

Relating Undrained Shear Strength of Clay with Blow-Count of Texas Cone Penetrometer

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ABSTRACT

Accurate undrained shear strength values of soils are vital to the successful design of geotechnical structures. Currently, the Texas Cone Penetrometer (TCP) test is the primary means for in-situ determination of undrained shear strength of cohesive soils by the Texas Department of Transportation (TxDOT). Graphs and equations relating undrained shear strength and blow-count of TCP have been developed by TxDOT for practical applications. However, it has been found that the available relations may not be able to provide accurate shear strength values for some soil and field conditions. This study attempts to improve the available relations between undrained shear strength and TCP blow-count for cohesive soils.

In this study, a database was created based on the field and laboratory test data collected by TxDOT from various places in southeast Texas sites in the past 11 years. This database together with the bearing capacity principle was used to develop relations between undrained shear strength and TCP blow-count. The effectiveness of the new relations was demonstrated by comparing with the existing TxDOT Design equations.

KEYWORDS: Texas Cone Penetrometer, Penetration Test, Blow Count, Correlation, Undrained Shear Strength, Undrained Cohesion, CH (Clay with High Plasticity), CL (Clay with Low Plasticity)

INTRODUCTION

The Texas Cone Penetrometer (TCP) is the primary device used by the Texas Department of Transportation (TxDOT) for determination of in-situ undrained shear strength of cohesive soils. The device is composed of a conical driving point having 78 ± 1 mm ($3.0 \pm 1/16$ inches) in diameter with an apex angle of 60° as illustrated in Fig. 1. The TCP test procedures resemble that of the Standard Penetration Test (SPT) utilizing a drop hammer to drive the cone into the ground. The drop weight is 77.11 kg (170 lb) and the drop height is 60.69 cm (24 in). The blow-counts (N_{TCP}) required for 30.48 cm (12 in) penetration is recorded for determination of the undrained shear strength of the soil at the test site. According to Texas Department of Transportation Design Manual (2006), the TCP tests should be performed at 1.574 m to 3.048 m (5 ft to 10 ft) intervals for depicting subsurface soil strata variation.

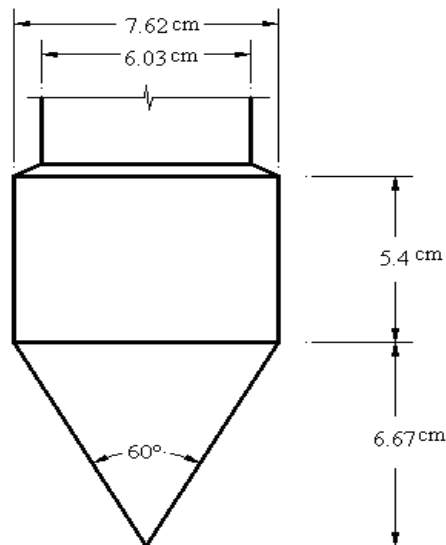


Figure 1: Texas cone Penetrometer (after, 2000 TxDOT Geotechnical Manual Cone Tip)

Although the TCP test procedures are similar to that of SPT, there is no soil samples recovered directly from the TCP tests. Soils samples are obtained from the bore holes using 7.62 cm (3 in) ID thin-wall tube samplers. The thin-wall tube samplers are pushed downward using hydraulic pressures to a distance of about 121.92 cm (48 in). After the tubes are extracted from the bore holes, the soil samples are extruded from the samplers, secured in containers, and then transferred to the laboratory for testing.

All TCP test data and laboratory test data collected by TxDOT from various places in southeast Texas sites were compiled. These data involved moisture content, liquid limit, plastic limit, unit weight, undrained shear strength, undrained cohesion, and blow-count at the test sites. The entire data set was carefully reviewed for their usefulness. All useless data were discarded. For examples, the data sets for the sites without records of cohesion or blow-count were deleted from the database. Also, any data sets without adequate liquid limit and plastic limit values were removed from the database, because both limits are needed for soil classification using the Unified Soil Classification System (USCS). The detailed information of the database has been presented by Palla [2008].

