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This paper presents a qualitative and quantitative evaluation of the predictive validity of the Texas Cone Penetration (TCP) foundation design method. Allowable loads were determined using both strength-based and serviceability-based models and were further compared to predicted allowable loads using the TCP foundation design charts. The predictive validity of the TCP method was evaluated using a final dataset consisting of 60 full-scale load tests comprising 33 driven piles and 27 drilled shafts, all founded in soil materials. The qualitative evaluation consisted of a visual assessment of the scatterplot compared to the equal prediction line. In the case of the quantitative assessment, regression models were fitted to the dataset, and the accuracy and precision of the models were evaluated based on statistical analyses. Results show that the predictive validity of the TCP-based foundation design method is accurate with low precision. The qualitative evaluation of the strength-based data showed slight data scatter around the equal prediction line. In the case of the serviceability-based model, data points indicated the same slight scatter with major concentration above the equal prediction line in the conservative prediction region. With a p-value <.05, results from the quantitative analyses showed a statistically significant relationship between the proposed models and the allowable loads predicted using the TCP. The *R*-square value for the models was between 0.776 and 0.814.

Keywords: Allowable stress design, Serviceability, Predictive validity, Deep foundations, Full-scale load test, Texas cone penetration test

Introduction

This paper presents an evaluation of the Texas Department of Transportation (TxDOT) predictive model based on qualitative and quantitative approaches where allowable loads determined from the TCP foundation design method were compared to allowable geotechnical loads determined from full-scale load tests.

The TCP field test procedure is introduced, and its associated foundation design charts are presented. The application and use of the TCP charts for the design of deep foundations is discussed in detail. The effort associated with field data collection including geotechnical borings using the TCP test is described, followed by a detailed discussion of the development of the project dataset. It is important to note that throughout the manuscript, the term *capacity* will refer to the ultimate limit state, and the term *allowable load* is the capacity divided by a safety factor (SF).

Also, considering the use of predictive models and full-scale load test data throughout this paper, the appropriate term will be used with a method identifier. Three types of allowable loads were determined in this study: (1) TCP-based, (2) strength-based, and (3) serviceability-based. The allowable load *predicted* based on TCP test blowcount values and related geotechnical data will be referred to as the 'TCP-based allowable load'. The *measured* load interpreted from a full-scale load test which corresponds to the foundation capacity divided by a SF will use the term 'strength-based allowable load'. The *measured* load interpreted from a full-scale load test which corresponds to a tolerable foundation displacement will use the term 'serviceability-based allowable load'.

The TCP-based allowable loads were determined using the TCP foundation design charts which have a built-in

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SF of 2.0. The strength-based loads were determined using the Davisson's criteria for driven piles and modified Davisson's criteria for drilled shafts with a SF of 2.0, and the serviceability-based loads were determined using the full-scale load test results and a prescribed tolerable displacement. After determining loads, these data were analyzed based on (1) qualitative evaluation of relevant scatterplots, and (2) quantitative evaluation where statistical analyses and linear regression models were developed to analyze the relationship between strength-based and TCP-based allowable loads as well as serviceability-based and TCP-based allowable loads.

According to FHWA (2016), Texas currently maintains over 53,000 bridges in the National Bridge Inventory, and most of these bridges are supported by foundations designed in accordance with the TCP method. Similarly, the Oklahoma DOT has been using the TCP method for the design of the foundations extensively. The TCP test is discussed in *NCHRP Synthesis 360* (Turner 2006) and owing to competitive opportunities for major transportation infrastructure projects nationwide, geotechnical practitioners and academics have had occasion to learn about and use the TCP test. Recently, a comprehensive research programme in Missouri evaluated a modified version of the TCP test for bridge foundation design applications using LRFD concepts (Loehr *et al.* 2011). Internationally, 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, Park and Park 2013). Given these applications, the scope of the TCP test and its associated foundation design charts is significant well beyond its regional origins, and an evaluation of results compared to measured data seems to be helpful and contributory to the geotechnical engineering community using the TCP method as part of their foundation design practice.

The TxDOT Texas cone penetration test

The TCP field test is a dynamic penetration test which assesses the strength of the geologic material encountered during geotechnical exploration. This test method is considered to be a simple, rugged, yet sufficiently reliable tool for characterization of a broad range of geologic material that includes clays, sands, intermediate geomaterials and hard rock. The TCP test method is documented as TxDOT Designation Tex-132-E, 'Test Procedure for Texas Cone Penetration' (TxDOT 1999). It uses a 77.0-kg (170-lb) hammer with 0.61-m (24-in) drop to force a 76-mm (3-in) diameter steel cone into the soil or rock formation, Fig. 1.

In current practice, penetration for the TCP test is to be achieved in three separate increments. The first increment is the seating blows and consists of driving the cone 12 blows or approximately 150-mm (6-in), whichever comes first. The TCP blowcount is then determined as the sum of the number of blows required to achieve the second and third 150-mm (6-in) increments. The total blowcount or (N_{TCP}) corresponding to 305-mm (12-in) 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 values for the first and second 50 blows are recorded, with the N_{TCP} value reported as millimetres (inches) of penetration per 100 blows.

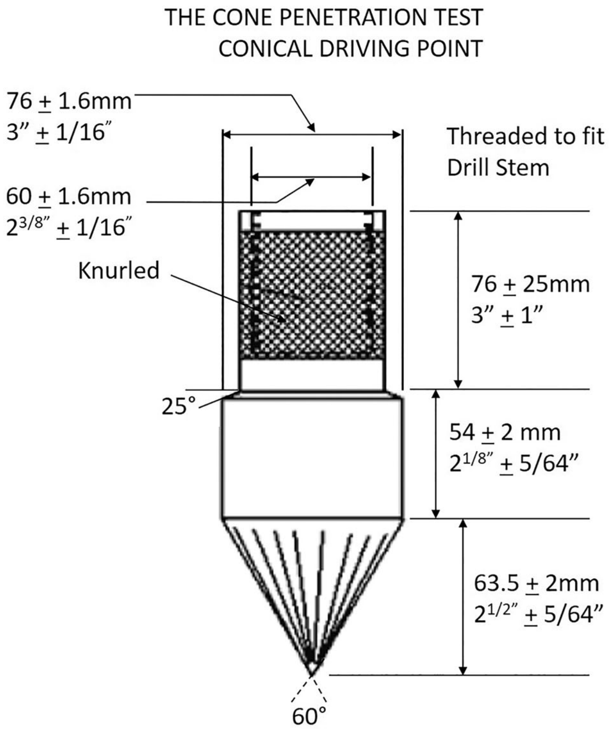
The closest analog to the TCP test in geotechnical engineering practice is the internationally known Standard Penetration Test (SPT), and it is the SPT with which the TCP test is most frequently compared. Like the SPT, the TCP test measures the strength of geomaterials by means of hammer strikes, and blowcount data from both SPT (N_{SPT}) and TCP tests (N_{TCP}) are directly used for the design of both driven pile and drilled shaft foundations. But these tests are different in key ways including (1) the TCP test uses a solid cone rather than a split barrel (hollow tube) so the mechanics of penetration resistance are different, (2) the TCP test does not and cannot collect a soil sample, (3) several details of the TCP test differ from the SPT, and (4) the TCP and SPT blowcount values are not equivalent. More specifically, sampler size, geometry and hammer energy configurations are such that SPT blowcounts ($N_{60,\ SPT}$) are typically 30–60% lower than $N_{60,\ TCP}$ in fine-grained soils, and corresponding $N_{60,\ SPT}$ blowcounts are 10–70% lower than $N_{60,\ TCP}$ in coarse-grained soils (Lawson *et al.* 2018).

