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CALIBRATION OF RESISTANCE FACTORS FOR AXIAL LOAD CAPACITY OF DRILLED SHAFT IN LOUISIANA SOILS

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ABSTRACT

This paper presents reliability based analyses for calibration of resistance factor for axially-loaded drilled shafts. A total of 16 cases of drilled shaft load test are available in Louisiana Department of Transportation and Development (LADOTD) archives. Only 11 out of the 16 cases meet the FHWA "0.05D" settlement criterion. Due to the limited number of available drilled shaft cases in Louisiana, additional cases were collected from the neighboring state, i.e. Mississippi, which has subsurface soil conditions similar to Louisiana soils in its drilled shaft load test database. 15 drilled shafts from Mississippi were finally selected from 50 available cases based on selection criteria of subsurface soil conditions and final settlement. As a result, a database of 26 drilled shafts representing the typical design practice in Louisiana was created for statistical reliability analysis. Predictions of load-settlement behavior of drilled shafts from soil borings were determined using FHWA design method (O'Neill and Reese method) via SHAFT computer program. Measured drilled shaft axial nominal resistance was determined from either the Osterberg cell (O-cell) test or the conventional top-down static load test. Statistical analyses were performed to compare the predicted total drilled shaft nominal axial resistance and the measured nominal resistance. Results show that the selected design method underestimates the measured drilled shaft resistance by an average of 35%. The Monte Carlo simulation method was selected to perform the LRFD calibration under strength I limit state. Total resistance factors for different reliability indexes (β) were determined and compared with those in literature. LRFD calibration showed that the FHWA design method has a resistance factor (ϕ) of 0.40 at the target reliability index (β_T) of 3.0.
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This paper presents reliability based analyses for calibration of resistance factor for axially-loaded drilled shafts. A total of 16 cases of drilled shaft load test are available in Louisiana Department of Transportation and Development (LADOTD) archives. Only 11 out of the 16 cases meet the FHWA "0.05D" settlement criterion. Due to the limited number of available drilled shaft cases in Louisiana, additional cases were collected from the neighboring state, i.e. Mississippi, which has subsurface soil conditions similar to Louisiana soils in its drilled shaft load test database. 15 drilled shafts from Mississippi were finally selected from 50 available cases based on selection criteria of subsurface soil conditions and final settlement. As a result, a database of 26 drilled shafts representing the typical design practice in Louisiana was created for statistical reliability analysis. Predictions of load-settlement behavior of drilled shafts from soil borings were determined using FHWA design method (O'Neill and Reese method) via SHAFT computer program. Measured drilled shaft axial nominal resistance was determined from either the Osterberg cell (O-cell) test or the conventional top-down static load test. Statistical analyses were performed to compare the predicted total drilled shaft nominal axial resistance and the measured nominal resistance. Results show that the selected design method underestimates the measured drilled shaft resistance by an average of 35%. The Monte Carlo simulation method was selected to perform the LRFD calibration under strength I limit state. Total resistance factors for different reliability indexes (β) were determined and compared with those in literature. LRFD calibration showed that the FHWA design method has a resistance factor (ϕ) of 0.40 at the target reliability index (β_T) of 3.0.

Introduction

Load and resistance factor design (LRFD) has been used increasingly and become mandatory for all bridge projects funded by the Federal Highway Administration (FHWA). Compared to the allowable stress design (ASD) method, LRFD can achieve a compatible reliability between the bridge superstructure and substructure. The uncertainty of load and resistance are quantified separately and reasonably incorporated into the design process. Therefore, this reliability-based design approach will generally produce a more efficient and consistent design than the traditional factor of safety approach [1]. To achieve these goals, many researchers have been working to develop a reasonable way to implement the LRFD method in bridge substructure design and to determine appropriate resistance factors for different regional soil conditions [2, 3, 4, 5, 6, 7, 8, and 9].