REGRESSION ANALYSIS OF DATABASE

The compiled database was analyzed using the statistical software “MINITAB”. The “BOX PLOT” utilizing the median method was adopted to eliminate the outliers and extremes in the database. As shown in *Fig 2*, the box plot contains Q1 (first quartile), Q3 (third quartile), and hinge spread (HS) (i.e., $Q3 - Q1$). Q1 and Q3 can be used to define the so-called inner fences, beyond which the data would be labeled as outlier. By definition, left/lower extremes lie outside first quartile minus 3.0 times hinge spread (i.e., $< Q1 - 3.0 HS$) and right/upper extremes lie outside third quartile plus 3.0 times hinge spread (i.e., $> Q3 + 3.0 HS$). Meanwhile, left/lower outliers lie between left extreme and less than first quartile minus 1.5 times hinge spread (i.e., $< Q1 - 1.5 HS$) and right/upper outliers lie between right extreme and greater than third quartile plus 1.5 times hinge spread (i.e., $> Q3 + 1.5 HS$). After the outliers were removed, the remaining CL and CH soils data were used for subsequent analysis. *Fig 3* shows the flow chart of preliminary data analysis.

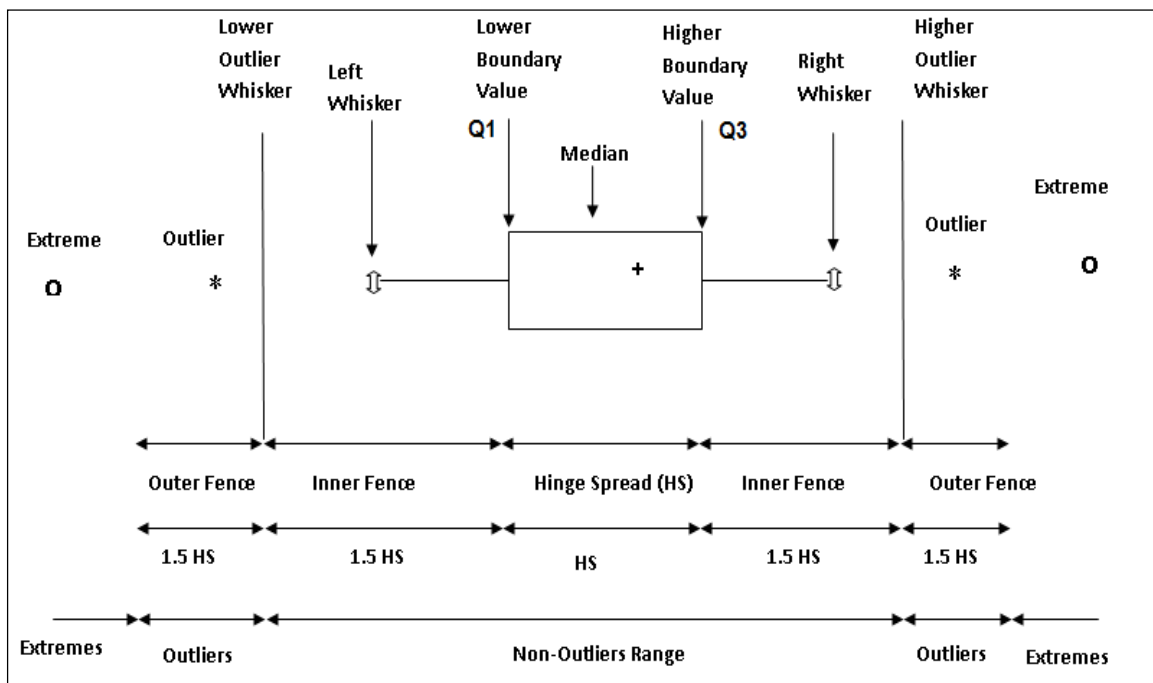


Figure 2: Analysis of Database using BOX-PLOT
(Revised after Wessa P., & Borghers E., 2006)

The data of undrained cohesion (c_u) and blow-count (N_{TCP}) in the database were divided into two groups -- CH soils and CL soils. Each group of data was subjected to statistical regression analysis to develop relation equations between c_u and N_{TCP} . *Fig 4* summarizes the graphical relations between c_u and N_{TCP} for CH soils. The relations for CL soils resemble that for CH soils, although the magnitude differs. Table 1 tabulates the resulting relation in equation form. Also shown in *Fig 4* are the 95% prediction intervals (PI) of the c_u values. Meanwhile, the current relations of TxDOT for CH soils without and with a factor of safety equal to 2.0 ($FS = 2.0$) are included for comparison.

