Epistemic Uncertainty Effects on Resistance Factors Calibrated from FHWA Drilled Shafts in Sands Static Top-down Tests

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Abstract

Drilled shafts are often used as deep foundations for many structures and buildings due to their high axial and lateral resistance bearing capacity. For example, many highway bridges are built on drilled shafts foundations. This paper focuses on a calibration of resistance factors based on the statistical data of 18 conventional top-down compression load tests with drilled shafts embedded in sands from National Cooperative Highway Research Program (NCHRP) Project 24-17 sponsored by FHWA (Federal Highway Administration). The drilled shafts field test data were used to determine the actual measured total resistance while the in-situ soil properties from Standard Penetration Test (SPT) tests correlated with knowledge-based uncertainty (correction factors in American Association of State Highway Transportation Officials (AASHTO) [1] (2007) and Liao & Whitman [18] (1986)) and dimensions of drilled shafts were used to calculate the predicted total resistance using the SHAFT program which is consistent with the FHWA (1999) method [10]. To further consider the knowledge and data-based uncertainty due to the fact that available data are "incomplete" and inevitably contains variability, a *Monte Carlo* simulation method was selected to perform calibration. Based on the normally distributed loads and log-normally distributed resistance bias from the test data, the resistance factors for Strength I limit state were determined at a target reliability index of 3.0 and the obtained results are compared with those reported in literature.

Introduction

Drilled shafts are often used as deep foundations for many structures and buildings due to their high axial and lateral resistance bearing capacity. For example, many highway bridges are built on drilled shafts foundations. As a more rational approach to consider uncertainty in design, load and resistance factor design (LRFD) has increasingly been used and become a mandatory design for all state DOT (Department of Transportation) and FHWA funded bridge projects since 2007. LRFD needs to maintain a compatible reliability index β in each component of a foundation, substructure or superstructure. To achieve this goal, the resistance factors are required to be updated and calibrated with an adequate number of good-quality test data for each design method (Liang and Nowari [15], 2000; Allen et al. [2], 2005; Yang and Liang [27], 2007; Yang et al. [28], 2008; Liang and Li [16], 2009). The resistance factor calibration is demanded since high quality test data are often not available in geotechnical engineering. Thus many researchers choose to calibrate resistance factors by fitting LRFD to ASD (Allowable Stress Design) to maintain a consistent level of reliability with the past practice. The early work by Barker et al. [7] (1991) is one of the examples. The LRFD bridge design specifications based on American Association of State Highway Transportation Officials (AASHTO) [1] (2007) provide resistance factors for design of drilled shafts under axial loads. In fact, in AASHTO (2007), a significant number of resistance factors in the foundation design are selected based on the calibration with ASD. In addition, to improve the implementation of the LRFD and achieve compatible reliability with the superstructure design, the efforts to calibrate resistance factors based on actual field load test data are in a great demand.

Uncertainties are unavoidable in the analysis and design of engineering systems. Traditionally, engineers have to deal with significant uncertainties through conservative assumptions and apply safety factors to cover the effects of the underlying uncertainties [3, 4]. These assumptions and safety factors are invariably determined on the basis of engineering judgments, therefore, the level of conservativeness is difficult to quantify. The sources of uncertainty can be classified into two types: 1) aleatory type uncertainty associated with natural randomness; and 2) epistemic type or knowledge-based uncertainty associated with inaccuracies in our prediction and estimation of reality.

In the drilled shaft resistance factor calibration, available data are often incomplete or insufficient; and invariably contain variability. First, this fact can result in the aleatory uncertainty which is associated with randomness of drilled shaft calculated and measured capacity from the collected data. Second, there is the epistemic or knowledge-based uncertainty which is associated with the imperfect knowledge of the real world, for example, the effects of different soil parameters correlated from the AASHTO and Liao & Whitman correction factors [1, 18] for Standard Penetration Test (SPT) numbers. Again, aleatory (data based) uncertainty is associated with the inherent variability of basic information, which is part of the real world (within our ability to observe and describe, may not be reduced or modified). On the other hand, the epistemic (knowledge-based) uncertainty is associated with imperfect knowledge of the real world and may be reduced through applications of better prediction models and/or improved experiments. Therefore, the objective of this study is to develop the total resistance factors for axially loaded drilled shafts in sand collected in the National Cooperative Highway Research Program (NCHRP) Project 24-17 and to investigate the knowledge-based uncertainty effects, in particular, the statistical effects of the two most widely used SPT number correction factors in AASHTO and Liao & Whitman methods [1, 18], respectively, on the final drilled shaft calibrated total resistance factors.

