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Side-by-Side Correlation of Texas Cone Penetration and Standard Penetration Test Blowcount 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). The comparisons yielded statistically-significant regression models for both coarse-grained soils and fine-grained soils. Consistent with expected trends and published data, the TCP–SPT relationship is nonlinear, with weak to fair correlation strength ($R^2 = 23$–44%). For TCP blowcounts ($N_{60,\ TCP}$) varying from 25 to 200 blows/30 cm (1 ft), corresponding SPT blowcounts ($N_{60,\ SPT}$) are typically 30–60% lower than $N_{60,\ TCP}$ in fine-grained soils. Likewise, corresponding $N_{60,\ SPT}$ blowcounts are 10–70% lower than $N_{60,\ TCP}$ in coarse-grained soils, all other things being equal. Comparative data were obtained from published sources and from project-specific field research sites used for full-scale deep foundation load tests. The final dataset consisted of 225 test pairs obtained in similar soils and geomaterials, at equivalent depths, with all blowcounts normalized to 30 cm (12 in.) penetration (i.e., blows/30 cm or blows/ft) within the bounds of typical test precision, and corrected to 60% hammer efficiency. The generally weak correlations do not support conversion of $N_{60,\ TCP}$ to $N_{60,\ SPT}$ (or vice versa) to compute foundation capacity for final design. But, engineers can certainly get an intuitive feel about site conditions and preliminary foundation capacity by using the correlation equations to translate their knowledge of one test to the other. This study extends previous work by formally comparing and contrasting the similar yet different SPT and TCP test methods in such a way as to make the results useful to users of both tests and to the broader geotechnical engineering community.

Keywords Standard penetration test · SPT · Texas cone penetration · TCP · Side-by-side correlation · Blowcount

1 Introduction

This paper compares and contrasts the standard penetration test (SPT) and the Texas cone penetration (TCP) test, both of which geotechnical engineers use

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to measure penetration resistance in order to evaluate (or estimate) shear strength and other properties of soil and geomaterials for the purpose of foundation design. Results presented herein include side-by-side correlations of N_{SPT} and N_{TCP} blowcount values for fine-grained and coarse-grained soils for these similar-yet-different field penetration tests.

This paper builds on and extends a significant body of research dating to the 1970s and continuing through recent times where SPT blowcounts have been correlated with parameters such as undrained shear strength, relative density, cone penetration test tip resistance, seismic P- and S-wave velocity, liquefaction triggering, and more (DeMello 1971; Schmertmann and Palacios 1979; Kasim et al. 1986; Mayne and Kemper 1988; Jefferies and Davies 1993; Rogers 2006; Ulugergerli and Uyanik 2007; Youd et al. 2008; Hettiarachchi and Brown 2009; Idriss and Boulanger 2012). The empirical analyses reported herein do not attempt to directly model the complex interactions of test parameters, soil parameters, and other physical factors that influence how the SPT and the TCP test each develop their resistance to penetration. It is stipulated these are different. Rather, from the perspective of site characterization, this paper recognizes that both SPT and TCP tests are used to measure penetration resistance in terms of blowcounts. Thus, the question of interest is, what are the differences in blowcounts obtained from the two methods under the same soil conditions?

This paper is motivated by the idea that engineers who are familiar with the SPT may benefit from knowing about the TCP test with a view to considering the TCP test as another tool for site characterization and foundation design work.[1] Conversely, engineers who are familiar with the TCP test may want to know more about how the SPT compares so as to leverage the significant body of research and experience associated with the SPT. The carefully-developed, side-by-side correlations presented in this paper are intended to help achieve this goal.

1.1 The Standard Penetration Test (SPT)

The SPT is an international standard for measuring soil penetration resistance and obtaining a representative disturbed soil sample for identification purposes (ASTM 2015). 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 15 cm (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. The SPT is used “extensively” in a great variety of geotechnical exploration projects (ASTM 2011). Widely-accepted design methods for both driven piles and drilled shafts use the SPT to determine foundation capacity (AASHTO 2012, FHWA 1998, 2010).

1.2 The Texas Cone Penetration (TCP) Test

First used by the Texas Department of Transportation, TxDOT (then, the Texas Highway Department) in 1949, the TCP test determines penetration resistance that can be used to estimate the relative density or

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[1] An anecdote will illustrate this claim. During the early phase of the authors’ TCP research, a nationally-known foundation consulting firm contacted us. This firm was partnering on a multi-billion dollar, privately-funded, design-build transportation project in western Texas. Because the project was to be constructed in Texas, all bridge foundations had to meet Texas Department of Transportation (TxDOT) specifications including satisfactory design using TxDOT’s TCP-based foundation design procedure. But the principal engineers for this national firm were more familiar with the SPT, not the TCP, and they only had preliminary SPT blowcount data, not TCP blowcount data. Thus they were seeking an SPT–TCP blowcount correlation so they could do some preliminary foundation design estimates in support of their proposal. Because our research was not complete at that time, we provided the best information

Footnote 1 continued
available—namely, the 1972 Touma–Reese correlation. Again the firm principals contacted us, asking questions about the correlation and wanting to know more details. This experience is one of the reasons why the authors think practicing engineers will find this paper helpful and the geotechnical research community will also find it interesting.

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 15 cm (6 in.) increments.

Further, 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 where $N_{TCP} \leq 100$ blows/30 cm (1 ft) and harder geomaterials where $N_{TCP} \geq 100$ blows/30 cm (1 ft) for both skin friction and point bearing. TxDOT updated their foundation design charts in 1972 and again in 1982, with the current versions appearing in the TxDOT *Geotechnical Manual* (TxDOT 2012). The TCP test and associated design charts have been used successfully for design of thousands of bridge foundations and other transportation structures throughout Texas and in parts of Oklahoma. Recent research studies sponsored by the Arkansas State Highway and Transportation Department (Transportation Research Board 2014) and the Missouri Department of Transportation (Loehr et al. 2011) have also evaluated the TCP test and foundation design method.

1.3 Comparison of SPT and TCP Test Methods

How do the SPT and TCP test methods compare? Notwithstanding the similarities identified above, the TCP test differs from the SPT in certain ways, summarized in Table 1. First, the TCP test does not use a split-barrel sampler but rather the solid steel conical point (Fig. 1), one implication being that the TCP test *cannot* and *does not* collect a soil sample. Second, because the TCP test uses a solid cone it is considered a displacement test; whereas, the SPT with its hollow tube is considered a non-displacement test, or more correctly (because of coring effects) a partial-displacement test (Paikowsky et al. 1989). Third, owing to its more robust solid steel design, TCP test refusal is defined as resistance to penetration greater than 6.4 mm (1/4 in)/100 blows (practical limit), so the TCP test is suitable not only for evaluating soils but also harder geomaterials and rock. In contrast, SPT refusal is customarily achieved at resistance to penetration > 50 blows/15 cm (6 in.) or when there is no observed advance of the sampler during the application of 10 successive blows. Finally, several details of the TCP test procedure vary from the SPT.

Owing to its international prominence, a very large body of literature exists on the SPT test method. Multiple studies document the history of the SPT including Broms and Flodin (1988), Rogers (2006), and Massarsch (2014). Schnaid (2009) identified four state-of-the-art reviews on the SPT—DeMello (1971), Nixon (1982), Decourt (1989), and Clayton (1995)—most of which appear in the proceedings of international conferences on cone penetration testing and site characterization. In the late 1970s, Schmertmann (1978) and Kovacs and Salomone (1982) initiated a literature stream that focused on hammer energy as the most significant factor influencing the measured SPT *N*-value. Recent studies have explored the influence of SPT data in soil liquefaction evaluations (Idriss and Boulanger 2012), among other things.

