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Implementation of LRFD Geotechnical Design for Deep Foundations Using Texas Cone Penetrometer (TCP) Test

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Performed in Cooperation with the Texas Department of Transportation
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16. Abstract:

This study provides resistance factors (ϕ) for design of deep foundations to implement Load and Resistance Factor Design (LRFD) for bridge foundations using Texas Cone Penetrometer (TCP) Test data. Initial efforts were made to determine resistance factors using Davisson's criterion in Research Project 0-6788: Reliability Based Deep Foundation Design Using Texas Cone Penetrometer (TCP) Test, completed on 8/31/2014. In this study, additional LRFD reliability analyses were performed using 5%, and 10% relative settlement criteria to determine ultimate capacities. The resistance factors obtained using Davisson, 5%, and 10% criteria were 0.30, 0.32, and 0.31, respectively, for total capacity of driven piles in soils with target reliability index (β) of 3.0. Similarly, the resistance factors obtained using Davisson, 5%, and 10% criteria were 0.38, 0.40, and 0.39, respectively, for total capacity of drilled shafts in soils with β of 3.0. These resistance factors reflect TCP blow counts not corrected for hammer efficiency. Based on the size and scope of the dataset, literature review, and statistical analyses, it is recommended that resistance factors from Davisson and 5% criteria be used for driven piles in soils ($\phi = 0.44$ and 0.30 with β of 2.33 and 3.0, respectively) and drilled shafts ($\phi = 0.54$ and 0.40 with β of 2.33 and 3.0, respectively) in soils, respectively. It is considered that these values are suitable for implementation for small projects. For large projects, it is recommend consideration of determining ultimate capacity from static or dynamic load tests in accordance with AASHTO policy which will yield higher resistance factors.

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REVIEW OF ULTIMATE CAPACITY CRITERIA IMPLEMENTED BY OTHER STATE DOTs

This report presents a summary of the work completed under the TxDOT Implementation Project 5-6788-01: Implementation of LRFD Geotechnical Design for Deep Foundations Using Texas Cone penetrometer (TCP) Test and final recommendations.

As part of this literature review effort, a large number of research reports, bridge design manuals, geotechnical manuals, and standard specifications published by each state Department of Transportation (DOTs) were collected and reviewed in detail. These publications discuss topics related to the development and implementation of the Load and Resistance Factor Design (LRFD) for deep foundations and the ultimate capacity criteria to determine a foundation's load carrying capacity.

1.1 Research Studies Published by Other DOTs Which Have Explored the Implementation of LRFD for Deep Foundations

Ever since the Federal Highway Administration (FHWA) mandated the use of the load and resistance factor design (LRFD) approach for all new bridges initiated after September 2007 (Densemore 2000), most DOTs have been working on implementation of LRFD for design of bridge foundations. AbdelSalam et al. (2010) conducted a nationwide survey of more than 30 DOTs on the bridge deep foundation practices in 2008. According to AbdelSalam et al. (2010), as of 2008 24 states had implemented the LRFD method to a certain extent, five states were still using the allowable stress design (ASD) method, and 21 states were in the process of transitioning to the LRFD method. Figure 1 shows the status of LRFD implementation for bridge foundation design at the time of the survey.

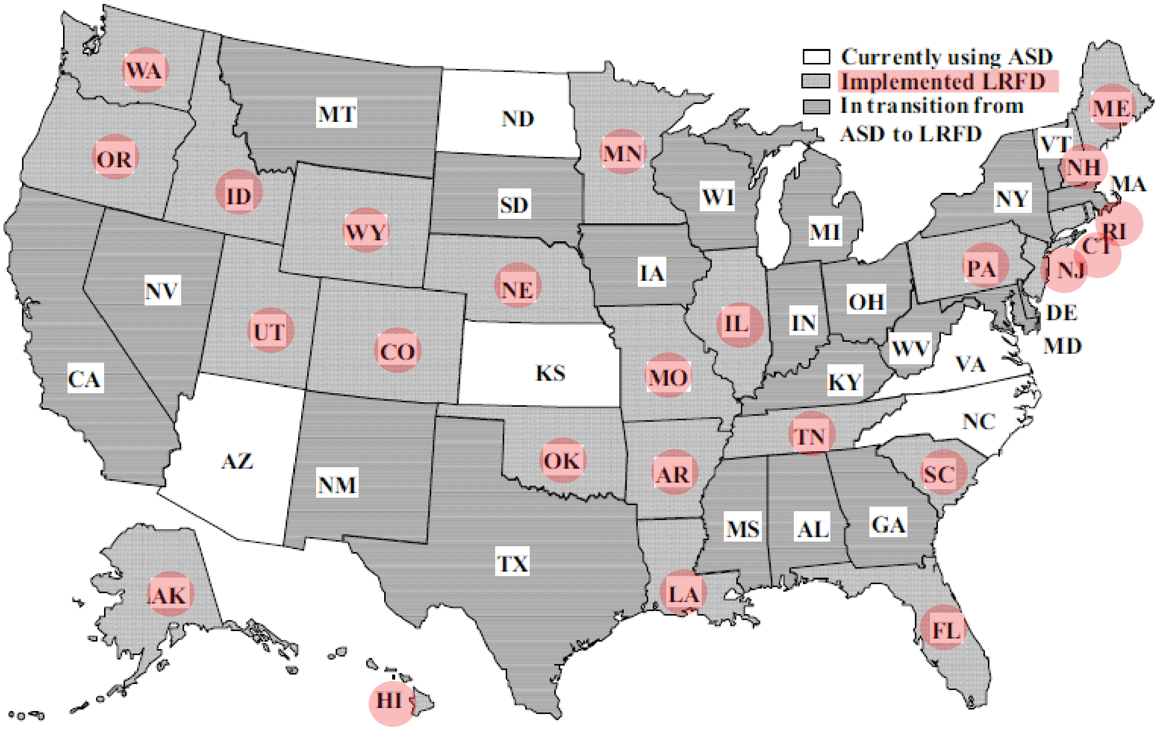


Figure 1. Status of LRFD Implementation of State DOTs as of 2008 (AbdelSalam et al. 2010)

Although the survey completed by AbdelSalam et al. (2010) indicated that 24 states had implemented the LRFD method, not all research reports were available at the time of preparation of this report. In fact, it appears that many DOTs did not perform any research study to calibrate region-specific resistance factors against target reliability index, but rather obtained resistance factors by fitting to the ASD factor of safety based on past local experience, or simply recommended using the resistance factors suggested in AASHTO LRFD Bridge Design Specifications (AASHTO 2012). On the other hand, some of the states identified as transitioning from ASD to LRFD in the survey by AbdelSalam et al. (2010) now published preliminary reports presenting the implementation of the LRFD method for their corresponding states. The results of review of research reports, bridge design manuals, geotechnical manuals, and standard specifications published by each state DOT are summarized in Table 1.

Table 1. Summary Table Presenting Findings about Ultimate Capacity Criteria LRFD Implementation Status Reported by State DOTs

No.	State	Implemented LRFD according to AbdelSalam et al. (2010)	Refers to AASHTO LRFD manual	Resistance factor obtained by fitting to ASD factor of safety based on past local experience	Resistance factor obtained from reliability analysis	Ultimate Capacity Criteria		Comments	References
						Driven Pile	Drilled Shaft		
1	Alabama		x	x				Resistance factors for driven piles were obtained by fitting to the ASD factor of safety through a research project, but current ALDOT design manual recommends AASHTO LRFD resistance factors.	Ashour et al. (2012); ALDOT (2015)
2	Alaska	x						No documents available	
3	Arizona		x						ADOT (2011)
4	Arkansas	x						Research project for LRFD calibration for drilled shaft foundations is underway by University of Arkansas.	AHTD (2014); Coffman (2015)
5	California			x				Resistance factors obtained by fitting to the ASD factor of safety have been used for a transition period. Research project to perform a California specific calibration of resistance factors is underway by University of Texas, Arlington.	Caltrans DRISI (2014)
6	Colorado	x						Strategic plan to implement LRFD was released by CDOT in 2006, but no research report on resistance factor calibration is available.	Chang et al. (2011)
7	Connecticut	x	x					Uses AASHTO LRFD resistance factors for driven piles. Resistance factors for drilled shafts are not available in the Geotechnical Engineering Manual.	ConnDOT (2005)
8	Delaware		x						DelDOT (2005)
9	Florida	x			x	Davisson	5%		Kuo et al. (2002); FDOT (2015)
10	Georgia							Resistance factors for structural capacity of H and Prestressed Concrete (PSC) piles are available, but not for geotechnical capacity.	GDOT (2015)
11	Hawaii	x				Davisson		Resistance factors for deep foundations are not available in Standard Specifications, but Davisson's criterion to determine ultimate capacity of driven piles is recommended.	HDOT (2005)
12	Idaho	x	x						ITD (2008)

