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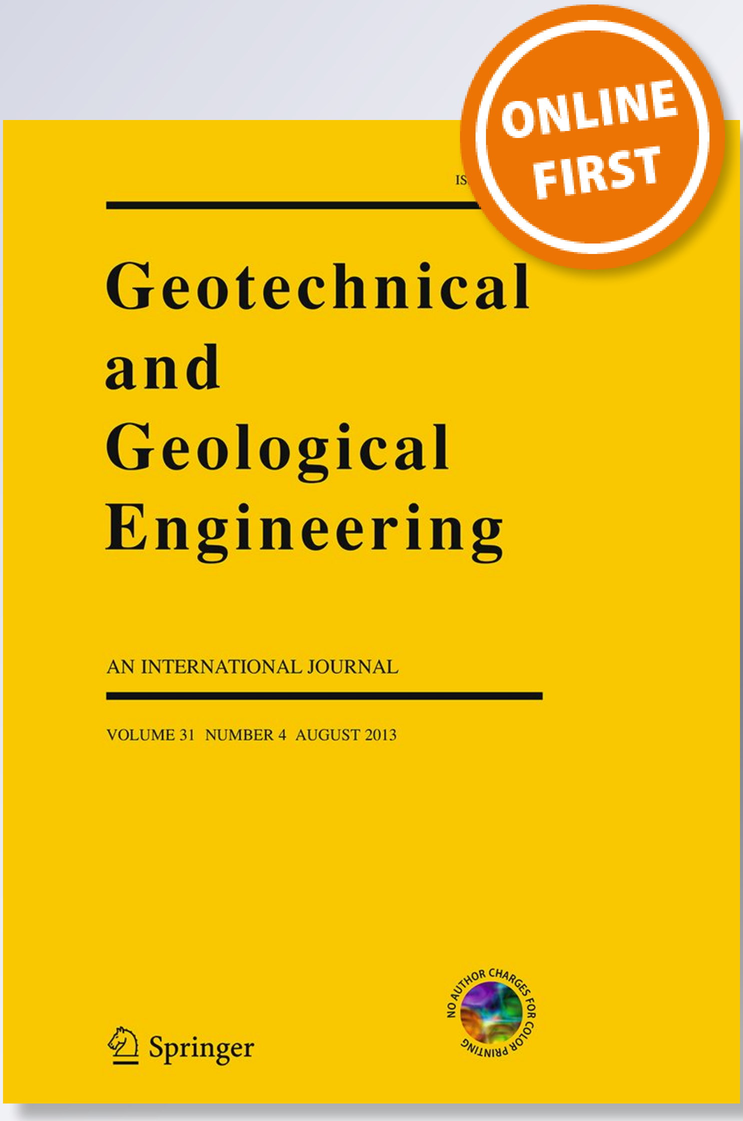

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ORIGINAL PAPER

# Hammer Efficiency and Correction Factors for the TxDOT Texas Cone Penetration Test

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**Abstract** This study analyzes blowcount data from instrumented Texas Cone Penetration (TCP) tests. TCP hammer efficiency, rod length influence on the hammer efficiency, and overburden pressure correction factors for the TCP blowcounts ($N_{TCP}$) are explored. Results are compared to published correction factors for the standard penetration test (SPT). The final dataset analyzed for this study consisted of 293 TCP tests from which 135 tests were instrumented. TCP hammer efficiency values for automatic trip hammers ranged from 74 to 101% with an average of 89%. Analyses showed a statistically-significant relationship between the TCP hammer efficiency and the rod length below ground surface. Statistical models were developed for undifferentiated soils, and corresponding rod length correction factors for the TCP test ($C_{R\text{-}TCP}$) were obtained ranging from 0.90 to 1.00. In a second analysis, the relationship between the overburden pressure and $N_{TCP}$ was explored and a mathematical expression for the overburden correction factor for the TCP blowcount value ($C_{N\text{-}TCP}$) was determined. This work represents the first study where corrections to $N_{TCP}$ are explored, and the outcome of this research benefits the geotechnical engineering community using the TCP test and its associated foundation design method.

**Keywords** Texas Cone Penetration test · TCP · Standard penetration test · SPT · Rod length correction factor · Overburden correction factor · Hammer efficiency · Correction factors

## List of symbols

| | |
|---|---|
| a and b | Skempton (1986) soil dependent parameters |
| $C_b$ | Borehole diameter correction factor for SPT |
| CI | Confidence intervals |
| $C_N$ | Overburden correction factor for SPT |
| $C_{N\text{-}TCP}$ | Overburden correction factor for TCP |
| COV | Coefficient of variation |
| $C_r$ | Rod length correction factor for SPT |
| $C_{R\text{-}TCP}$ | Rod length correction factor for TCP |

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| | |
|---|---|
| $C_s$ | Sampler type correction factor for SPT |
| $D_R$ | Relative density |
| $E_m$ | Measured hammer energy |
| $E_r$ | Hammer efficiency-SPT |
| $E_{r\text{-TCP}}$ | Hammer efficiency-TCP |
| $E_t$ | Theoretical hammer energy |
| K | Exponent of the power function developed for overburden correction factor |
| $N_{1\text{-}60}$ | SPT blowcount standardized to 60% energy and corrected for overburden |
| $N_{1\text{-}60\text{-}TCP}$ | TCP blowcount standardized to 60% energy and corrected for overburden |
| $N_{60}$ | SPT blowcount standardized to 60% energy |
| $N_{60\text{-}TCP}$ | TCP blowcount standardized to 60% energy |
| $N_{N\text{-}TCP}$ | Normalized TCP blowcount to a blowcount corresponding to a reference stress |
| $N_{SPT}$ | SPT blowcount |
| $N_{TCP}$ | TCP blowcount |
| PI | Prediction intervals |
| SPT | Standard penetration test |
| TCP | Texas Cone Penetrometer |
| $z$ | Depth |
| $z_1$ | Depth of interest |
| $z_{Baseline}$ | Depth at which the fitted model has flattened |
| $\beta_1$ | Slope for a linear model equation |
| $\beta_o$ | Intercept for a linear model equation |
| $\sigma'_v$ | Effective vertical stress |
| $\sigma'_{ref}$ | Reference stress (i.e. 100 kPa, 2000 psf) |
| $\sigma'_N$ | Normalized effective vertical stress to a reference stress |

## 1 Introduction

This paper presents correction factors for blowcount values ($N_{TCP}$) from the Texas Cone Penetration (TCP) test, a dynamic field penetration test which is similar to yet different from the standard penetration test (SPT). For over 60 years, the TCP test and its associated foundation design charts have been used successfully for the design of drilled shaft and driven pile foundations that support tens of thousands of bridges and other major transportation infrastructure throughout Texas and parts of Oklahoma. Data for this study were obtained as part of a program of 293 TCP tests obtained from 21 geotechnical borings in five states located in the south-central United States. These data were used to identify the average hammer efficiency for the TCP test using an automatic hammer, and also to develop rod length correction factors and overburden pressure correction factors for the $N_{TCP}$ values.

The main purpose of correction factors for field penetration blowcount values is to achieve consistent and reliable input data for the foundation design procedures associated with the tests. In the case of SPT, several studies have been completed to address the impact of different factors on the hammer efficiency which further influences $N_{SPT}$. In contrast to SPT, no published work discusses a corrected $N_{TCP}$ nor addresses the influence of different factors on TCP hammer efficiency. This paper contributes to the geotechnical engineering community where the TCP design charts are used as the primary method for the design of deep foundations. The factors presented in this paper help to standardize $N_{TCP}$ and further obtain accurate design parameters for foundation design based on the TCP design charts.

The TCP test and its associated foundation design method are introduced and compared to the SPT to further highlight similarities and differences. To set the stage for the analyses presented in this paper, a review of the history of the TCP test and the development of correction factors for the SPT are described. Tasks associated with the field data collection for this study followed by statistical analyses and results are discussed in detail. Finally, hammer efficiency for the TCP test and rod length correction factors for $N_{TCP}$ are developed and compared to existing factors for the SPT. Furthermore, the effect of the overburden pressure on the variation of $N_{TCP}$ is analyzed and discussed.