The total resistance of an axially loaded drilled shaft consists of skin resistance and tip resistance. The recommended design methods for these two components by AASHTO and FHWA are based on O'Neill and Reese (1999) study in [10]. From traditional top-down load tests, it is difficult to separate tip and skin resistance from the measured total resistance. In this study, the FHWA (1999) method based on O'Neill and Reese's (1999) and load test data are used for the calibration of the total resistance factors for drilled shafts in sand soils. Since there are no available measured skin and tip resistance of drilled shafts in the database, therefore, in the present study, only the total resistance factors are calibrated for drilled shafts in sands based on 18 valid drilled shaft datasets.

Conventional Top-Down Load Tests

The conventional top-down load test simulates more realistically the actual loading conditions from superstructures for drilled shaft foundations which measure axial load versus settlement. In this study, data from 18 loaded drilled shafts in sands were collected from NCHRP drilled shaft database. The load corresponding to a settlement at 5% of the shaft diameter ("0.05B") or plunging load was defined as the nominal capacity, which is recommended by O'Neill and Reese [10]. The selection of this criterion was based on the previous study by Paikowsky [22] for the LRFD calibration consistency. Statistical analysis showed that the FHWA's "0.05B" method produced the closest and most consistent capacities with the mean value of the capacities, which has been further confirmed and used by Zhang et al. [30]. The FHWA drilled shaft database contains 261 conventional top-down statically loaded tests. Among them, the data for18 drilled shafts in sands of the conventional statically top-down tests' failure load with strictly exhibiting FHWA failure load criterion [10] have been collected for the resistance factors calibration in this particular study reported in this paper.

FHWA Design Method

The FHWA design method [9] for cohesive, cohesionless soils, and weak rock geomaterials was based on the work by O'Neill and Reese [10] assuming smooth rock sockets surface with closed joints (see [25]). In [22], Paikowsky study for LRFD is also partly based on FHWA method, where the rough sockets were assumed. The assumption of smooth surface is more commonly used in practice and expected to yield a lower predicted load capacity of drilled shafts. Some drilled shaft data collected in this study were for sandy granular soil with less than 50 blow count/foot and weak rock having a wider range of unconfined compressive strengths than those for IGMs (0.5MPa to 5MPa) defined in [10]. The methods for calculating skin, tip and total resistance in cohesionless soils are documented in [9, 10]. In this study, the following conditions were met or assumed: (a) the geomaterials are sands, and (b) concrete had slump of 152.4 mm (127 ~ 229 mm or 5~9 inches) recommended from SHAFT) and sand unit weight of 18.86 kN/m^3 (120 lb/ft^3) if no information was available.

According to AASHTO (2007) and Das and Sobhan [6], the knowledge-based uncertainty effects, in particular, the two most widely used SPT number correction factors, in AASHTO and Liao & Whitman methods [1, 18], are listed in the following Table 1. Das and Sobhan compared the different correction factors proposed by Liao & Whitman (1986), Skempton (1996), Seed et al. (1975), AASHTO, Peck et al. (1974) and Bazarra (1967); and concluded that Liao & Whitman method is better to be used for all calculations. In this paper, we limit and focus our investigation on the epistemic or knowledge based uncertainty effects using Liao & Whitman (1986) and AASHTO correction factors, C_N, for SPT number and soil internal friction angle in the resistance factors calibration study.

TABLE 1. Liao & Whitman [18] (1986) and AASHTO [1] Correction Factors, C_N, for SPT Number.

