Correlation of Texas Cone Penetration and Standard Penetration Test N-Values

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ABSTRACT:

This paper presents side-by-side comparisons of blowcount values for the Texas Cone Penetration (TCP) test and the Standard Penetration Test (SPT) from 225 test pairs in coarse-grained soils, fine-grained soils, and intermediate geomaterials. The objective of this study was to generate blowcount (N-value) correlations between N_{TCP} and N_{SPT} for these similar-yet-different field penetration test methods. Data were obtained from published sources and from project-specific field research sites for full-scale deep foundation load tests. The identified correlations depict statistically-significant, expected trends, yet the data exhibit considerable scatter. These correlations build upon and extend existing comparative relationships by virtue of the size of the dataset, the range of blowcount values considered, differentiation of materials, and the statistical analysis methods employed.

INTRODUCTION

This paper compares and contrasts the Standard Penetration Test (SPT) and the Texas Cone Penetrometer (TCP) test, both of which geotechnical engineers use to evaluate (or estimate) shear strength and other properties of soil and geomaterials with a view to foundation design. Results presented herein include side-by-side correlations of N_{SPT} and N_{TCP} blowcount values for fine-grained soils, coarse-grained soils, and intermediate geomaterials for these similar-yet different field penetration tests.

The Standard Penetration Test

The SPT is an international standard for measuring soil penetration resistance and obtaining a representative disturbed soil sample for identification purposes (ASTM 2011). The origin of the Standard Penetration Test (SPT) has been traced to 1902 when Charles Gow used driven samplers in exploratory borings to aid in estimating the cost of hand-excavating belled caissons (Rogers 2006). In 1947, Karl Terzaghi christened the procedure the “Standard Penetration Test,” and the first published correlations between SPT N-values and soil properties such as relative density, consistency and shear strength appeared in Terzaghi and Peck’s *Soil Mechanics in Engineering Practice* in 1948 (Rogers 2006). The conventional SPT driving procedure wherein blows are recorded for each of three 6-in. increments was introduced in 1954, and the SPT was adopted in 1958 as ASTM Standard D 1586, “Standard Test Method for Standard Penetration Test (SPT) and Split Barrel Sampling of Soils,” with the current version being ASTM D 1586-11 (ASTM 2014). Widely-accepted design methods for both driven piles and drilled shafts use the SPT to determine foundation capacity (AASHTO 2012, FHWA 1998, FHWA 2010).

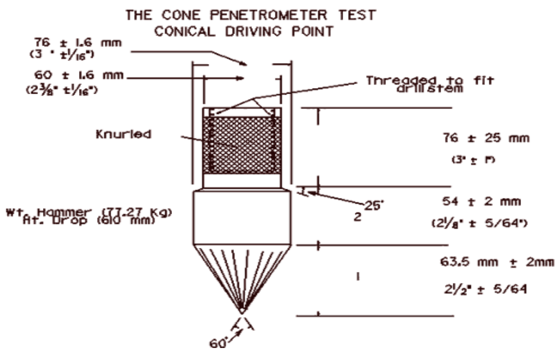
The Texas Cone Penetration Test

First used by the Texas Highway Department (now, Texas Department of Transportation, TxDOT) in 1949, the TCP test determines the relative density or consistency and load bearing capacity of geomaterials encountered in foundation exploration work. The TCP test method is documented as TxDOT Designation Tex-132-E, “Test Procedure for Texas Cone Penetration” (TxDOT 1999). The form of the TCP test is similar to the SPT in that a steel driving point is advanced into subsurface material at the bottom of a borehole by hammer strikes, with blowcounts recorded in three 6-in. increments. However, the TCP test differs from the SPT in certain ways, summarized in Table 1.