TCP design charts

The 1956 edition of the Texas Highway Department (THD) *Foundation Exploration and Design Manual* provides a series of correlation curves illustrating shear strength estimation based on N_{TCP}. These correlation curves were based on relationships established between TCP test data and laboratory-measured shear strength. To obtain soil strength parameters for this purpose, undisturbed samples were collected and tested using the triaxial test procedure (THD 1956). Based on data obtained from field and laboratory studies, correlation charts between N_{TCP} and foundation capacities were developed and published in two separate sets of design charts.

Deep foundations such as driven piles and drilled shafts derive their axial load capacity from both shaft resistance and base resistance. The TxDOT *Geotechnical Manual* (2018) refers to these resistances as 'skin friction' and 'point bearing', respectively. The manual provides two separate sets of charts for each one of these resistances, one set for soil-like materials and another set for intermediate geomaterials and rock. Inasmuch as the focus of this paper is on TCP test data for deep foundations in soils, Fig. 2 shows the TCP design charts used for soil-like materials, i.e. materials in which the TCP blowcount per 305-mm (12-in) is less than 100 blows.

The TCP foundation design charts reflect the allowable stress design (ASD) philosophy and present allowable unit loads (either unit skin friction or unit point bearing) for a safety factor of 2.0. Furthermore, it can be seen that these design charts are categorized based on soil classification where separate correlations are provided for fat clay (CH), lean clay (CL), clayey sand (SC), and OTHER soils. The solid lines on each chart represent the corresponding allowable strength models. According to the design procedure, any soil classified as SP, SW, SM, and ML is considered as OTHER category.



(a) A schematic from TxDOT manual (1999)

(b) Field application

1 TCP test conical driving point, *a* a schematic from TxDOT manual (1999), *b* a photo from a project in Missouri (Moghaddam, 2016)

Figure 2*a* and Figure 2*b* include tables that identify soil constants 'C' specific to each of the design models. These constants represent the inverse of the slope of the allowable geotechnical load model lines, and the slopes vary based on soil classification. One aspect of the TCP chart for skin friction (Fig. 2*a*) discussed in the *Geotechnical Manual* but not obvious from the chart is that all predictive models present a maximum blowcount value beyond which the unit skin friction resistance becomes constant. For example, in Fig. 2*a* the model for fat clays (CH) reports varying unit skin friction from $N_{TCP} = 5$ to $N_{TCP} = 70$ blows/305-mm (12-in), but constant skin friction of 134-kPa (1.4-tsf) for blowcounts beyond 70 blows.

TCP design method for deep foundations

In deep foundation design, the total capacity (Q_t) is the sum of the shaft (Q_s) and base (Q_b) capacity, which could be expressed in terms of unit shaft (q_s) resistance, foundation surface area (A_s), unit base resistance (q_b), and foundation base area (A_b):

$$Q_t = Q_s + Q_b = q_s A_s + q_b A_b \quad (1)$$

For a TCP-based design, the unit shaft and unit base resistance values are read directly from the TCP design charts. The main parameters required to determine these resistances are the TCP test blowcount (N_{TCP}) and the type of soil described based on the Unified Soil Classification System (USCS) group symbol.

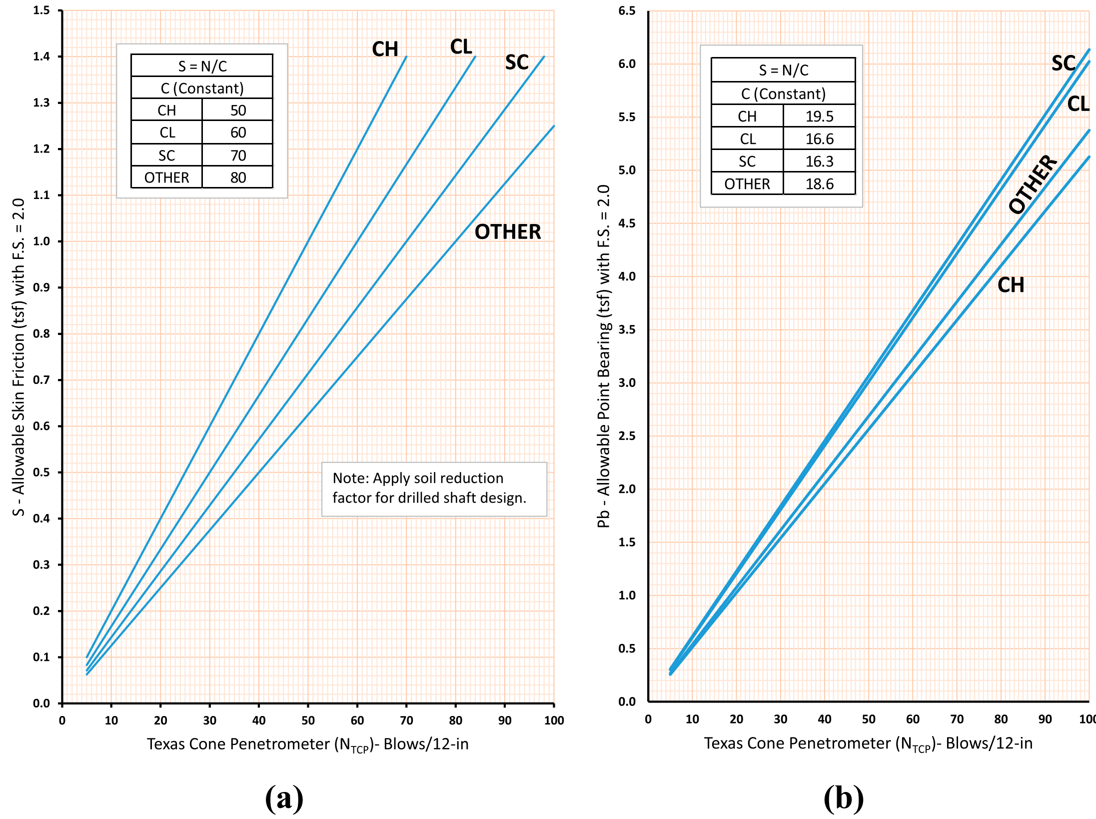
The TxDOT *Geotechnical Manual* (2018) identifies two capacity adjustments for the TCP-based design of deep foundations. The first adjustment is the *disregard depth* which applies to all types of foundations and refers to the portion of shaft capacity neglected during design. According to the *Geotechnical Manual*, the shaft resistance from the ground surface to a depth of 1.5-m (5-ft) to 3.0-m (10-ft) is to be disregarded, depending on whether the deep foundation will be installed over a non-water crossing or over a stream crossing. The second capacity adjustment is the application of a soil reduction factor of 0.7 to the shaft resistance for the design of drilled shafts. This reduction factor is recommended for use in order to account for soil disturbance during the drilling procedure.