A less massive but still significant literature exists on the TCP test. As would be expected due to its Texas origins, most research on the TCP test has been sponsored by TxDOT. In addition to various internal agency reports and papers, some of the significant research studies include Reese and Hudson (1968), Vijayvergiya et al. (1969), O’Neill and Reese 1970, Butler (1973), Hamoudi et al. (1974), Duderstadt et al. (1977), Nam (2004), Vipulanandan et al. (2008), Garfield et al. (2009), and Varathungarajan et al. (2009). The early studies explored relationships between TCP blowcounts and shaft and base resistance for drilled shafts and driven piles in soil. Many of the later studies explored direct correlations between TCP blowcount values and laboratory measurements of shear strength for both soil and rock. However, prior to this paper, only one published study (Touma and Reese 1972) directly compared TCP and SPT blowcount values.

The remainder of this paper focuses on the direct comparison of TCP and SPT blowcount values. This is justified given the similarities between the SPT and TCP test in both procedure and in application to foundation design. For even though their resistance mechanisms are different, both tests are in situ methods that attempt to measure shear strength of soils. For this reason, given the same soil condition, there *should be* a correlation between blowcount values—unless

Table 1 Features of the SPT and TCP test methods

Parameter	SPT method	TCP test method
First introduced	1902	1949
First year published	1958	1956
Official test documentation	ASTM D 1586	Tex-132-E
Sampler description	Steel; hollow split barrel; 0.457–0.762 m long (18–30 in. long)	Steel; solid conical driving point; 0.194 m long (7.625 in. long)
Sampler dimensions	50.8 ± 1.3–0.0 mm O.D. (2.00 ± 0.05 in. O.D.) 34.9 ± 1.3–0.0 mm I.D. (1.375 ± 0.005 in. I.D.)	76 ± 1.6 mm O.D. (3.00 ± 0.063 in. O.D.)
Hammer type	Automatic, safety, donut	Automatic, safety, donut
Hammer weight	623 ± 9 N (140 ± 2 lb_f)	756 ± 9 N (170 ± 2 lb_f)
Hammer drop height	0.76 ± 0.030 m (30 ± 1.0 in.)	0.61 ± 0.013 m (24 ± 0.5 in.)
Theoretical hammer energy	475 N-m (4200 in.-lb_f)	461 N-m (4080 in.-lb_f)
Suitable for in situ evaluation of:	Fine-grained and coarse-grained soils	Fine-grained and coarse-grained soils, intermediate geomaterials, rock
Test penetration increments	3 total	3 total
Seating increment (not included in N-value)	First 15 cm (6 in.) penetration	First 12 blows or 15 cm (6 in.) penetration
Refusal (nominal)	Resistance to penetration more than 50 blows/15 cm (6 in.)	Resistance to penetration more than 6.4 mm (1/4 in)/100 blows (practical limit)
Obtains sample for soil identification	Yes, disturbed	No
Test unit of measure	N_{SPT}, blows/30 cm (N_{SPT}, blows/ft)	N_{TCP}, blows/30 cm (N_{TCP}, blows/ft) <or> cm (in) 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

the soil is either too weak or too strong to make any difference in terms of blowcounts regardless of penetration mechanism. Thus, it is reasonable to explore correlations between N_{SPT} and N_{TCP}.

2 Blowcount Correlation Approaches

The history of the SPT is replete with correlation attempts arising from test parameter variations over the long period during which the SPT developed. Two basic correlation approaches have been used, and these are energy-area equations and side-by-side correlations (Rogers 2006). 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 relationships derived from (as the name implies) side-by-side penetration tests using two or more methods where key variables such as drilling equipment, test depth, soil material, and soil strength are held constant for the test pairs.

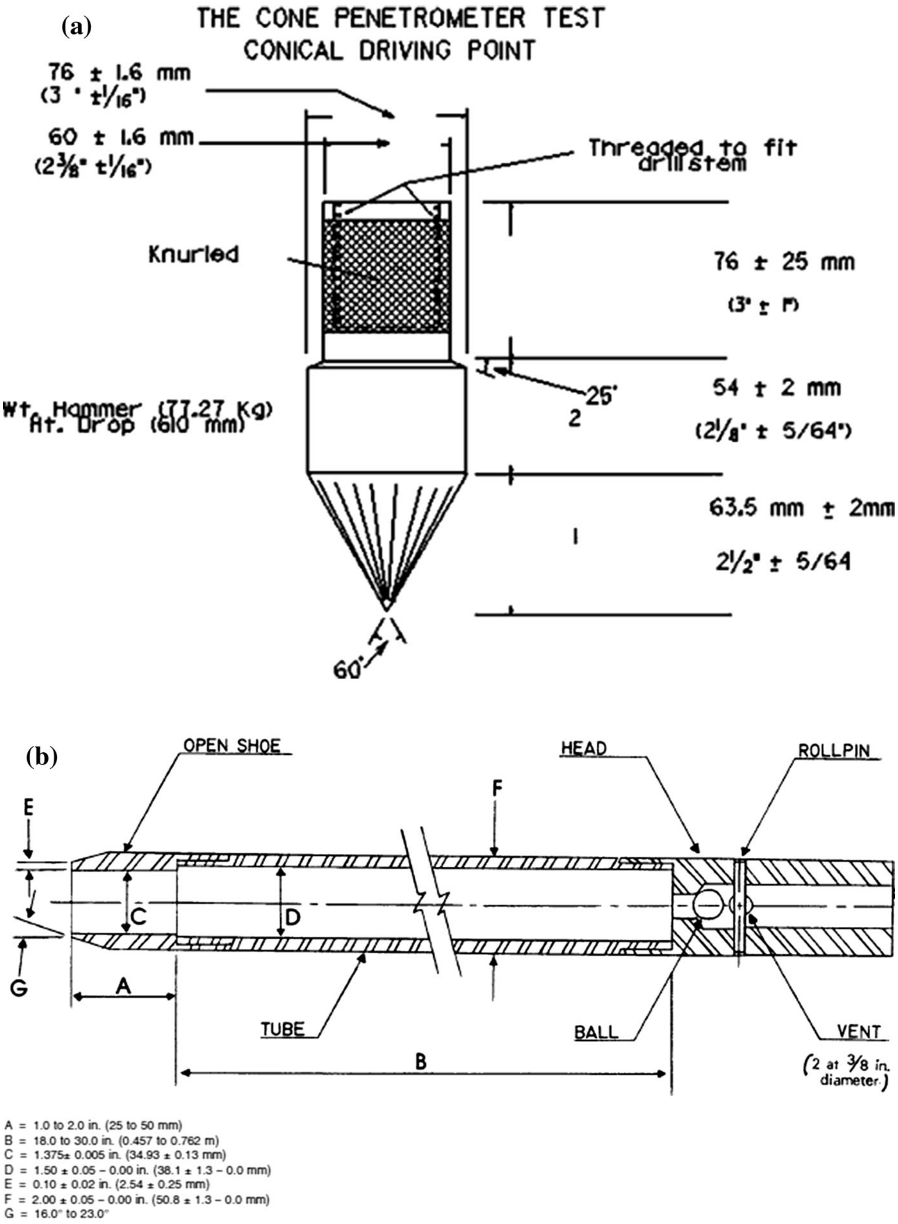

Fig. 1 TCP conical driving point and SPT split-barrel sampler. **a** TCP conical driving point (TxDOT 1999). **b** SPT split-barrel sampler (ASTM 2015). **a** Permission: This image appears in a TxDOT specifications document in the Public Domain. **b** Permission: Reproduced, with permission from "ASTM D1586-11 Standard Test Method for Standard Penetration Test (SPT) and Split-Barrel Sampling of Soils," copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428

2.1 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 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). More specifically, Burmister (1948) created a correlation between raw blowcounts from the Moran and Proctor drive sampler—having an internal diameter of 76.2 mm (3 in.) and blowcounts from the Gow (Raymond) split-spoon sampler—having an internal diameter of 34.9 mm ($1^{3}/_{8}$ in.), the main difference between these two open-ended samplers being their diameters (Rogers 2006).

