LRFD RESISTANCE FACTORS FOR DESIGN OF DRIVEN PILES USING THE TEXAS CONE PENETRATION (TCP) TEST

Hoyoung Seo, Ph.D., P.E., Texas Tech University, Lubbock, Texas, hoyoung.seo@ttu.edu
William D. Lawson, P.E., Ph.D., Texas Tech University, Lubbock, Texas, william.d.lawson@ttu.edu
James G. Surles, Texas Tech University, Lubbock, Texas, james.surles@ttu.edu
Priyantha W. Jayawickrama, Ph.D., Texas Tech Univ., Lubbock, Texas, priyantha.jayawickram@ttu.edu
Rozbeh Moghaddam, Ph.D., P.E., GRL Engineers, Inc., 30725 Aurora Road, Solon, OH 44139

ABSTRACT

This study provides calibration of resistance factors (ϕ) for design of driven piles to implement Load and Resistance Factor Design (LRFD) for bridge foundations using Texas Cone Penetration (TCP) Test data. The basic research approach was to compile a database of published full-scale load tests including projects from the Texas Department of Transportation's (TxDOT) historical archive and projects from neighboring state DOTs. Load test results from neighboring states were leveraged by performing new geotechnical borings with TCP tests at the project sites. The final dataset consisted of 30 load tests performed on precast square concrete piles, with pile widths ranging from 356 to 508 mm and penetration depths ranging from 5.2 to 25.5 m, driven in soils. Ultimate capacities for each load test were interpreted based on Davisson, 5%, and 10% settlement criteria. These measured ultimate capacities were compared against predicted capacities estimated from TCP blow count values (N_{TCP}) and design charts following the procedures outlined in TxDOT's *Geotechnical Manual*. From the comparisons, statistical parameters of the biases (λ = measured capacity/predicted capacity) such as mean and coefficient of variation were obtained. Resistance factors (ϕ) for LRFD were then determined using Monte-Carlo simulations for each ultimate capacity criteria with the target reliability indices of 2.33 and 3.00.

Keywords: Texas Cone Penetration (TCP) test, Driven piles, LRFD, Resistance factor

INTRODUCTION

The Texas Department of Transportation (TxDOT) has used the Texas Cone Penetration (TCP) test since its development in the 1940s. The TCP test is an in-situ penetration test to characterize the materials encountered during geotechnical exploration. Texas currently maintains over 53,000 bridges in the National Bridge Inventory (FHWA 2016), and most of these bridges plus other transportation infrastructure in Texas are supported by foundations designed using the TCP test and its associated foundation design 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. With this significant body of experience, the TCP method has been viewed as a straightforward, relatively easy-to-use foundation design method that consistently yields safe, serviceable, economical, and maintainable foundations. TxDOT's deep foundation design method is documented in the TxDOT *Geotechnical Manual* (TxDOT 2012) and currently employs the allowable stress design (ASD) approach. However, the Federal Highway Administration (FHWA) has mandated that the states begin to implement the LRFD method in place of the older ASD approach (Densmore 2000). This paper presents resistance factors at ultimate limit state (ULS) for design of driven piles using the TCP test, resulting from efforts to be in compliance with the FHWA policy.

TCP TEST AND FOUNDATION DESIGN METHOD

Description of 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 60-cm drop to force a 76-mm diameter steel cone into the soil or rock formation. Details of cone geometry are presented in Fig. 1. In current practice, the penetration is to be achieved in three separate increments. The first increment is completed to ensure proper seating, which consists of driving the cone 12 blows or approximately 15-cm (6-in), whichever happens first. The TCP blowcount is then determined as the sum of the number of blows required to achieve second and third 15-cm (6-in) increments of cone penetration. The total blowcount or N_{TCP} corresponding to 30-cm (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 is completed, the cone is driven 100 blows and the penetration value for the first and second 50 blows is recorded.