The TCP-based allowable loads presented in this study include the soil reduction factor of 0.7 for the determination of shaft capacity for drilled shafts. The disregard depth is intended to account for possible long-term soil strength reduction effects such as scour, soil shrinkage, or near-surface erosion. Considering the nature of this study, a design assumption such as the disregard depth was not applicable.

Research design and method

The dataset for this study was compiled based on available load test projects from TxDOT's historical archive supplemented by load test projects from neighbouring state DOTs as presented by Seo, Moghaddam, Surles and Lawson (2015). TCP boring data corresponding to full-scale load test projects retrieved from TxDOT's historical archive were identified and recorded. For the non-TxDOT projects, new geotechnical borings using the TCP test method were completed in close proximity to the load test location.

TxDOT Historical Archive: The TxDOT *Bridge Division* compiled an archive of load tests completed for the driven pile and drilled shaft projects at various locations in Texas. The TxDOT archive was reviewed in detail and



2 Design charts representing *a* allowable unit shaft resistance and *b* allowable unit base resistance vs. TCP blows/305-mm (12-in), (TxDOT 2018)

organized according to (1) availability of TCP data, (2) full-scale load test information, and (3) pertinence to this particular study. Based on this organization, a preliminary dataset was compiled comprising 31 load test projects in soils for driven piles and 15 load test projects in soils for drilled shafts, including their corresponding TCP data.

Non-TxDOT Full-Scale Load Tests: With the objective of supplementing the TxDOT historical archive, available load test project sites located in Missouri, Arkansas, Louisiana, and New Mexico were identified and, at each site, new geotechnical borings with TCP tests were completed in accordance with the guidelines stated in the TxDOT *Geotechnical Manual* (2018). All TCP tests were carried out at 1.5-m (5-ft) intervals, starting at a depth of 1.5-m (5-ft) below the ground surface, and ending at the maximum depth of boring. 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. These samples were used for identification and classification of the subsurface materials associated with the TCP test. After field data collection, two load test projects for driven piles and 12 load test projects for drilled shafts were added to the preliminary dataset.

From this work, the final dataset compiled for this study consisted of 60 full-scale load tests comprising 33 driven piles and 27 drilled shafts in soils. Driven piles selected for this project were precast square concrete piles ranging in width from 360-mm (14-in) to 510-mm (20-in) with embedment lengths varying between 5-m (15-ft) and 25-m (84-ft). For the drilled shafts, the diameters ranged from 460-mm (18-in) to 1830-mm (72-in) with embedment length varying between 6-m (20-ft) and 30-m (99-ft). Tables 1 and 2 present the dataset used for the analyses presented in this paper.

TCP-based allowable load

TCP-based allowable loads for driven piles and drilled shafts were calculated following the design procedure specified by the TxDOT's *Geotechnical Manual* (2018). For this purpose and for each load test project, a synthesized soil profile showing the stratigraphy and N_{TCP} per strata was generated from geotechnical TCP borings, as illustrated in Fig. 3 as an example.

For the profile shown in Fig. 3, an allowable shaft load of 2893-kN (650-kips) and an allowable base load of 1073-kN (241-kips) were determined using the TCP design charts. After applying the 0.7 reduction factor for soil disturbance, a reduced allowable shaft load of 2025-kN (455-kips) was obtained. Summing up the allowable reduced shaft load and the allowable base load, the TCP-based allowable load of 3098-kN (696-kips) was determined. This process was completed for all driven piles and drilled shafts included in the compiled dataset and the results are summarized in Tables 1 and 2.

Here it is appropriate to comment on the use of TCP blowcount data to determine allowable predicted capacity as compared to alternative predictive approaches that rely on conventional geotechnical data. Unfortunately no comprehensive published studies exist that directly and formally