## 2 The TxDOT Texas Cone Penetration Test

### 2.1 Description of the TCP Test

The TCP test is a dynamic field penetration test which assesses the consistency of the material encountered during geotechnical exploration. This test method is documented as TxDOT Designation Tex-132-E, “Test Procedure for Texas Cone Penetration” (TxDOT 1999). The TCP test uses a 77.0-kg hammer with

0.61-m drop to force a 7.6-cm diameter steel cone into the soil or rock formation, Fig. 1.

In current practice, penetration for the TCP test is performed in three separate increments. The first is to achieve proper seating, consisting of driving the cone 12 blows or approximately 15-cm, whichever comes first. The TCP blowcount is then determined as the sum of the number of blows required to achieve the second and third 15-cm increments. The total blowcount or $N_{TCP}$ corresponding to 30-cm penetration is used to obtain design parameters. In very hard materials such as rock and intermediate geomaterials (IGM), after the proper seating process, the cone is driven 100 blows and the penetration value for the first and second 50 blows are recorded, with the $N_{TCP}$ value reported as centimeters of penetration per 100 blows.

## 2.2 History and Development of the TCP Test

In the 1940s, the newly-formed Bridge Foundation Soils group of the Texas Highway Department (THD) Bridge Division identified the need for developing a unified method for the characterization of geomaterials and the design of deep foundations. The TCP test method was developed by the Bridge Group as an in situ test method for evaluating the broad range of geologic materials encountered in foundation construction (TxDOT 2000).

The TCP-based foundation design method was introduced in the 1956 edition of the Foundation Exploration and Design Manual (THD 1956). This manual provided a series of correlation relationships for foundation design which were established based on TCP test blowcount data ($N_{TCP}$) and laboratory-measured shear strength using the triaxial test procedure (THD 1956). The charts published in 1956 were refined in 1972, 2000, and 2012, and two sets of design charts now exists. The first set was developed for the prediction of unit shaft resistance (i.e. skin friction) and unit base resistance (i.e. point bearing) for soils with TCP blowcounts less than 100 blows/30-cm, Fig. 2. The second set is for geomaterials with blowcounts greater than 100 blows/30-cm (i.e. penetration per 100 blows), Fig. 3. The current design charts reflect the allowable stress design philosophy and present allowable unit shaft and base resistances based on $N_{TCP}$ and soil types.

## 2.3 Application of the TCP Test

The TCP test and its associated foundation design method have been used regionally, nationally and internationally. As would be expected with its Texas roots, the TCP test has seen extensive application throughout the state to evaluate subsurface materials ranging from very soft coastal clays, to shales and weathered/fractured limestones, to hard and brittle rock. Texas currently maintains over 53,000 bridges in the National Bridge Inventory (FHWA 2016), and most of these bridges plus other transportation

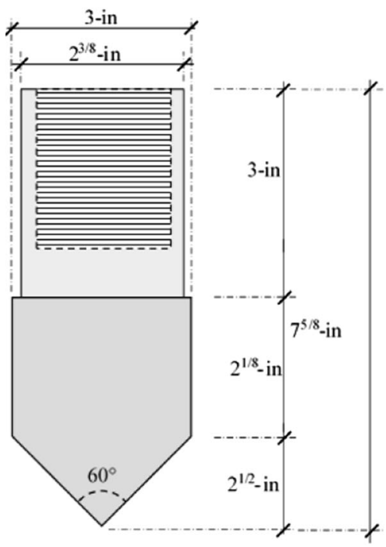




**Fig. 1** TCP test conical driving point and field application. **a** TCP conical driving point (Moghaddam 2016), **b** field application of the TCP test (Moghaddam 2016)

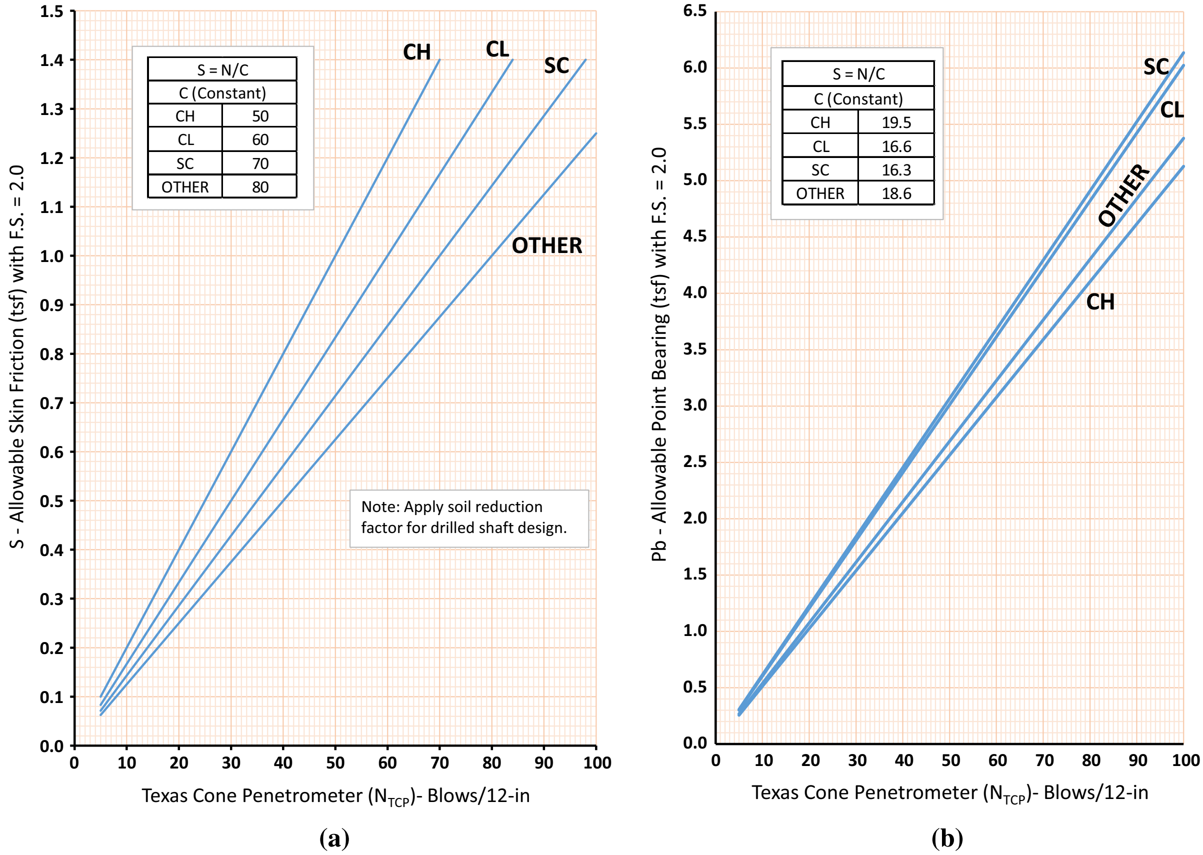



**Fig. 2** **a** Allowable shaft resistance and **b** base resistance versu TCP blows/30-cm (blows/12-in) (TxDOT 2012)

infrastructure in Texas are supported by foundations designed in accordance with the TCP method. The Oklahoma DOT adopted the TCP test and foundation design approach in the 1970s, so the foundations for most of the 23,000 bridges in Oklahoma's inventory were also designed using the TCP method. Collectively this means over 12% of U.S. bridges are associated with the TCP test. The TCP test is discussed in NCHRP Synthesis 360 (Turner 2006), and owing to competitive opportunities for Texas' major transportation infrastructure projects, geotechnical practitioners and academics nationwide have had occasion to learn about and use the TCP test. More recently, a comprehensive research program in Missouri evaluated a modified version of the TCP test for bridge foundation design applications using LRFD concepts (Loehr et al. 2011). The TCP test was introduced to an international audience of deep foundation engineers in Japan (Vipulanandan 2007), and the TCP test has been used in Korea for field explorations associated with a bridge abutment overlying intermediate geomaterials and soft rock where cores would have been recovered in fragments because of joint structures (Nam et al. 2013). In fact, it is this particular application—i.e., fractured intermediate geomaterials and rock—where the TCP test can add the most value to a field exploration program because no other test is available to assess these types of materials. For these reasons, the TCP test is of practical benefit, and the scope of the TCP test is significant well beyond its regional origins.