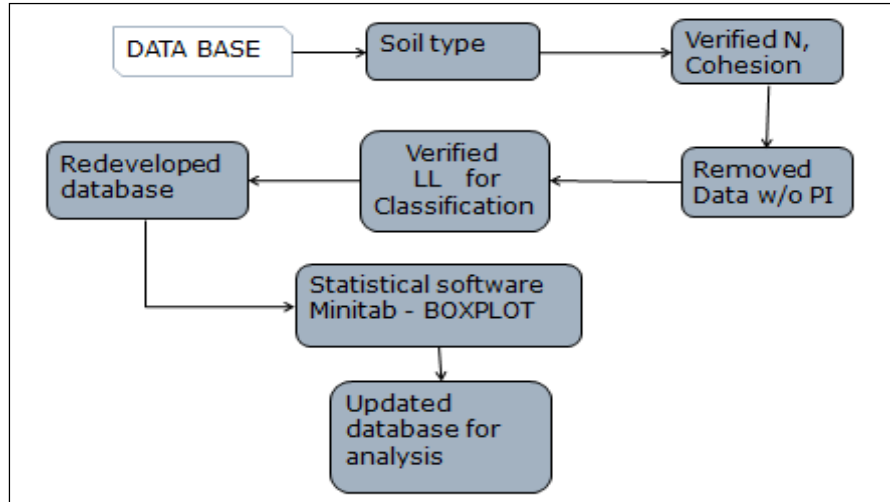


Figure 3: Flow-Chart for Database Analysis

Table 1 c_u vs. N_{TCP} Relation Equations for CH Soils

TxDOT Line	$c_u = 3.79N_{TCP}$ $c_u = 0.55N_{TCP}$	[kPa] [psi]	(a)
TxDOT Design Line	$c_u = 1.89N_{TCP}$ $c_u = 0.27N_{TCP}$	[kPa] [psi]	(b)
Upper bound Prediction Interval	$c_u = 5.012N_{TCP} + 52.055$ $c_u = 0.727N_{TCP} + 7.55$	[kPa] [psi]	(c)
Lower bound Prediction Interval	$c_u = 4.96N_{TCP} - 52.055$ $c_u = 0.719N_{TCP} - 7.55$	[kPa] [psi]	(d)
Developed c_u	$c_u = 4.98N_{TCP}$ $c_u = 0.723N_{TCP}$	[kPa] [psi]	(e)