No.	State	Implemented LRFD according to AbdelSalam et al. (2010)	Refers to AASHTO LRFD manual	Resistance factor obtained by fitting to ASD factor of safety based on past local experience	Resistance factor obtained from reliability analysis	Ultimate Capacity Criteria		Comments	References
						Driven Pile	Drilled Shaft		
13	Illinois	x	x		x			IDOT used WSDOT driving formula for calibration of resistance factor for driven piles. For drilled shafts, IDOT refers to AASHTO LRFD resistance factors.	IDOT (2012)
14	Indiana				x	10%	10%		Salgado et al. (2011)
15	Iowa				x	Davisson		Resistance factors were obtained only for driven piles.	AbdelSalam et al. (2012)
16	Kansas				x		5%	Resistance factors were obtained only for drilled shafts.	Yang et al. (2010)
17	Kentucky		x						KYTC (2014)
18	Louisiana	x			x	Davisson	5%		Abu-Farsakh et al. (2009); Abu-Farsakh et al. (2010)
19	Maine	x	x						Maine DOT (2014)
20	Maryland							No documents available	
21	Massachusetts		x						MassDOT (2013)
22	Michigan		x						MIDOT (2012)
23	Minnesota	x			x	Davisson			Paikowsky et al. (2014)
24	Mississippi		x						MDOT (2010)
25	Missouri	x			x	Davisson			Loehr et al. (2011); Luna (2014)
26	Montana		x						MDT (2008)
27	Nebraska	x		x					Nowak et al. (2007)
28	Nevada		x						NevadaDOT (2008)

No.	State	Implemented LRFD according to AbdelSalam et al. (2010)	Refers to AASHTO LRFD manual	Resistance factor obtained by fitting to ASD factor of safety based on past local experience	Resistance factor obtained from reliability analysis	Ultimate Capacity Criteria		Comments	References
						Driven Pile	Drilled Shaft		
29	New Hampshire	x				Davisson		New Bridge Design Manual is to be released. The NHDOT Spec Book does not provide resistance factors but specify Davisson's criterion to be used to determine ultimate capacity.	NHDOT (2010)
30	New Jersey	x	x						NJDOT (2009)
31	New Mexico				x				Ng and Fazia (2012)
32	New York		x						NYSDOT (2014)
33	North Carolina				x	Davisson		Resistance factors were obtained only for driven piles.	Rahman et al. (2002)
34	North Dakota		x						NDDOT (2013)
35	Ohio		x			Davisson	Davisson	Construction Manual specifies Davisson's criterion to be used to determine ultimate capacity.	OHDOT (2013); OHDOT (2015)
36	Oklahoma	x	x			Davisson		Standard and Specifications Book specifies Davisson's criterion to be used to determine ultimate capacity	OKDOT (2009)
37	Oregon	x			x	Davisson		Bridge Design and Drafting Manual requires Foundation Designer to provide the resistance factor in the Foundation Report.	Smith et al. (2011); ODOT (2015)
38	Pennsylvania	x		x				Design Manual generally refers to AASHTO LRFD manual but recommends higher resistance factors than AASHTO values.	PennDOT (2015)
39	Rhode Island	x	x						RIDOT (2007)
40	South Carolina	x		x				Geotechnical Manual generally refers to AASHTO LRFD manual but recommends slightly different resistance factors.	SCDOT (2010)
41	South Dakota							Standards and Manuals do not mention LRFD design of deep foundations. Research report on implementation plan of LRFD was published in 2008.	Foster and Huft (2008); SDDOT (2014); SDDOT (2015)
42	Tennessee	x						No documents available	
43	Texas								

No.	State	Implemented LRFD according to AbdelSalam et al. (2010)	Refers to AASHTO LRFD manual	Resistance factor obtained by fitting to ASD factor of safety based on past local experience	Resistance factor obtained from reliability analysis	Ultimate Capacity Criteria		Comments	References
						Driven Pile	Drilled Shaft		
44	Utah	x	x						UDOT (2011); UDOT (2015)
45	Vermont		x						VTrans (2010)
46	Virginia							Geotechnical manual for LRFD design of deep foundation is under development	VDOT (2010)
47	Washington	x	x		x			Resistance factors for driven piles using WSDOT driving formula or Wave Equation analysis were obtained from reliability analyses. All other resistance factors are referred to AASHTO LRFD manual.	Allen (2005); WSDOT (2015)
48	West Virginia		x						WVDOH (2014)
49	Wisconsin		x						WisDOT (2015) Bridge Manual
50	Wyoming	x						Bridge design manual for LRFD design of deep foundation is under development.	WYDOT (2013)

According to our review, 12 state DOTs performed research projects in an effort to calibrate resistance factors against target reliability index for driven piles, drilled shafts or both. Five state DOTs obtained resistance factors by fitting to the ASD factor of safety based on local experience. The remaining DOTs either refer to AASHTO LRFD manual for resistance factors or do not specify resistance factors in their design manuals. Fig. 2 shows the LRFD implementation status of 49 states (Texas not included) based on our review of research reports, bridge design manuals, geotechnical manuals, and standard specifications published by each DOT. It should be noted that among the 12 DOTs that performed research projects to calibrate resistance factors against target reliability index, only four DOTs (Florida, Indiana, Louisiana, and Missouri) performed calibration for both driven piles and drilled shafts. The remaining eight DOTs performed calibration either for driven piles or for drilled shafts only. Further details are given in Table 2.

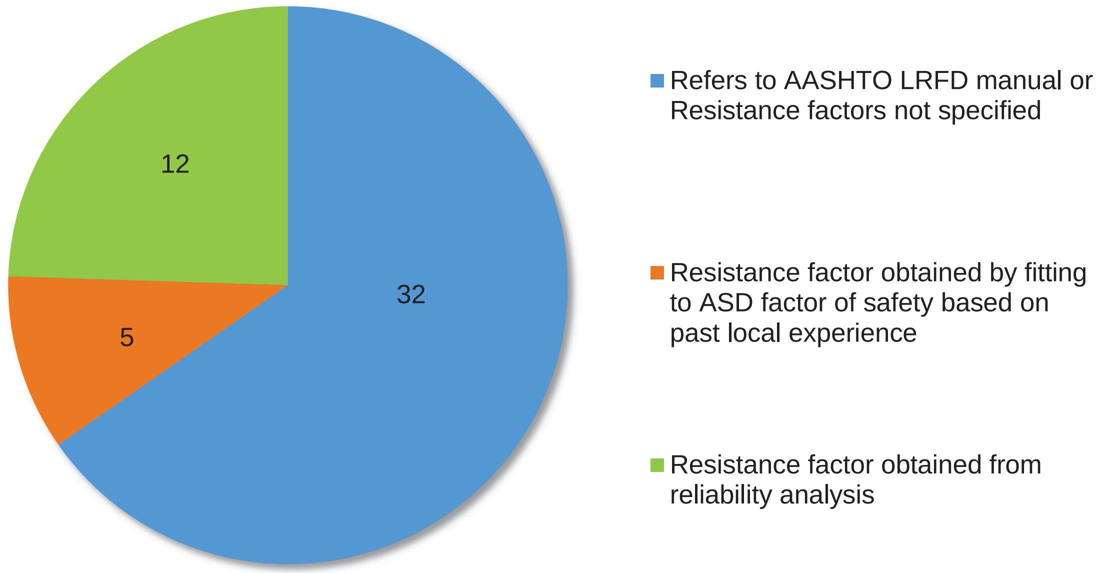


Fig. 2 Status of LRFD Implementation Based on Review of Research Reports, Bridge Design Manuals, Geotechnical Manuals, and Standard Specifications Published by Each DOT

Table 2. Summary of Other DOTs' Datasets Used for LRFD Reliability Analyses

State	Reliability Analysis		Number of Datasets	
	Driven Piles	**Drilled Shafts**	**Driven Piles**	**Drilled Shafts**
Florida	x	x	NS	273
Illinois	x		NS	NA
Indiana	x	x	NA*	NA*
Iowa	x		264**	NA
Kansas		x	NA	26
Louisiana	x	x	53**	26
Minnesota	x		270**	NA
Missouri	x	x	NS	31
New Mexico		x	NA	24
North Carolina	x		175**	NA
Oregon	x		322**	NA
Washington	x		141**	NA
Texas	x	x	30	40 (29 in soils and 11 in IGMs)

* Research framework is different from conventional resistance calibration process.