## 3 Comparison of SPT Versus TCP Tests

The SPT is an international standard for measuring soil penetration resistance and obtaining a representative disturbed soil sample for identification purposes (ASTM 2016) and has adopted a 63-kg hammer mass with a falling height of 76-cm to force a 45-cm sampler (i.e. split spoon) with a coupler and driving

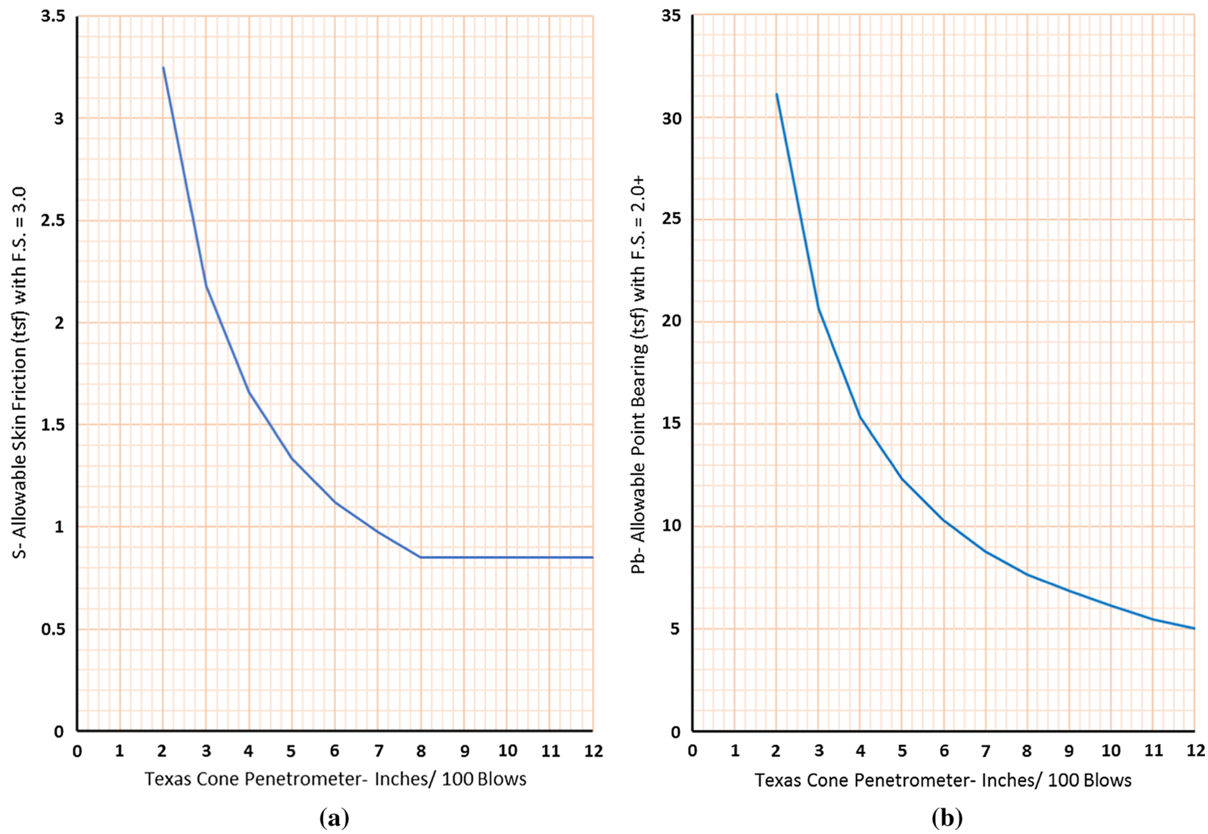



**Fig. 3** **a** Allowable shaft resistance, **b** allowable base resistance versus TCP penetration/100 blows (TxDOT 2012)

shoe to penetrate into soil strata. The conventional SPT driving procedure where blows are recorded for each of three 15-cm 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".

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 increments. However, in certain aspects the TCP test differs from the SPT. The TCP test does not use a split-barrel sampler but rather a solid steel conical point with 60° apex angle, Fig. 1. Hence, the TCP test cannot and does not collect a soil sample. Also, because of its more robust solid steel design, TCP test refusal is defined as resistance to penetration greater than 100 blows/30-cm, 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/15-cm, or when there is no observed advance of the sampler during the application of 10 successive blows.

Another difference between the SPT and the TCP test is the magnitude of their blowcount values. The correlation between $N_{TCP}$ and $N_{SPT}$ is not linear, and $N_{SPT}$ values are typically 20–60% lower than $N_{TCP}$ values, other things being equal (Touma and Reese 1972). It is possible to gain an intuitive sense about this by comparing the hammer energy and the sampler area for the two tests. The theoretical hammer energy for the tests is roughly equivalent—475 N-m for the SPT versus 461 N-m for the TCP. But the cross-sectional area of the samplers is quite different. The nominal cross-sectional area for an unplugged SPT split spoon is 1071 mm$^2$ compared to the TCP conical point with cross sectional area of 4561 mm$^2$. Thus, it ought to take a lot less energy to drive an SPT split barrel sampler than the TCP cone, so SPT blowcounts should be significantly lower than TCP blowcounts in the same material. This is in fact the case.

Since the 1970s, research has shown that blowcounts obtained from the SPT ($N_{SPT}$) are sensitive to factors such as hammer energy, rod length, type of soil, borehole diameter, and others. In the case of SPT a significant body of literature and research exists to facilitate direction and guidance for correcting $N_{SPT}$ values and further use a standardized $N_{SPT}$ for design. In contrast, for the TCP test, published work has not been completed exploring the effects of these same factors, and perhaps other factors influencing the resistance to penetration.

It is important to mention that throughout this paper, detailed discussion and mathematical expressions regarding the SPT and the TCP test are presented. For purposes of clarity and consistency all factors, equations, and parameters associated with the TCP test will have the subscript "TCP". Any other geotechnical field testing parameter presented without the subscript will be associated with the SPT.

## 4 Development of Correction Factors for SPT

### 4.1 Standardization of the SPT Blowcount

To reduce the variability of $N_{SPT}$ due to multiple factors associated with the test, several researchers have recommended the standardization of $N_{SPT}$ to a specific level where the influence of these factors has been addressed through correction factors. Numerous technical reports and research studies have been published addressing the factors that may influence the $N_{SPT}$ including hammer type, sampler, driving mechanism, depth of test, borehole diameter, and physical aspects of tools used during the test. See Palmer and Stuart (1957), Fletcher (1965), Ireland (1970), DeMello (1971), Brown (1977), Schmertmann et al. (1979), Kovacs and Salomone (1982), Seed et al. (1984), Skempton (1986), Daniel et al. (2004), Odebrecht et al. (2005), and Schnaid (2009). The work completed by these researchers mainly focused on the determination of a standard $N_{SPT}$ where all the variabilities associated with the test procedure are accounted for. In later years, this topic continued to evolve with slightly different focus. Work done by Aggour and Radding (2001) and Idriss and Boulanger (2012) focused on the calibration of $N_{SPT}$ for purposes of liquefaction and corrections for overburden pressure after the work presented by Skempton (1986).