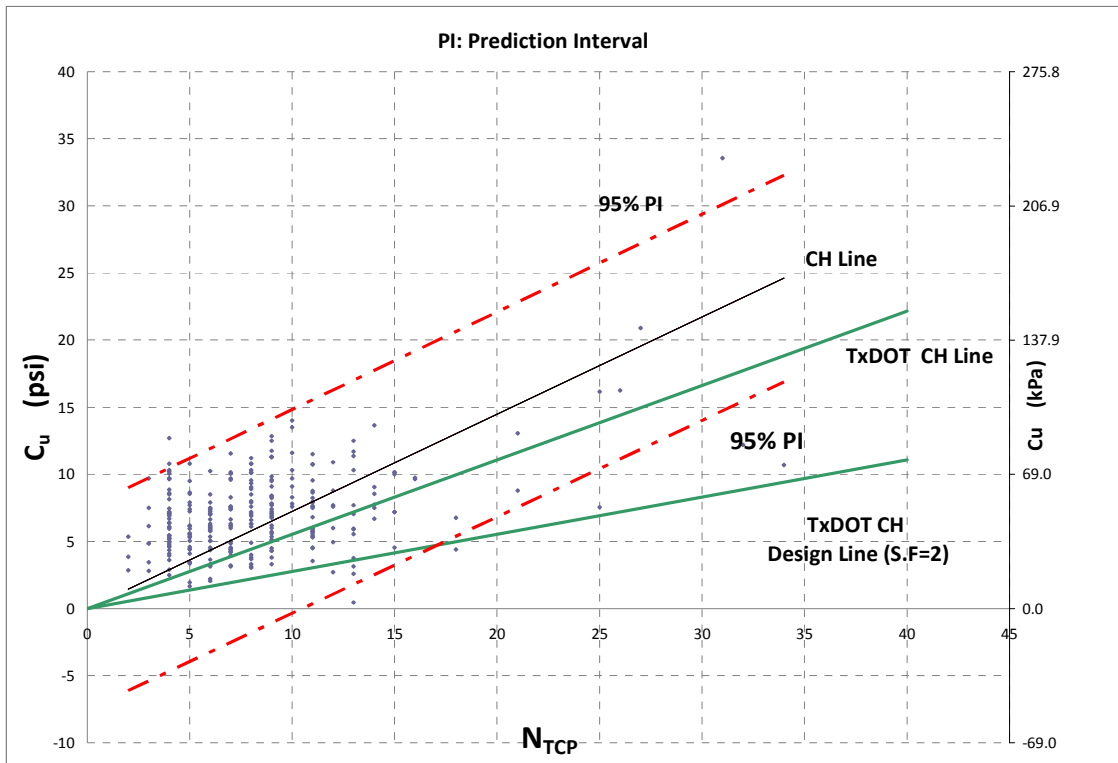


Figure 4: Graphical c_u vs. N_{TCP} Relations for CH Soils

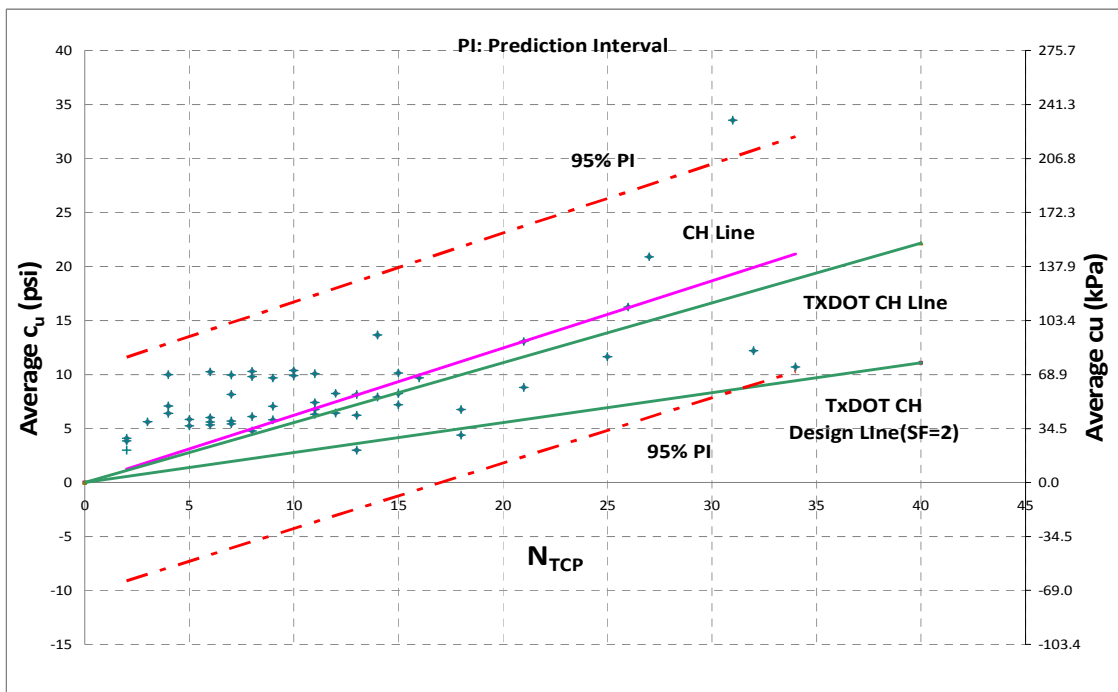


Figure 5: Graphical Average c_u vs. N_{TCP} Relations for CH Soils

Examination of the overall database shows a wide spread of both undrained cohesion and blow-count data. The cohesion data range between 3.1 and 231.32 kPa (0.45 and 33.55 psi) with a difference of 228.2 kPa (33.10 psi). The standard deviation of cohesion data was 22.27 kPa (3.23 psi) with a mean of 49.3 kPa (7.15 psi). The blow-count data range between 2 and 34 with a standard deviation of 4.74 and a mean of 8.43. The wide-spread undrained cohesion values were re-examined with respect to their associated blow-count data. The cohesion values of same blow-count are averaged and plotted against the blow-count in *Fig 5*. As shown, the relation between the average data sets is very close to TxDOT equation. The developed relationship is shown as expression (h) in Table 2.