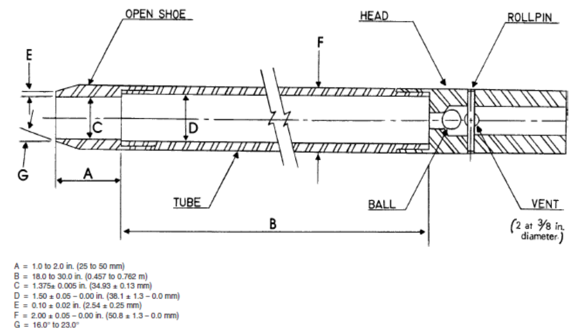
Table 1: Comparison of the SPT and TCP test methods

Parameter	SPT	TCP
First year published	1958	1956
Official test documentation	ASTM D 1586	Tex-132-E
Sampler description	Steel; hollow split barrel; 18 to 30 in. long	Steel; solid conical driving point; 7.625 in. long
Sampler dimensions	2.00 ± 0.05 in I.D. 1.375 ± 0.005 in O.D.	3.00 ± 0.063 in.
Hammer type	Automatic, safety, donut	Automatic, safety, donut
Hammer weight	140 ± 2 lbs.	170 ± 2 lbs.
Hammer drop height	30 ± 1.0 in.	24 ± 0.5 in.
Theoretical hammer energy	4200 in-lbs	4080 in.-lbs.
Suitable for in situ evaluation of:	Fine-grained and coarse-grained soils	Soils, intermediate geomaterials, rock
Test penetration increments	3 total	3 total
Seating increment (not included in N-value)	First 6 in. penetration	First 12 blows or 6 in. penetration
Refusal (nominal)	Resistance to penetration more than 50 blows/ 6 in.	Resistance to penetration more than 100 blows/ 12 in.
Obtains sample for soil identification	Yes, disturbed	No
Test unit of measure	N_{SPT}, blows/ft.	N_{TCP}, blows/ft. <or> inches of penetration/100 blows
N-values correlated to shear strength	Yes	Yes
N-values used for foundation design	Yes, driven piles and drilled shafts	Yes, driven piles and drilled shafts

First, the TCP test does not use a split-barrel sampler but rather the solid steel conical point (Figure 1), so the TCP test cannot and does not collect a soil sample. Second, owing to its more robust solid steel design, TCP test refusal is defined as resistance to penetration greater than 100 blows/ft., so the TCP test is suitable for evaluating harder geomaterials and rock. In contrast, SPT refusal is customarily achieved at resistance to penetration greater than 50 blows/6 in. or when there is no observed advance of the sampler during the application of 10 successive blows. Third, several details of the TCP test procedure vary from the SPT.



(a) TCP Conical Driving Point
image source: TxDOT 1999



(b) SPT Split-Barrel Sampler
image source: ASTM 2014

Figure 1. TCP Test Conical Driving Point and SPT Split-Barrel Sampler

In a similar manner to the SPT, blowcount data from the TCP test are directly used for foundation design for both driven piles and drilled shafts. In 1956, TxDOT first published a series of design charts that provide allowable foundation capacity for both soil-like materials ($N_{TCP} \leq 100$ blows/ft.) and harder geomaterials ($N_{TCP} \geq 100$ blows/ft.) for both skin friction and point bearing. TxDOT updated their foundation design charts in 1972 and again in 1982, with the current version appearing in the TxDOT *Geotechnical Manual* (TxDOT 2012). The TCP test and associated design charts have been used extensively for design of bridge foundations other transportation structures throughout Texas and in parts of Oklahoma. Recent research studies sponsored by the Arkansas Highway and Transportation Department and the Missouri Department of Transportation have also evaluated the TCP test and foundation design method.

