Numerical Analysis of Texas Cone Penetration Test

Nutan Palla
Project Engineer, Tolunay-Wong Engineers, Inc.
10710 S Sam Houston Parkway W Houston Texas, -77031, USA

Suresh Gudavalli
Engineering and Testing Department Manager
Atser, LP., 1150 Richcrest Drive, Houston, Texas – 77060, USA

Liang Chao
Assistant Professor
Taipei Chengshih University of Science and Technology
Taipei, Taiwan- 11202.

Mien Jao
Professor
Department of Civil Engineering
Lamar University, Beaumont
Texas, USA-77706.

M. C. Wang
Professor Emeritus
Department of Civil and Environmental Engineering
Pennsylvania State University
University Park, Pennsylvania, USA-16802.

Abstract

The Texas Cone Penetration Test (TCP) is the most common field test method used by Texas DOT (TxDOT) for determination of in-situ shear strength parameters of soils. In an attempt to improve the current TxDOT's design manual involving TCP, a study was conducted to determine the relationship between blow count (N_{TCP}) and undrained cohesion (c_u). In the study, a finite difference computer program FLAC was adopted for numerical analysis. The results of numerical analysis provided the stresses and yielding pattern of soil underlying the TCP as well as the displacement of the TCP. Based on the results of analysis together with available field and laboratory TCP data, statistical regression analyses were performed to obtain mathematical relations between N_{TCP} and c_u with due consideration of depth effect. Results of the study provided the N_{TCP} vs. c_u relations which indicate that the current relations used by TxDOT appear to be depth dependent and can be effectively used mainly for a depth less than 25-ft.

Keywords: Cohesion, N_{TCP} (Blows/ft), Texas Cone penetrometer, Displacement, Converging Stress, Depth.

1.0 Introduction

The Texas Cone Penetrometer (TCP) is the primary device of Texas DOT (TxDOT) for determining the in-situ shear strength parameters of cohesive soils. TCP is composed of a metal cone, a driving rod, and a weight (or hammer). The metal cone has a base diameter of 3-inch with a 60^0 vertex angle as illustrated in Fig. 1. The driving rod has a diameter of 2.375-inch. The hammer, which drops from a height of 24-inch, has a weight of 170 lb. The test procedures resemble that of the Standard Penetration Test (SPT). The number of blows required for the hammer to drive the cone through every 6-inch of soil is recorded. The blow counts (N) required for the cone to penetrate 12-inch of soil is then used to evaluate the undrained shear strength of the soil at the test site. The current Geotechnical Engineering Design Manual of TxDOT provides relations between blow count (N_{TCP}) of Texas Cone Penetration test and the in-situ undrained cohesion (c_u) of cohesive soils.

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However, it has been found that the existing relations may lead to unsatisfactory design of geotechnical structures. This study was undertaken in an attempt to improve the existing relations in the Design Manual. In the study, a fundamental approach based on work-energy principle was adopted to determine the equivalent impact hammer loading for numerical analysis to formulate the relationship between TCP blow-count and soil resistance. The numerical analysis was performed using a two-dimensional finite difference computer program named FLAC (Fast Lagrangian Analysis of Continua) [ITASCA, 2005]. Furthermore, based on the results of numerical analysis together with the available laboratory and field TCP database, statistical regression analyses were performed to formulate relations between N_{TCP} and C_u.

2.0 Available Database

All field and laboratory TCP data obtained by TxDOT from various places throughout southeast Texas were compiled and scrutinized. Any set of data without cohesion, blow count, plasticity index or liquid limit was removed from the database. All data sets were also checked for any inconsistency to make sure that every data set is complete and consistent. Also, the soil of each test set is correctly classified based on the Unified Soil Classification System (USCS). From the database, graphical relations between blow-count (N_{TCP}) and undrained cohesion (c_u) are plotted for high plastic clay soils (CH) in Fig. 2. Also plotted in Figure 2 for comparison are the current TxDOT relation line and the design line for a safety factor of 2.0 (TxDOT. 2006). It is seen that the data points widely scattered around the TxDOT design line indicating that the N_{TCP} vs c_u relations used for design purpose need further improvement.