Table 2: Average c_u vs. N_{TCP} Relations for CH Soils

Upper bound Prediction Interval	$c_u = 4.4N_{TCP} + 71.15$ [kPa] $c_u = 0.638N_{TCP} + 10.32$ [psi]	(f)
Lower bound Prediction Interval	$c_u = 4.17N_{TCP} - 71.15$ [kPa] $c_u = 0.605N_{TCP} - 10.32$ [psi]	(g)
Developed Average c_u	$c_u = 4.29 N_{TCP}$ [kPa] $c_u = 0.622N_{TCP}$ [psi]	(h)

The average cohesion data range between 20.68 and 231.32 kPa (3 and 33.55 psi) with a difference of 210.63 kPa (30.55 psi). The standard deviation of cohesion data was 33.502 kPa (4.86 psi) with a mean of 60.12 kPa (8.72 psi). The blow-count data range between 2 and 34 with a standard deviation of 7.87 and a mean of 12.18. It is seen that the great majority of data points are located above the TxDOT design line (FS = 2). In other words, the foundation design based on the current design line would be on the safe side. The 95% prediction intervals shown in *Figures 4* and *5* are fairly wide implying that some critical factors should be considered to improve the correlations. One factor considered in this study is the effect of depth.

DEVELOPMENT OF EQUATION BASED ON BEARING CAPACITY THEORY

The principle of bearing capacity theory is adopted to consider depth effect in correlating undrained cohesion (c_u) with blow-count (N_{TCP}). The following ultimate bearing capacity equation for deep foundations is used:

$$q_{ult} = c N_c + q N_q \dots \dots \dots (1)$$

in which, q_{ult} = the ultimate bearing capacity,

c = undrained cohesion (c_u)

q = effective vertical pressure = γh

h = depth to cone tip

$$N_q = 1$$

According to TxDOT's Geotechnical Manual (TxDOT-2006)

$$q_{ult} = 2 P_b = 2[NTCP/1.87] = NTCP/ 0.93 \text{ [MPa] for CH soils and}$$

$$(q_{ult} = 2 P_b = 2[NTCP/19.5] = NTCP/ 9.75 \text{ [tsf] for CH soils)}$$

$$q_{ult} = 2 P_b = 2[NTCP/1.59] = NTCP/ 0.79 \text{ [MPa] for CL soils}$$

$$(q_{ult} = 2 P_b = 2[NTCP/16.6] = NTCP/ 8.30 \text{ [tsf] for CL soils)}$$

and

in which, P_b = point bearing

Substituting these expressions into Equation (1) yields

$$NTCP/ 0.93 = c_u N_c + \gamma h \text{ for CH soils(2)}$$

$$NTCP/ 0.79 = c_u N_c + \gamma h \text{ for CL soils(3)}$$

and

$$N_c = ((1.07 NTCP) - (\gamma h))/ c_u \text{ [kPa] for CH soils ..(4)}$$

$$N_c = ((1.25 NTCP) - (\gamma h))/ c_u \text{ [kPa] for CL soils ..(5)}$$

Based on Equations (4) and (5), the average N_c values are plotted against depth (h) in Fig 6.