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Although the AASHTO LRFD specification [10] was first approved for use in 1994, the implementation of the specifications has been slow [11]. The ϕ factors proposed in the specifications were obtained from ASD safety factors to maintain a consistent level of reliability with past practice. As a result, little improvement has been made toward a more efficient design. One outstanding problem with the resistance factor calibration is the lack of good data [3 and 12]. Even in the latest edition of the AASHTO [13], a significant number of resistance factors in the foundation design were still selected based on the fitting with ASD. Research has been carried out in an effort to calibrate resistance factors for drilled shafts from case histories [3, 11, 12, and 14] nationally and locally.

The use of single drilled shafts to support individual columns in bridges and buildings is widely practiced. When superstructures are sensitive to foundation movements, the settlement of a drill shaft is important to the normal operation of supported superstructures. Generally, the nominal resistance of drilled shafts is defined as the load carried by the shaft at the head displacement equal to 5% of the shaft diameter, if the shaft has not plunged prior to this displacement [15and 16].

Currently, AASHTO specifications [13] recommend using resistance factors (ϕ) for single drilled shafts in an axial compression range from 0.40 to 0.60 at the reliability index (β) of 3.0 depending on different soil conditions. The recommended resistance factors, however, were calibrated based on a drilled shaft database that was collected from limited number of sites and do not necessarily reflect the local soil condition or local design practice. As a result, the resistance factors recommended by the existing AASHTO LRFD design code should be verified and recalibrated to account for local soil conditions and design practice.

The main objective of this study is to calibrate the total resistance factor for LRFD design of axially loaded drilled shafts in Louisiana soils. The FHWA method suggested by O'Neill and Reese [15] is used for the design of drilled shafts. The nominal resistance of drilled shafts was determined at a settlement of 5% of the shaft diameter or at plunging failure. 66 drilled shaft cases with different lengths and sizes that were tested using the O-cell method or the conventional top-down static load test were collected from Louisiana and Mississippi. The collected drilled shafts were screened based on selected criteria and only 26 drilled shaft cases that met the settlement criterion were selected in this study. Statistical analyses were first conducted to evaluate the FHWA design method [15] for predicting the measured drilled shaft resistance. Reliability analysis was conducted on collected database using the Monte Carlo simulation approach to calibrate resistance factors (ϕ) for the LRFD design of drilled shafts at different reliability indexes (β).

LRFD Background

The basic concept behind LRFD is illustrated in Figure 1. Here, the distributions of random load (Q) and resistance (R) are shown as normal distributions. The performance limit state function of the structural system can be described as follows:

$$g\,(R, Q) = R - Q \tag{1}$$

where R is the resistance of a given structure, which is a random variable, and Q is the applied load, which is also a random variable.

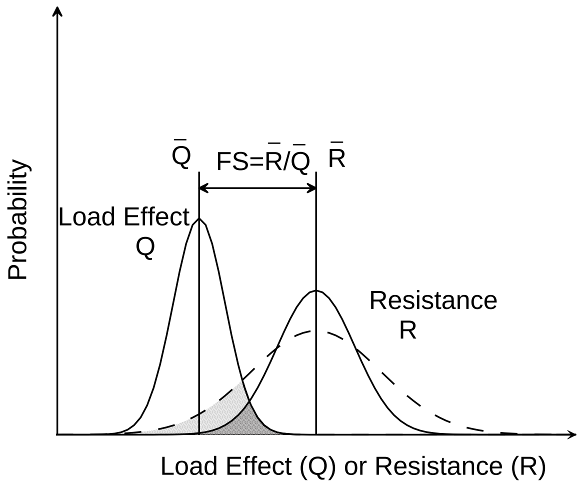

Figure 1. Probability density functions for structure load and resistance.

The probability of the structure failure is defined as the shaded area in Figure 1, where the resistance is less than the applied load. The probability of failure, P_f, is then defined mathematically as:

$$P_f = P[g(R,Q) \le 0] = P[R \le Q] \tag{2}$$

For a normal distribution of g values, the probability of failure can be equated explicitly to the value of reliability index $\beta = u_g/\sigma_g$, where u_g is the mean value of g and σ_g is the standard deviation of g. The relationship between probability of failure and reliability index can be calculated using the following function.

$$p_f = 1 - NORMSDIST(\beta) \tag{3}$$

Where *NORMSDIST* is a standard normal cumulative function in Microsoft Excel.