C_N, Correction Factor, Methods	C_N (σ' in ksf)	C_N (σ' in US ton/ft^2)	C_N (σ' in kN/m^2, or kPa)
Liao & Whitman (1986) [18]	$\sqrt{\frac{2000}{\sigma'}}$	$\sqrt{\frac{1}{\sigma'}}$	$9.78\sqrt{\frac{1}{\sigma'}}$
AASHTO (2007) [1], Peck et al. (1974) [23]	$0.77\ \log_{10}^{\left(\frac{40}{\sigma'}\right)}$	$0.77\ \log_{10}^{\left(\frac{20}{\sigma'}\right)}$, $\sigma' \geq 0.25\,\text{tsf}$	$0.77\ \log_{10}^{\left(\frac{1912}{\sigma'}\right)}$, $\sigma' \geq 25\,\text{kPa}$

As shown in Table 1, σ' is the current overburden effective stress while the correction factor, C_N, comes from: Liao & Whitman (1986) method [18], and AASHTO (2007) method [1] based on the work by Peck et al. [23] (1974). Some epistemic (knowledge-based) uncertainty associated with imperfect knowledge of the real world is considered, for example, correction factors, C_N, may involve some epistemic (knowledge-based) uncertainty.

The soil internal friction angle, ϕ (or PHT as shown in Table 3) for computing the predicted capacity has correlation with SPT number according to Peck, Hanson and Thornburn [23] (1974) as shown in the following equation (1):

$$\phi \approx 54 - 27.6034e^{(-0.014N')} \tag{1}$$

The calibrated soil internal friction angle, ϕ (or PHT), will be used in the SHAFT program [9] (Reese et al., 2001) for evaluating the predicted bearing capacity which is consistent with the FHWA (1999) design method [10]. Notice that the SHAFT program has been developed based on the drilled shaft FHWA design methodology.

Summary of Resistance and Bias Statistics

The FHWA database contains drilled shaft dimensions and different construction methods. In addition, in-situ soil profiles, elevation, soil descriptions and parameters are also available for calculating the nominal total resistance via predicted skin and tip resistance. The shaft-soil profiles and parameters, which are required for obtaining the predicted capacity using the FHWA method via the SHAFT program, were employed for calculating predicted skin, tip and total resistance. The actually measured total resistance versus settlement can be obtained and graphically interpreted. The statistical information for the drilled shafts measured (interpreted) resistance, and calculated (predicted) resistance is summarized in Table 2.

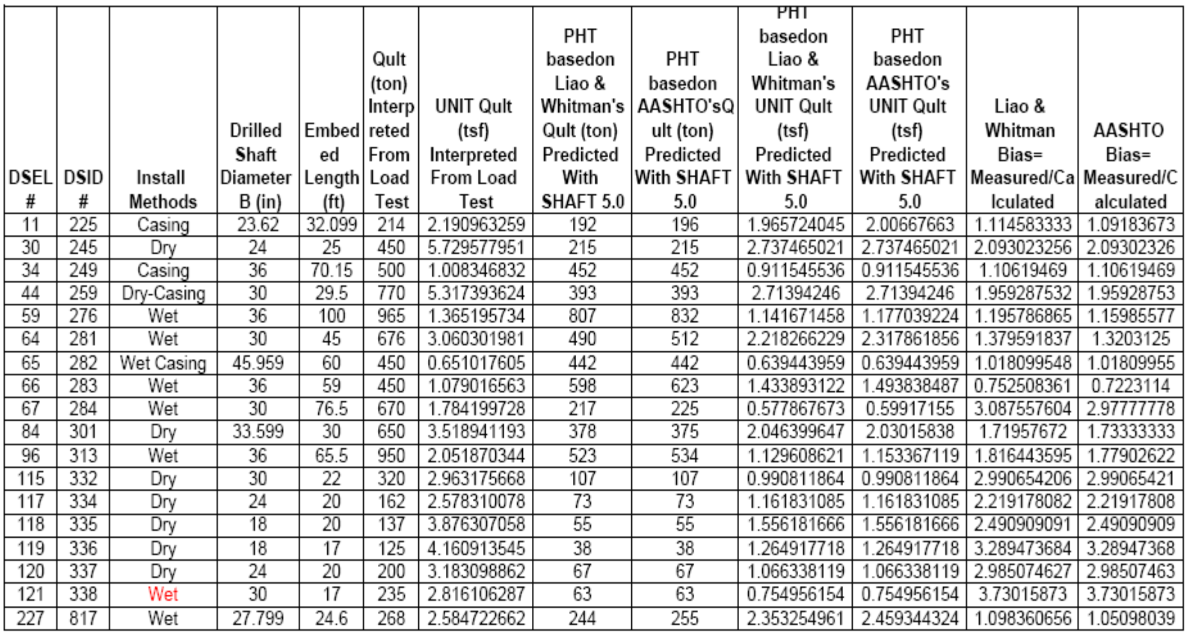
TABLE 2. Measured and predicted unit resistance parameters of drilled shafts in sand