### 4.2 Development of Correction Factors for SPT N-Values

The energy delivered into the drilling rod and the sampler is impacted by the release method and type of hammer (Skempton 1986). Based on the results of studies described above and recommendations presented by Seed et al. (1984), a correction to the $N_{SPT}$ was proposed by Skempton (1986) based on the hammer energy ratio reported in the United States. The hammer energy ratio ($E_r$), also termed "hammer efficiency", refers to the relationship between measured energy ($E_m$) and theoretical energy ($E_t$), $E_r = E_m/E_t * 100\%$. $N_{SPT}$ values with a known energy ratio can be normalized to 60% of hammer efficiency using Eq. (1).

$$N_{60} = N_{SPT}\frac{E_r}{60} \tag{1}$$

In Eq. (1), $N_{60}$ is the normalized $N_{SPT}$ for 60% hammer efficiency, $N_{SPT}$ is the SPT blowcount for 30-cm penetration, and $E_r$ is the hammer efficiency in percentage for a specific type of hammer.

In addition to the energy ratio, Skempton (1986) further developed work done by Schmertmann and Palacios (1979) who determined that the required energy to drive the sampler is increased as the rod length increases. He also considered research completed by Seed et al. (1984) who showed that approximately 20% more blows corrected for 60% of hammer efficiency were required to drive a SPT sampler with a liner. From this work, Skempton (1986) determined correction factors for rod length, sampler type, and borehole diameter, and modified Eq. (1) by introducing correction factors:

$$N_{60} = N_{SPT}\frac{E_r}{60}C_rC_bC_s \tag{2}$$

In Eq. (2), $C_r$, $C_b$, and $C_s$ are correction factors to the SPT blowcounts to account for rod length, borehole diameter, and type of sampler, respectively. These corrections have appeared in standard geotechnical textbooks such as *Geotechnical Engineering: Principles and Practice* by Coduto et al. (2011) *and Fundamentals of Geotechnical Engineering* by Das and Sobhan (2014).

### 4.3 The Overburden Pressure Correction for SPT

According to Meyerhof (1957) the penetration resistance increases linearly with depth, and at a constant vertical stress, the resistance to penetration also increases at a rate approximately equal to the relative density squared, Eq. (3).

$$N_{SPT} = D_R^2\left(a + b\sigma'_v\right) \quad (3)$$

In Eq. (3), a and b are soil-dependent factors, $D_R$ is the relative density, and $\sigma'_v$ is the effective vertical stress at the depth of test.

The effect of overburden pressure on the $N_{SPT}$ is further expressed by introducing a correction factor for overburden pressure ($C_N$). Skempton (1986) presented results of two trials completed for sand deposits with different particle size. For these trials, a laboratory model was built where the variation of $N_{SPT}$ with depth was determined while maintaining a constant relative density ($D_R$) of the sand. During the second trial, the test was carried out with different relative densities of the sand. The results followed the relationship presented by Meyerhof (1957) shown in Eq. (3). In addition, results from field testing at different sites were compared to the laboratory model leading to the development of an overburden correction factor $C_N$. With the overburden pressure correction factor, the $N_{SPT}$ and $N_{60}$ can further be corrected as shown in Eqs. (4) and (5).

$$N_{1-SPT} = C_N N_{SPT} \quad (4)$$

$$N_{1-60} = \frac{E_r}{60} C_r C_b C_s C_N N_{SPT} \quad (5)$$

In Eq. (4) $N_{1\text{-}SPT}$ refers to SPT blowcounts corrected for overburden pressure. In Eq. (5) $N_{1\text{-}60}$ refers to SPT blowcounts corrected for both 60% hammer efficiency and overburden pressure. Researchers have developed many expressions for $C_N$ where results have been supported by laboratory models and field test results. Table 1 presents a summary of typical expressions developed for $C_N$.

### 4.4 Contemporary Practice for Correcting SPT Blowcount Data

According to Schnaid (2009), in current practice, the SPT is the most common and popular in situ test method to obtain subsurface information and predict soil strength parameters. As comparator and to assess the standard practice of corrected or normalized $N_{SPT}$, geotechnical manuals published by all 50 State DOTs were reviewed. Results show that 72% of the state DOTs specify correction factors shown in Eq. (2) and further correction for effect of the overburden pressure using Eq. (4) is suggested. For the selection of design parameters, the $N_{1\text{-}60}$ value is used. Furthermore, in some states such as Florida, the specification requires the consultants to report $N_{SPT}$ in the boring logs but mandates the design of all elements to be based on $N_{1\text{-}60}$. Also, most DOTs require the consultant to show proof of calibration of the hammer prior to any work completed for the agency.

## 5 Corrections to TCP Blowcount

### 5.1 Need for TCP Correction Factors

The predictive allowable foundation capacity models represented in both SPT and TCP foundation design methods source to empirical data obtained during an era when the use of conventional donut hammers and safety hammers was a standard practice for the completion of geotechnical field penetration tests. Because of similarities between SPT and TCP test procedures where hammer, anvil, drill rod, and blowcounts are common aspects in both tests, it is reasonable to consider that all uncertainties and variabilities associated with the SPT could very well be present in the TCP test. Therefore, blowcounts obtained from both SPT and TCP tests using today's automatic hammers should be corrected to a standard measurement of blowcounts.

### 5.2 TxDOT Policy

TxDOT's current *Geotechnical Manual* (2012) presents the guidelines for the use of TCP as a field test and further refers to TEX 132-E as the approved TCP test method. The use of an automatic hammer is specified in the *Geotechnical Manual*, but neither the *Geotechnical Manual* nor the test method provides information regarding the need for correction of $N_{TCP}$ or evaluation of the hammer efficiency. The use of an automatic trip mechanism is specified to ensure the 0.61-m required falling height, and this requirement is part of TxDOT's current geotechnical service

**Table 1** Summary of existing overburden correction factors ($C_N$)

| Reference | $C_N$ | Observations |
|---|---|---|
| Peck et al. (1974) | $0.77\log\frac{20}{\sigma'_v}$ | $\sigma'_v$ in tsf |
| Seed et al. (1984) | $1 - 1.25\log\sigma'_v$ | $\sigma'_v$ in tsf |
| Tokimatsu and Yoshimi (1983) | $\frac{1.7}{0.7+\sigma'_v}$ | $\sigma'_v$ in kg/cm$^2$ |
| Skempton (1986) | $\frac{200}{100+\sigma'_v}$ $D_R = 40–60\%$ and NC Sand | $\sigma'_v$ in kPa |
| | $\frac{300}{200+\sigma'_v}$ $D_R = 60–80\%$ and NC Sand | |
| | $\frac{170}{70+\sigma'_v}$ for OC Sand | |
| Liao and Whitman (1986) | $\sqrt{\frac{100}{\sigma'_v}}$ for NC Sand | $\sigma'_v$ in kPa |
| | $\left[\frac{\sigma'_{REF}}{\sigma'_v}\right]^k$ for $k = 0.4$ to $0.6$ | |
| Clayton (1995) | $\frac{143}{43+\sigma'_v}$ for OC Sand | $\sigma'_v$ in kPa |
| Robertson et al. (2000) | $\left[\frac{\sigma'_v}{\sigma'_{atm}}\right]^{-0.5}$ for NC Sand | $\sigma'_v$ in kPa |

contracts. Further, TxDOT's current geotechnical service contracts require that drilling subcontractors provide annual certification of TCP hammer efficiency.

## 6 Research Design and Method

### 6.1 The TCP Reliability Research Study

The dataset for this paper was obtained from a research study where the reliability of the TCP foundation design method was assessed (Seo et al. 2015). Based on the energy data and soil information collected during field operations for that study, a complementary research study was designed to further explore the TCP test hammer efficiency ($E_{r\text{-}TCP}$), rod length correction factor ($C_{R\text{-}TCP}$), and overburden pressure correction factor ($C_{N\text{-}TCP}$). A dataset of 293 TCP tests was compiled. These data source to 21 geotechnical borings at 16 different sites in the states of Louisiana, Arkansas, Missouri, New Mexico and Texas as shown in Table 2.