It is recognized, of course, that the penetration mechanics for a split-spoon and a conical tip are different. In the split-spoon case, the major factor impacting the *N*-value is the internal friction created between the split-spoon wall and the soil, whereas, in the case of a conical tip, the failure mechanism is based on the general bearing capacity theory and soil displacement (in the case of sands) and plastic flow (in case of clays). So direct application of Burmister's correction to the TCP test goes beyond Burmister's original specific usage.

Conceptually however—given that both SPT and TCP tests are used to measure penetration resistance in terms of blowcounts—Burmister's correction can be adapted for the SPT-TCP relationship, as per Eq. 1:

$$N^{*} = N_R \frac{W * H}{623N * 0.762\,\mathrm{m}} \left[\frac{(50.8\,\mathrm{mm})^2 - (34.9\,\mathrm{mm})^2}{(D_o)^2 - (D_i)^2} \right] \quad (1\mathrm{a} - \mathrm{SI\ Units})$$

$$N^{*} = N_R \frac{W * H}{140\,\mathrm{lb} * 30\,\mathrm{in.}} \left[\frac{(2.00\,\mathrm{in.})^2 - (1.375\,\mathrm{in.})^2}{(D_o)^2 - (D_i)^2} \right] \quad (1\mathrm{b} - \mathrm{US\ Customary\ Units})$$

N^* is the correlated SPT blowcount equivalent to the measured TCP blowcount, N_R. W is the TCP hammer weight in N ($\mathrm{lb_f}$), H is the TCP hammer drop height in m (in), and D_o and D_i are the outer and inner sampler diameters of the TCP conical point in mm (in.), 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 Eq. 2. This is a lower-bound value for Burmister.

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

While Burmister's method does not distinguish between coarse-grained versus fine-grained soils, nor does this adaptation account for variation in skin friction and other differences between the SPT split-spoon and the TCP cone, the Burmister Correction *does* rightly capture the intuition that it ought to take a lot less energy to drive a split barrel sampler with cross sectional area of 1071 mm^2 (1.66 $\mathrm{in.}^2$) than a TCP conical point with cross sectional area of 4561 mm^2 (7.07 $\mathrm{in.}^2$). Thus, SPT blowcounts *should be* significantly lower than TCP blowcounts in the same material, other things being equal.

2.2 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 *approximately* correlated by taking into account the different driving energies and penetrations (Rogers 2006). In their words, "…when an approximate correlation is acceptable, we believe that it is satisfactory to assume that the number of blows required to drive the split spoon or conical point to a penetration depth is directly proportional to the square of the outside diameter of the split spoon or conical point and the depth of penetration, and inversely proportional to the energy per blow" (Lacroix and Horn 1973).

Equation 3 provides an adaptation of the Lacroix and Horn relationship to raw (uncorrected) blowcount data from SPT and TCP tests.

$$N = \frac{166 N_1 W_1 H_1}{D^2 L_1} \quad (3\mathrm{a} - \mathrm{SI\ units})$$

$$N = \frac{N_1 W_1 H_1}{88 D^2 L_1} \quad (3\mathrm{b} - \mathrm{US\ Customary\ Units})$$

N is the correlated SPT blowcount equivalent to the measured TCP blowcount, N_1. W_1 is the TCP hammer weight in N ($\mathrm{lb_f}$), H_1 is the TCP hammer drop height in m (in.), D is the diameter of the TCP conical point in mm (in.), and L_1 is the distance the sampler is advanced during sampling—typically the last 30 cm (12 in.) of a 45 cm (18 in.) sampling round.

Using nominal test parameters, the relationship between N_{SPT} and N_{TCP} is as shown in Eq. 4.

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

Lacroix and Horn recognized the approximate nature of this relationship and cautioned that "when possible, correlations should be developed for the specific nonstandard equipment or methods being used, and for the particular soil deposit being developed." They went on to illustrate such a refinement for the case of dynamic cone penetration resistance obtained using lightweight equipment in cohesionless soils having loose to medium relative densities for depths less than 4.6 m (15 ft) (Lacroix and Horn 1973). 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). Specific to this present study the Lacroix and Horn correction, like that of Burmister, 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 less conservative estimate of SPT blowcounts than Burmister.

2.3 Touma–Reese Side-by-Side Correlation (1972)

Side-by-side correlations are established by direct comparison of blowcounts from any two test methods, and these correlations could be for either raw or corrected blowcount data. As such, the side-by-side correlation is an expression of the test-specific, refined approach recommended by Lacroix and Horn. 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 Reese 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 Reese performed SPT and TCP tests in both coarse-grained and fine-grained soils. Although their research objectives focused on drilled shaft behavior, Touma and Reese 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 Reese 1972). Refer to Fig. 2.

The Touma–Reese dataset contains 44 data pairs in fine-grained (clay) soil, with measured N_{SPT} values ranging from 5 to 46, average 20 blows/30 cm (1 ft), and measured N_{TCP} values ranging from 7 to 91, average 28 blows/30 cm (1 ft). The dataset contains 54 data pairs in coarse-grained (sand) soil, with measured N_{SPT} values (expressed in terms of *equivalent* blows/30 cm) ranging from 12 to 200, average 69 blows/30 cm (1 ft), and measured N_{TCP} values (expressed in terms of *equivalent* blows/30 cm) ranging from 26 to 722, average 162 blows/30 cm (1 ft). These data yield the following correlations, established by best fit linear regression from plots of $\mathrm{Log}_{10}(N_{SPT})$ versus $\mathrm{Log}_{10}(N_{TCP})$:

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

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

TxDOT published the Touma–Reese 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–Reese correlations are consistent with the expected blowcount trend; i.e., N_{SPT} is less than N_{TCP}.

3 The Project Dataset

In an effort to further establish and refine a functional correlation between SPT and TCP blowcount values, the researchers assembled a dataset of 279 N_{SPT}-N_{TCP} test pairs. These data source to the Touma–Reese study (1972) and to a recent TxDOT-sponsored research study focused on evaluating the reliability of the TCP foundation design method (Seo et al. 2015a, b, c).

3.1 Data from Touma–Reese

Published data which show side-by-side SPT and TCP blowcount values from the Touma–Reese report (1972) were digitized for the current analysis. The Touma–Reese data were obtained in 1965–1972 from five research test sites located in the Texas coastal prairie. Individual drilling logs were not provided but the research report presents "diagrammatic" charts for each site showing that the subsurface materials consist of lean clay, fat clay, silty clay, and sand to depths of 12–27 m (40–90 ft). The subsurface charts include side-by-side blowcount versus depth profiles for the SPT and TCP test data.

The report appendix describes the procedures for both types of tests. The study obtained TCP, SPT and other types of soil shear strength data simultaneously as part of the field site characterization process. Relative to the penetration testing, rotary drilling rigs were used to advance the boreholes, and the penetration test apparatus for both the SPT and the TCP tests used the same automatic tripping mechanism, driving