Unit Resistance KPa (tsf)	Measured	Predicted with two different correction factors, $C_{N.}$	
		AASHTO, Peck et al.(1974)	Liao & Whitman (1986)
μ_{UR}	265(2.77)	144 (1.50)	142 (1.48)
σ_{UR}	135(1.41)	67 (0.704)	66 (0.692)
COV_{UR}	0.51(0.51)	0.47 (0.468)	0.47 (0.467)

In Table 2, μ_{UR} is the mean of the 18 drilled shafts unit resistance; σ_{UR} is the standard deviation of unit shaft resistance; COV_{UR} is the coefficient of variation of unit resistance of drilled shafts installed in sand soils.

Table 3 below lists the reference that summaries the 18 load test cases. Table 4 summarizes the bias parameters used for resistance factor calibration via a Monte Carlo simulation method.

TABLE 3. Summary of 18 load test cases (including shafts diameter, embedded length, dominant type of sandy soil, method of installation, measured load at displacement of 0.05 diameter B, predicted failure load from SHAFT, and bias factor defined as ratio of actually measured capacity over predicted capacity)



DSEL #	DSID #	Install Methods	Drilled Shaft Diameter B (in)	Embeded Length (ft)	Qult (ton) Interpreted From Load Test	UNIT Qult (tsf) Interpreted From Load Test	PHT basedon Liao & Whitman's Qult (ton) Predicted With SHAFT 5.0	PHT basedon AASHTO'sQult (ton) Predicted With SHAFT 5.0	PHT basedon Liao & Whitman's UNIT Qult (tsf) Predicted With SHAFT 5.0	PHT basedon AASHTO's UNIT Qult (tsf) Predicted With SHAFT 5.0	Liao & Whitman Bias= Measured/Calculated	AASHTO Bias= Measured/Calculated
11	225	Casing	23.62	32.099	214	2.190963259	192	196	1.965724045	2.00667663	1.114583333	1.09183673
30	245	Dry	24	25	450	5.729577951	215	215	2.737465021	2.737465021	2.093023256	2.09302326
34	249	Casing	36	70.15	500	1.008346832	452	452	0.911545536	0.911545536	1.10619469	1.10619469
44	259	Dry-Casing	30	29.5	770	5.317393624	393	393	2.71394246	2.71394246	1.959287532	1.95928753
59	276	Wet	36	100	965	1.365195734	807	832	1.141671458	1.177039224	1.195786865	1.15985577
64	281	Wet	30	45	676	3.060301981	490	512	2.218266229	2.317861856	1.379591837	1.3203125
65	282	Wet Casing	45.959	60	450	0.651017605	442	442	0.639443959	0.639443959	1.018099548	1.01809955
66	283	Wet	36	59	450	1.079016563	598	623	1.433893122	1.493838487	0.752508361	0.7223114
67	284	Wet	30	76.5	670	1.784199728	217	225	0.577867673	0.59917155	3.087557604	2.97777778
84	301	Dry	33.599	30	650	3.518941193	378	375	2.046399647	2.03015838	1.71957672	1.73333333
96	313	Wet	36	65.5	950	2.051870344	523	534	1.129608621	1.153367119	1.816443595	1.77902622
115	332	Dry	30	22	320	2.963175668	107	107	0.990811864	0.990811864	2.990654206	2.99065421
117	334	Dry	24	20	162	2.578310078	73	73	1.161831085	1.161831085	2.219178082	2.21917808
118	335	Dry	18	20	137	3.876307058	55	55	1.556181666	1.556181666	2.490909091	2.49090909
119	336	Dry	18	17	125	4.160913545	38	38	1.264917718	1.264917718	3.289473684	3.28947368
120	337	Dry	24	20	200	3.183098862	67	67	1.066338119	1.066338119	2.985074627	2.98507463
121	338	Wet	30	17	235	2.816106287	63	63	0.754956154	0.754956154	3.73015873	3.73015873
227	817	Wet	27.799	24.6	268	2.584722662	244	255	2.353254961	2.459344324	1.098360656	1.05098039

