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Calibration of Resistance Factors for Drilled Shafts for the New FHWA Design Method

INTRODUCTION

The load and resistance factor design (LRFD) has been increasingly used and has become mandatory for the design of 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 uncertainties 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 ASD factor of safety approach. 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. Although the American Association of State Highway and Transportation Officials (AASHTO) LRFD specifications were approved for use in 1994, the implementation of these specifications for bridge design has been slow. The resistance factors (ϕ) proposed in the specifications were derived from ASD safety factors to maintain a consistent level of reliability with past practices. 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 a good database. In the latest edition of the AASHTO specifications, a significant number of resistance factors in the foundation design were still selected based on the calibration. Several research efforts have been carried out to calibrate the resistance factors for drilled shafts from case histories available nationally. Currently, AASHTO specifications recommend using total resistance factors (ϕ) for single drilled shafts in an axial compression range from 0.40 to 0.60 at a reliability index (β) of 3.0, depending on different soil conditions. These factors were calibrated based on drilled shaft databases that were collected from various sites that do not necessarily reflect the local soil condition of individual states. As a result, the resistance factors recommended by the AASHTO LRFD design code should be verified and recalibrated to account for local soil conditions and design experience.

OBJECTIVE

The main objective of this study was to calibrate the total, side, and tip resistance factors (ϕ_{total}, ϕ_{side}, and ϕ_{tip}) of axially loaded drilled shafts installed in Louisiana soils at strength I limit state, using the 2010 FHWA design methodology based on the available drilled shaft load test database collected from Louisiana and Mississippi Departments of Transportation. For comparison purposes, the resistance factors for both the 1999 FHWA design method (O'Neill and Reese design method) and the 2010 FHWA design method (Brown et al. design method) will be developed at the target reliability β = 3.0. The findings of this research effort will aid the implementation of the LRFD design methodology for the design of drilled shafts.

SCOPE

To reach the objectives of this study, 26 drilled shaft tests collected from previous research (07-2GT) and 8 new drilled shaft tests were collected; among those cases, 30 drilled shafts were tested using O-cells and 4 drilled shafts were tested using the conventional top-down static load test. The load settlement curves of the drilled shaft from soil borings were predicted using both the 1999 FHWA design method (O'Neill and Reese method) and the 2010 FHWA design method (Brown et al. method). Statistical analyses were conducted on the collected data to evaluate both design methods for predicting the measured drilled shaft resistance. Following the AASHTO specification, a target reliability index of 3.0 was selected for calibration of the resistance factors. Based on the collected database, LRFD calibration of drilled shaft using Monte Carlo simulation method was performed to determine the resistance factors (tip, side, and total) for both design methods.

METHODOLOGY

In a previous research project (07-2GT), an extensive search was conducted to collect all available drilled shaft test data in Louisiana and Mississippi. A total of 26 drilled shaft cases, which meet the FHWA 5% B (B: diameter of the drilled shaft) settlement criterion, were collected at that time. Since the completion of that project, eight new drilled shaft test data became available and were added to the database in this study. The nominal resistance of drilled shafts was determined using the FHWA criterion at a settlement ratio of 5% the shaft diameter or at plunging failure, whichever came first. A statistical reliability analysis was then conducted on the combined 34 drilled shaft cases to evaluate both 1999 and 2010 FHWA design methods for predicting the measured drilled shaft resistance and to calibrate the resistance factors for both 1999 and 2010 FHWA design methods.

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The diameter of the collected drilled shaft cases ranged from 2 ft. to 6 ft. and the length ranged from 35 ft. to 138 ft. The soils encountered in the investigated databases included silty clay, clay, sand, clayey sand, and gravel. Most of the soil strata were not uniform and contained interlayers. Fifteen cases collected from Mississippi and fifteen cases collected from Louisiana were O-cell tests; in addition, four cases in Louisiana were conventional top-down load tests. 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 bearing capacities can be measured from the O-cell test. For the 30 drilled shafts that were tested using O-cells, the nominal tip and side resistances were deduced separately from the test results. An equivalent top-down curve was also constructed from the two component curves to estimate the total nominal drilled shaft resistance (R_m) using both 1999 and 2010 FHWA design method.

The mean, standard deviation, and coefficient of variation of the resistance bias factors (λ), which is the measured to predicted drilled shaft capacity ratio (R_m/R_p), for tip, side, and total resistances were calculated using both 1999 and 2010 FHWA design methods. The corresponding histogram and normal and lognormal distributions of (R_m/R_p) were plotted. Figure 1 presents the histogram and probability density function (PDF) of λ for the total shaft resistance using 2010 FHWA design method.