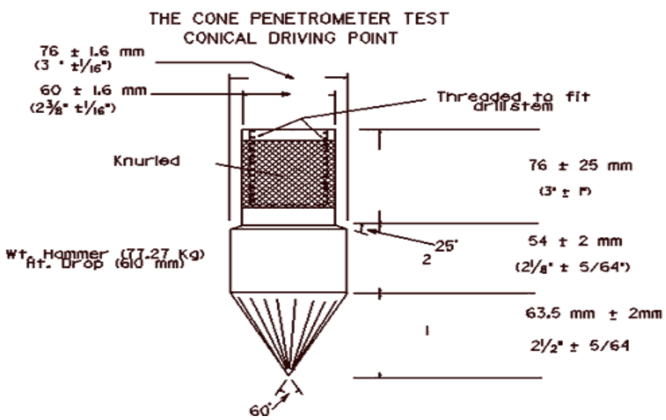

Fig. 1. TCP test conical driving point (TxDOT 1999)

Pile Design Method Using TCP. The TxDOT *Geotechnical Manual* (TxDOT 2012) provides two design charts for driven piles from which the allowable unit shaft and base capacities can be obtained for a given N_{TCP} value for various soil types. The design curves for determination of the allowable unit shaft resistance ($q_{s,all}$) are represented with the following equation for soils with N_{TCP} less than 100 blows per 30 cm:

$$q_{s,all}(kPa) = C_s N_{TCP} \leq 134\ kPa \qquad [1]$$

where N_{TCP} = average measured TCP blowcount (≤ 100 blows/30 cm) for the stratum and C_s = constants based on soil classification (= 1.92 for CH, 1.60 for CL, 1.37 for SC, and 1.20 for other types of soils). Note that the allowable unit shaft capacity is capped to a value of 134 kPa as per the TxDOT *Geotechnical Manual*.

Similarly, the design curves for determination of the allowable unit base capacity ($q_{b,all}$) are represented with the following equation for soils with N_{TCP} less than 100 blows per 30 cm:

$$q_{b,all}(kPa) = C_b N_{TCP} \qquad [2]$$

where N_{TCP} = average of measured TCP blowcounts (≤ 100 blows/30 cm) within two pile diameters below the base and C_b = constants based on soil classification (= 4.92 for CH, 5.78 for CL, 5.89 for SC, and 5.16 for other types of soils). According to TxDOT’s *Geotechnical manual*, both $q_{s,all}$ and $q_{b,all}$ include a factor of safety of two.

LOAD TEST DATABASE

Description. The load test data needed for this study were obtained from two separate sources. First, TxDOT possesses an archive of load tests which spans over several decades during which the TCP design method has been used for deep foundation design. The TxDOT data archive was supplemented with load test data available from Texas' neighboring states. In order to leverage these non-Texas load test data, new geotechnical borings were drilled and TCP tests conducted at those load test sites. The dataset compiled in this manner consisted of a total of 33 load tests on driven piles. All the 33 driven piles were precast square concrete piles with widths ranging from 0.356 to 0.508 m and penetration depths ranging from 4.6 to 25.5 m. Among the 33 load tests, 28 of them were conventional static top-down load tests and the remaining 5 tests were statnamic load tests. None of the 33 load tests were instrumented with strain gages and therefore resistance factors were determined only for total capacity in this study.

Among the 33 load tests, 22 of them were loaded beyond the ultimate capacity determined from Davisson's criterion (Davisson 1972). Among the 11 tests which did not reach the Davisson's offset line, eight of them reached at least an elastic line and were included in our dataset after extrapolation of the load-settlement curves. However, the remaining three tests which did not reach even the elastic line were deemed non-usable and therefore excluded from the dataset for the subsequent reliability analyses. Consequently, 30 tests on driven piles were included in the final load-test dataset. Fig. 2 shows an example of load-settlement curve and determination of the ultimate capacities for Case No. 15 from our dataset.