3.0 Determination of Input Loading

For numerical analysis, the hammer impact load of TCP was converted to a static load based on the principle of energy conservation. The sum of all external work generated by the impact hammer is equated to the total energy dissipated within the soil and along the soil/cone interface. The energy dissipated along soil/cone interface involves adhesive and frictional components. Its equation form is shown below:

$$WH = \tfrac{1}{2}PS + c_aA + [(\gamma h K_p \cos\theta + \gamma h \sin\theta).\tan\delta]A \quad \text{..........(1)}$$

in which

W = hammer weight

H = hammer drop height

P = pseudo dynamic load

S = cone penetration depth

c_a = soil adhesion

γ = soil unit weight

h = depth to cone tip

θ = one-half of cone's apex angle = 30^0

δ = cone/soil friction angle

A = cone surface area

$K_p = \tan^2(45^0 + \varphi/2)$

φ = soil internal friction angle

Incorporating the geometric relations between A and θ together with the assumptions of $c_a = 2c/3$ and $\delta = 2\varphi/3$ yields the following equations:

$$P = k_2 W \quad \text{..........(2)}$$

and

$$k_2 = \frac{W.(h+S) - 1.613\, c.(\delta_{max})^3}{k_1.W.S} \quad \text{..........(3)}$$

in which

$k_1 = \tfrac{1}{2}$ for linear relation between P and S, which is used in the analysis.

δ_{max} is used to calculate the energy dissipated between the cone and soil interface. If the calculated S is less than the vertical height of cone tip, i.e., 2-5/8 inch, δ_{max} equal to S. Otherwise, δ_{max} = 2-5/8 inch. Details of equation derivation are available elsewhere [Palla, 2008].

Computation of input loading requires an iteration process. Initially, a value of k_2 is assumed, and the load P is calculated from Equation (2). The calculated load P is used as the input load in FLAC to compute cone penetration depth S. The computed value of S is then plugged in Equation (3) to recalculate k_2.

If the calculated k_2 value and the assumed k_2 are not equal, the new k_2 value is used to calculate the load. The process is repeated until both assumed and calculated values are close to each other within +/- 1%. In other words, the P value will converge to a load which represents the true loading. The converged load expressed in terms of stress is named the converging stress. Fig. 3 illustrates the iteration process.

4.0 Numerical Modeling of Soil-Cone System

Interaction between cone and surrounding soil was analyzed using FLAC (Fast Lagrangian Analysis of Continua), which is a two-dimensional finite difference program. Fig. 4 (a) and (b) show the schematic view and mesh of the soil-cone system used in the analysis. It is an axi-symmetric model. The bottom boundary at a depth of 50 ft is hinge supported, and both vertical boundaries 10 ft apart are roller supported. The left vertical boundary depicts the centerline of the cone. In the analysis, the soil is characterized as a linear elastic material. Five different soil conditions ranging from very stiff to very soft were analyzed for three cone positions; they are at ground surface, and at 10 ft and 25 ft below the ground surface. The steel and soil properties used in the analysis include mass density (ρ), modulus of elasticity (E), undrained shear strength (c_u), and Poisson's ratio (υ); their values are tabulated in Table 1. These values are obtained from the literature [Das, 2009, DeBeer et al, 2009, and Terzaghi et al, 1996].

4.1 Converging Stress

From the results of finite difference analysis, the converging stresses for different depths and soil conditions are tabulated in Table 2. As would be expected, the converging stress increases with soil strength; the softer the soil is, the smaller the converging stress will be. The relation between converging stress and Young's Modulus is shown in Table 3. It is also seen that the converging stress increases with depth due primarily to the increased overburden pressure effect.