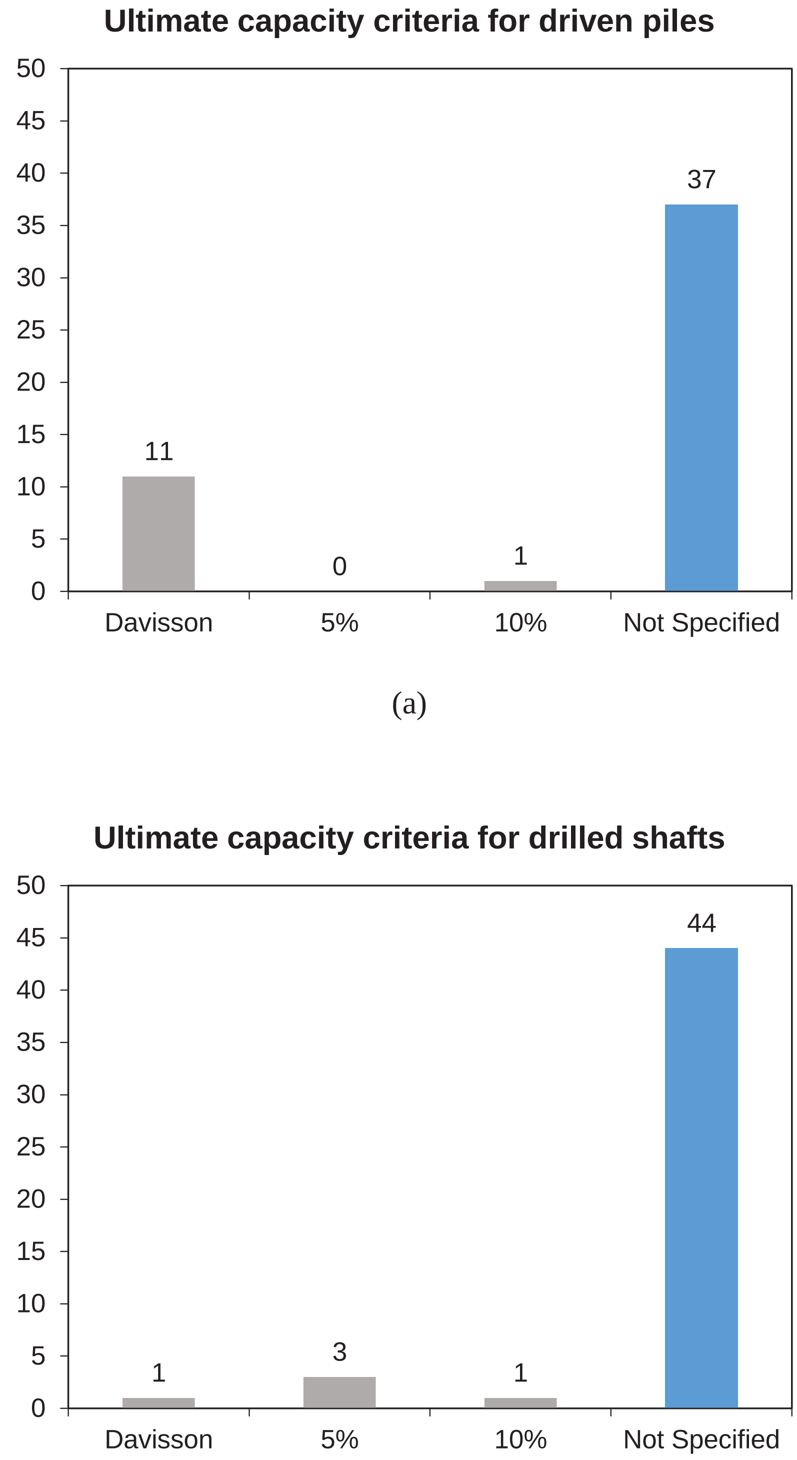
** Dataset includes dynamic load tests using PDA.

1.2 Ultimate Bearing Capacity Methods Used by Other DOTs

In order to investigate which ultimate capacity criterion is employed by other DOTs to determine measured ultimate bearing capacity for deep foundations, a review of published research reports and design manuals corresponding to state DOTs was completed. A summary of our review on the ultimate capacity criteria is presented in Table 1.

As shown in Fig. 3(a), for driven piles, 37 states out of 49 states (76%) do not specify which criterion is used to determine the ultimate capacity. Among the 12 states which specified the ultimate capacity criterion, 11 states use Davisson's criterion as an ultimate capacity criterion (seven states explicitly used Davisson's criterion for calibration of resistance factors and four states specify Davisson's criterion to be used to determine ultimate capacity of driven piles in Bridge Design Manuals or Geotechnical Manuals, even though calibrations of resistance factors were not performed). Finally, only one state (Indiana) used the 10% relative settlement criterion as an ultimate capacity criterion (*i.e.*, defining the load at pile head settlement corresponding to 10% of pile diameter as an ultimate capacity) for calibration of resistance factors for driven piles.

In case of drilled shafts, 44 states out of 49 states (90%) do not specify which criterion is used to determine the ultimate capacity, as shown in Fig. 3(b). Three states used the 5% relative settlement criterion as an ultimate capacity criterion (*i.e.*, defining the load at pile head settlement corresponding to 5% of pile diameter as an ultimate capacity) for calibration of resistance factors for drilled shafts. Again, only one state (Indiana) used the ultimate capacity based on 10% criterion for calibration of resistance factors for drilled shafts.



(a)

(b)

Fig. 3 Ultimate Capacity Criteria Implemented by State DOTs for (a) Driven Piles and (b) Drilled Shafts

2. Reliability Analyses and Development of Resistance Factor for Total Capacity of Driven Piles in Soils

2.1 Determination of Ultimate Capacities Based on 5% and 10% Relative Settlement Criteria

The dataset for the previous Research Project 0-6788 consisted of 33 driven piles. All 33 driven piles are precast square concrete piles with widths ranging from 14 to 20 inches and penetration depths ranging from 15 to 83.5 ft. Among the 33 load tests, 28 of them were conventional static top-down load tests and the remaining five tests were statnamic load tests. None of the 33 load tests were instrumented with strain gages; therefore, resistance factors were determined only for total capacity.

Among the 33 load tests, 22, 12, and one were loaded beyond the Davisson's criterion, 5% relative settlement criterion, and 10% relative settlement criterion, respectively. Among the 11 tests which did not reach the Davisson's offset line, eight reached at least an elastic line and were included in our dataset. 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 in the previous Research Project 0-6788. Consequently, 30 tests on driven piles were included in the final load-test dataset. The same 30 load tests were used in this Implementation Project 5-6788-01.

For the 29 load tests that did not reach a settlement of 10% of diameter at the pile head, the load-settlement curves were extrapolated up to 10% pile diameter. In doing so, the research team used the weighted hyperbolic fitting technique. In the original Chin's method (Chin 1970), it is assumed that the load-settlement curves of deep foundations are hyperbolic as follows:

$$Q = \frac{w}{C_1 w + C_2} \qquad \text{(Eq. 1)}$$

where Q = applied load, w = pile head settlement, and C_1 & C_2 = fitting constants. Chin (1970) suggested that C_1 and C_2 be determined by fitting a straight line through load test results in w/Q versus w space. In this fitting process, it is implicitly assumed that each data point carries the same weight. On the other hand, the weighted hyperbolic technique, which was developed in the previous Research Project 0-6788, takes the squared values of each settlement data point as weights to determine the fitting parameters for the hyperbolic curve. Mathematically, the fitting constants C_1 and C_2 are the parameters found using a weighted least-square regression method and expressed as follows:

$$C_1 = \frac{\left(\sum \frac{w_i^2}{Q_i}\right) - C_2\left(\sum w_i\right)}{\sum w_i^2} \qquad \text{(Eq. 2a)}$$

$$C_2 = \frac{\left(\sum \frac{w_i}{Q_i}\right)\left(\sum w_i^2\right) - \left(\sum w_i\right)\left(\sum \frac{w_i^2}{Q_i}\right)}{n\left(\sum w_i^2\right) - \left(\sum w_i\right)^2} \qquad \text{(Eq. 2b)}$$

where Q_i = each applied load, w_i = each measured settlement, and n = summation of weights. The weighted hyperbolic curve is then constructed using the C_1 and C_2 obtained from Eqs. (2a) and (2b), respectively. In the previous Research Project 0-6788, it was found that the weighted hyperbolic fitting technique yielded slightly less scatter than the original Chin's method, when comparing the Davisson capacity from the extrapolated curve with that from the measured load-settlement curve.

In this Implementation Project 5-6788-01, ultimate capacities based on 5% and 10% relative settlement criteria were determined from the weighted hyperbolic curves using the aforementioned technique. Table 3 presents a summary of the ultimate capacities based on Davisson, 5%, and 10% criteria of driven piles (the three tests disregarded in the subsequent analysis, highlighted with red color and struck-through, were also included in Table 3). It should be noted that the ultimate capacity values in Columns 18 through 20 represent measured capacities based on corresponding ultimate capacity criteria if those criteria were met. Otherwise, these values were obtained from extrapolation using the weighted hyperbolic method.