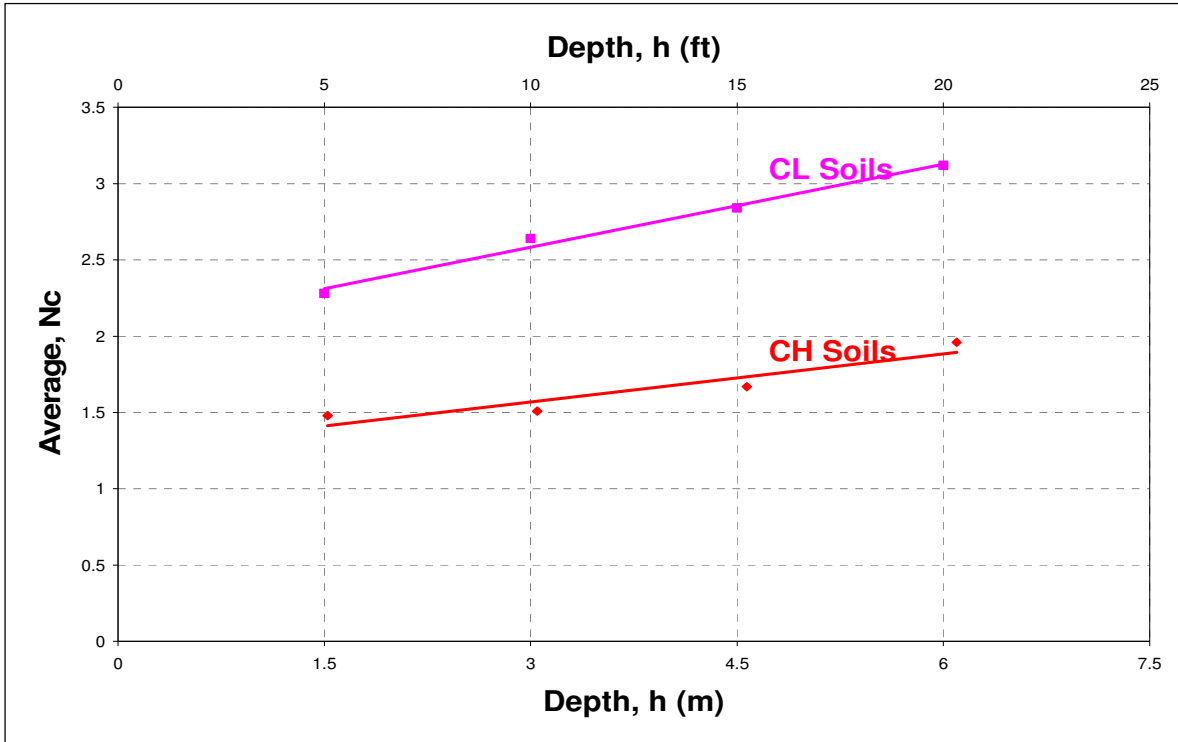


Figure 6: Variation of Average N_c with Depth

The corresponding relation equation for CH soils is

$$N_c = 0.032h + 1.254 \dots\dots\dots(6)$$

with $R^2 = 88.2\%$ and adjusted $R^2 = 82.3\%$.

and for CL soils is

$$N_c = 0.054h + 2.048 \dots\dots\dots(7)$$

with $R^2 = 98.8\%$ and adjusted $R^2 = 98.4\%$

The regression line for CH soils has standard error (ϵ) of 9.2% and the error of probability value (P-value) for slope and intercept is 6% and 0.8%, respectively. The regression line for CL soils has standard error (ϵ) of 5.3% and the error of probability value (P-value) for intercept and slope is 5.6% and 0.3%, respectively. According to Fig 6, within the conditions analyzed, the values of N_c increase almost linearly with depth. Within the range of depth investigated for CH and CL soils, N_c value increases approximately from 1.4 to 1.9 and 2.3 to 3.1, respectively.

DEPTH EFFECT

Both Equations (4) and (5) are used to plot the relationships between c_u and N_{TCP} for four different depths of 1.524 m, 3.048 m, 4.572 m and 6.096 m (5 ft, 10 ft, 15 ft, and 20 ft). Figures 7a and 7b show the developed relationships for CH soils and CL soils, respectively. The corresponding correlation equations are summarized in Table 3.