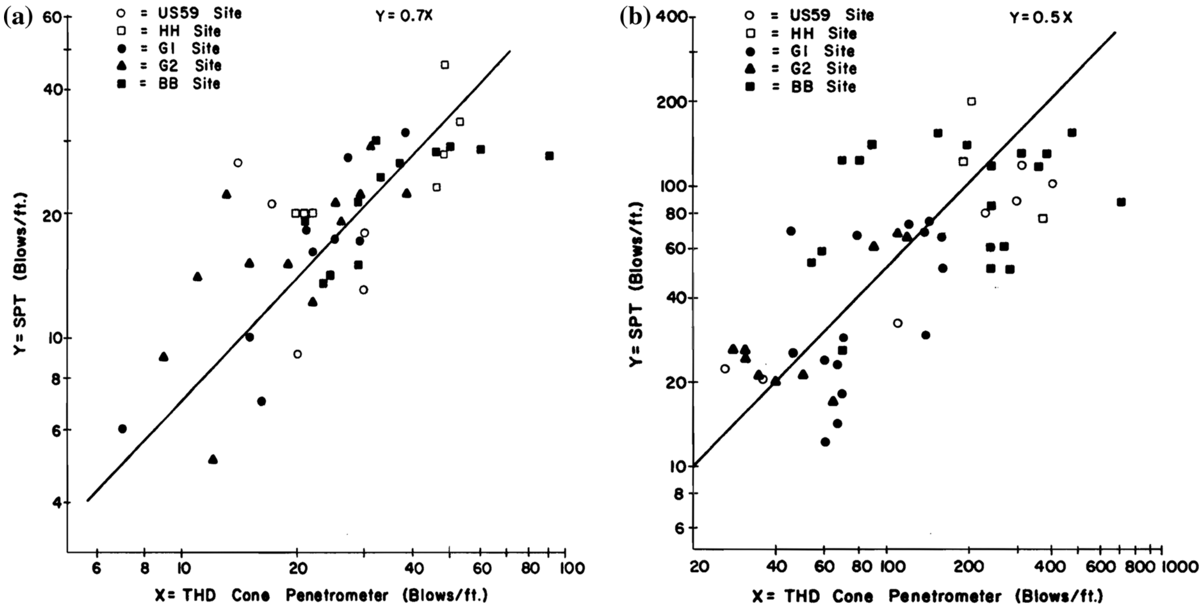

Fig. 2 Side-by-side SPT-TCP correlations published by Touma and Reese (1972). **a** Correlation for clay, **b** Correlation for sand **a** Permission: This image is from a published TxDOT research report. Permission to use image is granted by TxDOT through its copyright liaison at the Center for Transportation Research Library, Austin, TX. **b** Permission: This image is from a published TxDOT research report. Permission to use image is granted by TxDOT through its copyright liaison at the Center for Transportation Research Library, Austin, TX

rod, and steel anvil. Test procedures were in substantial accordance with the test methods published at that time, but varied slightly between the different sites and the soils encountered. Further, Touma and Reese noted that to minimize error, comparisons were only made for SPT and TCP tests taken in similar soils, at about equal depths.

For purposes of analysis, it was necessary to identify both the hammer type and corresponding hammer efficiency (actual/theoretical hammer energy) for these tests. From the provided description, the hammer type was inferred to be a safety-type donut hammer (same for both tests). No hammer efficiency data were available. Based on when the data were obtained, a nominal hammer efficiency of 60% was assumed.

3.2 Data from the TCP Reliability Study

The researchers obtained additional TCP and SPT blowcount data from field borings drilled at deep foundation load test sites located in Texas and five surrounding states. This data collection effort was part of a 2012–2015 research study that evaluated the reliability of TxDOT's TCP-based design method. The reader is referred to the research report for a comprehensive discussion of test methods and procedures (Seo et al. 2015a, b, c). This present blowcount correlation study does *not* explore reliability aspects of the TCP test or the TCP foundation design method. However, the blowcount dataset from the TCP Reliability research project was used for purposes of this correlation study. The following paragraphs describe the research approach, field penetration testing program, and data reduction and corrections.

3.2.1 *Research Approach*

The TCP Reliability study provided a load test dataset comprised of projects from TxDOT's archive files supplemented with other full-scale load test projects from neighboring states including Louisiana, Arkansas, Missouri, Oklahoma and New Mexico. Site characterization activities for the load test projects in neighboring states typically included SPT and other conventional laboratory shear strength tests, but not TCP tests. Therefore, to leverage these data, it was necessary to augment the original site characterization effort with new geotechnical borings including TCP tests. Ultimately this resulted in drilling 21 geotechnical borings in five states at 16 field test sites representing 50 load test projects for both driven piles and drilled shafts (Seo et al. 2015a). However, unlike the Touma-Reese study where side-by-side TCP and SPT data were obtained simultaneously, here the TCP data were obtained after the fact from a follow-on drilling and sampling event, months or perhaps years after the original site characterization was performed

3.2.2 Field Penetration Testing

Archive documentation from the original site characterization activities at each site typically was not published but instead was made available from project files by the agency or research university that performed the work. Documentation, including SPT blowcount data, varied from detailed presentations in project reports to simple test boring logs obtained from bridge construction drawings. Documentation for all follow-on geotechnical borings including TCP tests was complete. Table 2 presents the data sources

For SPT, in all cases the research documentation or the project contact person affirmatively stated that the SPT data were obtained in substantial accordance with the test standard. Usually the documentation included information about the SPT hammer type and direct measurements of SPT hammer efficiency. Where documentation did not specifically include hammer data, the project contact provided such data or reasonable values were assumed to facilitate subsequent analysis.

For TCP, field tests were also performed in substantial accordance with the test standard. Further, the researchers determined hammer efficiency by using Pile Dynamics' *SPT Analyzer* to directly measure the energy transferred into an instrumented TCP rod (Pile Dynamics, Inc. 2009). Two variances were noted. In Oklahoma, the project engineer reported that TCP tests were performed using an automatic SPT hammer at standard SPT drop height. For the Missouri projects, the Missouri researchers also performed TCP tests using an SPT hammer/drop height but these data were excluded from this project and replaced with regulation TCP data.

3.2.3 Data Reduction and Corrections

The project dataset obtained from exploratory test borings drilled at deep foundation load test sites in Texas and surrounding states yielded a total of 181 TCP–SPT data pairs. These data were evaluated to ensure test pairs were obtained at similar elevations/depths; i.e., within 0.8 m (2.5 ft). Further, data were only used for analysis if the general soil types were substantially equivalent; i.e., both tests were conducted in either fine-grained soil, coarse-grained soil, or intermediate geomaterials (IGMs). The "fine-grained soil" category included soils identified on drilling logs as low-plasticity clays, high-plasticity clays, silts, and undifferentiated clay. The "coarse-grained soil" category mostly consisted of soils identified as sand with a very few gravel tests. The "IGMs" category consisted of materials identified on the boring logs as shale, sandy shale, weathered shale, and gypsum. No test pairs were taken at transitions from one stratum to a substantially different stratum. This filtering effort yielded a dataset for evaluation of 127 data pairs, which, when combined with the Touma–Reese data, yielded a total project dataset of 225 N_{SPT}–N_{TCP} test pairs as shown in Table 3.

The researchers introduced three additional data-processing steps. The first step was to normalize all blowcount values to a uniform standard of measure (i.e., blows/30 cm or blows/ft) using Eq. 7. This was necessary for any SPT and TCP tests where refusal was achieved prior to completing a full 15 cm (6 in.) penetration increment during the test.

$$N_{EQ} = \frac{30\,\text{cm}\langle\text{or}\rangle 12\,\text{in} * N}{P} \tag{7}$$

N_{EQ} is the equivalent blowcount (SPT or TCP) normalized to 30 cm (12 in.) penetration; i.e., blows/30 cm (1 ft). N is the recorded total blowcount (number of blows), and P is the recorded total penetration for the test (cm or in.). All results presented on the following charts utilize N_{EQ} blowcounts.

The second step was to remove outliers defined as N_{EQ}-values > 2400 blows/30 cm (1 ft) for both SPT and TCP tests. This decision reflects the practical limit to the precision with which field drilling crews typically measure field penetrations; namely, 6.4 mm (1/4 in.) per test increment. Whereas a driller might record penetration values less than 6.4 mm (1/4 in.), rarely are these measured precisely.

The third data-processing step was to correct the SPT and TCP blowcount values for variations in hammer efficiency, also termed hammer energy ratio.