Table 3. Summary Table for Driven Piles

Project Identification and Location Data							Pile Dimensions		Soil Conditions	Source of Shaft Resistance		Soil Below Base [13]	Ultimate Capacity Criteria				Q_{ult} from Davisson's Criterion$^{a)}$	Q_{ult} from 5% Criterion$^{a)}$	Q_{ult} from 10% Criterion$^{a)}$	Predicted Total Capacity (kips)	Data Quality Score		
CaseNo [1]	ProjectID [2]	LoadTestID [3]	City [4]	County [5]	State [6]	Year [7]	B (in) [8]	L_p (ft) [9]	General Stratigraphy [10]	Fine Grained [11]	Coarse Grained [12]		Test Type [14]	Davisson [15]	5% [16]	10% [17]	Total (kips) [18]	Total (kips) [19]	Total (kips) [20]	TCP RAW [21]	Predictive [22]	Measured [23]	Composite [24]
1	27-13-52	Test Pile Bent 3L-4	Houston	Harris	TX	1971	14	30.0	CL/SM	100%	0%	Fine	Static Top Down	x			112	119	122	194	3.4	5	8.4
2	27-13-52	Test Pile Bent 24R-3	Houston	Harris	TX	1971	14	25.5	CL/SM/CL/SC	29%	71%	Fine	Static Top Down	x			372	397	423	173	3.4	5	8.4
3	27-13-52	Test Pile Bent 35R-1	Houston	Harris	TX	1971	14	22.0	CL/SM/CL	100%	0%	Fine	Static Top Down	x	x		261	292	310	196	3.4	5	8.4
4	27-13-52	Test Pile Bent 36R-2	Houston	Harris	TX	1971	14	34.5	CL/CL/SC/CL	73%	27%	Coarse	Static Top Down	x	x		195	204	211	363	3.4	5	8.4
5	331-4-15	Pile No. 1 Load No. 1	Port Isabel	Cameron	TX	1972	20	69.3	WATER/CL/SP/CH/SM	71%	29%	Fine	Static Top Down				652	733	830	336	4.0	2.4	6.4
6	535-5-6	Bridge "G" Laod Test	Gonzales	Gonzales	TX	1969	15	35.0	CL/SC/SM	60%	40%	Coarse	Static Top Down	x			354	425	498	279	4.2	5	9.2
7	535-5-6	Bridge "C" Load Test	Gonzales	Gonzales	TX	1969	15	33.0	CL/SC/SM	33%	67%	Coarse	Static Top Down	x	x		307	334	358	304	4.2	5	9.2
8	~~508-4-1~~	~~Test Pile No. 1~~	~~Port Arthur~~	~~Jefferson~~	~~TX~~	~~1954~~	~~16~~	~~49.3~~	~~MH/SC/CL/SP/CL~~	~~48%~~	~~52%~~	~~Fine~~	~~Static Top Down~~							~~248~~	~~3.4~~	~~0~~	~~0~~
9	28-9-22	Test Pile No. 2F	Orange	Orange	TX	1953	16	42.6	CL/SW/CL/SP	33%	67%	Fine	Static Top Down				235	261	277	442	3.4	4.4	7.8
10	28-9-22	Test Pile No. 3B	Orange	Orange	TX	1953	16	44.0	MH/SP/SM/CL/SP	37%	63%	Fine	Static Top Down	x			290	326	353	235	3.4	5	8.4
11	65-6-15	Test Pile No. 1	Beaumont	Hardin	TX	1952	16	46.8	CL/SP/CL/SP	84%	16%	Fine	Static Top Down				371	421	469	558	3.6	2.8	6.4
12	327-8-39	Test Pile No. 2	Harlingen	Cameron	TX	1972	16	16.3	CL/SC/CH	84%	16%	Coarse	Static Top Down	x	x		235	274	293	141	3.6	4.8	8.4
13	327-8-39	Test Pile No. 3	Harlingen	Cameron	TX	1972	16	15.0	SM/SP/CL	79%	21%	Coarse	Static Top Down	x	x		359	403	428	106	3.6	4.8	8.4
14	617-2-7	Intracoastoal Waterway	Corpus Christi	Nueces	TX	1971	16	46.8	SP/CL/SP/CL/SP	19%	81%	Fine	Static Top Down	x	x		293	324	354	409	3.6	4.8	8.4
15	39-16-6 (1)	Test Load Pile No. 1	Brownsville	Cameron	TX	1967	16	30.0	CH	100%	0%	Fine	Static Top Down	x	x		236	258	271	301	3.4	5	8.4
16	39-16-10	Test Pile No. 1	Brownsville	Cameron	TX	1967	16	31.0	CH/SM/CL	54%	46%	Coarse	Static Top Down	x	x		302	317	337	198	3.8	5	8.8
17	39-16-6	Pile Test No. 1	Brownsville	Cameron	TX	1967	16	40.0	CH/SM/CH	80%	20%	Fine	Static Top Down	x	x	x	130	225	329	210	3.2	5	8.2
18	39-7-18	Test Pile No. 4	Brownsville	Cameron	TX	1957	15	31.0	CL/SM	100%	0%	Fine	Static Top Down				282	339	380	182	3.4	3.2	6.6
19	500-1-39	Test Pile Extra	Galveston	Galveston	TX	1958	20	77.0	SM/CL/SM	54%	46%	Fine	Static Top Down				251	265	271	605	3.4	3.8	7.2
20	271-7-61	Bent No. 3 Pile No. 18	Houston	Harris	TX	1966	14	26.5	CL	100%	0%	Fine	Static Top Down	x			353	388	400	740	4.0	5	9
~~21~~	~~180-4-34~~	~~Test Pile No. 6~~	~~Rockport~~	~~Aransas~~	~~TX~~	~~1964~~	~~18~~	~~33.0~~	~~MH/CL/CL/SP~~	~~100%~~	~~0%~~	~~Fine~~	~~Static Top Down~~							~~237~~	~~3.4~~	~~0~~	~~0~~
22	180-4-34	Test Pile No. 1	Rockport	Aransas	TX	1964	18	83.5	MH/SM	68%	32%	Coarse	Static Top Down				275	305	329	289	2.8	2.6	5.4
~~23~~	~~180-4-34~~	~~Test Pile No. 10~~	~~Rockport~~	~~Aransas~~	~~TX~~	~~1964~~	~~18~~	~~44.4~~	~~OH/CL~~	~~69%~~	~~0%~~	~~Fine~~	~~Static Top Down~~							~~394~~	~~3.6~~	~~0~~	~~0~~
24	500-3-126	Bent 15-L Column C	Houston	Harris	TX	1965	14	25.8	CL/SM	100%	0%	Fine	Static Top Down	x			252	265	273	238	4.0	5	9
25	AFT107007	Bent 2 Pile O	Bay Town Area	Chambers	TX	2007	18	42.0	CH/SM/CH	32%	68%	Coarse	Statnamic	x			387	452	497	275	3.6	5	8.6
26	AFT107007	Bent 3 Pile E2	Bay Town Area	Chambers	TX	2007	18	42.0	CH/SM/CH	32%	68%	Coarse	Statnamic	x			385	408	424	275	3.6	5	8.6
27	AFT107007	Bent 4 Pile O	Bay Town Area	Chambers	TX	2007	18	40.0	CH/SM/CH	34%	66%	Coarse	Statnamic	x	x		341	391	420	254	3.6	5	8.6
28	AFT107007	Bent 5 Pile E2	Bay Town Area	Chambers	TX	2007	18	42.0	CH/SM/CH	32%	68%	Coarse	Statnamic				600	728	860	275	3.6	3.8	7.4
29	AFT107007	Bent 14 Pile E	Bay Town Area	Chambers	TX	2007	18	55.0	CH/SM/CH	44%	56%	Fine	Statnamic	x			704	1086	2087	455	3.6	5	8.6
30	508-02-076	River Bridge Bent 20	Baytown Area	Chambers	TX	1992	20	72.0	CH/SC/CH/SP/CH/SP	27%	73%	Fine	Static Top Down	x	x		681	654	838	738	3.4	5	8.4
31	508-02-076	River Bridge Bent 44	Baytown Area	Chambers	TX	1992	20	72.0	CH/SP/CH/SP/CH	66%	34%	Fine	Static Top Down	x			488	571	587	521	3.0	5	8
32	450-15-0100	Test Pile No. 1	New Orleans	New Orleans	LA	2008	14	43.0	CH/SM/CH/SM	12%	88%	Coarse	Static Top Down	x	x		246	266	273	218	4.2	4.6	8.8
33	450-15-0100	Test Pile No. 3	New Orleans	New Orleans	LA	2008	14	80.0	SM/CH/SP/CH/SP	55%	45%	Fine	Static Top Down				677	646	890	596	3.6	1.8	5.4

Notes: 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.

b) B = width of precast square concrete pile; L_p = penetration depth; Q_{ult} = ultimate pile capacity

2.2 Determination of Statistical Distribution of Bias of the Resistance and Development of Resistance Factors

The measured (or extrapolated) ultimate capacities for each ultimate capacity criteria were compared with the predicted capacities obtained using TCP raw blow counts (TCP Raw) without hammer energy correction. Biases (λ_i = measured resistance/predicted resistance) for each test were then computed for each ultimate capacity criterion. In order to compute the mean and coefficient of variation (COV) of the biases, a weighting factor that ranged from 0 to 1 was used to consider the uncertainties associated with the data quality, as done in the previous Research Project 0-6788. Detailed procedures to obtain the weighted mean and COV of the biases are as follows:

a) Take the log transformation of the data (*i.e.* $x_i = \ln(\lambda_i)$).