If both the load and resistance distributions are lognormal and the limit state function is a product of random variables, then β can be calculated using a closed-form solution reported by Withiam et al. [17] and Nowak [9] as follows

$$\beta = \frac{\ln\left[\overline{R}/\overline{Q}\sqrt{\left(1+COV_Q^2\right)/\left(1+COV_R^2\right)}\right]}{\sqrt{\ln\left[\left(1+COV_Q^2\right)\left(1+COV_R^2\right)\right]}} \tag{4}$$

Where $\overline{R}$ is the mean value of the resistance R, and $\overline{Q}$ is the mean value of the load Q; COV_R and COV_Q are the coefficients of variation for the resistance and load values, respectively.

The limit state function for LRFD design is given below:

$$g(R,Q) = \sum \gamma_i Q_n - \sum \phi R_n \tag{5}$$

The term bias is used to refer to individual measured values of load or resistance divided by the predicted value corresponding to that measured value.

Drilled Shaft Load Test Database

An extensive search was conducted on the Louisiana Department of Transportation and Development's (LADOTD's) archives to collect drilled shaft test data in Louisiana. Only 16 drilled shaft test cases are available in LA. Among these 16 cases, only 11 meet the FHWA settlement criterion. Due to the limited number of available cases in Louisiana, statistical reliability analysis of drilled shafts in Louisiana based on the available database is not reliable. The geotechnical research team at Louisiana Transportation Research Center (LTRC) decided to search for more drilled shaft cases in neighboring states, i.e. Mississippi and Texas. The authors were able to collect 50 drilled shaft cases in MS. Among these 50 cases provided by MSDOT, 26 cases were selected based on initial screening to identify cases with subsurface soil conditions similar to Louisiana soils. 15 of the initial selected cases meeting the FHWA settlement criterion were chosen as the sample data for statistical reliability analysis. The combined database has 26 cases in total and is able to represent the typical soils occurred in LA. The geographical locations of drilled shafts in the final selected database are approximately shown in the maps of Figure 2.

Diameter of drilled shafts in the database ranges from 0.61m to 1.83m and length ranges from 6m to 42.1m. All the 15 cases from MS and 7 cases from LA were tested using O-cell and only 4 cases in LA were tested using conventional top-down load test. The soils encountered in the investigated database include silty clay, clay, sand, clayey sand, and gravel. Most of the soil strata are not uniform and contain interlayer.

O-cell Shaft Test

The O-cell test has been widely used in the United States to determine resistance of drilled shafts. Unlike the conventional top-down load test, the load in an O-cell test is applied at the bottom or near the bottom of drilled shafts via a preinstalled hydraulic cell. During an O-cell load test, the shaft above the cell moves upward, and the shaft below the cell moves downward. As a result, both side friction and end bearings can be measured from O-cell test as shown in Figure 3. The upward load shown in the figure was the net upward load (the O-cell measured upward load minus buoyant weight of the drilled shaft). An equivalent top-down curve can be constructed from the two component curves to investigate the combined two-component pile resistance. Construction of the equivalent top-down curve begins by determining the side shear at an arbitrary deflection point on the side shear-deflection curve (the top curve in Figure 4a). The shaft is assumed rigid; its top and bottom move together and have the same deflection at this load. By adding the side shear to the mobilized end bearing at the chosen deflection, one determines a single point on the equivalent top-down curve [18]. Figure 3 shows an example of the construction of an equivalent top-loaded settlement curve (Figure 3 b) from O-cell test results (Figure 3 a). The solid line in Figure 3 b shows the modified top-down curve to include the additional elastic compression of the shaft.