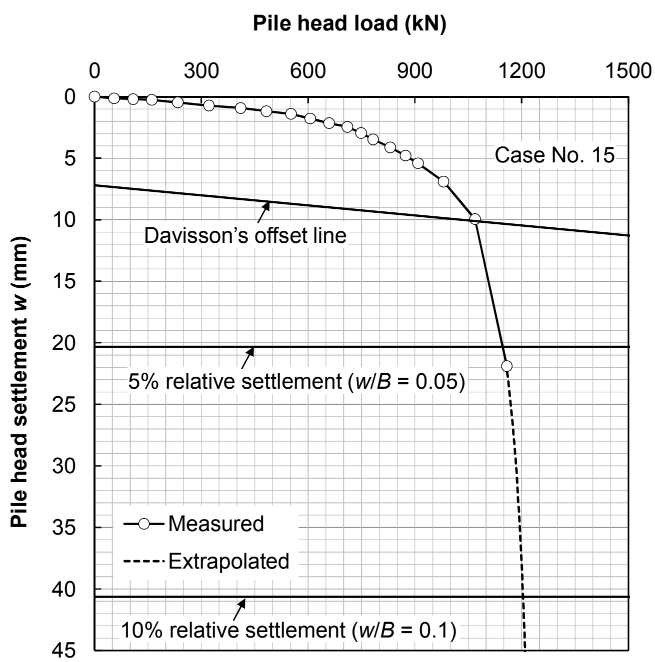

Fig. 2. Example of load-settlement curve and determination of ultimate capacities (Case No. 15)

Ultimate capacity of deep foundations is generally defined based on the load-settlement relationship obtained from a full-scale load test. In this study, Davisson, 5%, and 10% relative settlement criteria were used to determine the ultimate capacity (Q_{ult}) for driven piles. The prediction of the ultimate capacity of each test pile was accomplished using the procedure outlined in the TxDOT *Geotechnical manual* (TxDOT 2012). It should be noted that the TCP design charts provide allowable unit shaft and base capacities rather than ultimate values. Therefore, allowable capacities were multiplied by factors of safety of two, as was provided in the Design Manual, to obtain ultimate shaft and base capacities. Table 1 presents summary of the measured and predicted ultimate capacities of the test piles used in this study, excluding the three tests disregarded in the subsequent analysis.

Table 1. Summary of load test database for driven piles in soils

Case No	Pile Dimensions B (m)	Pile Dimensions L_p (m)	General Stratigraphy	Q_{ult} from Davisson's Criterion[a)] Total (kN)	Q_{ult} from 5% Criterion[a)] Total (kN)	Q_{ult} from 10% Criterion[a)] Total (kN)	Predicted Total Capacity (kN)	Composite Data Quality Score
1	0.356	9.1	CL/SM	497	528	543	861	8.4
2	0.356	7.8	CL/SM/CL/SC	1654	1765	1882	769	8.4
3	0.356	6.7	CL/SM/CL	1161	1300	1380	874	8.4
4	0.356	10.5	CL/CL/SC/CL	866	909	940	1615	8.4
5	0.508	21.1	WATER/CL/SP/CH/SM	2901	3261	3692	1497	6.4
6	0.381	10.7	CL/SC/SM	1574	1891	2214	1243	9.2
7	0.381	10.0	CL/SC/SM	1365	1487	1595	1354	9.2
9	0.406	13.0	CL/SW/CL/SP	1044	1162	1231	1969	7.8
10	0.406	13.4	MH/SP/SM/CL/SP	1291	1452	1572	1046	8.4
11	0.406	14.2	CL/SP/CL/SP	1652	1873	2087	2482	6.4
12	0.406	5.0	CL/SC/CH	1047	1218	1305	626	8.4
13	0.406	4.6	SM/SP/CL	1598	1792	1906	472	8.4
14	0.406	14.2	SP/CL/SP/CL/SP	1304	1443	1577	1820	8.4
15	0.406	9.1	CH	1049	1147	1205	1338	8.4
16	0.406	9.4	CH/SM/CL	1344	1409	1501	881	8.8
17	0.406	12.2	CH/SM/CH	579	1000	1464	933	8.2
18	0.381	9.4	CL/SM	1255	1507	1692	808	6.6
19	0.508	23.5	SM/CL/SM	1117	1177	1205	2690	7.2
20	0.356	8.1	CL	1570	1728	1779	3293	9
22	0.457	25.5	MH/SM	1222	1359	1466	1285	5.4
24	0.356	7.8	CL/SM	1122	1179	1214	1060	9
25	0.457	12.8	CH/SM/CH	1722	2011	2212	1222	8.6
26	0.457	12.8	CH/SM/CH	1712	1817	1887	1222	8.6
27	0.457	12.2	CH/SM/CH	1519	1739	1869	1132	8.6
28	0.457	12.8	CH/SM/CH	2668	3239	3827	1222	7.4
29	0.457	16.8	CH/SM/CH	3132	4832	9288	2026	8.6
30	0.508	21.9	CH/SC/CH/SP/CH/SP	3031	2910	3728	3285	8.4
31	0.508	21.9	CH/SP/CH/SP/CH	2173	2539	2614	2316	8
32	0.356	13.1	CH/SM/CH/SM	1096	1185	1216	970	8.8
33	0.356	24.4	SM/CH/SP/CH/SP	3014	3962	3962	2653	5.4