Calibration of Drilled Shaft Total Resistance Factor

Although many reliability analysis methods are available to conduct the calibration, two of them have gained the most widely acceptance: the first order reliability method (Hasofer and Lind [13], 1974; Ellingwood et al.[8], 1980; Phoon et al. [24], 1995; Yang [28], 2006) and the *Monte Carlo* method (Allen et al.[2], 2005; Roberts [26], 2006). In this paper, the *Monte Carlo* method was adopted. The calibration in this study followed the recommended procedures in [2].

In this study, only the Strength I limit state was considered and the limit state function was selected as:

$$g = \phi R - \gamma_{LL} LL - \gamma_{DL} DL \tag{2}$$

where g is the safety margin, ϕ is the resistance factor, R is the nominal resistance, γ_{LL} and γ_{DL} are the live load and dead factors while LL and DL are the nominal live and dead loads. The same parameters used by Paikowsky [22] were adopted in this study as shown in Table 4. Both live and dead loads were assumed to be normally distributed. This assumption is consistent with Nowak's study [19] (1995).

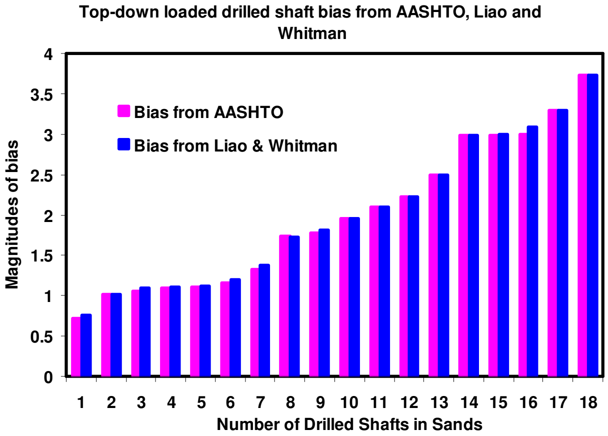


FIG. 1. Histogram of the bias of total resistance.

Note that bias λ is calculated by dividing the measured nominal resistance from the top-down load test data by the corresponding predicted value using SHAFT 5.0. Statistical analysis on the bias λ values was then performed as shown in Figure 1 and listed in Table 4.

TABLE 4. Bias lognormal distribution parameters used for the *Monte Carlo* simulation for resistance factors calibration

Bias λ Statistics	AASHTO (18 Cases)		Liao & Whitman (18 Cases)	
	total and unit resistance lognormal distribution	"Fit to tail " 10 total and unit resistance bias of sand	total and unit resistance lognormal distribution	"Fit to tail " 10 total and unit resistance bias of sand

μ_{λ_R}	1.984	1.294	2.003	1.312
σ_{λ_R}	0.916	0.398	0.912	0.392
COV_{λ_R}	0.462	0.308	0.456	0.298
ϕ	0.45	0.50(0.47)	0.45	0.50 (0.48)

Figures 1 and 2 show the histogram and cumulative distribution function (CDF) curves of the bias values of the total resistance ranging from 0.72 to 3.73. Based on the current and previous study (Li and Liang [17], 2008; Yang et al. [29], 2008; Allen [2], 2005), the bias was assumed to follow the lognormal distribution. Note that the mean values and the standard deviation values in Figures 1 and 2 can be used in the calibration for engineering conservativeness. Furthermore, the bias mean value μ_λ and the bias standard deviation σ_λ in Table 4 can be determined following a "fit to tail" strategy recommended in [2]. Detailed procedures to develop the standard normal variables z and the CDF plots can be found in Transportation Research Circular E-C079 (Allen et al. [2], 2005). The "best fit" lognormal distribution parameters used in the calibration were summarized in Tables 4.