Table 2 Data sources for the SPT and TCP N-value dataset

State	Load test project location (Town)	Year	Data source	Project contact	SPT hammer type/efficiency	TCP hammer type/efficiency
AR	Monticello Turrell Siloam Springs	2013	Univ. of Arkansas/ AHTD	R. Coffman	Automatic 77%	Automatic 89–91%
LA	Baton Rouge Caddo New Orleans Ragley	1999–2011	LADOTD	S. Meunier	Automatic 81%*	Automatic 89%
MO	Frankford Warrensburg	2010	Univ. of Missouri/ MoDOT	E. Loehr	Automatic 80%	Automatic 89–91%
NM	Sunland Park Albuquerque Ohkay Owingeh	1995	NMDOT	R. Meyers	Automatic 80%	Automatic 88%
OK	Hollis	2013	Circuit Engr. Dist. No. 7	M. Goucher	Automatic 81%*	Automatic 81%*
TX	Crosby	2004	Univ. of Houston/ TxDOT	C. Vipulanandan	Automatic 81%*	Automatic 89%
TX	Houston and George West (near Corpus Christi)	1965–1972	Univ. of Texas-Austin	F. Touma and L. Reese	Safety* 60%*	Safety* 60%*

Hammer efficiency data marked with an asterisk (*) were assumed

Table 3 Dataset for side-by-side correlation of SPT and TCP N-values

Description	AR	LA	MO	NM	TX	OK	Touma–Reese (TX)	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
Total, usable test pairs	53	26	14	27	1	6	98	225

Direct measurement of hammer energy for SPT blowcounts began in the 1970s with SPT hammer energy correction factors appearing in the 1980s (Skempton 1986). As a matter of practice, much of the SPT blowcount data analyzed in this study had direct measurements for hammer efficiency. However, in contrast to the SPT, direct measurement of TCP hammer energy has been rare to non-existent, the TCP blowcount data used for this correlation study being the one notable exception (Moghaddam et al. 2017). Further, while SPT blowcounts are typically corrected to 60 percent efficiency (i.e., N_{60}) so as to align with the nominal hammer energy typical of the era when the SPT-based foundation design relationships were identified, no target efficiency value currently exists for TCP tests. Given the range of hammer efficiencies represented in the project dataset (Table 2), standardization was required. Therefore, consistent with industry convention, all TCP and SPT blowcount data for this study were corrected to 60 percent hammer efficiency. That is, the reported equivalent blowcount data are standardized as $N_{60\ TCP}$ and $N_{60\ SPT}$ values.

It is noted that other corrections to SPT blowcounts such as those for rod length, borehole diameter, type of sampler, and overburden pressure were not applied. The data did not contain a complete record of the test-specific details for all SPT-TCP test pairs, so those corrections were not uniformly available.

3.3 Dataset for Analysis

Figure 3 shows the complete project dataset. As noted, this dataset reflects side-by-side TCP-SPT data pairs obtained in similar soils and geomaterials, at equivalent depths, with all blowcounts normalized to 30 cm (12 in.) penetration (i.e., blows/30 cm (1 ft) and corrected to 60% hammer efficiency. Further, all blowcount correlations have been established within the bounds of normal test precision; that is, N_{EQ} values of 2400 blows/30 cm (1 ft) or lower, with any larger blowcount values identified as outliers.

How does this dataset improve on the Touma-Reese dataset? Relative to size, this dataset significantly expands the Touma–Reese dataset in that it features a total of 69 data pairs in fine-grained soils (over 1.5× larger) and 137 data pairs in coarse-grained soils (over 2.5× larger). Further, this project includes some data pairs for IGMs, a type of material not evaluated in the Touma–Reese study. Relative to diversity, the Touma–Reese data are limited geographically in that their data source to borings taken in the coastal prairie of Texas, mostly in Houston and near Corpus Christi. In contrast, data from this study represent more diverse materials from five other states—Louisiana, Arkansas, Missouri, New Mexico and Oklahoma. Finally, with respect to quality, the data filtering process used for this study followed the same quality provisions used by Touma–Reese in that SPT and TCP tests were taken in similar soils, at about equal depths, using the approved test method. But for this study, the data were established within the bounds of normal test precision and all *N*-values were standardized to 60% hammer efficiency. Collectively, this represents the largest, most diverse, and highest quality dataset available for obtaining side-by-side TCP-SPT correlations.

4 Results and Discussion: Texas Tech University TCP-SPT Correlations

With the test pairs established, the data were transformed to the log scale so that the required statistical conditions of normality and uniformity of variance were satisfied for a linear regression model. The researchers then performed statistical analyses using Minitab 17 (Minitab 2014) to determine numerical correlations between $N_{60,\ SPT}$ and $N_{60,\ TCP}$ for coarse-grained soils, fine-grained soils, and IGMs.

4.1 Coarse-Grained Soils

Figure 4 presents SPT and TCP test blowcount data for coarse-grained soils in log–log scale and depicts the regression model with confidence intervals and predictive intervals. This chart also identifies the best-fit $N_{60,\ SPT}$–$N_{60,\ TCP}$ regression equation with its coefficient of determination (R^2 value). For comparison purposes, the chart also shows the Touma-Reese correlation model.

The $N_{60,SPT}$–$N_{60,TCP}$ relationship for coarse-grained soils, expressed as a power function, is:

$$N_{60,SPT} = 5.541 * N_{60,TCP}^{0.4303}\ [\text{coarse - grained soil}] \tag{8}$$

The relationship shows the expected trend; that is, $N_{60,\ SPT}$ is lower than the corresponding $N_{60,\ TCP}$.

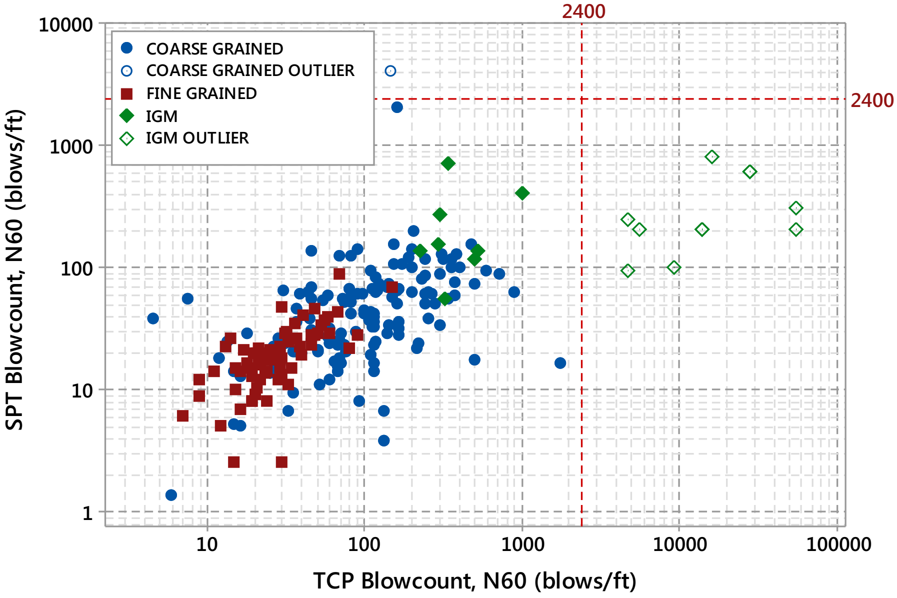

Fig. 3 Project dataset for establishing side-by-side N_{SPT}–N_{TCP} correlations. Permission: This image is original to this paper