Note: a) The ultimate capacity values in these columns represent measured capacities based on corresponding ultimate capacity criteria if those criteria were met. Otherwise, these values were obtained from extrapolation using weighted hyperbolic method.

Quality of Dataset. The quality and reliability of the load test data varied significantly from one project to another. As mentioned previously, some of the load tests records collected for this study were several decades old whereas others were very recent. Furthermore, although most of the load tests were loaded to the final loading step during the first loading cycle, some load tests were performed in multiple loading cycles. The level of capacity mobilization and extrapolation also varied widely. In order to capture and account for these differences in load test quality, we created and introduced an index called Measured Capacity Quality Rating for each load test project. The factors considered were (a) settlement level at the end of the load test, (b) straightforwardness of load test procedures, and (c) completeness of documentation and records. A quality score assigned for each category was multiplied by a weight and summed up to give final quality rating, varying from 1 to 5, with larger numbers representing greater quality.

The reliability of the predicted load capacity estimated based on site characterization data also varied. In order to capture differences in site characterization data quality associated with load capacity prediction, we created and introduced an index which we termed the Load Capacity Prediction (LCP) Data Quality Rating. The LCP data quality rating was calculated based on an arguably-subjective-yet-systematic assessment of site characterization data quality for factors including (a) proximity of the geotechnical borings used to develop generalized soil profile to test shaft or pile, (b) site uniformity, (c) completeness of available data, (d) ease of interpretation of data, and (e) TCP and shear strength data. The LCP data quality rating also varied from 1 to 5, with larger numbers representing greater quality.

Combining the quality ratings for measured and predicted capacities for a given load test yielded a composite quality index ranging from 2 to 10, and these values are presented in Table 1. Among the 30 driven pile load tests, 22 of them have a composite quality rating of 8 or higher. To facilitate the statistical analyses for this study, the composite quality index was converted into a weighting factor that ranged from 0 to 1. Details of the quality-rating rubrics, composite quality index, and weighting factor are presented in research reports published by the authors (Seo et al. 2015a and 2015b).

DEVELOPMENT OF ULS RESISTANCE FACTORS

Bias Calculations. The measured ultimate capacities from the load tests were compared with the predicted capacities obtained using TCP blow counts (N_{TCP}), and biases (λ_R = measured capacity/predicted capacity) for each test were then computed for each ultimate capacity criterion. The form of the bias distribution was evaluated using histograms and probability plots to compare them to the normal and lognormal distributions. Examples of bias distributions using Davisson's criterion are given in Figs. 3(a) and 3(b). In Fig. 3(b), the "AD" value represents the value of the Anderson-Darling statistic to test whether data are represented by the hypothesized distribution, and the associated p-value is given beneath (Anderson and Darling 1954). As the p-value for the lognormal fit is 0.749, the lognormal cannot be rejected as the underlying distribution (i.e. the data are consistent with a lognormal). However, in the case of the normal distribution, the p-value was smaller than 0.05 indicating that the normal distribution can be rejected as the underlying distribution. Bias distributions using 5% and 10% relative settlement criteria also followed lognormal distributions.