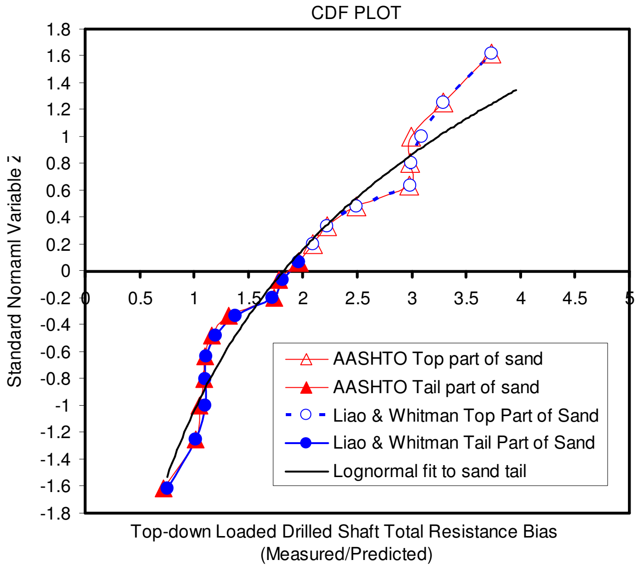


FIG. 2. CDF plot of the bias of total resistance.

Prior to the *Monte Carlo* simulation, a target reliability index β_T of 3.0 (approximately corresponds to the probability of failure $P_f = 0.001$) and a ratio of dead load over live load (say DL / LL = 2.0) are selected. The variation of DL/LL does not appear to influence the calibrated resistance factors (see [2]). It is easy to appreciate that depending on the different methods of predicting the resistance, there will be considerable uncertainty related to the analysis method especially when the soil profile properties are not accurately available. To consider and implement the uncertainty into the reliability-based LRFD design, the *Monte Carlo* simulation method therefore can be employed to investigate the uncertainty effects on resistance factors for the total, unit resistance and ultimately the drilled shaft load and resistance factors calibration. Additional information on *Monte Carlo* simulation details and its applications are available in [3, 4]. For the *Monte Carlo* simulation and calibration of resistance factors, an MATLAB program was written for the reliability analysis based on actual measured drilled shaft static load test results and predicted nominal resistance. The statistical information of load components for calibration is listed in Table 5.

TABLE 5. Statistics and load factors (Paikowsky et al. [22], 2004)

Load Type	Bias	Coefficient of Variation	Load Factor Used
Dead load	λ_{DL} = 1.05	COV_{DL} = 0.1	γ_{DL} = 1.25
Live load	λ_{LL} = 1.15	COV_{LL} = 0.2	γ_{LL} = 1.75

The required number of *Monte Carlo* trials is based upon the need for achieving a particular level of reliability (Harr [12], 1996; Baecher and Christian [5], 2003). The number of *Monte Carlo* trials required for a confidence level of 90% is approximately 4500 (Harr 12], 1996). For the results reported in this paper, a *Monte Carlo* simulation with 10,000 trials was conducted. The mathematical expressions of the functions are complicated and omitted here. Details of the functions and calibration procedures can be found in the Circular E-C079 (Allen et al. [2], 2005). If the calculated β value is different from the target reliability index, β_T, the trial resistance factor must be changed and iterations must continue until $\beta = \beta_T$. The corresponding resistance factors calibrated from this procedure are achieved.