4.2 Cone Displacement

Based on the converging stresses shown in Table 2, the analyzed cone displacements are tabulated in Table 4. The data show that, under a given input energy, cone displacement increases with decreasing soil strength as would be expected. Also, as depth increases, cone displacement decreases because of the greater overburden pressure effect.

4.3 Cohesion vs. Blow Count (N_{TCP})

The analyzed blow counts for 12-inch cone displacement are tabulated in Table 5. The tabulated data are also expressed graphically relating undrained cohesion (c_u) vs. blow count (N_{TCP}) for three different depths in Fig. 5. Along with the data is the TxDOT design line. The graph indicates that the c_u vs. N_{TCP} relation is quite linear and is depth dependent. The dependency of blow count on depth can be expected based on the concept of correction for overburden pressure effect needed for the blow count of Standard Penetration Test (SPT). Comparing the analyzed c_u vs N_{TCP} relations and the TxDOT line, it suggests that the current TxDOT design line is most applicable to a depth up to 25 ft.

5.0 Summary and Conclusion

In an attempt to improve TxDOT design relations of undrained cohesion (c_u) vs. blow count (N_{TCP}), the Texas Cone Penetrometer Test (TCP) was analyzed numerically using a commercially available computer program FLAC. In the analysis, the hammer impact loading was converted to a static loading based on the principle of conservation of energy. The analysis was made for five different soil conditions each with three cone positions – one at the ground surface and the others at 10 ft and 25 ft below the ground surface. From the analysis, cone displacements as well as the blow count for 12 inch cone displacement were obtained for every soil condition and cone position analyzed. Meanwhile, graphical relations of undrained cohesion (c_u) vs. blow count (N_{TCP}) were developed. The results indicate that c_u vs. N_{TCP} relations are depth dependent. The results also reveal that the current TxDOT design line can be used most effectively for depth up to 25 ft only.

6.0 References

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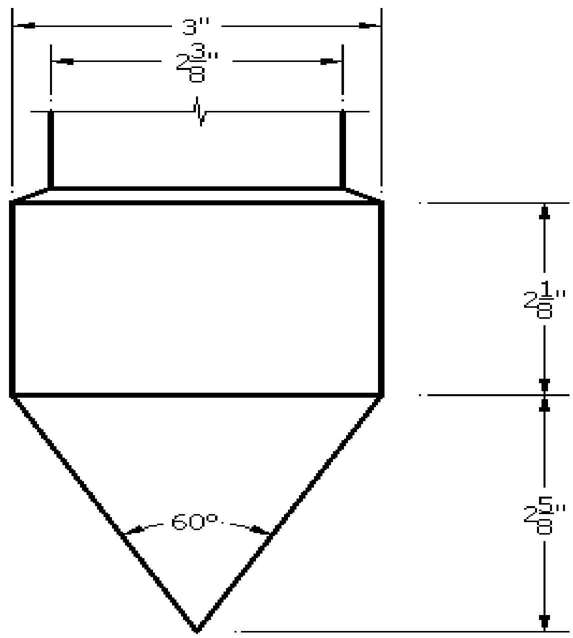


Fig. 1 Texas cone Penetrometer (after, 2000 TxDOT Geotechnical Manual Cone Tip)