Table 1 Compiled dataset for driven piles in soils

Case	Pile dimensions		Predominant source of total capacity from TCP method (%)			TCP-based capacity	TCP-based allowable load[3]	Strength-based capacity[4]	Strength-based allowable load[3]	Serviceability-based allowable load at δ = 12.5-mm
No.	Width (mm)	Length[1] (m)	Shaft (%)	Base (%)	Soil[2]	(kN)	(kN)	(kN)	(kN)	(kN)
1	360	9	96	4	Fine	862	431	497	248	543
2	360	8	97	3	Coarse	770	385	1,654	827	1,682
3	360	7	91	9	Fine	874	437	1,161	581	1,246
4	360	11	96	4	Fine	1616	808	866	433	894
5	510	21	97	3	Fine	1496	748	2901	1450	2670
6	380	11	92	8	Fine	1244	622	1574	787	1647
7	380	10	94	6	Coarse	1354	677	1365	682	1424
8	410	15	98	2	Coarse	1104	552	2297	1148	1709
9	410	13	99	1	Coarse	1968	984	1044	522	1090
10	410	13	96	4	Coarse	1046	523	1291	646	1308
11	410	14	97	3	Fine	2482	1241	1652	826	1669
12	410	5	93	7	Fine	626	313	1047	524	1135
13	410	5	93	7	Fine	472	236	1598	799	1691
14	410	14	99	1	Coarse	1820	910	1304	652	1335
15	410	9	98	2	Fine	1338	669	1049	525	1090
16	410	9	96	4	Fine	882	441	1344	672	1371
17	410	12	96	4	Fine	932	466	579	289	734
18	380	9	95	5	Fine	808	404	1255	627	1357
19	510	23	98	2	Fine	2690	1345	1117	558	1126
20	360	8	94	6	Fine	3294	1647	1570	785	1780
21	460	10	93	7	Fine	1052	526	1580	790	1647
22	460	25	89	11	Fine	1284	642	1222	611	1224
23	460	14	97	3	Fine	1754	877	2406	1203	1059
24	360	8	96	4	Fine	1060	530	1122	561	1148
25	460	13	95	5	Coarse	1648	824	1722	861	1736
26	460	13	95	5	Coarse	1648	824	1712	856	1736
27	460	12	97	3	Coarse	1526	763	1519	760	1580
28	460	13	95	5	Coarse	1648	824	2668	1334	2603
29	460	17	95	5	Coarse	2680	1340	3132	1566	3004
30	510	22	97	3	Coarse	4406	2203	3031	1515	3026
31	510	22	96	4	Fine	3136	1568	2173	1086	2474
32	360	13	99	1	Coarse	1374	687	1096	548	1135
33	360	24	98	2	Fine	3674	1837	3014	1507	2359

[1]Embedment length; [2]Predominant soil type; [3]Safety factor of 2.0; [4]Davisson's criterion.

address this issue for any of the major, accepted foundation design methods which rely on conventional geotechnical site characterization data (including SPT, CPT, PMT, laboratory shear strength tests, etc.). This is because the conventional studies do not include TCP data and TCP-based studies typically do not include the other data. One published reliability-based study does discuss TxDOT's TCP-based foundation design method (Loehr *et al.* 2011), but that study did not formally and directly model the TCP approach but instead relied on modified TCP blowcount data.

The authors did explore the influence of alternative models for establishing predicted capacity based on SPT data but likewise had to rely on *correlated* SPT blowcounts (our research study did not include a full set of both types of data). Notwithstanding the approximate nature of the findings, the average total capacity for driven piles predicted using the TCP-based approach was about 4–13% *higher* than total pile capacity from the AASHTO method (AASTHO 2014) using correlated N_{SPT}, and about 26–38% *lower* than total pile capacity from the API method (API 2000), also using correlated N_{SPT} (Seo *et al.* 2015a). For drilled shafts, the average total capacity predicted using the TCP-based approach was about 60–95% *lower* than total capacity from the AASHTO method (AASHTO 2014) using correlated N_{SPT}, and about 52–85% *lower* than the capacity from the FHWA method (Brown *et al.* 2010), also using correlated N_{SPT} (Seo *et al.* 2015b). Granted the ranges are wide but not usual for geotechnical and foundation work, particularly considering that SPT blowcounts were obtained from correlation with TCP blowcounts. Collectively these approximations suggest that capacity predictions using the TCP test and its associated design method is not inconsistent with capacities determined using other conventional geotechnical approaches.

Strength-based allowable load

To investigate the TCP design method accuracy and precision, the predicted values using the TCP method must

Table 2 Compiled dataset for drilled shafts in soils

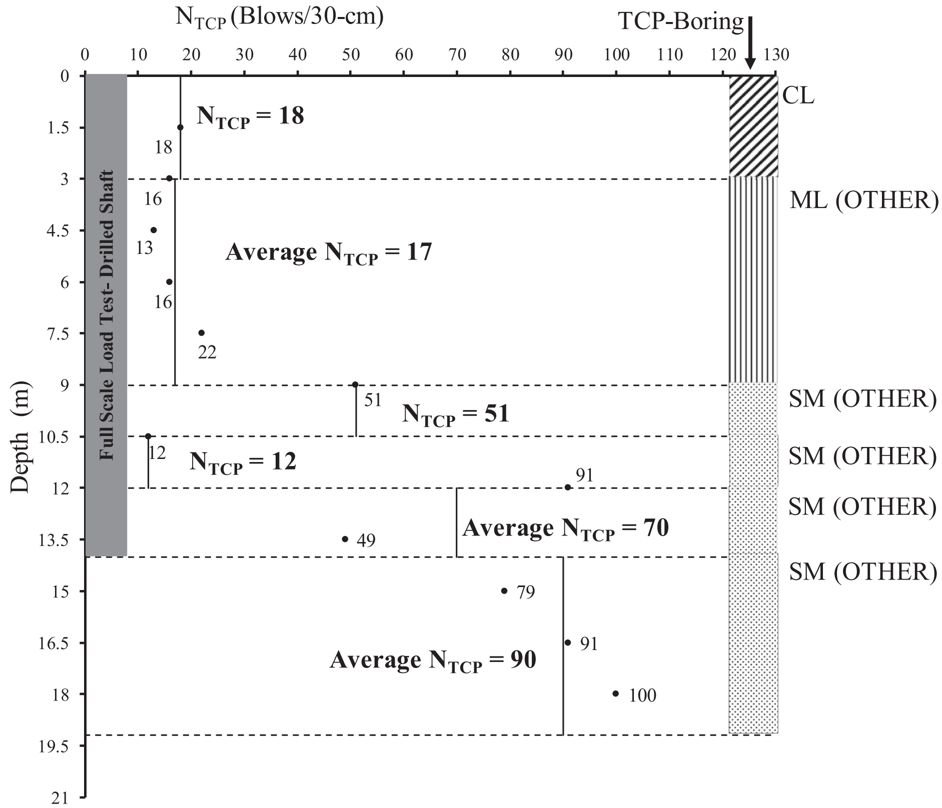
Case	Drilled shaft dimensions		Predominant source of total capacity from TCP method (%)			TCP-based capacity	TCP-based allowable load[3]	Strength-based capacity[4]	Strength-based allowable load[3]	Serviceability-based allowable load at $\delta = 12.5$-mm
No.	Diameter (mm)	Length[1] (m)	Shaft (%)	Base (%)	Soil[2]	(kN)	(kN)	(kN)	(kN)	(kN)
1	910	8	70	30	Fine	4170	2085	7958	3979	6008
2	1220	16	76	24	Coarse	10 922	5461	9531	4766	8277
3	1220	16	76	24	Coarse	10 922	5461	9126	4563	7209
4	1220	16	76	24	Coarse	10 922	5461	10 633	5316	8240
5	910	18	89	11	Fine	7400	3700	7521	3761	6542
6	610	6	82	18	Fine	2018	1009	2444	1222	2581
7	460	8	84	16	Fine	804	402	539	269	547
8	460	7	92	8	Fine	550	275	491	246	512
9	760	7	88	12	Fine	1090	545	1157	578	1121
10	760	7	88	12	Fine	1090	545	838	419	810
11	760	14	91	9	Fine	2228	1114	2702	1351	2537
12	760	18	90	10	Coarse	4560	2280	4372	2186	4139
13	760	23	96	4	Fine	3566	1783	6058	3029	5919
14	760	14	82	18	Coarse	7004	3502	5344	2672	4406
15	1830	20	76	24	Coarse	8846	4423	12 120	6060	7343
16	1220	26	93	7	Coarse	7300	3650	10 939	5470	7699
17	1220	27	91	9	Coarse	7546	3773	12 019	6010	7521
18	1680	19	84	16	Fine	7546	3773	4931	2466	4228
19	1680	12	85	15	Fine	4210	2105	5120	2560	4094
20	1830	25	87	13	Fine	9410	4705	8405	4202	7120
21	1220	30	92	8	Fine	8036	4018	11 176	5588	8277
22	1220	12	23	77	Fine	3766	1883	3756	1878	3427
23	1680	14	70	30	Coarse	6000	3000	6956	3478	6230
24	790	14	89	11	Coarse	10 134	5067	6491	3245	5518
25	790	14	89	11	Coarse	10 216	5108	7779	3890	6408
26	1220	23	85	15	Coarse	10 274	5137	8256	4128	4183
27	810	17	91	9	Coarse	5528	2764	6598	3299	3382