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 uniformly minimum variance unbiased estimators (UMVUE) for mean ($E[\lambda]$) and standard deviations ($SD[\lambda]$):

$$E[\lambda] = \exp(\bar{x})\, g(0.5 s_x^2), \text{ and} \qquad \text{(Eq. 3)}$$

$$SD[\lambda]^2 = \exp(2\bar{x})\, \{g(2s_x^2) - g\left(\tfrac{n-2}{n-1} s_x^2\right)\}, \text{ where} \qquad \text{(Eq. 4)}$$

$$g(t) = 1 + \frac{n-1}{n}t + \frac{(n-1)^3}{n^2 2!}\frac{t^2}{n+1} + \frac{(n-1)^5}{n^3 3!}\frac{t^3}{(n+1)(n+3)} + \cdots \qquad \text{(Eq. 5)}$$

d) Compute COV by dividing $SD[\lambda]$ by $E[\lambda]$ 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 4. 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 4. Summary Statistics for Biases of Resistances for Driven Piles

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

Resistance factors were obtained following the first order second moment (FOSM) method and the Monte Carlo simulation using the bias statistics presented in Table 4. In the FOSM method, resistance factor (ϕ) is obtained from the following equation:

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

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

β = target reliability index

In the Monte Carlo simulation, resistance factors are obtained by trying different values of resistance factors (ϕ_{Try}) 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.

For both the FOSM method and Monte Carlo simulation, the values presented in Table 5 were used for bias statistics for dead and live loads following recommendation by AASHTO (Nowak 1999).

Table 5. Summary Statistics for Biases of Loads used in This Study

Loads	Dead-to-Live Load Ratio	Load Factors (γ)	Mean of Bias (λ)	*COV* of Bias
Live Load (*LL*)	2	γ_{LL} = 1.75	λ_{LL} = 1.15	COV_{LL} = 0.2
Dead Load (*DL*)		γ_{DL} = 1.25	λ_{LL} = 1.05	COV_{LL} = 0.1

Tables 6 and 7 present LRFD resistance factors obtained both from the FOSM method and Monte Carlo simulations for target reliability indices of 2.33 and 3.00, respectively. Note that the 95% confidence intervals presented in the table are based on the FOSM resistance factors.

Table 6. Resistance Factors for Total Capacity of Driven Piles in Soils ($\beta = 2.33$)

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	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 7. Resistance Factors for Total Capacity of Driven Piles in Soils ($\beta = 3.00$)

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	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 the 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.

3. Reliability Analyses and Develop Resistance Factor for Total Capacity of Drilled Shafts in Soils

3.1 Determination of Ultimate Capacities Based on 5% and 10% Relative Settlement Criteria

The dataset for the previous Research Project 0-6788 consisted of 41 drilled shafts. Among the 41 drilled shafts, 29 of them were installed in soils and the remaining 11 were installed in IGMs or rocks. In this Implementation Project 5-6788-01, reliability analyses were done on the 29 load tests performed on drilled shafts installed in *soil layers only*. Among the 29 load tests in soils, 14 were conventional static top-down load tests, three were statnamic load tests, and the remaining 12 tests were O-cell load tests. Three of the 14 conventional static load tests were instrumented with strain gages, and separate measurements of shaft and base capacities were made. The 12 O-cell tests also provided separate measurements of shaft and base capacities.

Among the 29 load tests in soils, 13, 9, and two were loaded beyond the Davisson's criterion, 5% relative settlement criterion, and 10% relative settlement criterion, respectively. For the 27 load tests that did not reach a settlement of 10% of diameter at the pile head, the load-settlement curves were extrapolated up to 10% pile diameter. In doing so, the research team used the weighted hyperbolic fitting technique for top-down load tests and the *t-z* method for O-cell tests.

Table 8 presents a summary of the ultimate capacities based on Davisson, 5%, and 10% criteria of drilled shafts in soils (11 tests performed on drilled shafts installed in IGMs or rocks, highlighted with grey color, were also included in Table 8 for the sake of completeness of the dataset). Note that shaft and base capacities were also determined separately using 5% and 10% relative settlement criteria for the instrumented tests. Ultimate capacity values in Columns 19, 22, and 25 represent measured capacities based on corresponding ultimate capacity criteria if those criteria were met. Otherwise, these values were obtained from extrapolations.