Results of Total Resistance Factors Calibrated for Drilled Shafts LOAD TESTS

The total resistance factors calibrated from the load test data were summarized in Table 6. The knowledge-based uncertainty of SPT correction factor's effects from AASHTO (2007) and Liao & Whitman (1986) appear to be negligible because each calibrated total resistance factor is rounded up to 0.50. In comparison with the current total resistance factor of ϕ = 0.55 in cohesionless soils in AASHTO [1] (2007), the total resistance factors obtained in this investigation generally agree with the recommended resistance factor (0.55) reported by Paikowsky [22] (2004) and AASHTO (2007), but on the conservative side. It should be mentioned that resistance factor calibrated in AASHTO (2007) based on Paikowsky (2004) work was partly based on FHWA [9] (1988) while the current study is based on the FHWA [10] (1999) method via the SHAFT program [25]. The slight differences in the calibrated total resistance factors may partly be due to the calibration via the FHWA (1999) method instead of FHWA (1988).

TABLE 6. Comparison of calibrated total resistance factors for drilled shafts

Current study β_T = 3.0	ϕ calibrated by fit to tail
Based on AASHTO, SPT C_N	0.50 (0.47) in sand
Based on Liao & Whitman, SPT C_N	0.50 (0.48) in sand
Paikowsky (2004) and AASHTO (2007)	0.55 in cohesionless soils

CONCLUSIONS

The average resistance factors in consideration of epistemic or knowledge-based uncertainty effects, namely the two most widely SPT correction factors [AASHTO (2007) and Liao & Whitman (1986)] have been calibrated and rounded up to 0.50 for recommendation for drilled shafts design through the 18 cases study. The calibrated resistor factors using the knowledge-based uncertainty via the SHAFT program are very close to the calibrated resistance factor proposed in ASSHTO (2007). The slight difference in the calibrated resistance factors summarized in Table 6 may be due to the fact that current calibration is based on FHWA (1999) method instead of FHWA (1988) method. Future work will include using the methods recommended by Brown, Turner, and Castelli (2010), and FHWA (2010) [11]. Future work will also verify any further change in the resistance factors which are calibrated according to the latest FHWA (2010) method.

REFERENCES

[1] AASHTO (2007). LRFD Bridge Design Specifications. *American Association of State Highway and Transportation Officials,* Third Edition, Washington, DC.

[2] Allen, T.M., Nowak, A.S., and Bathurst, R.J. (2005). Calibration to Determine Load and Resistance Factors for Geotechnical and Structural Design. *Transportation Research Circular Number E-C079, Transportation Research Board*, Washington, DC, 83p.

[3] Ang, A.H-S., and Tang, W.H. (1984). Probability Concepts in Engineering Planning and Design, *Vol.* 2, *Decision, Risk and Reliability*. John Wiley & Sons, New York.

[4] Ang, A.H-S., and Tang, W.H. (2007). Probability Concepts in Engineering, Vol. 1, Emphasis on Applications to Civil and Environmental Engineering. John Wiley & Sons, New York.

[5] Baecher G. B. and Christian J. T. (2003). Reliability and statistics in geotechnical engineering. Wiley, West Sussex, UK

[6] Das, Braja M and Sobhan, Khaled (2014) Principles of Geotechnical Engineering, 8th Edition, CENGAGE Learning.

[7] Baker, R.M., Duncan, J.M., Rojiani, K.B., Ooi, P.S., Tan, C.K., and Kim, S.G. (1991). Manuals for the Design of Bridge Foundations. *NCHRP Report 343, TRB*, *National Research Council*, Washington, DC.

[8] Ellingwood, B., Galambos, T.V., MacGregor, J.G., and Cornell, C.A. (1980). Development of a Probability Based Load Criterion for American National Standard A58. *NBS Special Publication 577, National Bureau of Standards*, Washington, DC, 228p.

[9] Reese, L.C. and O'Neill, M.W. (1988). Drilled Shafts: Construction Procedures and Design Methods. *Report No. FHWA-HI-88-042, FHWA*, Washington, DC.

[10] O'Neill, M.W. and Reese, L.C. (1999). Drilled Shafts: Construction Procedures and Design Methods. *Report No. FHWA-IF-99-025, FHWA*, Washington, DC, 758p.

[11] Dan A. Brown, John P. Turner, and Raymond J. Castelli, (2010). Drilled Shafts: Construction Procedures and Design Methods. *Report No. FHWA NHI-10-016, FHWA*, Washington, DC, 972p.

