \cdot (N_{TCP})^{0.28} \ tsf$$

3. SC Soil

Based on the 29 data set, the undrained shear strength (S_u) varied from 3.5 to 38.55 psi with a mean of 10.8 psi. The COV was 60%. The PDF for the undrained shear strength (S_u) was lognormal. The TCP blow count (N_{TCP}) varied from 7 to 87 with a mean of 30. The COV was 66%. The PDF for the TCP blow count (N_{TCP}) was Weibull.

Based on the analyses of raw data and average values, the following relationships were developed for SC Soils in Texas.

Linear Relationships (Model-2 & Model-4)

(a) Least square fit of the data resulted in the following relationship (Note that the current TxDOT relationship is $S_u = \frac{N_{TCP}}{35}\ tsf$.) (Chapter 3).

$$S_u = 0.252 \cdot N_{TCP} = \frac{1.704}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{55} tsf \qquad \text{Where, } N_c = 6.762$$

(b) Considering the average strength ($\bar{S}_u$) for each blow count (N_{TCP}), the following relationship was developed (Chapter 4).

$$\bar{S}_u = 0.22 \cdot N_{TCP} = \frac{1.704}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{63} tsf \qquad \text{Where, } N_c = 5.355$$

(c) Taking the depth effect into account with the least square fit through the origin, the following relationship was developed (Chapter 5).

$$\bar{S}_u = 0.411 \cdot \bar{N}_{TCP} = \frac{1.704}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{34}\ tsf \qquad \text{Where, } N_c = 4.146$$

Nonlinear Relationships (Model-3)

(d) Nonlinear least square fit of the data resulted in the following relationship (Chapter 3).

$$S_u = 9.048 \cdot (N_{TCP})^{0.055}\ psi = 0.652 \cdot (N_{TCP})^{0.055}\ tsf$$

(e) Considering the average strength ($\bar{S}_u$) for each blow count (N_{TCP}), the following relationship was observed (Chapter 4).

$$\bar{S}_u = 5.23 \cdot (N_{TCP})^{0.23}\ psi = 0.38 \cdot (N_{TCP})^{0.23}\ tsf$$

4. Other Soil

Based on the 42 data set, the undrained shear strength (S_u) varied from 1.4 to 69.3 psi with a mean of 16.8 psi. The COV was 66%. The PDF for the undrained shear strength (S_u) was Weibull. The TCP blow count (N_{TCP}) varied from 10 to 93 with a mean of 45. The COV was 45%, which was the lowest for the soils investigated in this study. The PDF for the TCP blow count (N_{TCP}) was normal.

Based on the analyses of raw data and average values, the following relationships were developed for Other Soils in Texas.

Linear Relationships (Model-2 & Model-4)

(a) Least square fit of the data resulted in the following relationship (Note that the current TxDOT relationship is $S_u = \frac{N_{TCP}}{40}\ tsf$.) (Chapter 3).

$$S_u = 0.308 \cdot N_{TCP} = \frac{1.493}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{45} tsf \qquad \text{Where, } N_c = 4.847$$

(b) Considering the average strength ($\bar{S}_u$) for each blow count (N_{TCP}), the following relationship was developed (Chapter 4).

$$\bar{S}_u = 0.30 \cdot N_{TCP} = \frac{1.493}{N_c} N_{TCP}\ psi = \frac{N_{TCP}}{46} tsf \qquad \text{Where, } N_c = 4.928$$

(c) Taking the depth effect into account with the least square fit through the origin, the following relationship was developed (Chapter 5).

$$\bar{S}_u = 0.343 \cdot \bar{N}_{TCP} = \frac{1.493}{N_c} \bar{N}_{TCP}\ psi = \frac{\bar{N}_{TCP}}{40}\ tsf \qquad \text{Where, } N_c = 4.353$$

5. Analyses showed that the TCP blow count (N_{TCP}) was dependent on the depth for all the types of soils investigated. The depth dependency also varied from location to location.
6. The undrained shear strength versus TCP blow count relationships developed were also influenced by the locations.

6.2 Recommendations

1. Depth effect on TCP blow count must be considered in future studies on improving the design correlations used by TxDOT.
2. Consider modifying TCP test procedure to better correlate the undrained shear strength to TCP blow count.
3. Linear and nonlinear relationships developed in this study must be further verified with additional data and control studies.

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