Table 8. Summary Table for Drilled Shafts

Project Identification and Location Data							Drilled Shaft Dimensions		Soil Conditions	Source of Shaft Resistance			Soil Below Base [14]	Test Type [15]	Ultimate Capacity Criteria			Qult from Davisson's Criterion$^{a)}$			Qult from 5% Criterion$^{a)}$ (kips)			Qult from 10% Criterion$^{a)}$ (kips)			Predicted Capacity Using TCP RAW Blow Counts (kips)			Data Quality Score		
Case No. [1]	ProjectID [2]	LoadTestID [3]	City [4]	County [5]	State [6]	Year [7]	B (in) [8]	L_p (ft) [9]	General Stratigraphy [10]	Fine Grained [11]	Coarse Grained [12]	IGM/Rock [13]			Davisson [16]	5% [17]	10% [18]	Total [19]	Shaft [20]	Base [21]	Total [22]	Shaft [23]	Base [24]	Total [25]	Shaft [26]	Base [27]	Total [28]	Shaft [29]	Base [30]	Predictive [31]	Measured [32]	Composite [33]
34	AFT109054	Site 1A Load Test	Grapevine	Tarrant	TX	2009	36	50.0	CH/CH/R/R	9%	0%	91%	IGM/Rock	Statnamic				3300									5439	4562	877	4.2	3	7.2
35	AFT109054	Site 1B Load Test	Grapevine	Tarrant	TX	2009	36	25.0	CH/CH/R/R	100%	0%	0%	IGM/Rock	Statnamic	x	x		638									918	396	522	4.2	5	9.2
36	AFT109054	Site 3A Load Test	Grapevine	Tarrant	TX	2009	36	25.0	CH/CH/R/R/R	100%	0%	0%	Fine	Statnamic	x	x		1788									937	658	279	4.2	4.8	9
~~37~~	~~AFT109054~~	~~Site 3B Load Test~~	~~Grapevine~~	~~Tarrant~~	~~TX~~	~~2009~~	~~36~~	~~40.0~~	~~CH/CH/R/R/R~~	~~32%~~	~~0%~~	~~68%~~	~~IGM/Rock~~	~~Statnamic~~													~~3492~~	~~2616~~	~~877~~	~~4.2~~	~~2~~	~~6.2~~
38	AFT107001NC	Bent 4 Pier 2 Load Test	Sinton	San Patricio	TX	2007	48	51.0	SM/CL/SM/CH	25%	75%	0%	Coarse	Statnamic				2142			2174			2225			2454	1863	591	3.8	2.6	6.4
39	AFT107001NC	Bent 3 Pier 1 Load Test	Sinton	San Patricio	TX	2007	48	51.0	SM/CL/SM/CH	25%	75%	0%	Coarse	Statnamic				2051			2104			2188			2454	1863	591	3.8	2.6	6.4
40	AFT107001NC	Bent 3 Pier 2 Load Test	Sinton	San Patricio	TX	2007	48	51.0	SM/CL/SM/CH	25%	75%	0%	Coarse	Statnamic				5538			5677			6323			2454	1863	591	3.8	2.6	6.4
41	3-5-72-176	MTS-1	Montopolis	Travis County	TX	1974	30	23.0	CL/CL/CL/I	18%	0%	82%	Fine	Static Top Down	x			914			1001			1078			1906	1357	550	4.6	5	9.6
42	3-5-72-176	MTS-2	Montopolis	Travis County	TX	1974	30	24.0	CL/CL/CL/I	17%	0%	83%	Fine	Static Top Down	x			1052			1108			1156			2030	1480	550	4.6	5	9.6
43	3-5-72-176	MTS-3	Montopolis	Travis County	TX	1974	30	24.0	CL/CL/CL/I	24%	0%	76%	Fine	Static Top Down	x	x		977			1138			1279			2077	1528	550	4.6	5	9.6
44	271-14-60	Load Test No. 1	Houston	Harris	TX	1967	36	60.0	CL/SM/CL/CL	95%	5%	0%	Fine	Static Top Down				1690			1708			1763			1663	1475	188	3.2	3.8	7
45	74-2	Test No. 1	Hailey Hollow	Live Oak	TX	1969	24	20.0	CL/SC	100%	0%	0%	Coarse	Static Top Down	x	x	x	549			837			1130			454	372	81	2.4	4.6	7
46	2374-6	Test No. 2	Dallas	Dallas	TX	1975	36	20.0	CL/SM/I	82%	18%	0%	IGM/Rock	Static Top Down	x	x		840									664	346	317	2.8	5	7.8
47	177-11-7	Test No. 3	Houston	Harris	TX	1953	18	26.4	CL/CH/CL/CH/CL	100%	0%	0%	Fine	Static Top Down				121			124			125			180	151	29	4.0	4.4	8.4
48	177-11-7	Load Test No. 4	Houston	Harris	TX	1953	18	23.0	CL/CH/CL/CH/CL	100%	0%	0%	Fine	Static Top Down				110			121			124			124	114	9	4.0	4.4	8.4
49	89-8	Load Test Shaft 1 Test 3	Houston	Harris	TX	1970	30	23.0	CH/CL/CH	100%	0%	0%	Fine	Static Top Down	x			260	150	110	273	151	124	278	151	130	245	216	29	5.0	5	10
50	89-8	Load Test Shaft 3 Test 3	Houston	Harris	TX	1970	30	23.0	CH/CL/CH	100%	0%	0%	Fine	Static Top Down	x	x	x	188	104	84	197	107	90	199	105	93	245	216	29	5.0	5	10
51	89-8	Load Test Shaft 4 Test 1	Houston	Harris	TX	1970	30	45.0	CH/CL/CH	100%	0%	0%	Fine	Static Top Down	x	x		607	376	224	628	362	262	648	418	307	501	456	44	5.0	5	10
52	SS25-1	Test Shaft No. G1	Houston	Harris	TX	1973	30	59.0	CL/SM	24%	76%	0%	Coarse	Static Top Down				982			998			1017			1025	923	102	4.2	3.8	8
53	SS25-1	Test Shaft No. G2	Houston	Harris	TX	1973	30	77.0	CL/SM/CL	55%	45%	0%	Coarse	Static Top Down	x			1361			1380			1402			801	772	30	3.6	4.4	8
54	SS25-1	Test Shaft No. BB	Houston	Harris	TX	1973	30	45.0	CL/SM	23%	77%	0%	Coarse	Static Top Down	x	x		1201			1355			1597			1574	1298	276	3.8	5	8.8
55	TxDOT-UT-ADSC	Test Shaft No. 1	Austin	Travis	TX	2012	30	80.3	I/I	0%	0%	100%	IGM/Rock	O-Cell				2408	2066	343							5677	5068	609	4.4	3.4	7.8
56	TxDOT-UT-ADSC	Test Shaft No. 2	Austin	Travis	TX	2012	30	79.3	I/I	0%	0%	100%	IGM/Rock	O-Cell				2282	1912	370							5538	4930	609	4.4	4.4	8.8
57	TxDOT-Dallas	LT-1258 O-Cell Load Test	Dallas	Dallas	TX	2013	36	60.8	SC/SP/GP/I	0%	3%	97%	IGM/Rock	O-Cell				1316	746	569							6745	5866	879	4.6	5	9.6
58	UAR-ADSC-Turrell	LT-1138-5-2	Turrell	Crittenden	AR	2013	72	65.5	CH/ML/SP	26%	74%	0%	Coarse	O-Cell				2724	1651	1073	3148	1694	1454	4062	1737	2405	1988	1520	468	5.0	3.5	8.5
59	UAR-ADSC-Turrell	LT-1138-4-1	Turrell	Crittenden	AR	2013	48	86.2	CH/ML/SP	17%	83%	0%	Coarse	O-Cell				2458	2324	135	2560	2413	148	2726	2555	171	1641	1523	118	5.0	3.6	8.6
60	UAR-ADSC-Turrell	LT-1138-6-3	Turrell	Crittenden	AR	2013	48	87.0	CH/ML/SP	17%	83%	0%	Coarse	O-Cell				2701	2064	637	2918	2177	741	3417	2406	1011	1695	1543	153	5.0	3.4	8.4
61	UAR-ADSC-SiloamSpring	LT-1138-2	Siloam Springs	Benton	AR	2013	72	21.4	SC/R	0%	23%	77%	IGM/Rock	O-Cell				4724	1646	3078							5138	1632	3506	5.0	1.9	6.9
62	UAR-ADSC-SiloamSpring	LT-1138-1	Siloam Springs	Benton	AR	2013	48	25.2	SC/R	0%	13%	87%	IGM/Rock	O-Cell				5650	3060	2590							3577	2019	1558	5.0	1.7	6.7
63	024-03-0010	LT-8467 Ragley-1	Ragley	Beauregard	LA	1999	66	62.2	SM/CL/CH/CL/SM	94%	6%	0%	Fine	O-Cell				1108	437	672	1123	441	682	1141	447	694	1696	1432	263	3.6	3.2	6.8
64	024-03-0010	LT-8944 Ragley-2	Ragley	Beauregard	LA	1999	66	40.6	CL/CH/CL/SM	100%	0%	0%	Fine	O-Cell				1151	833	318	1218	836	382	1321	838	483	946	805	141	3.4	4.5	7.9
65	103-249-160	LT-9943 Highland Park	Baton Rouge	Baton Rouge	LA	2008	72	81.9	CL/CH/CL/CH/CL/CL	100%	0%	0%	Fine	O-Cell				1889	1569	320	1936	1575	361	2004	1583	422	2115	1839	276	3.2	4.3	7.5
66	103-249-160	LT-9459 Essen Ln	Baton Rouge	Baton Rouge	LA	2008	48	99.0	CL/CH/CL/CH/CL	100%	0%	0%	Fine	O-Cell				2511	2329	182	2594	2380	214	2792	2473	319	1806	1663	142	4.0	4.2	8.2
67	455-09-0006	LT-9934-2 Unknown Pond	Caddo	Shreveport	LA	2011	48	39.5	CH/SM/CL/SM/CL	100%	0%	0%	Fine	O-Cell				844	484	360	859	494	366	874	503	371	846	195	652	3.8	3.4	7.2
68	455-09-0006	US71 LT9934-1	Caddo	Shreveport	LA	2011	66	47.0	CL/ML/SM/CH	28%	71%	0%	Coarse	O-Cell				1563	909	654	1580	919	660	1596	929	667	1380	1099	281	4.2	3	7.2
69	LT-8249	Bentonite Slurry	Ohkay Owingeh	Rio Arriba	NM	1995	31	47.0	GW-GM/SM/SW-SM/SP-SM	0%	100%	0%	Coarse	O-Cell				1459	429	1029	1537	487	1050	1683	598	1085	2278	2031	247	3.8	2.8	6.6
70	LT-8249	Polymer Slurry Test No. 2	Ohkay Owingeh	Rio Arriba	NM	1995	31	47.0	GW-GM/SM/SW-SM/SP-SM	0%	100%	0%	Coarse	O-Cell				1748	529	1219	1808	584	1224	2000	763	1237	2296	2049	247	3.8	2.8	6.6
71	LT-9190	Sunland Park Test Shaft No. 1	Sunland Park	Dona Ana	NM	2006	48	74.5	SM/SM/SP/SM/SP	0%	100%	0%	Coarse	O-Cell				1855	1307	548	2118	1405	714	2916	1568	1348	2309	1965	344	3.8	2.2	6
72	FHWA-HPR-NM-90-03	FHWA-HPR-NM-90-03	Albequerque	Bernalillo	NM	1993	32	54.9	SP/SM/GW-GM/ML/SM	12%	87%	0%	Coarse	Static Top Down	x	x		1483			1637			2248			1247	1135	112	4.2	5	9.2
73	405-681-6737	LT-1025-1	Hollis	Harmon	OK	2013	72	80.1	SM/CL/CH/VOID/CH/R/VOID/R/R/R	61%	4%	35%	IGM/Rock	O-Cell				2415	1507	908							8306	7575	731	2.8	2.6	5.4
74	405-681-6737	LT 1025-2	Hollis	Harmon	OK	2013	72	101.3	SM/CL/CH/VOID/CH/R/VOID/R/R/R	48%	3%	49%	IGM/Rock	O-Cell				2794	2229	565							10340	9609	731	2.8	2.8	5.6

Notes: 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.

b) B = diameter of drilled shaft; L_p = embedment depth; Q_{ult} = ultimate pile capacity

3.2 Determination of Statistical Distribution of Bias of the Resistance and Development of Resistance Factors

The measured (or extrapolated) ultimate capacities for each ultimate capacity criteria were compared with the predicted capacities obtained using TCP raw blow counts (TCP Raw) without hammer energy correction. Biases (λ_i = measured resistance/predicted resistance) for each test were then computed for each ultimate capacity criterion. In order to compute the mean and coefficient of variation (COV) of the biases, a weighting factor that ranged from 0 to 1 was used to consider the uncertainties associated with the data quality, as done in the previous Research Project 0-6788. The same procedures described in Section 2.2 of this report were used to obtain the weighted mean and COV of the biases.

The weighted UMVUE summary statistics for the 29 load tests on drilled shafts in soils are given in Table 9. 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 9. Summary Statistics for Biases of Resistances for Drilled Shafts in Soils

Ultimate Capacity Criteria	Total number of load tests considered (Total sample size)	Effective sample size	Mean of Bias	COV of Bias
Davisson	29	26.4	1.027	0.393
5%	29	26.4	1.100	0.399
10%	29	26.4	1.219	0.443

As was done for the driven piles, resistance factors for drilled shafts in soils were obtained following the FOSM method and the Monte Carlo simulation using the bias statistics presented in Table 9. Tables 10 and 11 present LRFD resistance factors for total capacity of drilled shafts in soils obtained both from the FOSM method and Monte Carlo simulations for target reliability indices of 2.33 and 3.00, respectively. Note that the 95% confidence intervals presented in the table are based on the FOSM resistance factors.