[12] Harr, M. E. (1996). *Reliability-Based Design in Civil Engineering.* Dover Publications, Inc., Mineola, New York.

[13] Hasofer, A.M. and Lind, N.C. (1974). Exact and invariant second moment code format. *Journal of Engineering Mechanics Division*, ASCE, Vol. 100, No. EM1, pp. 111-121.

[14] Kulhawy, F.H. and Phoon, K.K. (1993). *Drilled shaft resistance in clay soil to rock, Design & Performance of Deep Foundations: Piles & Piers in Soil & Soft Rock (GSP 38),* Ed. Nelson P.P, Smith T. D & Clukey E.C, ASCE, New York, pp.172-183.

[15] Liang, R. and Nowari, N.O. (2000). “Resistance Factors for Driven Piles”, ASCE Geotechnical Special Publication No. 100, 178-191.

[16] Liang, Robert and Li, Jiliang (2009) “Resistance Factors Calibrated from FHWA Drilled Shafts Static Top-Down Tests Data Base”, Contemporary Topics in In Situ Testing, Analysis, and Reliability of Foundation (GSP 186). Proceedings of Selected Sessions of *2009 International Foundation Congress & Equipment Expo*, Orlando, FL.

[17] Li, J. and Liang, R. (2008). Skin Resistance Factors Calibrated from O-Cell Tested Drilled Shafts of FHWA Database”, submitted to International Geotechnical Conference "Geotechnical Challenges in Megacities" Moscow, 7-10 June 2010.

[18] Liao, S. and Whitman , R.V. (1986). “Overburden Correction Factor for SPT in Sand”, Journal of Geotechnical Engineering, ASCE, Vol. 112, No.3, 373-377.

[19] Nowak, A. (1995). *NCHRP Report 368: Calibration of LRFD Bridge Design Code*. Transportation Research Board, Washington, D. C.

[20] Fenton, G. A. and Griffiths, D.V. (2008) “Risk Assessment in Geotechnical Engineering”, John Wiley and Sons, Inc.

[21] O’Neill, M.W., Townsend, F.C., Hassan, K.M. and Chan, P.S. (1996). Load Transfer for Drilled Shafts in Intermediate Geomaterials. *Report No. FHWA-RD-95-172. FHWA*, McLean, VA, 194p.

[22] Paikowsky, S.G. et al. (2004). Load and Resistance Factor Design (LRFD) for Deep Foundations. *NCHRP (Final) Report 507, TRB*, Washington, DC, 87p.

[23] Peck, R. B., W. E. Hanson, and T. H. Thornburn (1974) "Foundation Engineering," John Wiley & Sons, pp. 514.

[24] Phoon, K.K., Kulhawy, F.H., Grigoriu, M.D. (1995). Reliability-based Design of Foundations for Transmission Line Structure, *Report TR-105000, Electric Power Research Institute*, Palo Alto, California.

[25] Reese, L.C., Wang S.T., and Arrellaga J.A. (2001). SHAFT Version 5.0 for Windows, A Program for the Study of Drilled Shafts Under Axial Loads, *Ensoft, Inc.*, Austin Texas.

[26] Roberts L.A. (2006). Reliability-based design and analysis of deep foundations at the service limit state. *PhD Dissertation*, Univ. of Missouri, Kansas City, Missouri, 207p.

[27] Yang, K. and Liang, R.Y. (2007). Resistance Factors for Lateral Design of Drilled Shafts*, DFI Annual Conference*, Denver Colorado.

[28] Yang, L. (2006). Reliability-Based Design and Quality Control of Driven Piles, *Ph.D. Dissertation,* University of Akron, Akron, Ohio.

[29] Yang, X., Han, J., Parsons, R.L. and Henthorne, R.W. (2008). Resistance Factors for Drilled Shafts in Weak Rock Based on O-cell Test Data*, TRB Meeting*, Washington, D.C.

[30] Zhang, L.M., Li, D.Q. and Tang, W.H. (2005). Reliability of bored pile foundations considering bias in failure criteria, *Canadian Geotechnical Journal*, Vol. 42. 1086 - 1093.

Biographies:

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