BLOWCOUNT CORRELATION APPROACHES

Given similarities between the SPT and TCP test in both procedure and in application to foundation design, it is reasonable to explore whether correlations exist between the blowcount values from these tests, that is, between N_{SPT} and N_{TCP}. In fact, the history of the SPT is replete with correlation attempts arising from test parameter variations over the long period during which the SPT developed (Rogers 2006). Two basic correlation approaches exist, and these are energy-area equations and side-by-side correlations. The energy-area equations are based on the idea that blowcounts are proportional to the driving weight and energy input versus the cross-sectional area of the sampler. Side-by-side correlations are empirical (statistical) relationships derived from (as the name implies) side-by-side penetration tests using two or more methods where key variables such as test depth, soil material, and soil strength are held constant for the test pairs.

Burmister's Input Energy Correction (1948)

Burmister's Input Energy Correction, developed by Columbia University Professor Donald Burmister, is the earliest of the published energy-area equations (Rogers 2006). Burmister's correction (Equation 1) assumes that blowcount values from similar-yet-different penetration tests are proportional to driving weight and energy input versus the cross-sectional area of the sampler (Rogers 2006).

$$N^* = N_R \frac{W*H}{140\ lbs*30in.}\left[\frac{(2.0in.)^2-(1.375in.)^2}{(D_o)^2-(D_i)^2}\right] \qquad \textbf{(1)}$$

N* is the SPT blowcount equivalent to the recorded TCP blowcount, N_R. W is the TCP hammer weight in pounds, H is the TCP hammer drop height in inches, and D_o and D_i are the outer and inner sampler diameters of the TCP conical point in inches, respectively. Using nominal SPT and TCP test parameters and assuming an unplugged SPT split-barrel shoe, the relationship between N_{SPT} and N_{TCP} is as shown in Equation 2.

$$N_{SPT} = 0.23 * N_{TCP} \qquad \textbf{(2)}$$

While Burmister's method does not distinguish between coarse-grained vs. fine-grained soils, nor does it account for variation in skin friction and other differences between samplers, the Burmister Correction *does* rightly capture the intuition that it ought to take a lot less energy to drive a split barrel sampler (cross sectional area of 1.66 in^2) than a TCP conical point (cross sectional area of 7.07 in^2). Thus, SPT blowcounts *should be* significantly lower than TCP blowcounts in the same material, other things being equal.

Lacroix and Horn Correction (1973)

In a 1973 article entitled, "Direct Determination and Indirect Evaluation of Relative Density and Its Use on Earthwork Construction Projects," Yves Lacroix and Harry Horn proposed that the penetration resistance from a non-standard and a standard test device could be correlated by taking into account the different driving energies and penetrations (Rogers 2006), as shown in Equation 3.

$$N = \frac{2N_1 W_1 H_1}{175 D^2 L_1} \quad \textbf{(3)}$$

N is the SPT blowcount equivalent to the recorded TCP blowcount, N_1. W_1 is the TCP hammer weight in pounds, H_1 is the TCP hammer drop height in inches, and D is the diameter of the TCP conical point. Using nominal test parameters, the relationship between N_{SPT} and N_{TCP} is as shown in Equation 4.

$$N_{SPT} \;=\; 0.43 * N_{TCP} \quad \textbf{(4)}$$

The Lacroix and Horn correction was adopted by many engineers, especially for soils of variable stiffness or when sampling near contacts between soft and stiff materials (Rogers 2006). Like Burmister, the Lacroix and Horn correction is consistent with the expected blowcount trend; *i.e.*, N_{SPT} *should be* less than N_{TCP}; however, the Lacroix and Horn method gives a more conservative estimate of SPT blowcounts than Burmister.

Touma-Reece Side-by-Side Correlation (1972)

Side-by-side correlations are established by direct comparison of blowcounts from any two test methods. The only published side-by-side comparison of SPT and TCP blowcounts in the geotechnical literature is Research Report 3-5-72-176-1 (Touma and Reece 1972) which focused on the analysis of behavior of full-scale instrumented drilled shafts loaded to failure in sandy soils. As part of the soil investigation program for their research, Touma and Reece performed SPT and TCP tests in both coarse-grained and fine-grained soils. Although their research objectives focused on drilled shaft behavior, Touma and Reece established side-by-side correlations between N_{SPT} and N_{TCP} "for the purposes of [the] study and for the purpose of making the results of [the] study useful to users of the [TCP test]" (Touma and Reece 1972).