### 6.2 Field work and TCP Blowcount Data Sources

Per TxDOT *Geotechnical Manual*, TCP tests were performed at 1.5-m intervals throughout the borings starting at the depth of 1.5-m below the ground surface and ending at the maximum depth of boring. For identification and classification of the subsurface materials associated with the TCP test, disturbed samples were collected using either SPT split-spoon or thin-walled tube samples obtained directly below the TCP test without having cleaned out the borehole. The sole purpose of the disturbed samples was to identify and classify the material associated with each TCP test at depth.

Throughout the geotechnical drilling and sampling phase, four different drill rigs, each one equipped with an automatic CME-hammer, were used. For the borings completed in Missouri and Arkansas Northeast, AWJ[1] rod was used; whereas, the rest of the borings were carried out using NWJ[2] rod. Prior to drilling operations, the automatic hammer was disassembled and the hammer mass was weighed to ensure conformance with TCP test standards (i.e. Tex-132-E).

### 6.3 Hammer Energy Readings

Force, acceleration, and rod length were measured for all TCP tests at 3.0-m intervals using the SPT Analyzer. This device includes a subassembly of a 0.61-m length of drill rod that is instrumented with two strain gage bridges and two piezo-resistive accelerometers. These sensors obtained measured force and

[1] AWJ refers to conventional taper threaded drill rod—outside diameter 44.5 mm, thread pitch 5.1 mm.

[2] NWJ refers to conventional taper threaded drill rod—outside diameter 66.7 mm, thread pitch 6.4 mm.

**Table 2** Field research sites and related TCP-borings

| State site location | Geotechnical borings | TCP tests in soils | TCP tests in rock/IGM | Instrumented TCP tests in soil | Instrumented TCP tests in rock/IGM |
|---|---|---|---|---|---|
| Missouri—Warrensburg | 2 | 2 | 8 | 1 | 4 |
| Missouri—Frankford | 2 | 0 | 16 | 0 | 7 |
| Texas—Houston | 1 | 12 | 0 | 7 | 0 |
| Arkansas—Siloam Springs | 2 | 5 | 9 | 2 | 0 |
| Arkansas—Monticello | 2 | 37 | 0 | 20 | 0 |
| Arkansas—Turrell | 2 | 38 | 0 | 20 | 0 |
| Louisiana—Various | 7 | 102 | 0 | 50 | 0 |
| New Mexico—Various | 3 | 55 | 9 | 19 | 0 |
| Total | 21 | 251 | 42 | 119 | 16 |

velocity signals for each hammer blow and transferred the data to the SPT-Analyzer console. These data were collected and processed using the Pile Dynamics. Inc. (PDA 2013) software which analyzes the force and acceleration recorded by the console for each hammer blow. The theoretical energy was determined from the product of weight of the hammer and the drop distance, measured during field operations.

After completion of field operations, data related to type of soil, drill rod size, drilling fluid, and depth were carefully logged and recorded. Also, necessary data to perform analyses on hammer efficiency were stored in the SPT-analyzer console. These data were used to assemble the final dataset analyzed for this study.

### 6.4 The TCP Blowcount Dataset

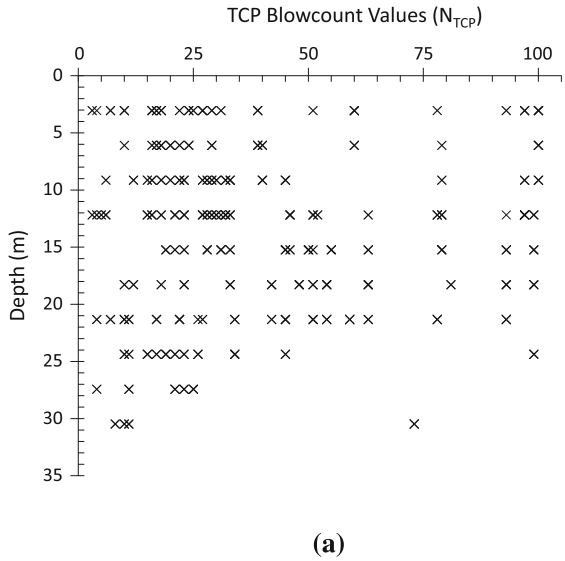
The final dataset consisted of 293 TCP tests comprising 251 tests completed in soils and 42 in IGM/rock. From the 293 TCP tests, 135 tests were instrumented to obtain energy measurements using the SPT Analyzer, with 119 instrumented tests in soils and 16 instrumented tests in IGM/rock. Because the IGM/rock data were limited and showed high variability, the study presented in this paper focuses solely on soils. Therefore, TCP blowcounts corresponding to the IGM/rock materials have not been included in the final dataset, and as observed in Fig. 4a, maximum TCP blowcounts reported are less than or equal to 100 blows per 30-cm of penetration. For the 119 instrumented TCP tests in soils (i.e. the data used for this study), the hammer energy for each TCP hammer strike was recorded resulting in 4901 hammer energy measurements, with the average hammer efficiency for each TCP test plotted in Fig. 4b.

## 7 Results from TCP Blowcount Data

A series of factors associated with the completion of the TCP test impacts the energy transferred to the TCP cone and thereby influences the measured $N_{TCP}$ blowcount values. Following the customary standardization process for correcting $N_{SPT}$ blowcounts identified in Eq. (5), this paper presents TCP hammer efficiency data, correction factors for rod length, and correction factors for overburden pressure. Correction factors for borehole diameter and sampler type are not presented however, since for the TCP study the borehole diameter was constant for all sites, i.e. 10-cm, and the factor for type of sampler does not apply since the TCP point is a solid steel cone.

### 7.1 Hammer Efficiency for the TCP Test ($E_{r\text{-}TCP}$)

All TCP tests performed for this study were completed using Central Mine and Equipment (CME) automatic hammers where the hammer mass is lifted by a



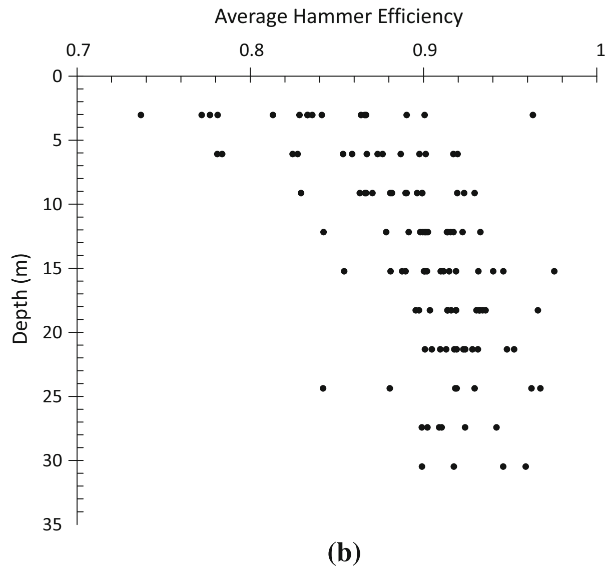




**Fig. 4** Compiled dataset. **a** TCP blowcount values $N_{TCP}$, **b** average hammer efficiency

hydraulically-operated chain cam mechanism and the hammer is released using an automatic finger cam, allowing the hammer to fall and impact an anvil located at the head of the drill string.

Figure 4b illustrates the TCP hammer efficiencies measured in this study. Using Minitab 17.3.1 (2016) basic statistical parameters such as mean and coefficient of variation (COV) for the TCP hammer efficiency were determined. Hammer efficiency values of all measurements without differentiating soil types range from 74 to 101% with mean of 89% and COV of 0.046. These are associated with TCP blowcounts ranging from 3 to 100 with an average of 38 blows/30-cm and measured at depths ranging from 3- to 30-m, average 13-m. Each data point represents the mean hammer efficiency for an individual TCP test. This was determined from the ratio of measured energy based on the SPT analyzer to the theoretical energy calculated for the TCP hammer system (and also verified by field measurements) for each hammer strike associated with a test. TCP hammer efficiency values ranged from 74 to 101% with an average of 90% and COV of 0.041 for coarse-grained soils, and from 77 to 97% with an average of 88% and COV of 0.04 for fine-grained soils.