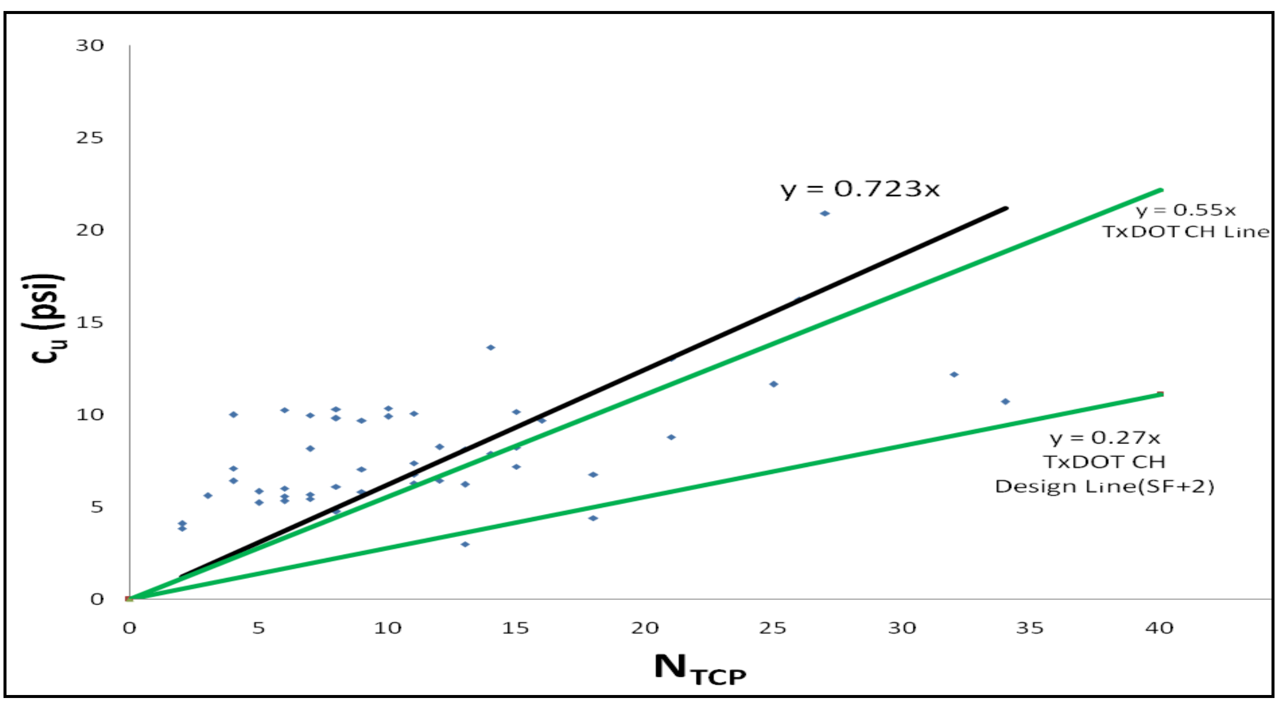


Fig. 2 Correlation between N_{TCP} vs. Cohesion for CH soils.