The Touma-Reece dataset contains 44 data pairs in fine-grained (clay) soil, with measured N_{SPT} values ranging from 5 to 46 blows/ft., average 20 blows/ft., and measured N_{TCP} values ranging from 7 to 91 blows/ft., average 28 blows/ft. The dataset contains 54 data pairs in coarse-grained (sand) soil, with measured N_{SPT} values (expressed in terms of *equivalent* blows/ft.) ranging from 12 to 200 blows/ft., average 69 blows/ft., and measured N_{TCP} values (expressed in terms of *equivalent* blows/ft.) ranging from 26 to 722 blows/ft., average 162 blows/ft. These data yield the following correlations, established by best fit linear regression from plots of $\text{Log}_{10}(N_{SPT})$ vs. $\text{Log}_{10}(N_{TCP})$:

$$N_{SPT} \;=\; 0.7 * N_{TCP} \;\text{ for fine-grained (clay) soil} \quad \textbf{(5)}$$

$$N_{SPT} \;=\; 0.5 * N_{TCP} \;\text{ for coarse-grained (sand) soil} \quad \textbf{(6)}$$

TxDOT published the Touma-Reece side-by-side correlations in the 2000 edition of their *Geotechnical Manual*, although this manual presents the relationship in reverse form as $N_{TCP} = 1.5*N_{SPT}$ (clay) and $N_{TCP} = 2.0*N_{SPT}$ (sand). As with the energy-area equations, the Touma-Reece correlations are consistent with the expected blowcount trend; *i.e.*, N_{SPT} *should be* less than N_{TCP}.

TEXAS TECH UNIVERSITY DATASET

In an effort to further establish and refine a numerical correlation between SPT and TCP blowcount values, researchers at Texas Tech University (TTU) assembled a dataset of 276 N_{SPT}-N_{TCP} test pairs. These data source to the Touma-Reece study and to a current TxDOT-sponsored research study underway at Texas Tech University focused on evaluating the reliability of the TCP foundation design method (TxDOT 2011). The TTU research team digitized the Touma-Reece data and obtained the remainder of the dataset from exploratory test borings drilled at deep foundation load test sites in Texas and surrounding states. Table 2 summarizes the TTU dataset.

Table 2: TTU Dataset for Side-by-Side Correlation of SPT and TCP N-values

Description	AR	LA	MO	NM	TX	OK	Touma-Reece	Total
Fine-Grained Soil	15	8	1	1	0	0	44	69
Coarse-Grained Soil	38	18	0	26	1	0	54	137
Intermediate Geomaterials	0	0	13	0	0	6	0	19
Subtotal, Usable Test Pairs	49	26	14	30	1	6	98	225
Not Used	26	11	1	10	0	0	0	51
Total TTU Dataset	75	37	15	40	1	6	98	276

All data in the TTU dataset represent test pairs obtained at similar elevations/depths (within 2.5 ft.). While test pairs were established based on elevation, these sets were only used for data analysis if the soil types were substantially equivalent; *i.e.*, both tests were conducted in either fine-grained soil, coarse-grained soil, or intermediate geomaterials (IGMs). No test pairs were taken at transitions from one stratum to a substantially different stratum. This effort yielded a final dataset for evaluation consisting of 225 N_{SPT}-N_{TCP} test pairs.

Further studies are underway to derive correlations between SPT and TCP blowcount values which have been corrected for variations in hammer efficiency. However, energy-corrected blowcount correlations are outside the scope of this paper.