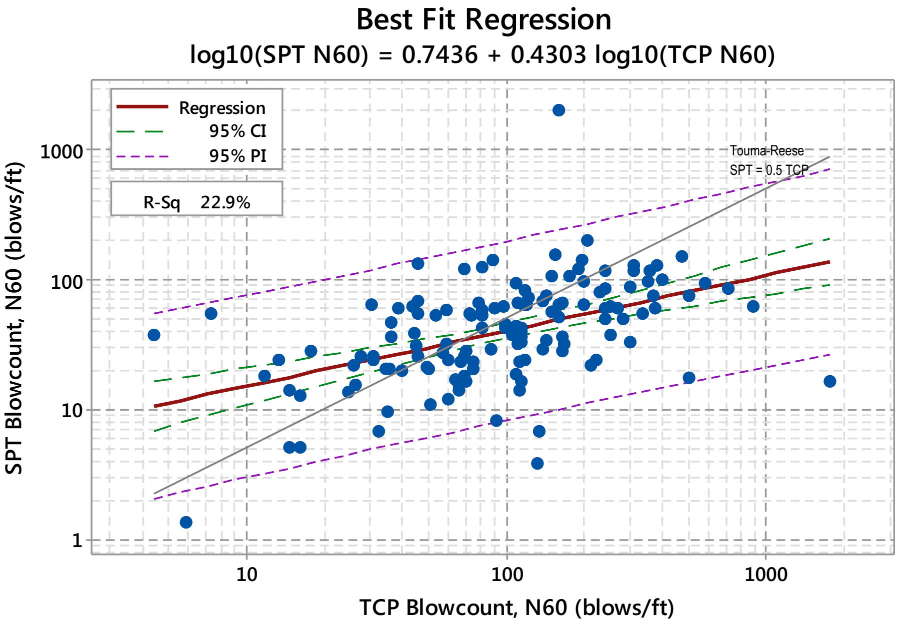

Fig. 4 N_{SPT}–N_{TCP} correlation for coarse-grained soils. Permission: This image is original to this paper

Further, regression parameters (intercept and slope) for coarse -grained soils are statistically significant with $p\ value = 0.000$, and this provides strong evidence that the identified correlation *does exist* for coarse-grained soils. The confidence interval, CI, is the range of values, derived from sample statistics, which is likely to contain the value of an unknown population parameter—in this case, the regression model. As calculated, there is 95% confidence that the regression model is within the identified CI range. The prediction interval (PI) is a range that is likely to contain the response value of a single observation. As calculated, for a given value of $N_{60,\ TCP}$, there is 95% confidence that $N_{60,\ SPT}$ is within this PI range (Minitab 2016).

Figure 4 shows much scatter in the relationship. For coarse-grained soils, $R^2 = 0.229$ which means that 23% of the $N_{60,\ SPT}$ variation is explained by the model.[2] This amount of explained variance is low, but is not atypical of many relationships in geotechnical engineering, in part because soil is a highly variable material and its physical behavior is difficult to predict. A weak correlation such as this is not adequate for engineers to convert $N_{60,\ TCP}$ to $N_{60,\ SPT}$ to compute foundation capacity for final design, as each penetration test specifically supports its own published foundation design methods. But, engineers can certainly get an intuitive feel about site conditions and preliminary foundation capacity by using the correlation equation to translate their knowledge of one test to the other.

It should also be noted that the regression function includes an intercept. For very low blowcount materials ($N < 5$), we expect the model will be highly nonlinear (even in the log scale) and pass through the origin for $N = 0$ (weight-of-hammer) material, but the dataset had almost no data in the very low blowcount range. The intercept allowed us to fit a statistically-significant model that encompasses the range of available data.

4.2 Fine-Grained Soils

Figure 5 shows the side-by-side TCP-SPT correlation, confidence intervals, and predictive intervals for fine-grained soils. For comparison purposes, the chart also shows the Touma–Reese correlation model. Expressed as a power function, the $N_{60,SPT}$–$N_{60,TCP}$ relationship for fine-grained soils is:

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[2] The coefficient of determination, R^2 is a goodness of fit statistic that indicates how close the data are to the regression line. Further R^2 is the square of the Pearson correlation coefficient, *r*.

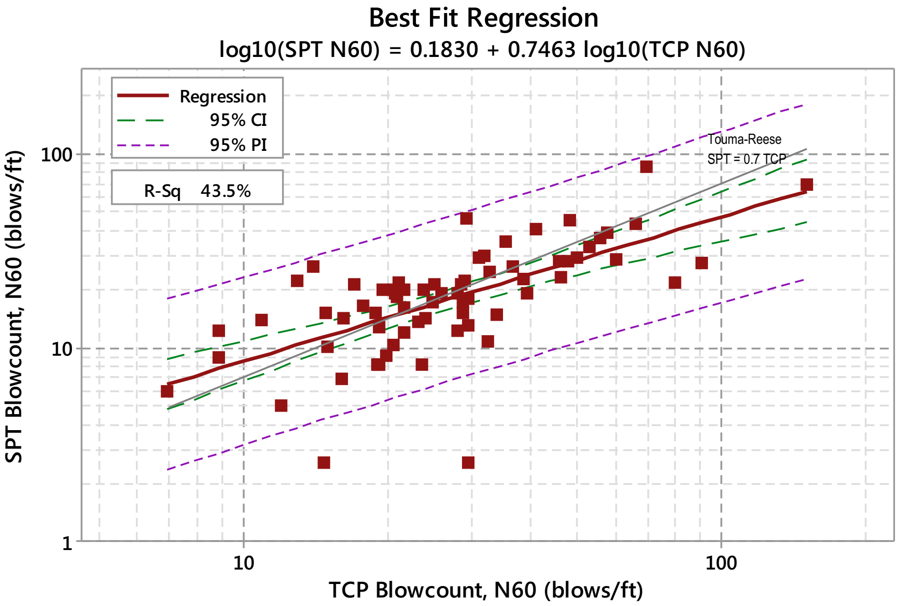

Fig. 5 N_{SPT}–N_{TCP} correlation for fine-grained soils. Permission: This image is original to this paper

$$N_{60,SPT} = 1.524 * N_{60,TCP}^{0.7463} \text{ [fine - grained soil]} \quad (9)$$

The relationship indicates the expected trend; that is, $N_{60,\ SPT}$ is lower than the corresponding $N_{60,\ TCP}$. Further, correlation parameters (intercept and slope) for fine-grained soils are statistically significant with *p value* $= 0.000$. The strength of the relationship is fair, with an R^2 value of 44%.

To provide context, Fig. 6 shows the correlation between N_{TCP} and undrained shear strength (s_u) of fine-grained soils as determined in the laboratory by unconfined compression testing. These data are from a major study by others that was intended to verify the design relationships used by TxDOT to determine the undrained shear strength of soil from TCP blow counts and to develop correlations with a high level of confidence based on the data. The study collected over 4000 sets of TCP blowcount data and undrained shear strength data from TxDOT project borings drilled during the period, 1994–2004 (Vipulanandan et al. 2008).

Data in Fig. 6 are presented in the normal scale. The nonlinear models for both CH soils and CL soils consider the average soil strength for each N_{TCP} value and depict the recommended N_{TCP}-s_u relationship with highest fidelity. The correlation for fat clay shows an R^2 value of 45–54% (depending on the model). The strength of this correlation is not inconsistent with that of the $N_{60,\ SPT}$–$N_{60,\ TCP}$ results from the present study for undifferentiated fine-grained soils. However, the N_{TCP}-s_u correlation for lean clay soils is much weaker, with R^2 values of 11–12%, indicative of significant scatter (Vipulanandan et al. 2008).

Collectively, the identified correlations help to explain the practical relationship between SPT and TCP blowcounts relative to site characterization and a general understanding of subsurface conditions and foundation bearing strength. Some correlations are very weak, and again, such findings do not justify use of the correlations to convert $N_{60,\ TCP}$ to $N_{60,\ SPT}$ or vice versa, in order compute foundation capacity for final design. The benefit is that those engineers who do not have experience with TCP will be able to relate their experience with SPT, and thus leverage insight from another subsurface characterization test and method.