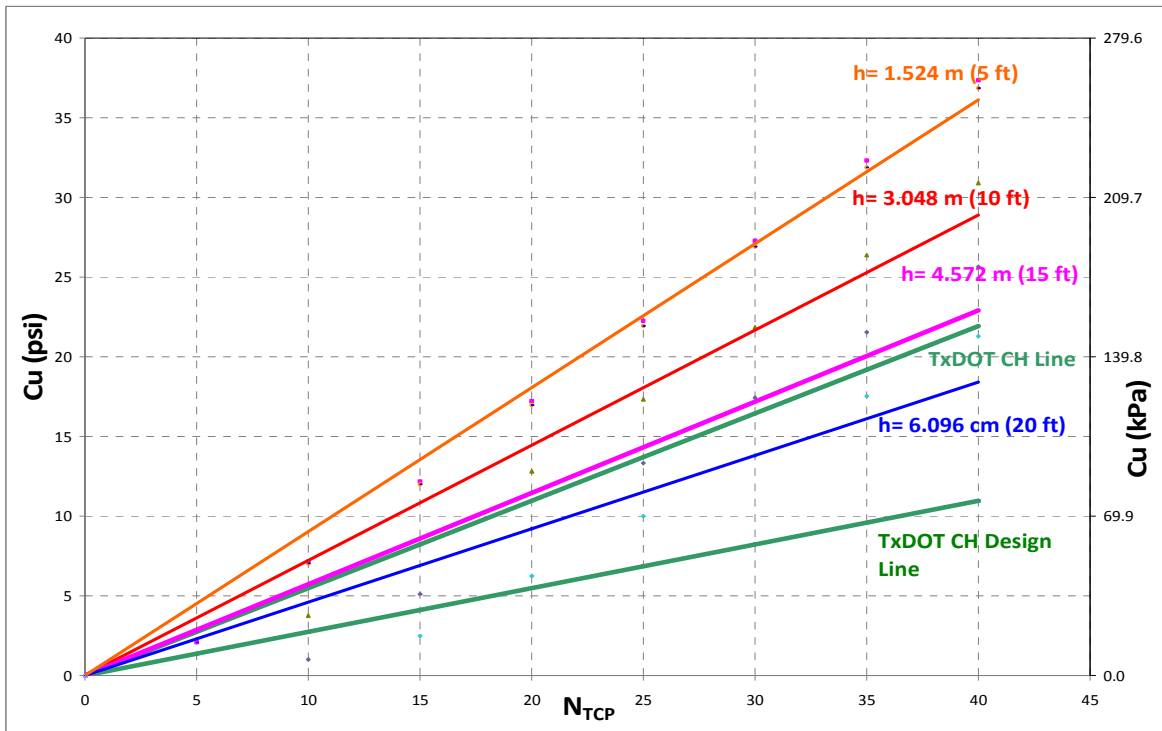


Figure 7a: Graphical c_u vs. N_{TCP} Relations for CH Soils

Table 3: Developed Relations for Various Depths

h (m)	CH soils		CL soils	
1.524 m 5 ft	$c_u = 6.22N_{TCP}$ $c_u = 0.903N_{TCP}$	[kPa] [psi]	$c_u = 4.69N_{TCP}$ $c_u = 0.681N_{TCP}$	[kPa] [psi]
3.048 m 10 ft	$c_u = 4.97N_{TCP}$ $c_u = 0.722N_{TCP}$	[kPa] [psi]	$c_u = 3.95N_{TCP}$ $c_u = 0.574N_{TCP}$	[kPa] [psi]
4.572 m 15 ft	$c_u = 3.94N_{TCP}$ $c_u = 0.572N_{TCP}$	[kPa] [psi]	$c_u = 3.37N_{TCP}$ $c_u = 0.489N_{TCP}$	[kPa] [psi]
6.096 m 20 ft	$c_u = 3.17N_{TCP}$ $c_u = 0.460N_{TCP}$	[kPa] [psi]	$c_u = 2.87N_{TCP}$ $c_u = 0.417N_{TCP}$	[kPa] [psi]