TEXAS TECH UNIVERSITY TCP-SPT CORRELATIONS

Statistical Analyses

With the test pairs established, the researchers performed statistical analyses using Minitab 17 (Minitab 2014) to determine numerical correlations between N_{SPT} and N_{TCP} for coarse-grained soils, fine-grained soils, and IGMs. As part of the analyses, the researchers introduced two data processing steps. The first step was to normalize all blowcount values to a uniform standard of measure (blows/ft.) using Equation 7. This was necessary for any SPT and TCP tests where refusal was achieved prior to completing a full 6-in. penetration increment during the test.

$$N_{EQ} = \frac{12 * N}{P} \tag{7}$$

N_{EQ} is the equivalent blowcount (SPT or TCP) normalized to 12 inches penetration; *i.e.*, blows/ft. N is the recorded total blowcount (number of blows), and P is the recorded total penetration for the test (inches). All results presented on the following charts utilize N_{EQ} blowcounts.

The second data processing step was to remove outliers defined as N-values greater than 2400 blows/ft. for both SPT and TCP tests. This decision sources to a practical limit on the precision with which field drilling crews typically measure penetrations; namely, ¼ in. per test increment. Whereas a driller might record penetration values less than ¼ in., rarely are these measured precisely.

TCP-SPT Correlations

Figure 2 shows the complete TTU dataset, including outliers. All blowcount correlations have been established within the bounds of normal test precision; that is, for N_{EQ} values of 2400 blows/ft. or lower. Figure 3, Figure 4, and Figure 5 show the TCP-SPT correlations, confidence intervals, and predictive intervals for coarse-grained soils, fine-grained soils, and IGMs, respectively. Each of these charts presents the blowcount data in log-log scale and each contains the best fit regression equation and R-Squared value for its respective soil type.

All correlations show the expected trend; that is, N_{TCP} is higher than the corresponding N_{SPT}. Further, correlation parameters (intercept and slope) for the coarse and fine-grained soils are statistically significant. However, the strength of the correlations is generally weak for each soil type, and in particular for IGMs. The highest R-squared value is 47%, for fine-grained soils. Though this is the highest value, it is still relatively weak. R-squared values are 25.9% for the coarse-grained soils and 6.8% for the IGMs.