In this study, a total dataset of 26 drilled shaft cases in silty clay, sand, sand-clay, and mixed soils were collected from the project libraries. The nominal load of drilled shaft was defined as the load corresponding to a settlement of 5% of the shaft diameter or the plunging load [15]. Selection of this criterion was based on recommendation from previous study performed by Paikowsky [3] for LRFD calibration consistency. Statistical analysis showed that the FHWA's "0.05D" method produced the closest and most consistent resistance with the mean value of the capacities determined by seven methods, which has been further confirmed and used by Zhang et al. [19] and Liang and Li [12]. Due to complexity of the soil conditions in Louisiana and the limit available cases of load tests of drilled shafts, it is impractical to calibrate the resistance considering the effect of soil type. The resistance factor developed in this study is the total resistance factor (without separation of side resistance and end bearing) for mixed soil conditions (the effect of soil type on the resistance factor is not considered).

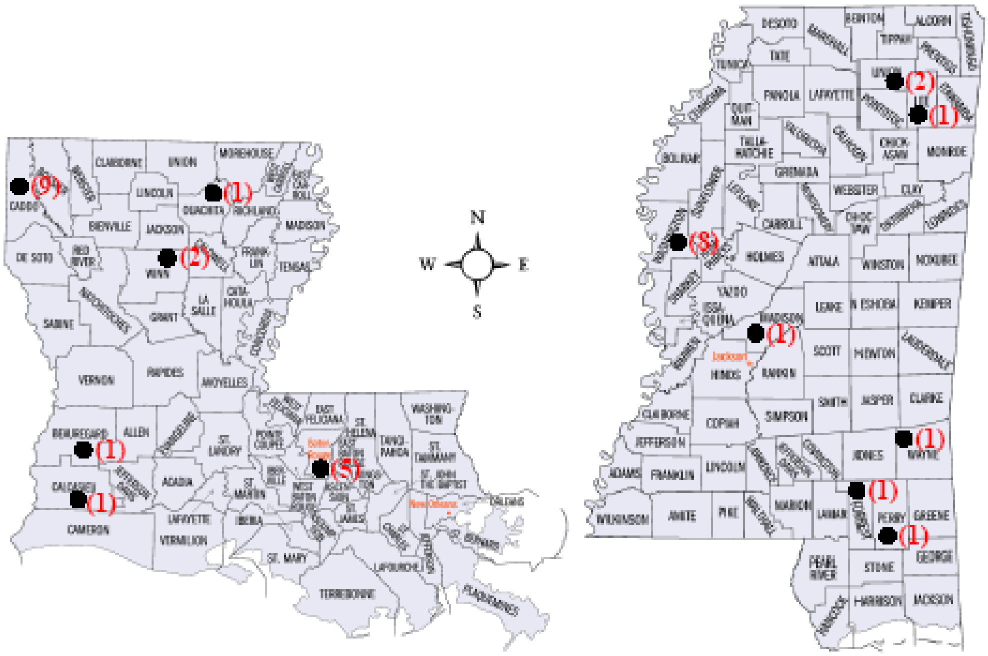

Figure 2. Approximate locations of the investigated drilled shafts.

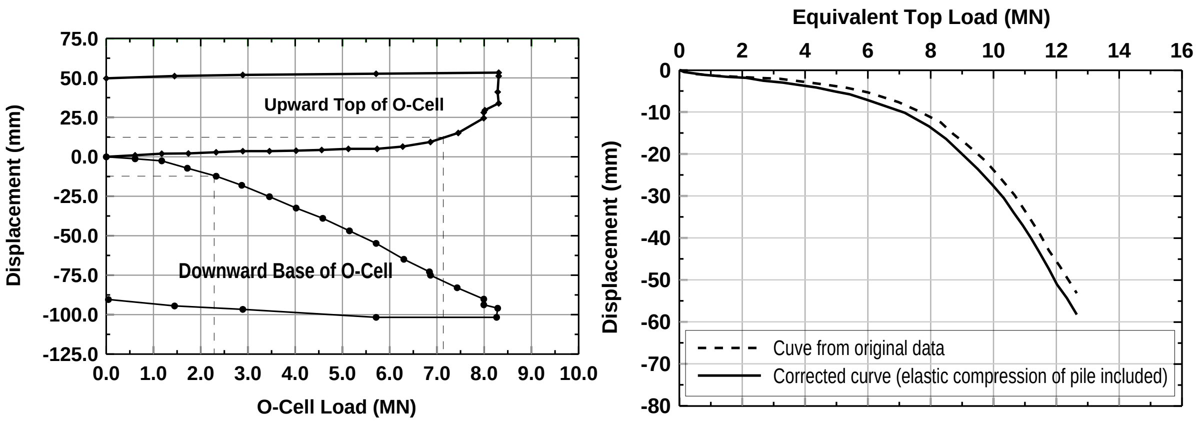

Figure 3. a) Settlement curves by O-cell b) equivalent top-down settlement curve.