4.3 An Example to Compare $N_{60,\ SPT}$–$N_{60,\ TCP}$ for Coarse and Fine-Grained Soils

Table 4 presents an example to facilitate further comparison of the $N_{60,\ SPT}$–$N_{60,\ TCP}$ correlations for both coarse-grained and fine-grained soils. The example starts with $N_{60,\ TCP}$ (this is known) and uses the correlation relationships identified in this paper to calculate $N_{60,\ SPT}$ values. The given $N_{60,\ TCP}$ values

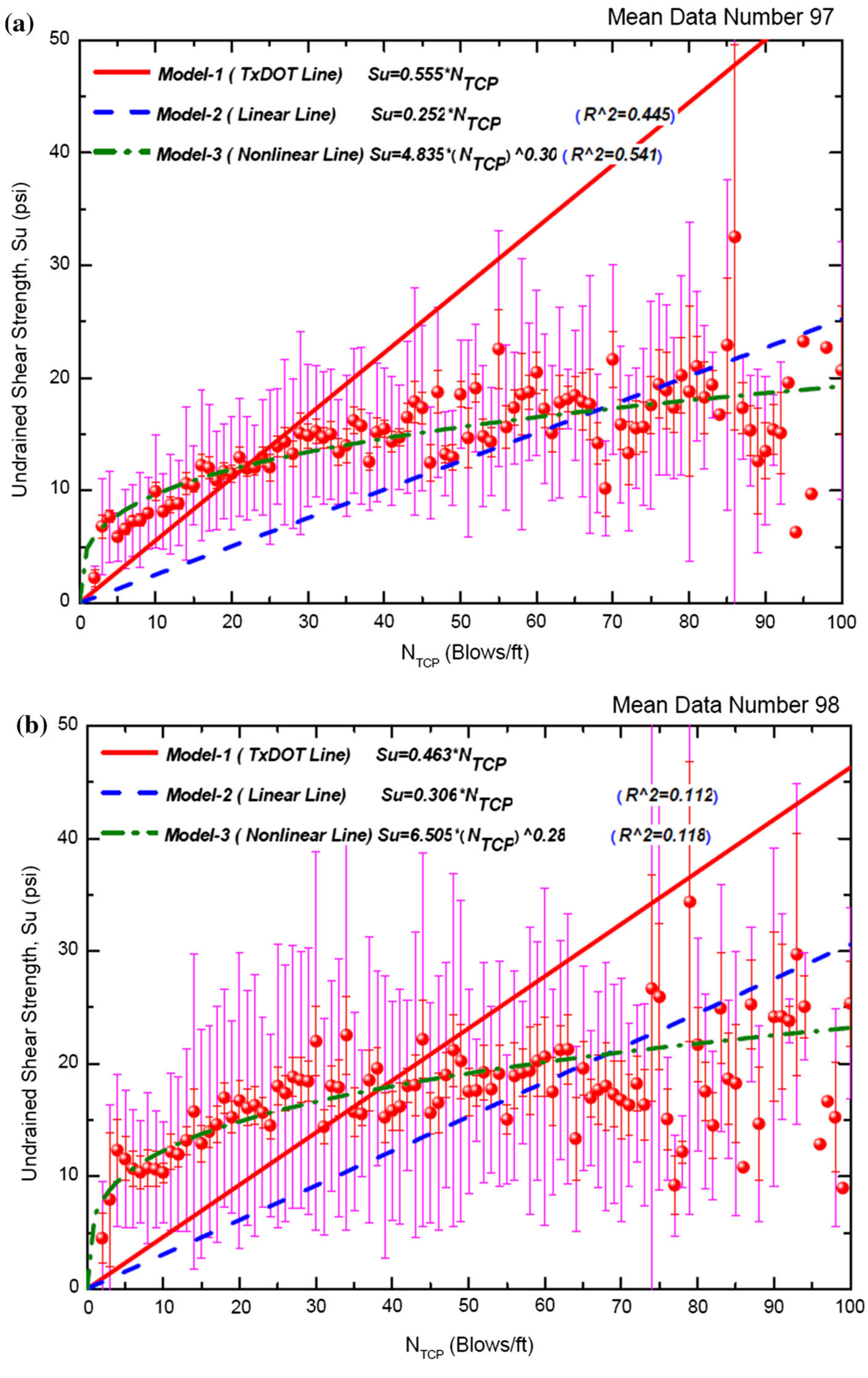

Fig. 6 Correlations between undrained shear strength (S_u) and TCP blowcount (N_{TCP}) for fine-grained soils (Vipulanandan et al. 2008). **a** S_u versus N_{TCP} for fat clay (CH), **b** S_u versus N_{TCP} for lean clay (CL). **a** Permission: This image is from a published TxDOT research report. Permission to use image is granted by TxDOT through its copyright liaison at the Center for Transportation Research Library, Austin, TX. **b** Permission: This image is from a published TxDOT research report. Permission to use image is granted by TxDOT through its copyright liaison at the Center for Transportation Research Library, Austin, TX

(left column, Table 4) range from 10 blows/30 cm (1 *ft*) to 500 blows/30 cm (1 ft).

Table 4 illustrates that all correlation approaches show the expected trend that N_{SPT} values are typically lower than N_{TCP} values for soils, 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, especially for lower *N*-values,

Table 4 Comparison of N_{SPT} and N_{TCP} correlation methods

N_{TCP} (example) (blows/30 cm (1 ft)	N_{SPT} (by correlation) (blows/30 cm (1 ft)					
	Texas Tech University		Touma-Reese		Burmister	Lacroix and Horn
	Fine grained	Coarse grained	Fine grained	Coarse grained		
10	8	15	7	5	2	4
25	17	22	18	13	6	11
50	28	30	35	25	12	22
100	47	40	70	50	23	43
200	79	54	140	100	46	86
500	157	80	350	250	115	215

blowcount values for the fine-grained soils are more consistent; whereas, blowcount values for the coarse-grained soils vary widely. Further, the Touma-Reese correlation is non-conservative for higher blowcount values in coarse-grained soils when converting from N_{TCP} to N_{SPT}.

The correlation equations identified in Figs. 4 and 5, and quantified in Table 4, are consistent with earlier observations about the nature of the SPT and TCP tests. When soil materials are very soft, it really does not matter whether we use a solid rod with a conical point or a hollow tube to penetrate the same distance. But, when materials becomes stiffer (or denser), it becomes harder to penetrate into the material with a solid section, and this is particularly evident for coarse-grained soils. So, clearly, the relationship should be nonlinear. Further, when materials are very soft, the penetration resistance is localized, similar to punching shear. But as materials become more stiff/dense, the influence zone below the cone becomes deeper and wider, more like general shear. So, the *N*-values from stiffer/denser materials reflect penetration resistance from a larger volume of soil as compared to softer materials; consequently, uncertainties or scatter in the correlation are larger for the stiffer/denser soils.

4.4 Intermediate Geomaterials

The project dataset contained 19 data pairs for IGMs, eight pairs of which survived the data filtering process and were suitable for analysis. However, unlike the data for coarse-grained and fine-grained soils, the regression analyses did *not* identify a publishable correlation for IGMs. The IGM dataset was very small and the relationship was not statistically significant ($p\ value = 0.51$), so the results failed to reject the null hypothesis.

Various observations can be made about field penetration tests in IGMs. First, SPT data are rarely used for design of foundations in materials other than coarse-grained and fine-grained soils. By virtue of their higher shear strength, IGMs are just too dense and hard to achieve anything other than refusal blowcounts or damage to the split spoon sampler. So a direct, side-by-side N_{TCP}–N_{SPT} correlation could only be achieved for softer IGMs.

Second, the TCP test *is* suitable for in situ evaluation of IGMs in that its solid steel conical point and robust manufacture are designed to withstand repeated hammer blows in very dense to hard materials. Accordingly, the TCP foundation design charts go beyond soil materials typified by N_{TCP} values harder than 100 blows/30 cm (1 ft) to include IGMs and rock with N_{TCP} penetrations less than 30 cm (12 in.)/100 blows.

Third, published research by others (Valluru et al. 2007) has explored the correlation between N_{TCP} and shear strength/compressive strength of IGMs as determined by uniaxial compression testing (see Fig. 7). These data are from site characterization associated with a major turnpike project (79 km [49 mi] in length) which included drilling approximately 660 soil borings with total drilling length of about 9100 m (30,000 ft).