[1]Embedment length; [2]Predominant soil type; [3]Safety factor of 2.0; [4]Davisson's criterion.

be compared to measured values determined from full-scale load tests. Within the context of deep foundations, a defined fully mobilized geotechnical resistance is determined from the measured load-displacement curves. Several defined methods exist for the determination of the capacity from the load-settlement curve including Davisson's criterion (1972), 5% relative settlement criterion (Reese, Wright, and Allen 1977; Reese and O'Neill 1988), and 10% relative settlement criterion. The TxDOT *Geotechnical Manual* (2018) does not provide any recommendation with regard to a preferred criterion for capacity calculations. Further, a review of research reports and foundation design manuals published by all 50 state DOTs (Seo *et al.* 2015c) showed that less than one-fourth of the states (12/50) specify a criterion for driven piles (mostly Davisson) and only 10% of states (5/50) specify a criterion for drilled shafts, and most use 5% relative settlement.

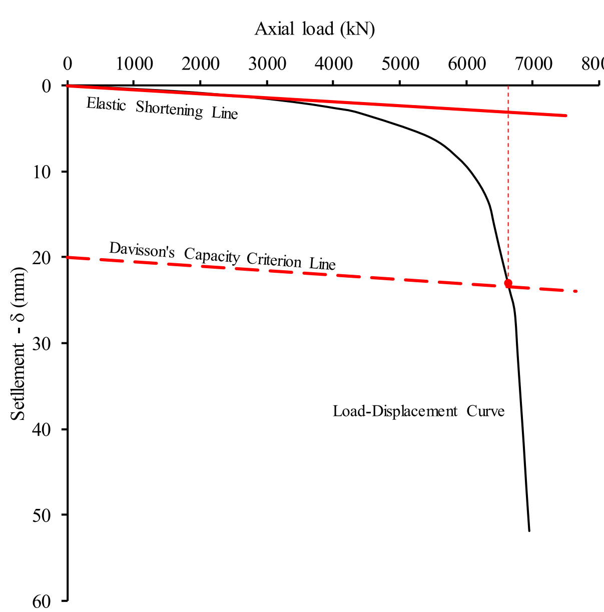
Based on these findings and following the guidance of AASHTO (2014), the Davisson's and modified Davisson's capacity criterion were selected for the interpretation of the full-scale load test results represented in this study. Davisson's criterion considers the foundation elastic shortening and an offset line. The capacity is the load corresponding to the point of intersection of the offset line and the load-settlement curve. Figure 4 illustrates the load-settlement curve corresponding to strength-based results showing the elastic shortening and the Davisson's line. For this study, the Davisson's capacity was divided by a SF of 2.0 to obtain the strength-based allowable loads as summarized in Tables 1 and 2.

Two aspects of the analysis warrant further comment: (1) the influence of using Davisson's criterion as opposed to other approaches for interpreting capacity from the full-scale load tests, and (2) the use of a SF = 2.0 for determining allowable measured capacity. The rationale for selecting Davisson's criterion has already been explained, but the major research study from which this paper derives did explore the use of alternative models for ultimate capacity, specifically the 5% relative settlement criterion and the 10% relative settlement criterion (Seo *et al.* 2015c). Focusing on capacity, as would be expected the 5% and 10% criteria did yield higher capacity values than Davisson with average capacities ranging from 14–31% greater than Davisson for driven piles and 7–19% greater than Davisson for drilled shafts. However, these alternative capacity values also reflected higher coefficients of variation (COV). Relative to using SF = 2.0 for establishing the allowable load from the measured capacity, no specific guidance exists from



3 Illustrative example of determining TCP-based capacity

TxDOT, so the identified value was selected both to (a) complement the built-in SF associated with the TCP-based allowable capacity charts, and (b) align with historical and accepted conventions associated with use of load tests in foundation engineering practice (Hannigan, Goble, Likins, and Rausche 2006).



4 Davisson's ultimate capacity criterion

Serviceability-based allowable load

In geotechnical engineering, deformations presented at the head of a deep foundation are translated to vertical settlements noted in the superstructure. When settlements are larger than an established *tolerable* settlement, then it is considered that the foundation element has reached a serviceability limit condition, and the performance of the superstructure is not satisfactory.