FHWA Design Method for Drilled Shafts

All collected drilled shaft data contain shaft dimensions and in-situ soil profiles, elevations, and parameters, which make it possible to predict the load and settlement relationship using the FHWA [15] method via SHAFT program [20]. The FHWA design method for clay, sand, and weak geomaterials was based on O'Neill and Reese [15] method. An example of a predicted load-settlement curve is shown in Figure 4.

Nominal resistance of drilled shaft at a settlement of 5% of the shaft diameter can be determined by interpreting the calculation results. The measured nominal resistance can be obtained from measured load-settlement curves by O-cell tests or top-down tests. Some of the measured settlements did not meet the 5% of the shaft diameter criterion. Therefore, it is necessary to extrapolate the measured load-settlement curves. Extrapolation of the measured load-settlement curves has been carefully performed on some cases that are close to the settlement criterion based on engineering judgments to determine the estimated load at a settlement of 5% of the shaft diameter. The extrapolation has been examined to ensure a most reasonable estimation. Data that needed large extrapolation were discarded. Details of extrapolation are beyond the scope of this paper, they will be published in other publication separately.

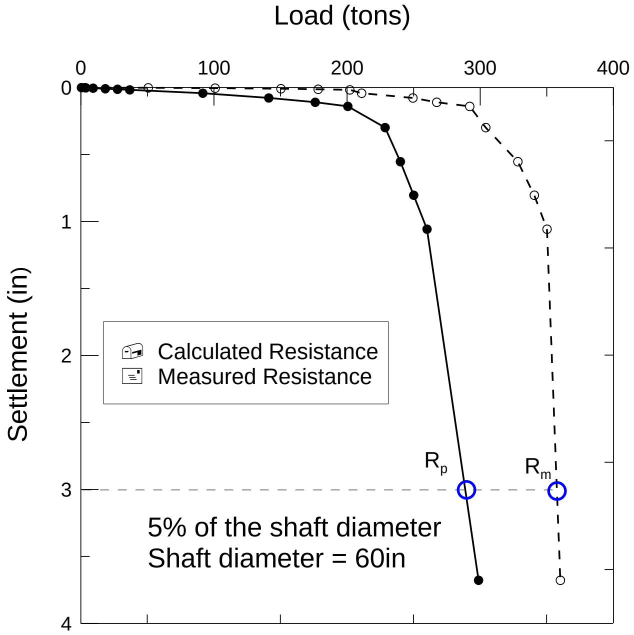

Figure 4. Example of load-settlement analysis and measured value.

Calibration of Total Resistance Factor for Drilled Shafts

Statistical Analyses

From the results of Table 1, a statistical analysis was conducted on the collected database to evaluate the statistical characteristics of the nominal drilled shaft resistance. The corresponding resistance bias factor (λ_R), which is the mean ratio between the measured resistance and the predicted resistance (R_m/R_p), was determined. The mean ratio (μ), standard deviation (σ), and coefficient of variation (COV) of the bias (the measured to the predicted drilled shaft resistance ratios R_m/R_p) were calculated and summarized in Table 1.

Figure 5 presents the comparison between the predicted and measured drilled shaft resistances. A simple regression analysis was also conducted to obtain a line of best fit of the predicted/measured drilled shaft resistances. The R_{fit}/R_m of the drilled shafts is equal to 0.51, while the mean ratio of R_p/R_m equals to 0.65. The R_p/R_m ratio indicates a 35% underestimation of measured values using the FHWA design method [15] in Louisiana soils. The COV of R_m/R_p for drilled shaft is 0.73, which is somewhat higher than the COV for the O'Neill and Reese design method (0.27 - 0.74) as reported by Paikowsky [3]. This may be due to the local soil conditions of the investigated drilled shafts.