Reliability analyses were conducted on the collected drilled shaft database using the Monte Carlo simulation to calibrate the resistance factors (ϕ) needed for the LRFD design of drilled shafts based on both the 1999 and 2010 FHWA design methods. The resistance factors corresponding to total, tip, and side resistances were determined at various reliability indices (β) for dead load to live load ratio QD/QL = 3. Figure 2 presents the total resistance factors determined for 2010 FHWA design method at different reliability indexes (β).

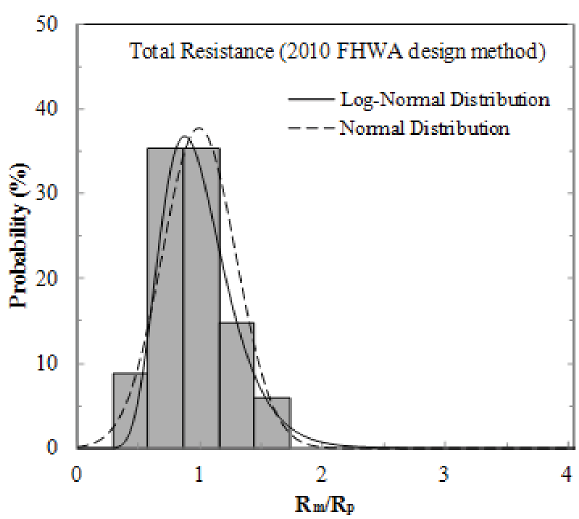

Figure 1
Histogram and probability density function of resistance bias for 2010 FHWA design method

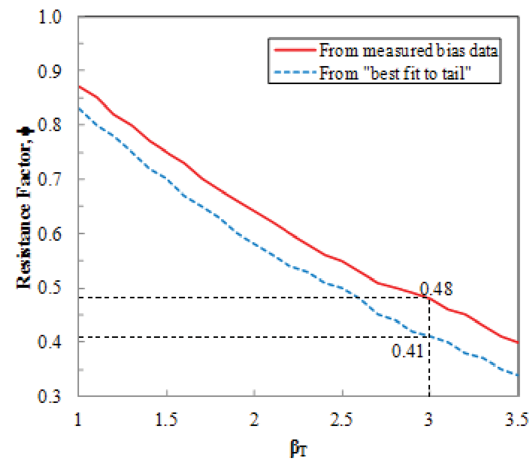

Figure 2
Resistance factors for different reliability indexes for 2010 FHWA design method

CONCLUSIONS

This study presented the LRFD calibration of both the 1999 FHWA (O'Neill and Reese) and 2010 FHWA (Brown et al.) design methods for drilled shafts based on the 5% B settlement criterion. Based on the results of this study, the following conclusions can be drawn:

- Statistical analyses comparing the predicted and measured drilled shaft resistances were conducted to evaluate the accuracy of both the 1999 and the 2010 FHWA design methods in estimating the measured drilled shaft capacity. Results of the analyses showed that the 2010 FHWA design method overestimates the total drilled shaft resistance by an average of 2 percent, while the 1999 FHWA design method underestimates the total drilled shaft resistance by an average of 21 percent. The prediction of tip resistance is much more conservative than that of side resistance.
- LRFD calibration based on the Monte Carlo simulation method was conducted to determine the resistance factors (ϕ) at different reliability indexes (β) that are needed to implement the LRFD design of axially loaded drilled shafts. Design input parameters for loads were adopted from the AASHTO LRFD design specifications for bridge substructures. The total resistance factor (ϕ_{total}) 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 found to be 0.60 for the 1999 FHWA design method and 0.48 for the 2010 FHWA design method. The total resistance factor determined from the 30 dataset (O-cell) only was found to be 0.61 for the 1999 FHWA design method and 0.50 for the 2010 FHWA design method. Based on the 30 O-cell drilled shaft tests, a tip resistance factor (ϕ_{tip}) of 0.52 and a side resistance factor (ϕ_{side}) of 0.39 were determined for the 1999 FHWA design method and 0.53 and 0.26 for the 2010 FHWA design method. It is interesting to notice that the side and total resistance factors calibrated using the 2010 FHWA design method are less than those calibrated using the 1999 FHWA design method. This may be due to more site variability in the 2010 FHWA design method than the 1999 FHWA design method. The presented resistance factors can be valuable reference values for the LADOTD engineers to design drilled shafts in Louisiana using the LRFD methodology.

RECOMMENDATIONS

It is recommend that LADOTD engineers begin implementing the resistance factors (ϕ) determined in this research study in design of drilled shafts for all future state projects; to select a few projects to demonstrate the comparison between the LRFD and the traditional ASD design methods for drilled shafts and conduct a cost benefit study; and to continue collecting drilled shaft test data from new projects, especially for cases in which the end bearing and side frictional capacities can be separated for possible future re-calibration of resistance factors.