The magnitude of the tolerable displacement may be specified by regulatory agencies such as AASHTO (2014), it can be determined based on behaviours of similar structures (Roberts and Misra 2010), or it can be calculated based on predictive models. The National Cooperative Highway Research Program (NCHRP) Report No. 343 (Barker *et al.* 1991) presents guidelines and specifications describing allowable total and differential settlement for transportation structures. According to AASHTO (2014), the tolerable differential settlement for highway bridges can be evaluated in terms of angular distortion (α). Moulton (1985) evaluated movements for approximately 314 bridges to develop a tolerable movement criterion for highway bridges. For multi-span and simple-span bridges, an angular distortion of 0.004 and 0.005 was recommended, respectively (Hannigan *et al.* 2016). Although the tolerable settlements determined based on angular distortions recommended by AASHTO (2014) ranged from 72-mm (2.83-in) to 84-mm (3.31-in), load-settlement curves compiled for this study did not reach those values of settlement. Therefore, to avoid introducing more uncertainties to the study by extrapolating all load-settlement curves to reach tolerable settlements, and to comport with typical practice associated with the use of the TCP method for deep foundation design, the serviceability-based analysis was performed based on a tolerable displacement of 12.5-mm (0.5-in).

Data analysis

The TCP foundation design method was evaluated qualitatively and quantitatively. The qualitative comparison consisted of preparing scatterplots to observe the overall prediction trends. The quantitative analysis consisted of evaluating the statistical relationship between predicted and measured values. For both evaluations, two sets of scatterplots were prepared: (1) strength-based allowable load (measured) vs. TCP-based allowable load (predicted), and (2) serviceability-based load (measured) vs. TCP-based allowable load (predicted).

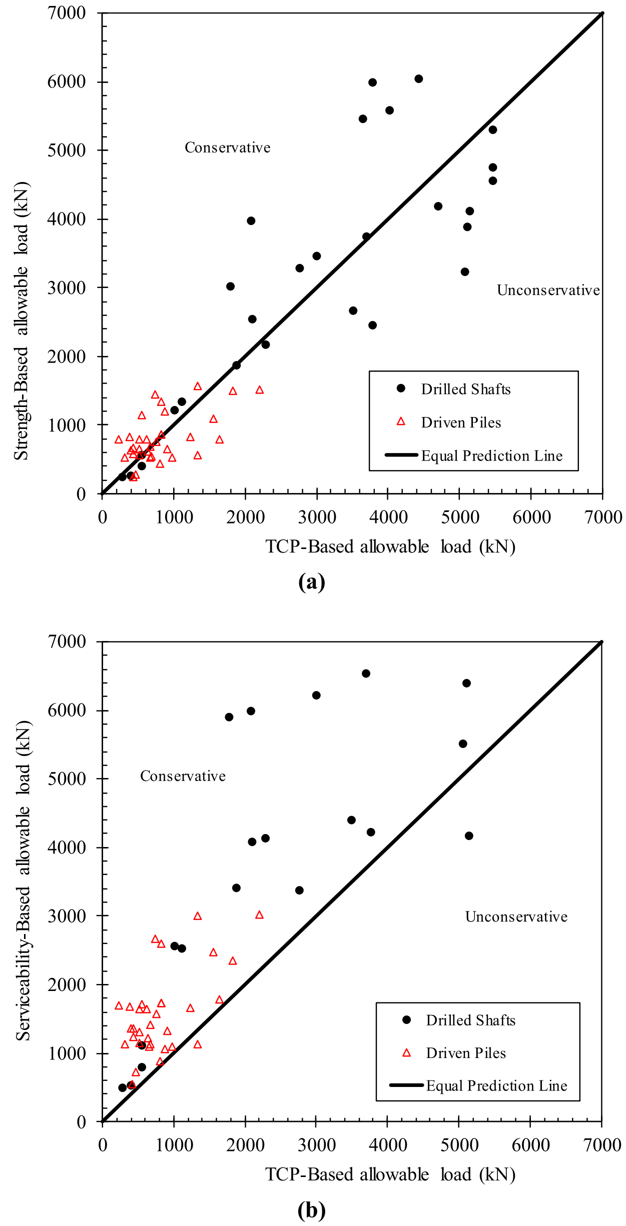
Qualitative evaluation

The primary objective of this qualitative evaluation was to explore different assessment criteria applied to the TCP design methodology. As a first step, two scatterplots were generated and compared to the equal prediction line, Fig. 5. The first plot, Fig. 5*a*, is representative of the strength-based evaluation where the allowable load was determined using the Davisson's criteria and a safety factor of 2.0 and compared to the allowable load determined from the TCP predictive model with the same safety factor. The second plot, Fig. 5*b*, represents the evaluation of a serviceability condition where loads corresponding to a defined tolerable displacement (in this case 12.5-mm) from load-settlement curve were compared to the allowable load obtained from the TCP predictive model.

In Fig. 5*a*, data points above the equal prediction line are *conservative* (that is, the TCP-based method predicts allowable load *smaller than* the measured value) and data points below the equal prediction line are *unconservative* (that is, the TCP-based method predicts allowable load *greater than* the measured value). It is noted that the data cloud corresponding to the driven piles is located within lower capacities compared to the drilled shafts data cloud. This difference is primarily associated with the lengths and widths of the driven piles.

From a visual evaluation of the plot, the first observation is that approximately 45% of the data are on the conservative side, 45% of the data are on the unconservative region, and 10% are on the equal prediction line. Considering the variability of prediction models in geotechnical engineering, these behaviours could be considered as a normal behaviour.

Of particular interest are those test cases that plot in the unconservative region. While the engineering design process requires conservatism, the fact that some of the data points in Fig. 5*a* plot below the equal prediction line does not necessarily mean that the *performance* of the foundation is in jeopardy. It is important to note that the concept of capacity (i.e. ultimate limit state) criterion is an engineer-defined computational condition (Foye, Abou-Jaoude,



5 Relationship between *a* strength-based and TCP-based allowable load and *b* serviceability-based and TCP-based allowable load

Prezzi and Salgado 2009). For example, in the case of a full-scale load test completed for a deep foundation, the plunging load is considered as the physical event of the ultimate limit state, but this is different from the load determined from an accepted ultimate criterion (e.g. Davisson's, 5% or 10% relative settlement) established as the computational condition. Therefore, unconservative design does not necessarily mean poor performance. This can be better illustrated with the serviceability-based approach.

As used in this study, serviceability refers to the condition where an element of a structure can suffer deformations due to applied loads but not to the extent of reaching deformation levels beyond capacity. In such case a collapse is not likely to occur, but the structure or the element of the structure is not *serviceable* and cannot meet its prescribed function. In geotechnical engineering and more specifically in the case of axially loaded deep foundations, deformations can be translated to vertical displacement of the foundation element which causes settlement in the superstructure. When the vertical displacement is larger than an established tolerable displacement, then it is considered that the foundation system has reached the serviceability limit state.