As has been noted, the TCP hammer is heavier and the drop is shorter compared to the SPT. The TCP hammer efficiency values presented herein are similar in range but about 7% higher on average than SPT hammer efficiency values published in the literature. For example, Honeycutt et al. (2014) report energy transfer data from a research database for CME automatic hammers and consisting of energy measurements from 17,825 individual SPT hammer blows (analogous to the 4901 hammer energy measurements obtained for this TCP study). Their dataset shows an average energy ratio of 82.9%, with a coefficient of variation of ±0.074. In contrast to the SPT where numerous studies exist that identify hammer efficiency, the data presented herein represent the first published TCP hammer efficiency values.

### 7.2 Development of Rod Length Correction Factors ($C_{R\text{-}TCP}$)

The relationship between the rod length and hammer efficiency has been explored considering that the rod length correction for $N_{TCP}$ will follow a similar form as the correction for $N_{SPT}$. A linear model was created for all the geomaterials analyzed in this study based on an equation following the form presented by Eq. (6):

$$E_{r-TCP} = \beta_0 + \beta_1 \log(z) \tag{6}$$

In Eq. (6), $E_{r\text{-}TCP}$ is the average hammer efficiency for the TCP test, $\beta_0$ and $\beta_1$ are coefficients which will differ based on the soil type, and $z$ is depth, i.e. length of rod below ground surface. To develop rod length correction factors, Eq. (6) is written for any depth and a baseline depth. In this context, the baseline depth refers to a depth at which the model line is flattened. At this depth (i.e. baseline depth) the correction factor would be considered as unity. The subtraction of Eq. (6) written for any arbitrary depth from Eq. (6) written for the baseline depth can be represented by Eq. (7):

$$\begin{aligned}\Delta &= \mathrm{E}_{\mathrm{r-TCP}} \text{ at } z_1 - \mathrm{E}_{\mathrm{r-TCP}} \text{ at } z_{\mathrm{Baseline}} \\ &= \beta_1\left(\log(z_1) - \log(z_{\mathrm{Baseline}})\right)\end{aligned} \tag{7}$$

In Eq. (7), $z_1$ is the depth of interest and $z_{\mathrm{Baseline}}$ is the depth at which $z_1$ is compared against. Identifying an estimate and confidence interval (CI) for $\Delta$ requires finding an estimate and confidence interval for $\beta_1$. For this analysis Minitab 17.3.1 (2016) was used to determine the value of $\beta_1$ for each type of soil with a 95% confidence interval. Substituting lower and upper endpoints of the CI in Eq. (7) will result in a 95% CI for $\Delta$. The result of this operation is an estimate and CI for the correction factor for rod length ($C_{R\text{-}TCP}$) determined by Eq. (8):

$$\mathrm{C}_{\mathrm{r-TCP}} = \log\frac{\mathrm{E}_{\mathrm{r-TCP}} \text{ at } z_1}{\mathrm{E}_{\mathrm{r-TCP}} \text{ at } z_{\mathrm{Baseline}}} \tag{8}$$

In Eq. (8), $C_{R\text{-}TCP}$ is the correction factor for rod length, and $E_{r\text{-}TCP}$ is the average hammer efficiency for the TCP test at the corresponding depth.

### 7.3 Presentation of TCP Rod Length Correction Factors

Considering that the TCP design charts were generated during a period of time when the use of hammers with nominal average efficiency of 60% was considered as the standard practice, it is reasonable to consider the normalization of the hammer efficiency for the TCP test by rewriting Eq. (1) for the TCP test:

$$\mathrm{N}_{60-\mathrm{TCP}} = \mathrm{N}_{\mathrm{TCP}}\frac{\mathrm{E}_{\mathrm{r-TCP}}}{60} \tag{9}$$

In Eq. (9), $N_{60\text{-}TCP}$ is the TCP blowcount standardized for 60% of hammer efficiency, $N_{TCP}$ is the TCP blowcount, and $E_{r\text{-}TCP}$ is the hammer efficiency for the TCP test in percent.

After standardization of the $N_{TCP}$ for 60% of hammer energy, Eq. (2) can be rewritten for the TCP test, Eq. (10).

$$\mathrm{N}_{60-\mathrm{TCP}} = \mathrm{N}_{\mathrm{TCP}}\frac{\mathrm{E}_{\mathrm{r-TCP}}}{60}\mathrm{C}_{\mathrm{r-TCP}} \tag{10}$$

Rod length correction factors ($C_{R\text{-}TCP}$) were developed by analyzing values corresponding to a baseline depth of 24-m and using the models shown in Eqs. (7) and (8). For this study, the baseline depth was considered as the rod length below ground surface at which the model flattened and presented a linear tendency. Figure 5 presents average hammer efficiency versus rod length below the ground surface.

Figure 5 presents two rod length correction datasets side-by-side, the SPT dataset (Skempton 1986) and the TCP dataset for this study. For the TCP data, the solid line represents the predictive model created based on Eq. (6) with an R-square value of 0.43, $p$ value of 0.000 ($p$ value <0.0001), and the 95% CI boundaries are represented by the dashed lines closer to the model line. Results for the TCP test suggest that the lowest data variability is presented at depths greater than 24-m where the depth correction factor is unity. In case of the SPT, it is noted that the model line flattens for depths greater than 10-m. Furthermore, observing the depth correction factors for each test at the same depth, a difference in value is observed. This difference could be primarily associated with the hammer used for the test and the type of samplers. The dataset analyzed by Skempton (1986)

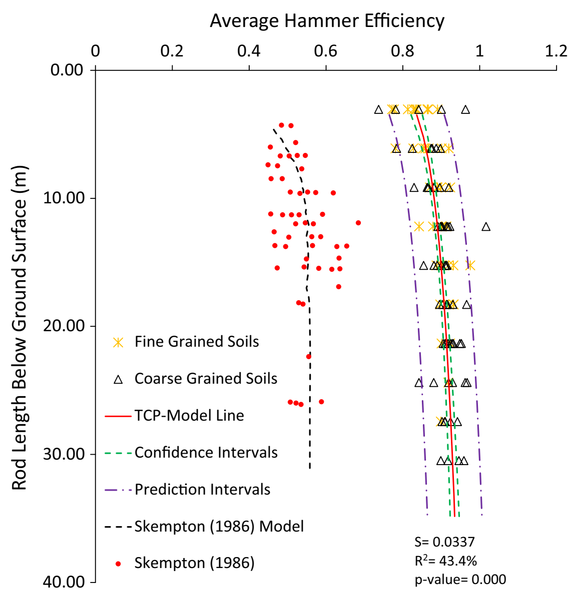



**Fig. 5** Scatterplot of average efficiency versus rod length for all soils

was based on SPT data obtained using a safety hammer; whereas, the data analyzed in this study were obtained from TCP tests completed using an automatic hammer.

Table 3 presents details of the TCP rod length correction factors. As analyzed in this dataset, coarse-grained soils consisted of poorly graded sands (SP), silty sands (SM), and clayey sands (SC) with SP being the predominant soil type. For the coarse-grained soils, rod length correction factors ($C_{R\text{-}TCP}$) were obtained ranging from 0.92 to 1.01. Similarly, the types of soil described as fine-grained consisted of lean clay (CL), fat clay (CH), and a low plasticity silt (ML) with CL being the predominant soil. For the fine grained soils, rod length correction factors ($C_{R\text{-}TCP}$) were obtained ranging from 0.90 to 1.01. A statistical test established that there are no significant differences between the correction factors for the coarse and fine soils based on calculated probability $p$ greater than 0.05 ($p$ value $= 0.48$).

Considering the narrow range of rod length correction factors for differentiated soils (i.e. fine grained and coarse grained soils), the factors recommended correspond to the model developed for undifferentiated data with values ranging from 0.9 to 1.0 as shown in Table 3.