Table 1. Statistical Analysis of Drilled Shaft Design Method

Arithmetic calculations				Best fit calculations
R_m/R_p			R_p/R_m	
Mean	σ	COV	Mean	R_{fit}/R_m
2.18	1.60	0.73	0.65	0.51

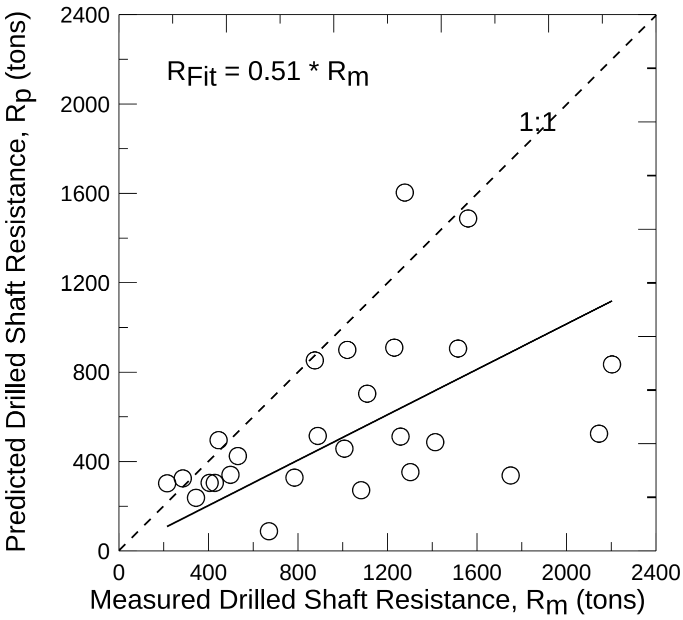

Figure 5. Measured (R_m) versus predicted (R_p) drilled shaft resistance**.**

LRFD Calibration

Several different reliability analysis methods are available in literature to perform LRFD calibration. The most widely used methods are the first order reliability method (FORM) and the Monte Carlo Method. This paper follows the calibration procedure based on the Monte Carlo method recommended in Transportation Research Circular E-C079 [21] to determine the total resistance factor of drilled shafts.

In this study, the strength I limit state was considered and the limit state function can be written as:

$$g = \phi R - \gamma_{LL} LL - \gamma_{DL} DL \quad (6)$$

where γ_{LL} and γ_{DL} are the live and dead load factors, LL and DL are the nominal live and dead loads, and the other symbols are the same as defined in previous sections. Many researchers, such as Zhang et al. [22], Kim et al. [23], McVay et al. [24], and Abu-Farsakh [25] used the load statistics and the load factors from the AASHTO LRFD Specifications, which was originally recommended by Nowak [9]. Both live and dead loads were assumed to be lognormally distributed. In this study, load statistics and factors from the AASHTO LRFD specifications [13] were also adopted as follows:

$\lambda_{DL} = 1.08$	$COV_{DL} = 0.13$	$\gamma_{DL} = 1.25$
$\lambda_{LL} = 1.15$	$COV_{LL} = 0.18$	$\gamma_{LL} = 1.75$

Where, COV_{DL} and COV_{LL} are the coefficient of variation values for the dead load and the live load, respectively, and γ_{DL} and γ_{LL} are the load factors for dead load and live load, respectively. Q_{DL}/Q_{LL} is the dead load to live load ratio, which is dependent on the bridge span length [27]. However, it is found that the calibrated resistance factor (ϕ) is insensitive to the Q_{DL}/Q_{LL} ratio greater than 3.0 [5 and 27]. In this study, a Q_{DL}/Q_{LL} value of 3.0 is used for LRFD calibration. This Q_{DL}/Q_{LL} ratio was also used in the previous studies conducted by Barker et al. [14] and Allen [26].

The Monte Carlo simulation method is used to generate random numbers to extrapolate the cumulative distribution function (CDF) values for each random variable (load and resistance). The values shown in Table 1 are used to generate random numbers of resistance.