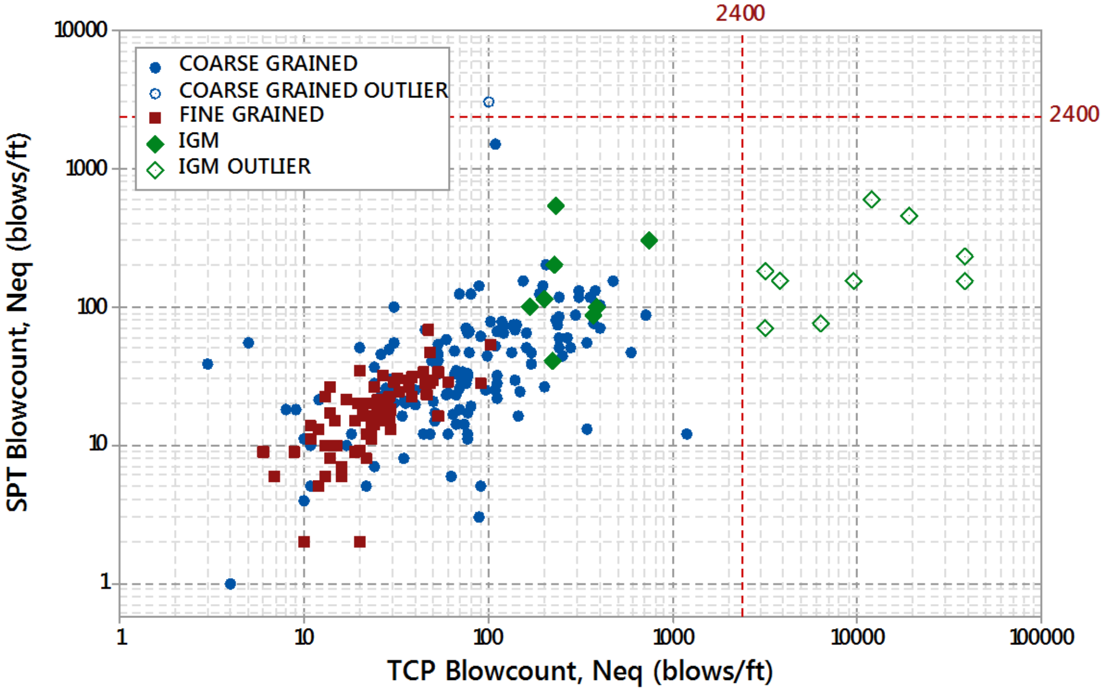


Figure 2: TTU Dataset for Establishing Side-by-Side N_{SPT}-N_{TCP} Correlations

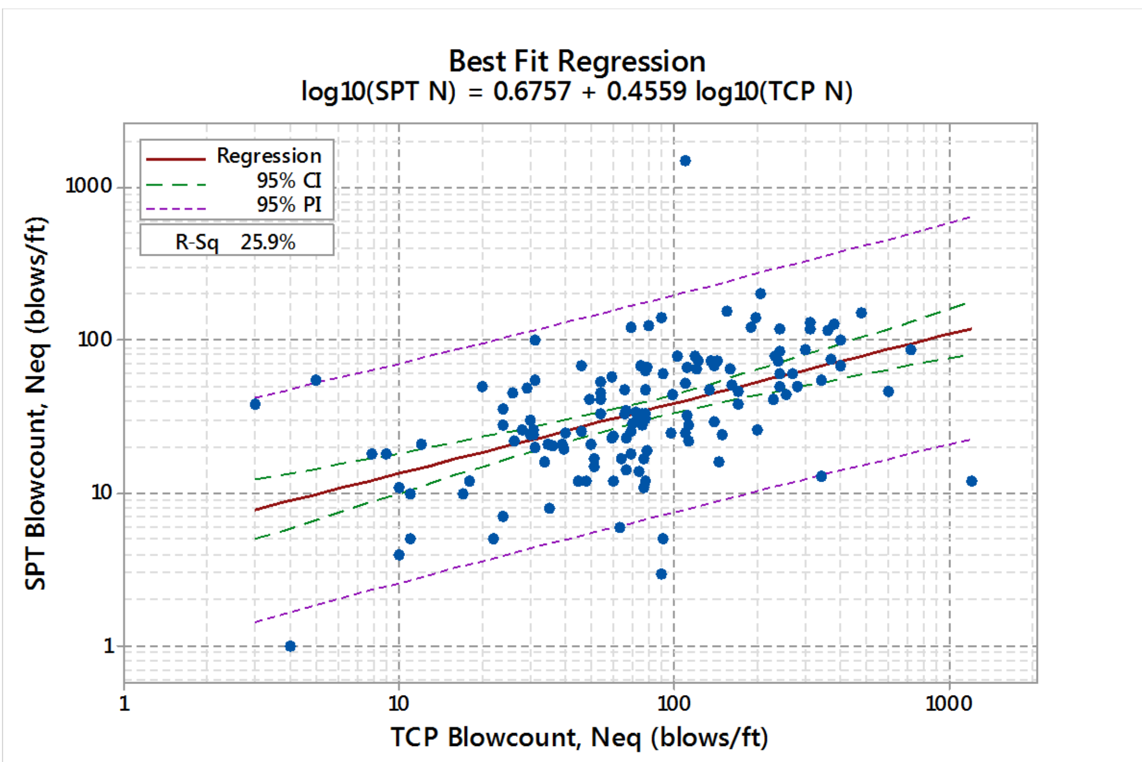


Figure 3: TTU Dataset: N_{SPT}-N_{TCP} Correlation for Coarse-Grained Soils

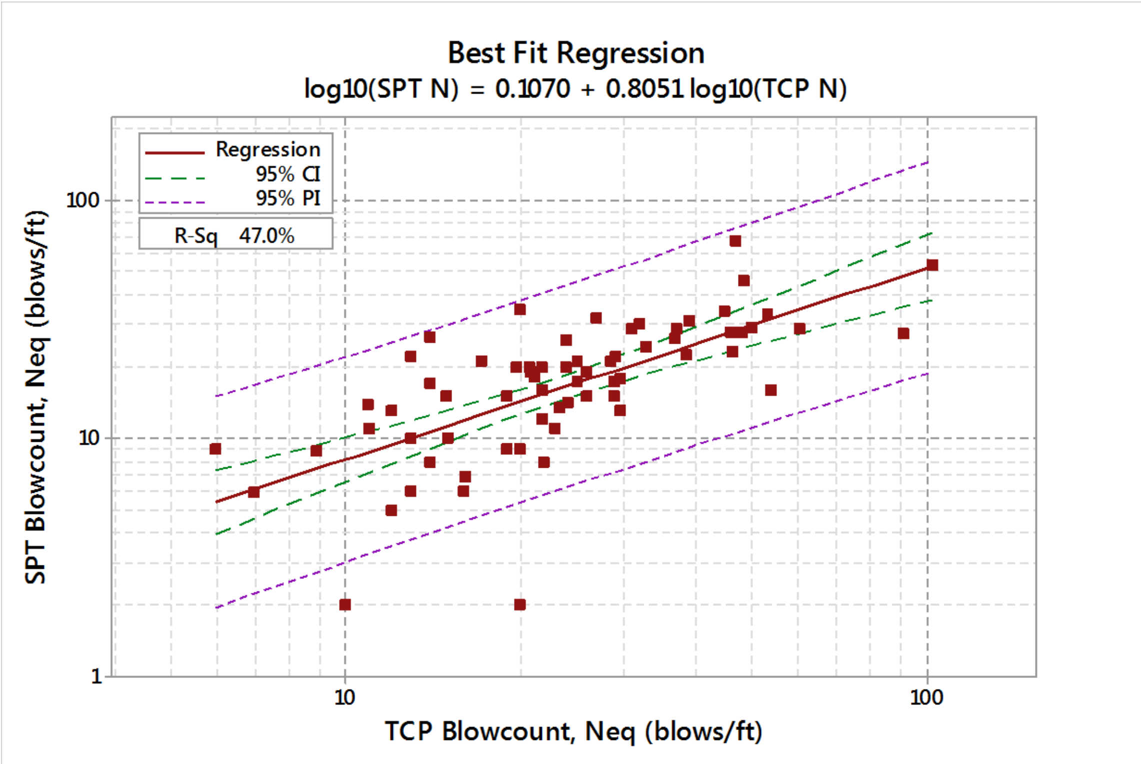


Figure 4: TTU Dataset: N_{SPT}-N_{TCP} Correlation for Fine-Grained Soils

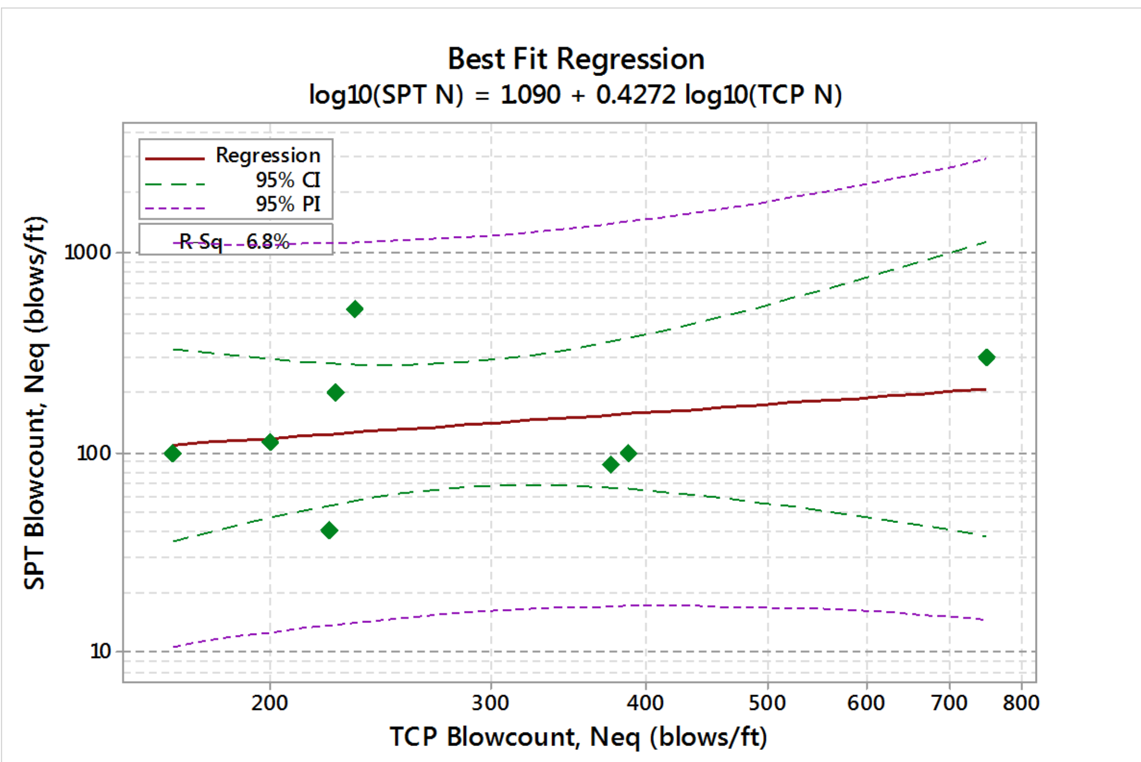


Figure 5: TTU Dataset: N_{SPT}-N_{TCP} Correlation for Intermediate Geomaterials

Table 3 facilitates comparison of the correlations by way of an example. Given N_{TCP} values of 20 blows/ft. and 200 blows/ft., N_{SPT} values have been correlated using the relationships identified in this paper.

Table 2: Comparison of N_{SPT} and N_{TCP} Correlation Methods

N_{TCP} *(example)* (blows/ft.)	N_{SPT} *(by correlation)* (blows/ft.)					
