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Calibration of Resistance Factors Needed in the LRFD Design of Drilled Shafts

INTRODUCTION

The load and resistance factor design (LRFD) has been used increasingly and has become mandatory for the design of all bridge projects funded by the Federal Highway Association (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. Even 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 with ASD. 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_t) 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.

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OBJECTIVE

The main objective of this study was to calibrate the resistance factors (ϕ_t, ϕ_{side}, and ϕ_{tip}) of axially loaded drilled shafts installed in Louisiana soils at strength I limit state based on the available drilled shaft load test databases collected from the Louisiana Department of Transportation and Development (LADOTD) and the Mississippi Department of Transportation (MDOT) as well as LADOTD's design experience. The findings of this research effort will help Louisiana geotechnical engineers implement the LRFD design methodology for the design of all drilled shafts in future Louisiana projects as mandated by AASHTO.

SCOPE

To reach the objectives of this study, 66 drilled shaft cases with different lengths and diameters that were tested using the Osterberg cell (O-cell) method or conventional top-down static load test were collected from LADOTD and MDOT. Out of those, 26 drilled shaft tests were finally selected based on specific screening criterion; among those cases, 22 drilled shafts were tested using O-cells and 4 drilled shafts were tested using the conventional top-down static load test. The SHAFT program was used to predict load settlement curves of drilled shafts from soil borings. Statistical analyses were conducted on the collected data to evaluate the O'Neill and Reese (FHWA) design method. A target reliability index of 3.0 was selected. Based on the collected database, the LRFD calibration of drilled shafts was performed to determine resistance factors (tip, side, and total) using the Monte Carlo simulation method.

METHODOLOGY

An extensive search was conducted on LADOTD's archives to collect drilled shaft tests conducted in Louisiana. Only 16 drilled shaft test cases were available in Louisiana, among which only 11 cases met the FHWA settlement criterion for nominal resistance. Due to the limited number of available cases in Louisiana, the geotechnical research team at LTRC decided to search for more drilled shaft cases in neighboring states, i.e., Mississippi and Texas. Researchers were able to collect an additional 15 drilled shaft test cases from MS that have subsurface soil conditions similar to Louisiana soils and also met the FHWA failure criterion. The nominal resistance of drilled shafts was determined using the FHWA criterion at a settlement ratio of 5 percent the shaft diameter or at plunging failure, whichever came first. A statistical reliability analysis was then conducted on the combined 26 drilled shaft cases to evaluate the FHWA design method for predicting the measured drilled shaft resistance and to calibrate the resistance factors for the FHWA design method.

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. All 15 drilled shaft cases from MS and 7 cases from LA were tested using the O-cell test method, while only 4 drilled shaft cases from LA were tested using the conventional top-down load test. 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 22 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 the FHWA design method.

The mean, standard deviation, and coefficient of variation of the resistance bias factors (λ), which is measured to predicted drilled shaft capacity ratio (R_m/R_p), for tip, side, and total resistances were calculated using the FHWA design method. The corresponding histogram and normal and log-normal 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.

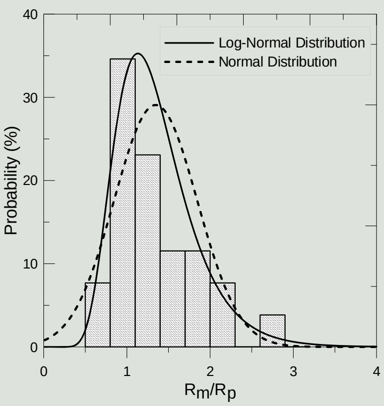

Figure 1: Histogram and PDF of total resistance bias

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 the FHWA design method. The resistance factors corresponding to total (ϕ_{total}), tip (ϕ_{tip}), and side (ϕ_{side}) resistances were determined at various reliability indices (β) for dead load to live load ratio $Q_D/Q_L = 3$. Figure 2 presents the total resistance factors determined for FHWA design method at different reliability indexes (β).

CONCLUSIONS

This study presented the LRFD calibration of the FHWA (O'Neill and Reese) method for drilled shaft design based on the 5% B criterion. Based on the results of this study, the following conclusions can be drawn:

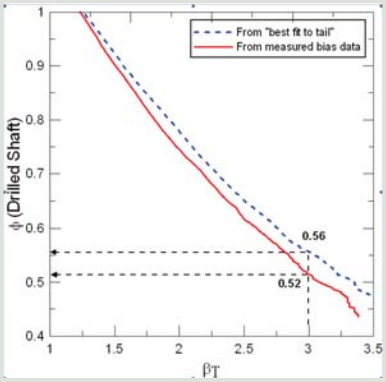

Figure 2: Resistance factors for different reliability indexes (static method)

- Statistical analyses showed that statistical analyses comparing the predicted and measured drilled shaft resistances were conducted to evaluate the accuracy of the FHWA design method in estimating the measured drilled shaft capacity. Results of the analyses showed that the FHWA 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. A large scatter in the prediction of side resistance was observed.
- Reliability analyses based on the Monte Carlo simulation method was conducted to determine the resistance factors (ϕ) for the FHWA (O'Neill and Reese) drilled shaft design method. The total resistance factor (ϕ_t) 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 0.50. This value is within the range of ϕ_{total} values (0.40 to 0.60) recommended by AASHTO. Tip resistance factor (ϕ_{tip}) of 0.75 and a side resistance factor (ϕ_{side}) of 0.20 were also determined.

RECOMMENDATIONS

Researchers recommend that LADOTD engineers need to begin implementing the resistance factors (ϕ) recommended for the FHWA (O'Neill and Reese) design method for all future state projects; to select a few projects to demonstrate the comparison between the LRFD and the traditional ASD design method 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.