### 7.4 Development of Overburden Pressure Correction Factors ($C_{N\text{-}TCP}$)

To develop the overburden correction factor for the TCP test, Eqs. (4) and (5) can be rewritten for the TCP blowcounts ($N_{TCP}$):

$$N_{1-TCP} = C_{N-TCP} N_{TCP} \tag{11}$$

$$N_{1-60-TCP} = \frac{E_r}{60} C_{r-TCP} C_{N-TCP} N_{TCP} \tag{12}$$

The relationship between standardized TCP blowcounts ($N_{60\text{-}TCP}$) and TCP test blowcounts corrected for overburden pressure ($N_{1\text{-}60\text{-}TCP}$) can be defined as the overburden correction factor for the TCP test.

$$\frac{1}{C_{N-TCP}} = \frac{N_{60-TCP}}{N_{1-60-TCP}} \tag{13}$$

In order to develop the correction factor for overburden pressure, a reference stress value should be defined first. In this study, the atmospheric pressure (100-kPa) is taken as the reference stress ($\sigma_{ref}$) following the standard practice for SPT. Therefore, $N_{60\text{-}TCP}$ value obtained at a vertical stress of 100 kPa becomes a reference value ($N_{60\text{-}TCP\text{-}ref}$) for the development of overburden correction factor. Then, three main steps were followed to develop overburden correction factors for the TCP test ($C_{N\text{-}TCP}$). These steps were: (1) normalizing the TCP blowcounts with respect to $N_{60\text{-}TCP\text{-}ref}$, (2) normalizing the effective vertical stress with respect to $\sigma_{ref}$, and (3) determining the relationship between Steps (1) and (2). Prior to these steps, all TCP blowcounts ($N_{TCP}$) were corrected for hammer efficiency and rod length following Eq. (10).

*Step 1* Normalized TCP Blowcounts ($N_{N\text{-}TCP}$)

For each TCP boring included in the compiled dataset, the relationship between $N_{60\text{-}TCP}$ and the effective vertical stress ($\sigma'_v$) was analyzed and a linear regression model was developed as shown in Fig. 6.

**Table 3** Rod length correction factors ($C_R$) for TCP and SPT

| Depth (m) | $C_{R\text{-}TCP}$ | | | | Depth (m) | $C_{R\text{-}SPT}$ |
|---|---|---|---|---|---|---|
| | Coarse grained | Fine grained | Undifferentiated | Recommended | | Undifferentiated soil type |
| 3 | 0.92 | 0.90 | 0.90 | 0.90 | 3–4 | 0.75 |
| 6 | 0.94 | 0.93 | 0.94 | 0.94 | 4–6 | 0.85 |
| 9 | 0.96 | 0.95 | 0.95 | 0.95 | 6–9 | 0.95 |
| 12 | 0.97 | 0.97 | 0.97 | 0.97 | >9 | 1.00 |
| 15 | 0.98 | 0.98 | 0.98 | 0.98 | >9 | 1.00 |
| 18 | 0.99 | 0.99 | 0.99 | 0.99 | >9 | 1.00 |
| 21 | 0.99 | 0.99 | 0.99 | 0.99 | >9 | 1.00 |
| 24 | 1.00 | 1.00 | 1.00 | 1.00 | >9 | 1.00 |
| 27 | 1.00 | 1.01 | 1.01 | 1.00 | >9 | 1.00 |
| 30 | 1.01 | 1.01 | 1.01 | 1.00 | >9 | 1.00 |

From the interception of the horizontal dashed line depicting the reference stress of 100-kPa and each solid line depicting the linear model fitted to the data corresponding to each boring, the $N_{60\text{-TCP-ref}}$ corresponding to the reference stress was determined. At the end of this step, each boring was associated with one TCP blowcount value ($N_{60\text{-TCP-ref}}$) and this value was used for the normalization of the TCP blowcounts:

$$N_{N-TCP} = \left(\frac{N_{60-TCP}}{N_{60-TCP-ref}}\right) \tag{14}$$

*Step 2* Normalized Effective Vertical Stress ($\sigma'_N$)
Based on available geotechnical information for each site, unit weights were assigned to each soil layer. In the case where measured unit weights of soil were not available, correlations published by TxDOT (2000) and Bowles (1996) were used to estimate the soil unit weight. For all TCP tests, the effective vertical stress was calculated at the depth of test. Furthermore, the effective vertical stress values determined in this step were normalized to a reference stress of 100 kPa using Eq. (15) below:

$$\sigma'_N = \left(\frac{\sigma'_v}{\sigma_{ref}}\right) \tag{15}$$

Each normalized effective vertical stress ($\sigma'_N$) was then associated with its corresponding normalized TCP blowcount.

*Step 3* Relationship between $N_{N\text{-TCP}}$ and $\sigma'_N$
After completion of Steps 1 and 2, a scatterplot was generated with $N_{N\text{-TCP}}$ ($=N_{60\text{-TCP}}/N_{60\text{-TCP-ref}}$) as dependent variable and $\sigma'_N(=\sigma'_v/\sigma'_{ref})$ as the independent variable and the relationship between these variables was further analyzed. Figure 7 presents a scatterplot for $N_{N\text{-TCP}}$ versus $\sigma'_N$ together with the fitted regression curve from a power model.

Linear and polynomial regression models were fit to the dataset, and it was observed that a key assumption of regression was violated; namely that of a constant (stable) variance. The variance issue was addressed by $\log_{10}$ transformation of the dependent and independent variables, and statistical models with reliable confidence intervals were determined. After the transformation, a model was generated for the dataset following Eq. (16) and converted from $\log_{10}$ scale back to natural scale to obtain Eq. (17), which