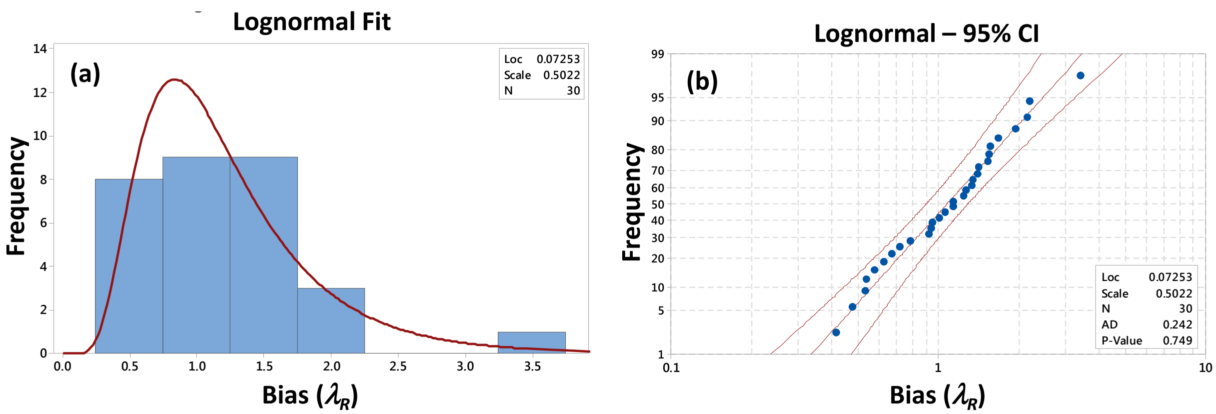

Fig. 3. (a) Histogram of biases and (b) Lognormal probability plot of biases using Davisson's criterion

Typically, Maximum Likelihood Estimators (MLE) are used to determine the mean and variance in LRFD study. However, in this study, the mean and variance for biases were estimated using the Uniformly Minimum Variance Unbiased Estimators (UMVUEs). Surles et al. (2016) explored the use of UMVUEs for lognormal distributions following the work presented by Finney (1941). An examination and comparison of MLE for the UMVUE method was presented with the conclusion that for a lognormal distribution, the UMVUE approach is more appropriate as it has higher precision and less data variability. Detailed procedures to obtain the weighted mean and coefficient of variation (COV) of the biases using UMVUEs are as follows:

a) Take the log transformation of the data (i.e. $x_i = \ln(\lambda_{Ri})$).
b) Compute the weighted mean ($\bar{x}$) and variance (s_x) of the log-transformed sample
c) Plug the weighted mean and variance of the log-transformed sample into the following equations to obtain weighted UMVUE for mean ($E[\lambda_R]$) and standard deviations ($SD[\lambda_R]$):

$$E[\lambda_R] = \exp(\bar{x})\, g(0.5 s_x^2), \text{ and} \quad [3]$$

$$SD[\lambda_R]^2 = \exp(2\bar{x})\left\{g(2s_x^2) - g\left(\frac{n-2}{n-1} s_x^2\right)\right\}, \text{ where} \quad [4]$$

$$g(t) = 1 + \frac{n-1}{n} t + \frac{(n-1)^3}{n^2 2!}\frac{t^2}{n+1} + \frac{(n-1)^5}{n^3 3!}\frac{t^3}{(n+1)(n+3)} + \cdots \quad [5]$$

d) Compute COV by dividing $SD[\lambda]$ by $E[\lambda_R]$ obtained from Eqs. (3) and (4), respectively.

The weighted UMVUE summary statistics for the 30 load tests on driven piles in soils are given in Table 2 (note that a weighting factor that ranged from 0 to 1 was used for calculations of mean and COV to consider the uncertainties associated with the data quality). As expected, the mean biases for 5% and 10% criteria are greater than that for Davisson's criterion. It was observed that the COVs for 5% and 10% criteria were also greater than that for Davisson's criterion.