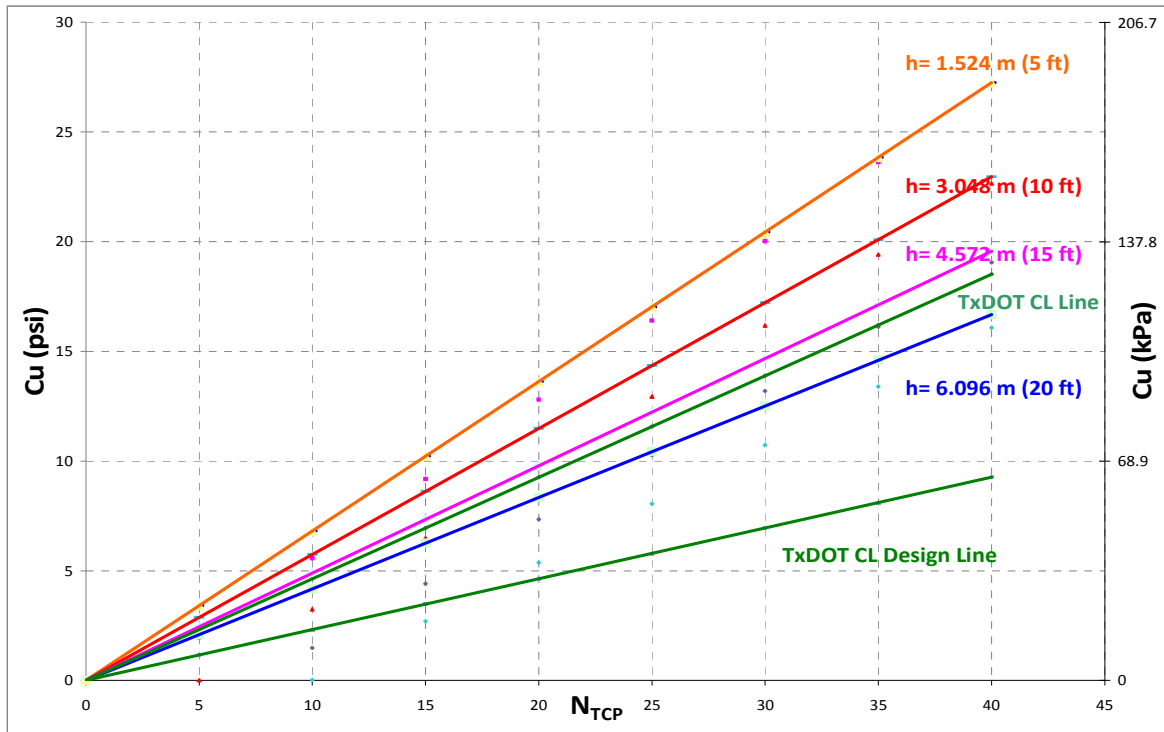


Figure 7b: Graphical c_u vs. N_{TCP} Relations for CL Soils

As Fig 7a illustrates, for a given depth, N_{TCP} increases with increasing cohesion. Meanwhile, for a given cohesion, N_{TCP} also increases with depth primarily because the impact energy required for the same amount of penetration is greater at a greater depth. Figures 7a and 7b also include the TxDOT relations for comparison. According to these figures, the TxDOT relations which did not consider depth effect lie very close to the developed relationships for depths between 4.572 m and 6.096 m (15 ft and 20 ft). The TxDOT design line (FS = 2) is also included in Figures 7a and 7b for comparison. It appears that the TxDOT design lines are on the safe side of the developed relations for depth below 6.096 m (20 ft).

SUMMARY AND CONCLUSION

Texas Department of Transportation predominantly uses Texas Cone Penetration Test to determine the in-situ undrained shear strength of clay. This research was undertaken to improve TxDOT's relations between undrained shear strength (c_u) and TCP blow-counts (N_{TCP}) by taking into consideration the effect of depth. The available record of TCP test results together with shear strength and classification properties of the soil at test sites was used as the database for developing the needed relationships. In the correlation development, the bearing capacity theory was utilized to consider the depth effect. It was found that using the current TxDOT's relation equations for design is most effective for depths ranging between 4.572 m and 6.096 m (15 ft and 20 ft).

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NOMENCLATURE

c	cohesion of soil
c_u	undrained cohesion of soil
h	depth to cone tip
N_{TCP}	Texas Cone Penetrometer blow-count expressed in number of blows/foot.
N_c	bearing capacity factor for cohesion

N_q	bearing capacity factor for surcharge
P_b	point bearing
q	effective vertical pressure
q_{ult}	ultimate bearing capacity
s	shear strength of soil
TCP	Texas Cone Penetrometer
γ	unit weight of soil
R^2	coefficient of correlation
PI	prediction interval
Q1	first quartile
Q3	third quartile
HS	hinge spread