Table 10. Resistance Factors for Total Capacity of Drilled Shafts in Soils (β = 2.33)

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	26.4	1.027	0.393	0.51	0.46	0.36	0.57
5%	26.4	1.100	0.399	0.54	0.49	0.39	0.59
10%	26.4	1.219	0.443	0.54	0.49	0.39	0.60

Table 11. Resistance Factors for Total Capacity of Drilled Shafts in Soils ($\beta = 3.00$)

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	26.4	1.027	0.393	0.38	0.34	0.26	0.44
5%	26.4	1.100	0.399	0.40	0.36	0.28	0.45
10%	26.4	1.219	0.443	0.39	0.36	0.27	0.45

According to our analyses, resistance factors for total capacity of drilled shafts installed in soils with β of 2.33 obtained from Monte Carlo simulations are 0.51, 0.54, and 0.54 for Davisson, 5%, and 10% criteria respectively. Similarly, resistance factors with β of 3.00 are 0.38, 0.40, and 0.39 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.

In addition to the resistance factors for total capacity of drilled shafts in soils, resistance factors for shaft and base capacities were also obtained using results from the 15 instrumented load tests. Tables 12 and 13 present LRFD resistance factors for shaft capacity of drilled shafts in soils obtained both from the FOSM method and Monte Carlo simulations for target reliability indices of 2.33 and 3.00, respectively.

Table 12. Resistance Factors for Shaft Capacity of Drilled Shafts in Soils ($\beta = 2.33$)

Ultimate Capacity Criteria	Total number of load tests considered (Total sample size)	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	15	13.6	0.968	0.717	0.23	0.22	0.11	0.37
5%	15	13.6	0.986	0.696	0.25	0.23	0.13	0.38
10%	15	13.6	1.029	0.66	0.28	0.26	0.15	0.4

Table 13. Resistance Factors for Shaft Capacity of Drilled Shafts in Soils ($\beta = 3.00$)

Ultimate Capacity Criteria	Total number of load tests considered (Total sample size)	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	15	13.6	0.968	0.717	0.14	0.14	0.06	0.25
5%	15	13.6	0.986	0.696	0.15	0.15	0.07	0.26
10%	15	13.6	1.029	0.66	0.18	0.17	0.09	0.28

Tables 14 and 15 present resistance factors for base capacity of drilled shafts in soils obtained both from FOSM method and Monte Carlo simulations for target reliability indices of 2.33 and 3.00, respectively.

Table 14. Resistance Factors for Base Capacity of Drilled Shafts in Soils ($\beta = 2.33$)

Ultimate Capacity Criteria	Total number of load tests considered (Total sample size)	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	15	13.6	2.760	0.674	0.72	0.67	0.34	1.17
5%	15	13.6	3.099	0.681	0.79	0.75	0.36	1.37
10%	15	13.6	3.747	0.709	0.90	0.85	0.37	1.68

Table 15. Resistance Factors for Base Capacity of Drilled Shafts in Soils ($\beta = 3.00$)

Ultimate Capacity Criteria	Total number of load tests considered (Total sample size)	Effective Sample Size	Mean of Bias	COV of Bias	ϕ (Monte Carlo)	ϕ (FOSM)	Lower 95% CI	Upper 95% CI
Davisson	15	13.6	2.760	0.674	0.45	0.44	0.20	0.82
5%	15	13.6	3.099	0.681	0.50	0.48	0.20	0.98
10%	15	13.6	3.747	0.709	0.56	0.54	0.20	1.20

4. Summary, Conclusions and Recommendations

This research study has developed resistance factors for total capacity of driven piles and drilled shafts in soils using 5% and 10% relative settlement criteria as ultimate capacity criteria. Among the final dataset of 70 load tests, 59 tests (30 for driven piles and 29 for drilled shafts) performed in soil layers only were considered in this study. With consideration to data quality, the effective sample sizes are 26.8 and 26.4 for driven piles and drilled shafts in soils, respectively. For drilled shafts, in addition to the resistance factors for total capacity, resistance factors for shaft and base capacities were also obtained using results from the 15 instrumented load tests.

4.1 Resistance Factors for Driven Piles in Soils

Resistance factors for total capacity of driven piles in soils predicted with raw TCP blowcounts are presented in Table 16 with target reliability index β of 2.33 and 3.0. The effective sample size used in the analysis for driven piles in soils was 26.8.

Table 16. Resistance Factors Obtained from Monte Carlo Simulations for Total Capacity of Driven Piles in Soils

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	Resistance factor ϕ ($\beta = 2.33$)	Resistance factor ϕ ($\beta = 3.00$)
Davisson	**26.8**	**1.224**	**0.532**	**0.44**	**0.30**
5%	26.8	1.397	0.559	0.47	0.32
10%	26.8	1.600	0.620	0.47	0.31

Based on the size and scope of the dataset, literature review, and statistical analyses, the following conclusions and recommendations are supported by this research:

- 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.
- Considering wide spread use of Davisson criterion for driven piles in United States and small increase in ϕ values when other criteria were used, resistance factors from Davisson capacity are recommended for driven piles in soils.
- The resistance factors of 0.44 and 0.30 (with target reliability index of 2.33 and 3.0, respectively) for total capacity of driven piles in soils using raw TCP blowcounts are suitable for implementation for small projects.
- For large projects, we recommend consideration of determining ultimate capacity from static or dynamic load tests in accordance with AASHTO policy (AASHTO 2012) which will yield higher resistance factors.

4.2 Resistance Factors for Total Capacity of Drilled Shafts in Soils

Resistance factors for total capacity of drilled shafts in soils predicted with raw TCP blowcounts are presented in Table 17 with target reliability index β of 2.33 and 3.0. The effective sample size used in the analysis for driven piles in soils was 26.4.

Table 17. Resistance Factors Obtained from Monte Carlo Simulations for Total Capacity of Drilled Shafts in Soils

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	Resistance factor ϕ ($\beta = 2.33$)	Resistance factor ϕ ($\beta = 3.00$)
Davisson	26.4	1.027	0.393	0.51	0.38
5%	**26.4**	**1.100**	**0.399**	**0.54**	**0.40**
10%	26.4	1.219	0.443	0.54	0.39

Based on the size and scope of the dataset, literature review, and statistical analyses, the following conclusions and recommendations are supported by this research:

- 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.

- Considering that FHWA suggests 5% criterion for drilled shafts (O'Neil and Reese 1999) and 5% yields the largest ϕ value among the three criteria considered in this study, resistance factors from 5% criterion are recommended for drilled shafts in soils.
- The resistance factors of 0.54 and 0.40 (with target reliability index of 2.33 and 3.0, respectively) for total capacity of drilled shafts in soils using raw TCP blowcounts are suitable for implementation.
- For large projects, we recommend consideration of determining ultimate capacity from static load tests in accordance with AASHTO policy (AASHTO 2012) which will yield higher resistance factors.

4.3 Resistance Factors for Shaft and Base Capacities of Drilled Shafts in Soils

Resistance factors for shaft and base capacities of drilled shafts in soils predicted with raw TCP blowcounts are presented in Tables 18 and 19, respectively, with target reliability index β of 2.33 and 3.0. The effective sample size used in the analysis for driven piles in soils was 13.6.

Table 18. Resistance Factors Obtained from Monte Carlo Simulations for Shaft Capacity of Drilled Shafts in Soils

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	Resistance factor ϕ ($\beta = 2.33$)	Resistance factor ϕ ($\beta = 3.00$)
Davisson	13.6	0.968	0.717	0.23	0.14
5%	**13.6**	**0.986**	**0.696**	**0.25**	**0.15**
10%	13.6	1.029	0.660	0.28	0.18

Table 19. Resistance Factors Obtained from Monte Carlo Simulations for Base Capacity of Drilled Shafts in Soils

Ultimate Capacity Criteria	Effective Sample Size	Mean of Bias	COV of Bias	Resistance factor ϕ ($\beta = 2.33$)	Resistance factor ϕ ($\beta = 3.00$)
Davisson	13.6	2.760	0.674	0.72	0.45
5%	**13.6**	**3.099**	**0.681**	**0.79**	**0.50**
10%	13.6	3.747	0.709	0.90	0.56

Based on the size and scope of the dataset, literature review, and statistical analyses, the following conclusions and recommendations are supported by this research:

- Resistance factors differentiated for shaft and base capacity and based on raw TCP blowcounts for drilled shafts in soils are *variable*:
  - Shaft: 0.25 and 0.15 (with target reliability index of 2.33 and 3.0, respectively)
  - Base: 0.79 and 0.50 (with target reliability index of 2.33 and 3.0, respectively)
- For small projects where differentiation between base and shaft resistances is not critical, the resistance factors for shaft and base resistance are suitable for implementation.

- For large projects where it is critical that base and shaft resistance be differentiated, we recommend consideration of determining ultimate capacity from static load tests in accordance with AASHTO policy (AASHTO 2012) which will yield higher resistance factors.