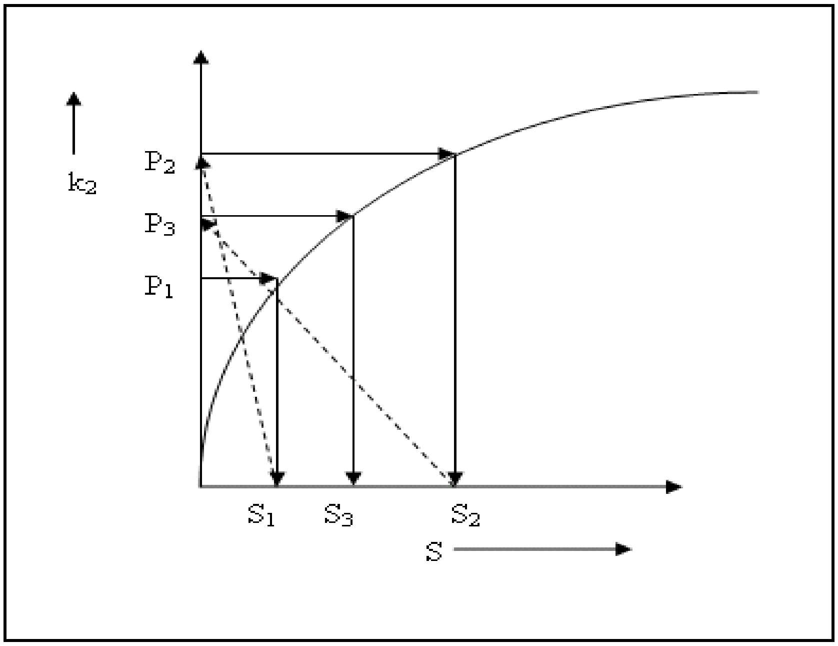
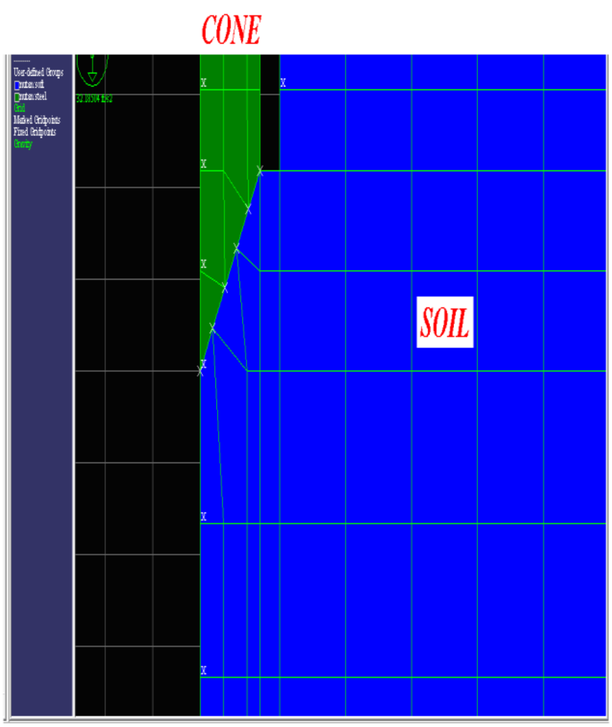