	Texas Tech University		Touma-Reese		Burmister	Lacroix & Horn
	Fine Grained	Coarse Grained	Fine Grained	Coarse Grained		
25	17	21	18	13	6	11
200	91	53	140	100	46	86

Table 4 illustrates that all correlation approaches show the expected trend that N_{TCP} values are higher than N_{SPT} values, all other things being equal. When converting from N_{TCP} to N_{SPT}, the area-energy corrections tend to provide more conservative correlations (that is, lower blowcount values) than the side-by-side correlations. Among the side-by-side correlation approaches, blowcount values for the fine-grained soils are fairly consistent; whereas, blowcount values for the coarse-grained soils vary widely. Further, the Touma-Reece correlation is non-conservative for higher blowcount values in coarse-grained soils when converting from N_{TCP} to N_{SPT}.

SUMMARY AND CONCLUSIONS

The objective of this research was to establish side-by-side correlations of SPT and TCP test blowcounts in coarse-grained soils, fine-grained soils, and intermediate geo-materials. A dataset of 225 TCP-SPT test pairs was assembled and analyzed using statistical regression techniques. This dataset yielded statistically-significant correlations for both fine-grained and coarse-grained soils. However, the correlation for intermediate geomaterials was not statistically significant. While these relationships have been defined, the dataset does contain a large amount of scatter and the R-squared values for even the significant correlations are generally weak. Overall, the correlations calculated from this research follow the anticipated trends and build on and extend existing correlation and correction methods.

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