Data in Fig. 7 are presented in the normal scale. The nonlinear correlations directly compare N_{TCP}

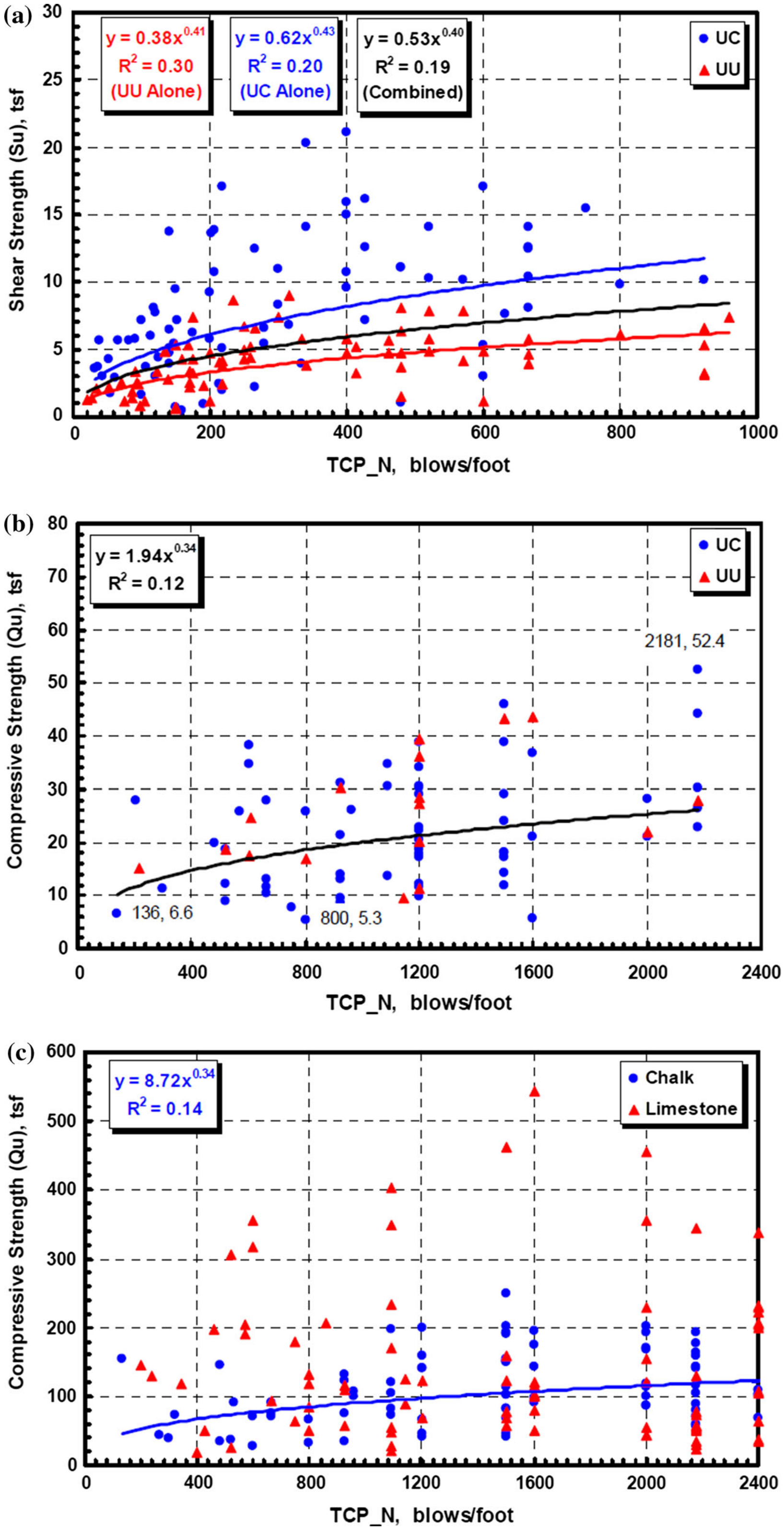

Fig. 7 Correlations between undrained shear strength (S_u) and compressive strength (Q_u) versus TCP blowcount (N_{TCP}) for intermediate geomaterials (Valluru et al. 2007). **a** S_u versus N_{TCP} for Shaley clay, **b** Q_u versus N_{TCP} for Shale, **c** Q_u versus N_{TCP} for limestone and chalk **a** Permission: Image copyright held by corresponding author, Shashank Valluru, Professional Services Industries, Inc., Houston, TX. Permission granted 12/15/2015. **b** Permission: Image copyright held by corresponding author, Shashank Valluru, Professional Services Industries, Inc., Houston, TX. Permission granted 12/15/2015. **c** Permission: Image copyright held by corresponding author, Shashank Valluru, Professional Services Industries, Inc., Houston, TX. Permission granted 12/15/2015

values to laboratory shear strength measured using both unconfined compression (UC) and unconsolidated-undrained (UU) test methods. Three types of IGMs were evaluated: shaley clay, shale, and limestone/chalk. The data show wide scatter, with R^2 values ranging from 19 to 30% for shaley clay, 12% for shale, and 14% for limestone and chalk. The correlations of Fig. 7 (Valluru et al. 2007) are consistent with findings from a study by Lawson et al. (2009) which analyzed 965 test pairs of TCP-UC data for IGMs and various types of weak rock. The basic finding is that N_{TCP}-shear strength/compressive strength correlations exist for IGMs, but these are, at best, very weak to weak.

5 Summary and Conclusions

This study presents a side-by-side comparison of SPT and TCP test blowcount values in coarse-grained soils, fine-grained soils, and intermediate geomaterials. A dataset of 225 TCP-SPT test pairs was assembled and analyzed using statistical regression techniques. This dataset more than doubles the size of the previously-published datasets for side-by-side blowcount correlations, especially for coarse-grained soils. These data pairs were obtained in similar soils and geomaterials, at equivalent depths, with all blowcounts normalized to 30 cm (12 in.) penetration (i.e., blows/30 cm or blows/ft) within the bounds of typical test precision, and corrected to 60% hammer efficiency.

The key findings from the side-by-side $N_{60,\ SPT}$–$N_{60,\ TCP}$ correlations established from this research are as follows:

1. The dataset yielded statistically-significant correlations for both coarse-grained soils and fine-grained soils. For coarse-grained soils, the dataset showed significant scatter and the strength of the correlation is weak ($R^2 = 23\%$). For fine-grained soils, the strength of the correlation is fair ($R^2 = 44\%$).
2. Consistent with expected trends and published data, the TCP-SPT relationship is nonlinear. Comparatively, for TCP blowcounts ($N_{60,\ TCP}$) varying from 25 to 200 blows/30 cm (1 ft), corresponding SPT blowcounts ($N_{60,\ SPT}$) are typically 30–60% lower than $N_{60,\ TCP}$ in fine-grained soils, and SPT blowcounts ($N_{60,\ SPT}$) are 10–70% lower than $N_{60,\ TCP}$ in coarse-grained soils, all other things being equal.
3. A limited dataset for intermediate geomaterials showed a large amount of scatter and this relationship was not statistically significant. However, the TCP test may be used for in situ evaluation of IGMs in that its solid steel conical point and robust manufacture are designed to withstand repeated hammer blows in very dense to hard materials. Accordingly the TCP foundation design charts go beyond soil materials to include IGMs and rock, and published studies by others identify a very weak to weak nonlinear correlation between N_{TCP} and shear strength of IGMs as determined by uniaxial compression testing.

Overall, the nonlinear correlation models identified from this study build on and extend previous studies which correlate TCP blowcounts with SPT blowcounts and with undrained shear strength of soils and IGMs. The findings of this study help to explain the practical relationship between SPT and TCP blowcounts relative to site characterization and a general understanding of subsurface conditions. Those engineers who do not have any experience with TCP will be able to relate their experience with SPT by using the correlation equations. The generally weak nature of the correlations does not support conversion of $N_{60,\ TCP}$ to $N_{60,\ SPT}$ to compute foundation capacity for final design. But, engineers can certainly get an intuitive feel about site conditions and preliminary foundation capacity by using the correlation equations to translate their knowledge of one test to the other.

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Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

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