Fig. 3 Iteration Process for k_2 Determination

Fig. 4 (a) Soil-Cone Axi-symmetric Model Used for Analysis



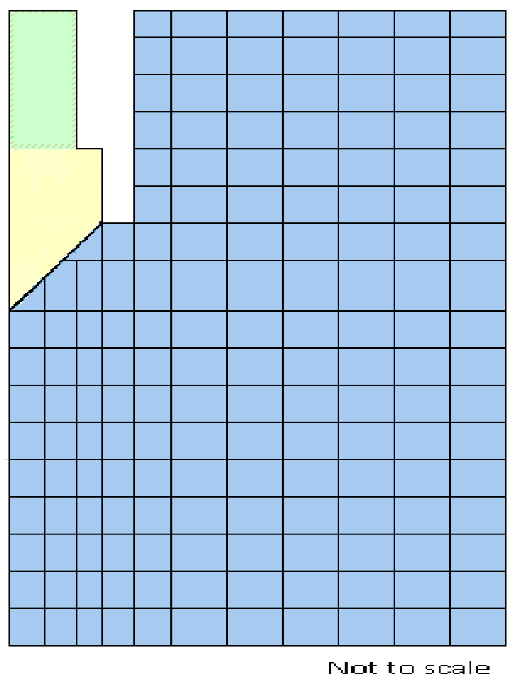


Fig. 4. (b) Finite Difference Mesh for TCP cone/Soil System

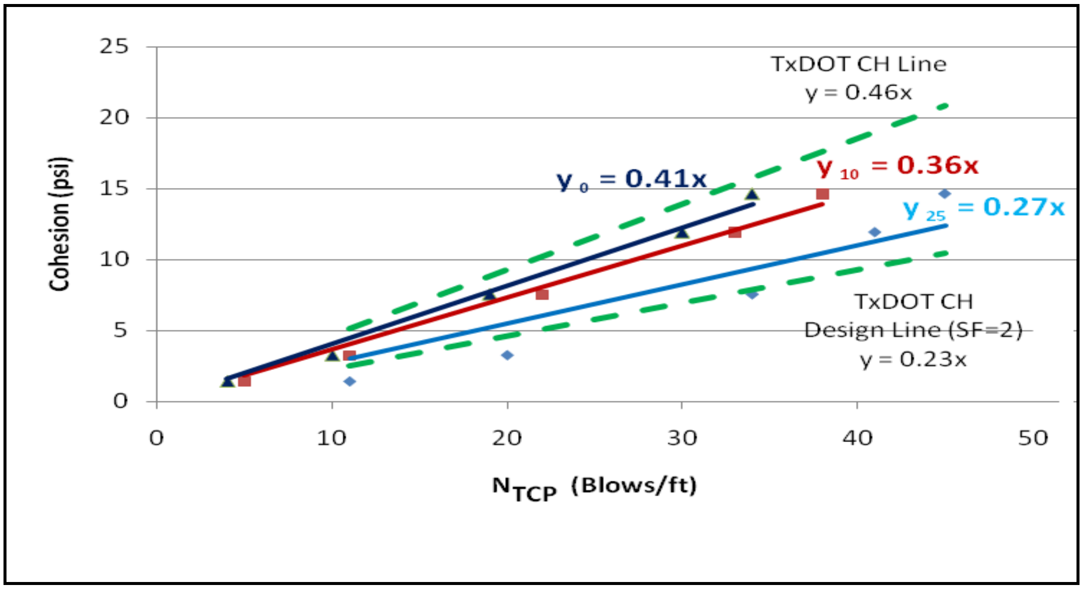


Fig. 5 Correlation of Blow Count with Cohesion for Various Depths

Table 1. Properties of Soil and Steel Used for Analysis

Consistency	Steel	Very Stiff	Stiff	Medium	Soft	Very Soft
Density (pcf)	488.6	135	120	110	100	85
Young's Modulus, E (tsf)	2087983	1000	750	325	87.5	25
Poisons ratio	0.29	0.45	0.45	0.45	0.45	0.45
C_u (tsf)	N/A	1.05	0.86	0.54	0.23	0.1

Table 2 Converging Stresses

Soil Properties	Very stiff	Stiff	Medium	Soft	Very soft
Young's modulus [tsf]	1000	750	325	87.5	25
Cohesion (psi)	14.62	11.91	7.53	3.24	1.39
Converging stress (psi) for surface depth	5285	4582	3074	1600	785
Converging stress (psi) for 10 ft depth	5936	5188	3422	1750	915
Converging stress (psi) for 25 ft depth	6880	6328	4870	2698	1725

Table 3 Converging stress vs. depth

Depth	Converging stress [psi]	Coefficient of correlation
0 ft	$Y = -0.003x^2 + 7.903x + 770.9$	99.2%
10 ft	$Y = -0.003x^2 + 8.864x + 857.7$	99.5%
25 ft	$Y = -0.006x^2 + 11.23x + 1641$	98.9%

Table 4 Analyzed Cone Displacements

Soil Properties	Very stiff	Stiff	Medium	Soft	Very soft
Young's modulus (tsf)	1000	750	325	87.5	25
Displacement (inch) at surface depth	0.3578	0.4052	0.627	1.214	2.673
Displacement (inch) at 10 ft depth	0.3179	0.3629	0.5568	1.111	2.213
Displacement (inch) at 25 ft depth	0.2646	0.2915	0.3508	0.6042	1.126

Table 5 Analyzed Blow Counts

Soil Properties	Very stiff	Stiff	Medium	Soft	Very soft
Cohesion (psi)	14.62	11.91	7.53	3.24	1.39
N (blow count/ft) for surface	34	30	19	10	4
N (blow count/ft) for 10-ft	38	33	22	11	5
N (blow count/ft) for 25-ft	45	41	34	20	11