Although the majority of deep foundation designs for highway projects have shifted towards the Load and Resistance Factor Design (LRFD) methodology, many private practices still use the ASD approach. Under this methodology, design loads defined as actual forces applied to the foundation are compared to resistance through a safety factor (Paikowsky *et al*. 2004). In other words, if the capacity divided by a safety factor is greater than the design load, then satisfactory foundation performance is expected.

The trend observed in Fig. 5*b* is that most of the data plot above the equal prediction line, and for a tolerable displacement of 12.5-mm (0.5-in), only 2 points are below the equal prediction line. This shows that when the serviceability-based loads are compared to the TCP-based allowable load, the data cloud shifts towards the conservative region.

From these observations, it is apparent that different assessment criteria will lead to different conclusions regarding the predictive validity of the TxDOT TCP method for deep foundation design. For a strength limit assessment, TCP predictions seem to be a *middle ground* case where some predictions are conservative and others are unconservative. In contrast, interpretations of the TCP foundation design charts based on the serviceability limit assessment (which would be closely associated with observed structure performance) will lead to the conclusion of a conservative outcome as shown in Fig. 5*b*. Collectively, as the magnitude of tolerable settlement increases, the TCP foundation design charts will tend to predict the allowable loads in a more conservative manner.

It is important to point out that it would not be reasonable to attribute all of the data scatter to the TCP test method. Many other factors such as differences in load testing procedures used (e.g. top-loaded versus bi-directional, loading rates, time lag between installation of test foundation and load testing), differences in foundation construction/installation methods (e.g. pile driving, use of slurry versus dry-hole installation for drilled shafts), and other factors would also have contributed to such scatter.

Quantitative evaluation

Linear regression analyses were completed for the same sets of data analyzed qualitatively; however, for the quantitative analysis these data were further differentiated by soil type, both fine-grained and coarse-grained. As used in this study, 'fine-grained' refers to predominately clayey and silty soils having greater than 50% passing the 75μm sieve and 'coarse-grained' refers to predominately sandy (and some gravelly) soil where 50% or more of the soil particles are retained on the 75 μm sieve. Hence, four analyses were completed for the quantitative evaluation as summarized in Table 3.

For each subset of data, the relationship between the independent variable and the dependent variable was identified in terms of a regression model. Prior to each regression analysis, the data were analyzed to ensure that all assumptions for a simple linear regression analysis were met (i.e. normality, homoscedasticity, etc.). Linear models were determined following the form of Equation (2) where y is the dependent variable, x is the independent variable, and β_o and β_1 are the intercept and the slope of the regression model, respectively.

$$y = \beta_0 + \beta_1 x \qquad (2)$$

For all sets of regression analysis, the x represents the TCP-based allowable load and y represents the strength-based or serviceability-based allowable load. For each model, the existence of a relationship between the variables was confirmed by *p-values* and the strength of the relationship was assessed by the coefficient of determination (R^2). The regression models were compared to the equal prediction line, to observe whether the equal prediction line was completely within the confidence boundaries of the regression model. The confidence intervals (CI) for the regression model were considered as the set of all reasonable linear models suggested by the data.

Results

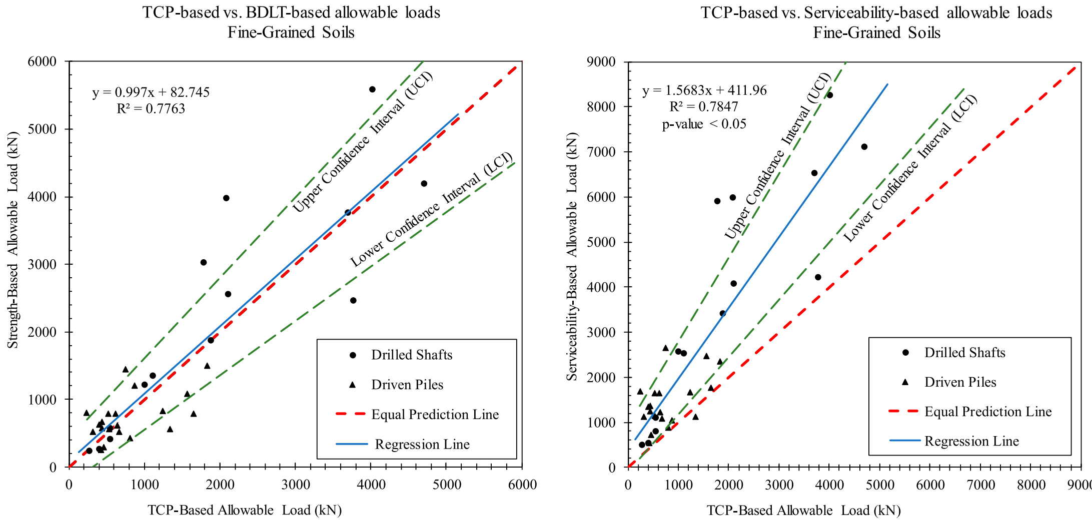
Regression models

Regression models were fitted to the corresponding data for fine-grained soils, Fig. 6, and coarse-grained soils, Fig. 7, following the form of Equation (2). In these figures, the regression models are shown as solid lines, the equal prediction line with dashed lines, and Upper (UCI) and Lower (LCI) confidence intervals are shown with long-dashed lines. For strength-based models in both soil types (Fig. 6*a*, Fig. 7*a*), the equal prediction line is within the 95% confidence intervals (CI) indicating that the equal prediction line is a plausible model that could describe the predictive validity of the TCP design charts as well as the relationship between analyzed variables.