Table 2. Summary statistics for biases of resistances for driven piles in soils

Ultimate Capacity Criteria	Total number of load tests considered (Total sample size)	Effective sample size	Mean of Bias	COV of Bias
Davisson	30	26.8	1.224	0.532
5%	30	26.8	1.397	0.559
10%	30	26.8	1.600	0.620

Calibrations of Resistance Factor. Resistance factors were obtained following the first order second moment (FOSM) method and the Monte Carlo simulation using the bias statistics presented in Table 2. In the FOSM method, resistance factor (ϕ) is obtained from the following equation:

$$\phi = \frac{\lambda_R \left(\gamma_{DL} \frac{Q_{DL}}{Q_{LL}} + \gamma_{LL}\right) \sqrt{\frac{1 + COV_{Q_{DL}}^2 + COV_{Q_{LL}}^2}{1 + COV_R^2}}}{\left(\lambda_{DL} \frac{Q_{DL}}{Q_{LL}} + \lambda_{LL}\right) exp\left\{\beta \sqrt{\ln\left[\left(1 + COV_R^2\right)\left(1 + COV_{Q_{DL}}^2 + COV_{Q_{LL}}^2\right)\right]}\right\}} \quad [6]$$

where λ_R = mean bias of the resistance, λ_{DL} = bias of the dead load, λ_{LL} = bias of the live load, COV_R = coefficient of variation of the resistance, COV_{QDL} = coefficient of variation of the dead load, COV_{QLL} = coefficient of variation of the live load, γ_{DL} = load factor for dead load, γ_{LL} = load factor for live load, Q_{DL}= dead load, Q_{LL} = live load, and β = target reliability index.

In Monte Carlo simulation, resistance factors were obtained by trying different values of resistance factors (ϕ_{trial}) until the target probabilities of failure of 0.01 (corresponding to $\beta \approx 2.33$) and 0.001 (corresponding to $\beta \approx 3.00$) were achieved. In this study, total simulation size was chosen to be 1,000,000. Since none of the 30 load tests was an instrumented test, resistance factor was calibrated for total capacity only.

For both FOSM method and Monte Carlo simulation (MCS), $Q_{DL}/Q_{LL} = 2$, λ_{LL}= 1.15, COV_{LL} = 0.2, λ_{DL}= 1.05, and COV_{DL}= 0.1 were used for statistics for biases of loads following suggestions by NCHRP (Paikowsky 2004). Tables 3 and 4 present LRFD resistance factors obtained both from FOSM method and MCS for target reliability indices of 2.33 and 3.00, respectively. Surles et al. (2016) advocated that confidence intervals should accompany the resistance factors when presenting the results from a calibration study because the resistance factor is subjected to sampling error as with any other statistic. The 95% confidence intervals presented in Tables 3 and 4 were obtained using a bootstrap method and based on the FOSM resistance factors.

Table 3. Resistance factors for total capacity of driven piles in soils (β = 2.33)

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo Simulation)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	26.8	1.224	0.532	0.44	0.41	0.30	0.53
5%	26.8	1.397	0.559	0.47	0.44	0.31	0.58
10%	26.8	1.600	0.620	0.47	0.44	0.30	0.59

Table 4. Resistance factors for total Capacity of driven piles in soils (β = 3.00)

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo Simulation)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	26.8	1.224	0.532	0.30	0.28	0.19	0.39
5%	26.8	1.397	0.559	0.32	0.30	0.20	0.42
10%	26.8	1.600	0.620	0.31	0.29	0.19	0.42

According to our analyses, resistance factors for β of 2.33 obtained from Monte Carlo simulations are 0.44, 0.47, and 0.47 for Davisson, 5%, and 10% criteria respectively. Similarly, resistance factors for β of 3.00 are 0.30, 0.32, and 0.31 for Davisson, 5%, and 10% criteria respectively. Although the mean bias is the greatest for 10% criterion, it does not necessarily yield the greatest resistance factors because the COV is also the largest for 10% criterion.

SUMMARY AND CONCLUSIONS

This research study has developed resistance factors for total capacity of driven piles in soils using Davisson, 5% and 10% relative settlement criteria as ultimate capacity criteria. A database containing 30 load tests performed for driven piles in soils was developed for this study. With consideration to data quality, the effective sample size was 26.8. Davisson's criterion yielded the resistance factors of 0.44 and 0.30 corresponding to target reliability indices of 2.33 and 3.00, respectively. Although the mean bias was the greatest for 10% criterion, it did not necessarily yield the greatest resistance factors because the COV is also the largest for 10% criterion. Considering the wide spread use of Davisson's criterion for driven piles in United States and the small increase in ϕ values when other criteria were used, resistance factors from Davisson's capacity are recommended for driven piles in soils for LRFD using TCP method.

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