REFERENCES

AASHTO (2012). *AASHTO LRFD Bridge Design Specifications, Customary U.S. Units, 6th Edition*. American Association of State Highway and Transportation Officials

AbdelSalam, S. S., Ng, K. W., Sritharan, S., Suleiman, M. T., and Roling, M. (2012). *Development of LRFD Procedures for Bridge Pile Foundations in Iowa - Volume III: Recommended Resistance Factors with Consideration of Construction Control and Setup*, Report No. IHRB Projects TR-584, Institute for Transportation, Iowa State University

AbdelSalam, S. S., Sritharan, S., Suleiman, M. T. (2010). "Current Design and Construction Practices of Bridge Pile Foundations with Emphasis on Implementation of LRFD." Journal of Bridge Engineering, 15(6), pp. 749-758

Abu-Farsakh, M. Y., Yoon, S., and Tsai, C. (2009). Calibration of Resistance Factors Needed in the LRFD Design of Driven Piles, Report No. FHWA/LA.09/449, Louisiana Transportation Research Center

Abu-Farsakh, M. Y., Yu, Xinbao, Yoon, S., and Tsai, C. (2010). Calibration of Resistance Factors Needed in the LRFD Design of Drilled Shafts, Report No. FHWA/LA.10/470, Louisiana Transportation Research Center

ADOT (2011). *Bridge Design Guidelines*, Arizona Department of Transportation

AHTD (2014). *Standard Specification for Highway Construction*. Arkansas State Highway and Transportation Department

ALDOT (2015). *Structural Design Manual*. Alabama Department of Transportation Bridge Bureau

Allen, T. M. (2005). *Development of the WSDOT Pile Driving Formula and Its Calibration for Load and Resistance Factor Design (LRFD)*. Final Report Prepared for Washington State Department of Transportation. Report No. WA-RD 610.1

Ashour, M., Helal, A., and Ardalan, H. (2012). *Upgrade of Axially Loaded Pile-Soil Modeling with the Implementation of LRFD Design Procedure*. Research Report submitted to State of Alabama Department of Transportation (ALDOT), Contract No. 930-769

Caltrans DRISI (2014). "Calibrating LRFD Geotechnical Axial (Tension and Compression) Resistance Factors (ϕ) for Driven Piles and Drilled Shafts." Research Notes, Caltrans Division of Research, Innovation and System Information

CDOT (2011). *CDOT Strategic Plan for Data Collection and Evaluation of Grade 50 H-Piles Into Bedrock*. Report No. CDOT-2011-11, Colorado Department of Transportation

Chin, F. V. (1970). "Estimation of Ultimate Load of Piles Not Carried to Failure." Proceedings of 2nd Southeast Asian Conference on Soil Engineering, pp.81-90

Coffman, R. A. (2015). *LRFD Calibration for Drilled Shaft Foundations*. Ongoing research project sponsored by the Arkansas State Highway and Transportation Department, the Deep

Foundations Institute, McKinney Drilling, Aldridge Drilling, and the University of Arkansas (Retrieved from http://trc1204-lrfd-drilled-shafts.uark.edu/ on June 23, 2015)

ConnDOT (2005). *Geotechnical Engineering Manual*. Connecticut Department of Transportation

DelDOT (2005). *Bridge Design Manual*. The State of Delaware Department of Transportation.

Densmore, D. H. (2000, May 30). *Load and Resistance Factor Design (LRFD) Memo*. Retrieved March 19, 2012, from http://www.fhwa.dot.gov/bridge/062800.htm

FDOT (2015). *Structures Design Guidelines*. Florida Department of Transportation

Foster, J. H. and Huft, D. L. (2008). *Review and Refinement of SDDOT's LRFD Deep Foundation Design Method*. Final Report Prepared for South Dakota Department of Transportation. Report No. SD2008-08-P

GDOT (2015). *Bridges and Structures Design Manual*. Georgia Department of Transportation

HDOT (2005). *Standard Specifications*. State of Hawaii Department of Transportation

IDOT (2012). *Bridge Manual*. Illinois Department of Transportation

ITD (2015). *LRFD Bridge Design Manual*. The Idaho Transportation Department

Kuo, C. L., McVay, M., and Birgisson, B. (2002). "Calibration of load and resistance factor design." Transportation Research Record 1808, Transportation Research Board, Washington, DC, 108–111.

KYTC (2014). *Structural Design*. Kentucky Transportation Cabinet

Loehr, J. E., Bowders, J.J., , Ge, L., Likos, W. J., Luna, R., Maerz, N., Rosenblad, B. L., and Stephenson, R. W. (2011). *Engineering Policy Guidelines for Design of Drilled Shafts*. Final Report Prepared for Missouri Department of Transportation, Project TRyy0922, Report No.: cmr12003

Luna, R. (2014). *Evaluation of Pile Load Tests for Use in Missouri LRFD Guidelines*. Final Report Prepared for Missouri Department of Transportation, Project TRyy1226, Report No.: cmr14-015

MaineDOT (2014). *Bridge Design Guide*. The Maine Department of Transportation

MassDOT (2013). *LRFD Bridge Manual – Part I*. Massachusetts Department of Transportation

MDOT (2010). *Bridge Design Manual*. Mississippi Department of Transportation

MDT (2008). *Geotechnical Manual*. Montana Department of Transportation

MIDOT (2012). *Bridge Design Manual*. Michigan Department of Transportation

NDDOT (2013). *Design Manual*. North Dakota Department of Transportation

NevadaDOT (2008). *Structures Manual*. Nevada Department of Transportation

Ng, T-T. and Fazia, S. (2012). *Development and Validation of a Unified Equation for Drilled Shaft Foundation Design in New Mexico*. Final Report Prepared for New Mexico Department of Transportation, Report No. NM10MSC-01

NHDOT (2010). *Standard Specifications for Road and Bridge Construction*. State of New Hampshire Department of Transportation.

NJDOT (2009). *Design Manual for Bridges and Structures*. New Jersey Department of Transportation

Nowak, A. (1999). "NCHRP Report 368: Calibration of LRFD Bridge Design Code". TRB, Washington, DC.

Nowak, A. S., Kozikowski, M., Larsen, J., Lutomirski, T., and Paczkowski, P. (2007). *Implementation of the AASHTO LRFD Code in Geotechnical Design-Piles*. Final Report Prepared for Nebraska Department of Roads, Report No. SPR-1(07) P595

NYSDOT (2014). *LRFD Bridge Design Specifications*. New York State Department of Transportation

ODOT (2015). Bridge Design and Drafting Manual. Oregon Department of Transportation

OHDOT (2013). *Bridge Design Manual*. State of Ohio Department of Transportation

OHDOT (2013). *Construction and Material Specifications*. State of Ohio Department of Transportation

OKDOT (2009). *Standard and Specifications Book*. Oklahoma Department of Transportation

Paikowsky, S. G., Canniff, M., Robertson, S., and Budge, A. S. (2014). Load and Resistance Factor Design (LRFD) Pile Driving Project – Phase II Study. Minnesota State University

PennDOT (2015). *Design Manual, Part 4*. Pennsylvania Department of Transportation

Rahman, M. S., Gabr, M. A., Sarica, R. Z., and Hossain, M. S. (2002). *Load and Resistance Factor Design (LRFD) for Analysis/Design of Piles Axial Capacity*. Final Report Prepared for North Carolina Department of Transportation, Report No. FHWA/NC/2005-08

O'Niel, M. W. and Reese, L. C. (1999). Drilled Shafts: Construction Procedures and Design Methods. Report No. FHWA-IF-99-025, Federal Highway Administration

RIDOT (2007). *LRFD Bridge Design Manual*. Rhode Island Department of Transportation

Salgado, R., Woo, S. I., and Kim, D. (2011). *Development of Load and Resistance Factor Design for Ultimate and Serviceability Limit States of Transportation Structure Foundations*. Publication FHWA/IN/JTRP-2011/03, Joint Transportation Research Program, Indiana Department of Transportation and Purdue University

SCDOT (2010). *Geotechnical Design Manual*. South Carolina Department of Transportation

SDDOT (2014). *Structures Construction Manual*. South Dakota Department of Transportation

SDDOT (2015). *Standard Specifications for Roads and Bridges*. South Dakota Department of Transportation

Smith, T. D., Banas, A., Gummer, M., and Jin, J. (2011). *Recalibration of the GRLWEAP LRFD Resistance Factor for Oregon DOT*. Final Report Prepared for Oregon Department of Transportation, Report No. FHWA-OR-RD-11-08

UDOT (2011). *Geotechnical Manual of Instruction*. Utah Department of Transportation

UDOT (2015). *Structures Design and Detailing Manual*. Utah Department of Transportation

VDOT (2010). *Geotechnical Manual for Structures*. Virginia Department of Transportation

VTrans (2010). *VTrans Structures Design Manual*. Vermont Agency of Transportation

WisDOT (2015). *Bridge Design Manual*. State of Wisconsin Department of Transportation

WSDOT (2015). *Geotechnical Design Manual*. Washington State Department of Transportation

WVDOH (2014). *Bridge Design Manual*. West Virginia Division of Highways

WYDOT (2013). *Bridge Design Manual*. Wyoming Department of Transportation

Yang, X., Han, J., Parson, R. L. (2010). *Development of Recommended Resistance Factors for Drilled Shafts in Weak Rocks Based on O-Cell Tests*. Report No. K-Tran:KU-07-4, A Cooperative Transportation Research Program between Kansas Department of Transportation and The University of Kansas