For fine-grained soils, the strength-based regression model (Fig. 6*a*) is highly in agreement with the equal

Table 3 Summary analysis of the quantitative evaluation of allowable loads

Soil type	Combination analysis	
Fine-grained	Strength-based vs. TCP-based	Serviceability-based vs. TCP-based
Coarse-grained	Strength-based vs. TCP-based	Serviceability-based vs. TCP-based



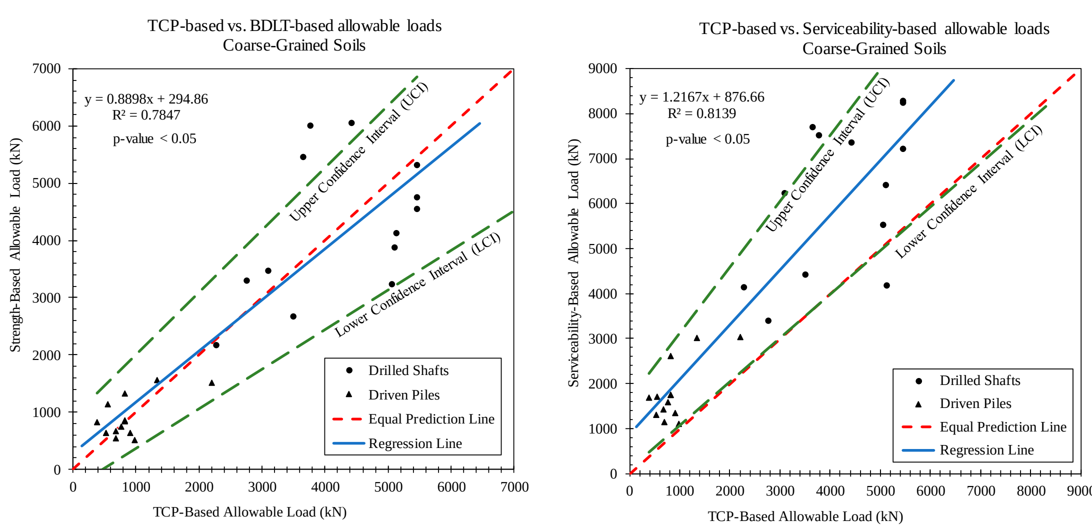
(a) (b)

6 Scatterplot and fitted regression model for fine-grained soils *a* strength-based allowable load and *b* serviceability-based allowable load

prediction line indicating that the TCP design chart predictions based on an ASD approach are within equal prediction when compared to the Davisson's results with a SF = 2.0. However, the LCI for the strength-based regression model is located beneath the equal prediction line indicating the possibility of some unconservative predictions. The interpretation is that the model does a good job predicting capacity but the foundation performance could still be jeopardized since the LCI is below the equal prediction line.

When the comparison for fine-grained soils is made using the serviceability-based allowable loads (Fig. 6*b*) it is noted that both the regression model as well as the UCI and LCI are moved above the equal prediction line, indicating all conservative predictions.

In the case of coarse-grained soils, the strength-based regression model (Fig. 7*a*) intersects the equal prediction line at an allowable load of about 2800 kN. This indicates that the strength-based regression model is slightly on the conservative side up to about 2800 kN (630 kips), and slightly unconservative at higher loads. In contrast, the analysis for serviceability-based allowable loads (Fig. 7*b*) shows the entire regression model and its corresponding CIs shift above the equal prediction line and the LCI is almost overlapped with the equal prediction line.



(a) (b)

7 Scatterplot and fitted regression model for coarse-grained soils *a* strength-based allowable load and *b* serviceability-based allowable load

Note the regression line shift in the comparison between Fig. 6b and Fig. 7b. In Fig. 6b the shifting has occurred as a pivoting or a notorious slope change; whereas, in Fig. 7b the shifting is a uniform translation, or parallel upward move.

From the statistical analyses, for both fine-grained and coarse-grained soils, it may be concluded based on the p-value <0.05 that a statistical relationship exists between strength-based allowable load and TCP-based allowable load as well as the serviceability-based allowable load and TCP-based allowable load. The data variability around the fitted regression lines is considered acceptable based on R-square values of 0.776 and 0.785 for the fine-grained soil models, and 0.785 and 0.814 for the coarse-grained soil models.

Overall, the quantitative evaluation indicates that strength-based assessments obtained using the TCP predictive model are aligned with the equal prediction line which supports the validity of the TCP foundation design model for both fine-grained and coarse-grained soils using the ASD method. Furthermore, the validity of predictions using the TCP design charts is strongly supported when the analysis is done for serviceability-based allowable loads where both the regression models and CIs are both above the equal prediction line.

Summary and conclusions

This paper presents an evaluation of the predictive validity of the TxDOT foundation design method for soil materials which in turn is based on blowcount data (N_{TCP}) obtained using the Texas Cone Penetration (TCP) test. This evaluation was accomplished using both qualitative and quantitative approaches. The qualitative evaluation relied on scatterplots and visual assessment of the results, and the quantitative evaluation was completed per statistical regression analyses by (1) comparing strength-based allowable loads to TCP-based allowable loads and (2) comparing serviceability-based allowable loads to TCP-based allowable loads, differentiated by soil type.

Findings from the qualitative evaluation show the strength-based regression models are in very close agreement with the equal prediction line with the lower confidence interval below the equal prediction line. This is an indication of a model that is accurate with low precision. Results from the serviceability evaluation show that as the magnitude of tolerable settlement increases from very small displacements to larger displacements, the TCP design charts will tend to predict allowable geotechnical loads for the foundation in a more conservative manner. Quantitatively, the strength-based regression models for both fine-grained soils and coarse-grained soils are typically coincident with the equal prediction line, again indicating in some cases that the TCP method over-predicts allowable load; whereas, the serviceability-based models are strongly predicting the allowable load in a conservative manner.

Thus this research has revealed an *apparent contradiction*; namely, that the TCP foundation design method can yield a foundation element that, when evaluated based on soil strength may not seem highly reliable, but when evaluated based on serviceability considerations (i.e. tolerable displacement) will perform exceedingly well to the point of perhaps being considered over-designed. This insight helps explain why (in the authors' experience) TxDOT geotechnical and bridge engineers have designed thousands of bridge foundations using the TCP method. The data from which these engineers render their judgment is reasonably influenced by their many years of experience observing safe, serviceable foundations which support bridge superstructure that does not excessively lean or settle. The findings of this research directly support the view of these engineers. But at the same time, this research also supports the view of other engineers who have voiced questions about the reliability of the TCP method based on their own experiences where the method may seem to over-predict soil shear strength. This also seems a reasonable assessment, because the origins of the TCP design method are strength-based, and to date, research on the TCP method has focused on shear strength approaches to determining allowable loads.

While this paper cannot definitively resolve the conundrum, a positive finding is that the data show that foundations designed according to the TCP method *perform well*. At this point, it is fair to say that both proponents and skeptics of the TCP design method are (or can be) considered correct in their assessments. The path to further productive inquiry would benefit from instrumented load test data so that differentiated base and shaft resistances per the TCP method can be evaluated. It would also be very important to obtain a body of load test data for foundations in intermediate geomaterials and rock, a domain where the TCP test has applicability beyond that of other *in situ* test methods.

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