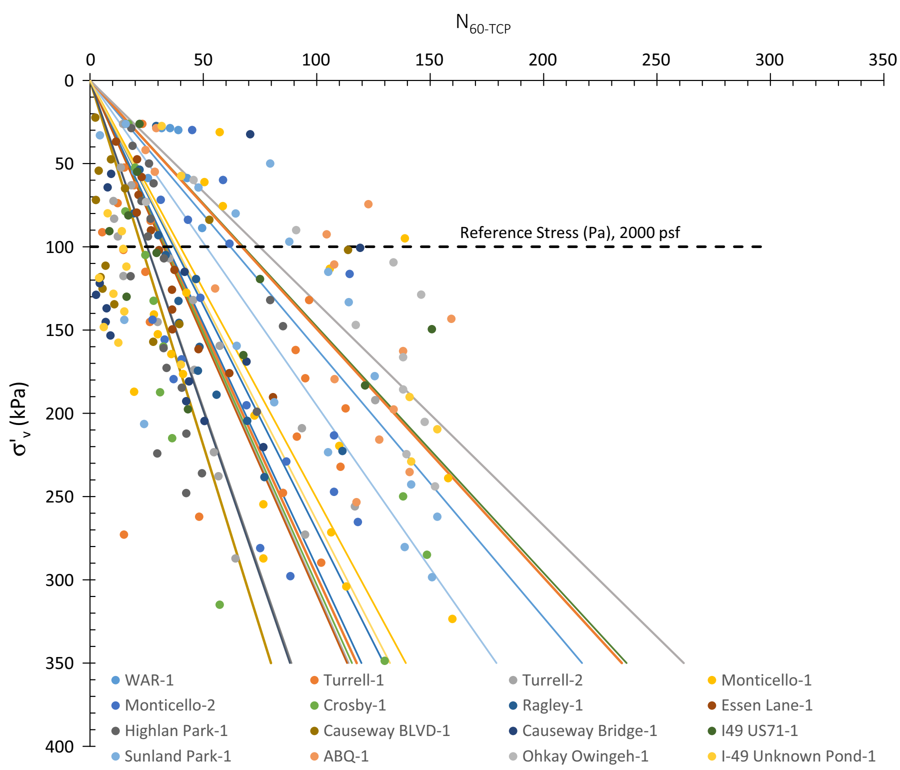



**Fig. 6** $N_{60\text{-TCP}}$ and effective vertical stress relationship for each TCP boring

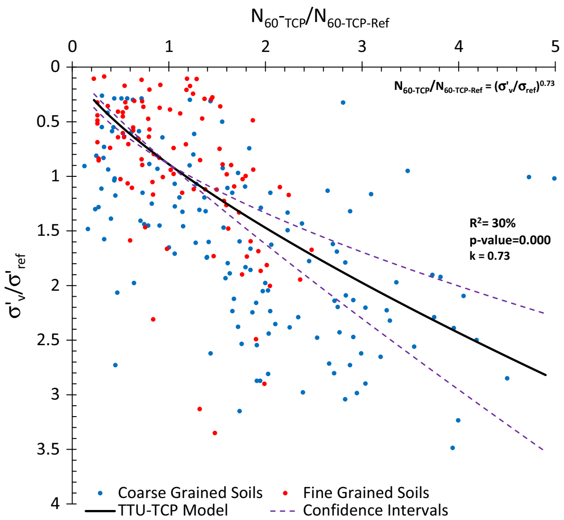



**Fig. 7** Scatterplot for normalized $N_{N\text{-}TCP}$ versus normalized effective vertical stress $\sigma'_N$

indicates a power function relationship between $N_{N\text{-}TCP}$ and $\sigma'_N$. Figure 7 presents the model fitted to the dataset based on Eq. (16) illustrated by the solid line including its corresponding 95% confidence intervals (CI) identified by dashed lines.

$$\log_{10}(N_{N-TCP}) = 0.73\log_{10}(\sigma'_N) \tag{16}$$

$$\left(\frac{N_{60-TCP}}{N_{60-TCP-Ref}}\right) = \left(\frac{\sigma'_v}{\sigma_{ref}}\right)^{0.73} \tag{17}$$

### 7.5 Overburden Correction Factor $C_{N\text{-}TCP}$ Results

From the combination of Eqs. (13) and (17), the overburden correction factor for the TCP test ($C_{N\text{-}TCP}$) is obtained as follows.

$$C_{N-TCP} = \frac{1}{\left(\frac{\sigma'_v}{\sigma_{ref}}\right)^{0.73}} \tag{18}$$

Equation (18) represents a power function which is the recommended overburden correction factor for the TCP tests with a power (k) of 0.73. To provide context, the expression determined for $C_{N\text{-}TCP}$ in this study was compared to the models published for $C_N$ for SPT shown in Table 1, by plotting the effective vertical stress ($\sigma'_v$) versus $C_N$, as shown in Fig. 8.

Figure 8 illustrates the relationship between the effective vertical stress and the overburden correction factors published for the SPT compared to the overburden correction factor for the TCP presented in this paper. The relationship for the TCP test is shown with the solid line with 95% CI dashed lines. From the comparison, it is noted that the overburden correction factors presented by other researchers for the SPT data vary between 0.35 and 2.1; whereas, the correction factors for the TCP test range from 0.4 to 3.05 for the vertical effective stress range of 30–330 kPa. It is inferred that the broad spectrum of the overburden correction factor for the TCP test may be associated with the fact that the TCP test data analyzed in this study included both fine-grained and coarse-grained soils whereas the factors developed for the SPT included coarse-grained soils only.

## 8 Other Factors that May Influence TCP Test Hammer Efficiency

Analyses of the TCP test data, observations of the TCP field procedure, and comments in the technical literature suggest that factors other than those corrected for herein could create variability in the $N_{TCP}$. Four additional factors—drill rod size, type of soil, drilling fluid, and depth—were identified and analyzed to explore their influence on TCP hammer efficiency.

Statistical analyses using ANOVA were performed using SAS9.3 (2015) and Minitab 17.3.1 (2016) to

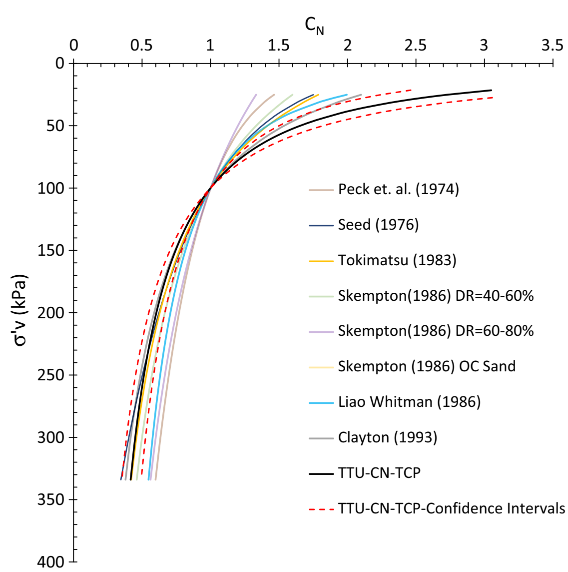



**Fig. 8** Effective Vertical Stress ($\sigma'_v$) versus $C_N$ for TCP and SPT

study the effect of drill rod size, type of soil, drilling fluid, and depth, on the hammer efficiency. For this process, the hammer efficiency was considered as dependent variable and all other factors as independent variables/factors. This ANOVA also tested for interactions between these factors. A three-way interaction is observed between drilling fluid, soil type, and depth. This implies that each of these are associated with hammer efficiency. Furthermore, drill rod size is involved in two significant two-way interactions, which implies that it is also associated with hammer efficiency.

Results from these analyses indicate that a statistically significant relationship exists between the identified factors and hammer efficiency, but because the data were obtained from a field-oriented study and not a controlled experiment, the exact nature of these relationships could not be determined. Hence, to develop correction factors that account for all the variables influencing TCP hammer efficiency, additional study is required where the research design allows each factor to be analyzed independently.

## 9 Summary and Conclusions

This paper presents TCP hammer efficiency data, rod length correction factors, and overburden correction factors for instrumented TCP tests completed in coarse-grained and fine-grained soils. Other factors that may influence TCP hammer efficiency were also identified.

A dataset of 293 TCP tests comprising 251 tests completed in soils and 42 in IGM/rock was compiled for this study. From the 293 TCP tests, 135 tests were instrumented to obtain energy measurements using the SPT Analyzer, with 119 instrumented tests in soils and 16 instrumented tests in IGM/rock. An adjusted dataset of 251 TCP tests were considered for the development of overburden correction factors for the TCP test in soils. A total of 119 instrumented TCP tests in soils were used for the analysis corresponding to the rod length correction factors.

Undifferentiated efficiency values range from 74 to 101% with mean of 89% and COV of 0.046 associated with TCP blowcounts ranging from 3 to 100 with an average of 38 blows/30-cm and measured at depths ranging from 3- to 30-m, average 13-m. TCP hammer efficiency values ranged from 74 to 101% with a mean of 90% and COV of 0.04 for coarse-grained soils, and from 77 to 97% with an average of 88% and COV of 0.041 for fine-grained soils. These TCP hammer efficiency values are similar in range but about 7% higher on average than efficiency values for automatic SPT hammers published in the literature.

Rod length correction factors for the TCP hammer efficiency ($C_{R\text{-}TCP}$) were developed by creating a non-linear model based on statistical analyses. Rod length correction factors ranging from 0.90 and 1.00 for undifferentiated data were determined and recommended for the TCP test.

In a separate set of analyses, the relationship between $N_{60\text{-}TCP}$ and soil overburden pressure was analyzed. Correction factors for the overburden pressure for the TCP test ($C_{N\text{-}TCP}$) were developed and normalized to a reference stress (100 kPa). The $C_{N\text{-}TCP}$ expression recommended in this paper is a power function with $k = 0.73$, and this is generally in agreement with the $C_N$ expressions published for the SPT.

Although the TCP test is in some ways similar to the SPT, the two tests are not the same, even though results from both tests are regularly used to design deep foundations. Therefore, it makes sense to take steps to ensure reliable data. In case of the TCP test, up until now, no published corrections for raw blowcount data existed. The work presented in this paper is intended as an initial step to further refine the TCP-based design method to achieve more reliable design of deep foundations.

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