Extrapolation of CDF makes estimation of β possible where otherwise limited quantity of data has restricted the reliable estimate of β. Once the reliability index (β) is estimated, the probability of failure can then be determined by assuming the lognormal distribution of g(x). For the probabilistic calculations reported in this paper, Monte Carlo simulations with 12,000 trials were conducted. The calculated reliability index and resistance factor are shown in Figure 6.

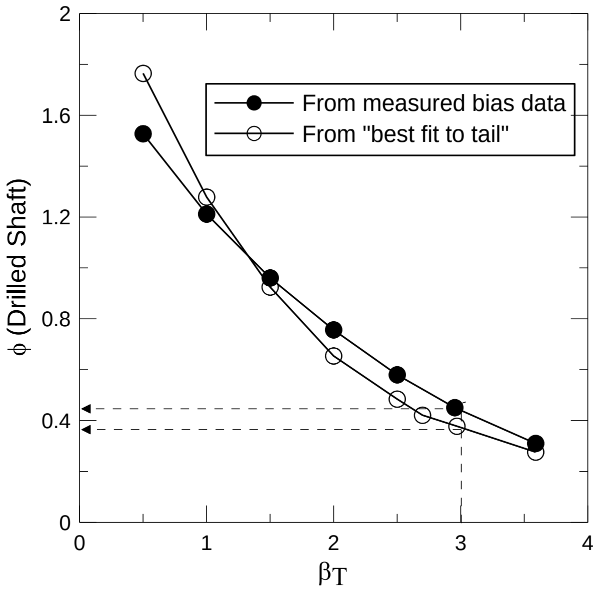

Figure 6. Resistance factors for different reliability indexes.

The calibration was conducted with a dead load to live load ratio of 3.0, since it is a typical value used in previous research as discussed previously [14 and 26]. Many researchers have suggested a required reliability index for the deep foundations between 2.33 and 3.0. Total resistance factors (ϕ) for the FHWA design method corresponding to a target reliability index of 3.0 is 0.45 (0.44) using "best fit to tail" method and 0.4 (0.38) using the measured bias. The authors believe the resistance factor based on measured bias is more favorable since the measured bias data can be utilized to its full extent. It should be noted that the resistance factors calibrated in AASHTO [13] based on Paikowsky [3] work were partly based on FHWA [34]. The work by Liang and Li [12] and current work are based on the FHWA [16] method via SHAFT [24] program. Resistance factor in mixed soils by Liang and Li [12] are less than the proposed value of 0.40 in this study. This might be due to the difference of soil conditions.

Summary and Conclusions

This paper presents an LRFD calibration of the FHWA method for drilled shaft design based on the criterion mentioned in previous sections. A drilled shaft load test database of 26 drilled shafts with different sizes and lengths was collected and used to calibrate the total resistance factors. For each drilled shaft, the load-settlement behavior was estimated using the FHWA method via SHAFT program. Total resistance factors (ϕ) for use in the LRFD design methodology of drilled shafts in Louisiana were determined at different reliability indexes (β) and ready for implementation.

Statistical analyses comparing estimated and measured drilled shaft resistances were conducted to evaluate the accuracy of the FHWA design method in estimating measured drilled shaft resistance. Results of the analyses showed that the FHWA method underestimates drill shaft resistance by an average of 35%.

LRFD calibration based on the Monte Carlo simulation method was conducted to determine resistance factors (ϕ) at different reliability indexes (β) that are needed to implement the LRFD design in single drilled shaft design. Design input parameters for loads were adopted from the AASHTO LRFD design specifications for bridge substructure. Total resistance factor (ϕ) for mixed soils corresponding to a dead load to live load ratio (Q_D/Q_L) of 3.0 with a target reliability index (β_T) of 3.0 was determined as 0.40. This value is slightly different than the value obtained by Paikowsky, recommended by AASHTO, and Liang and Li [12] probably due to the difference in subsurface soil conditions. The presented resistance factor can be a valuable reference value for the LADOTD engineers to design drilled shafts in Louisiana using LRFD methodology.

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