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Calibration of Resistance Factors Needed in the LRFD Design of Driven Piles

Introduction

The allowable stress design (ASD) method had been used for many years in the design of bridges, which involves applying a factor of safety (FS) to account for uncertainties in applied loads and soil resistance. The magnitude of FS depends on the importance of the structure, the confidence level of material properties, and design methodology. However, the selection of FS is empirical and does not distinguish between variations in various components of loads and resistances, even though there are significant differences in the risk among each load and resistance components. Bridge design specifications published by the American Association of State Highway and Transportation Officials (AASHTO) has introduced the load and resistance factor design method to separately address uncertainties associated with estimated loads and resistances in bridge design. Since then bridge superstructures have been designed using the load and resistance factor design (LRFD) method, while the ASD method is still used for the bridge foundation design due to difficulties in implementing the LRFD method to foundation designs. This practice can lead to inconsistent levels of reliability between super- and sub-structures. In an effort to maintain a constant level of reliability, the Federal Highway Administration and AASHTO set a transition date of October 1, 2007 after which all federally funded new bridges including substructures shall be designed using the LRFD method. The current AASHTO design specification recommends resistance factors for single driven piles in axial compression ranging from 0.10 to 0.65, depending on the design method. However, the existing resistance factors are recommended based on a pile load test a soil database that was collected from sites that do not necessarily reflect Louisiana soils or design practice. Therefore, resistance factors recommended by the AASHTO code need to be verified before being applied to local soil condition and design practice. Direct application of the AASHTO resistance factors without calibration may result in overconservative or unsafe design. When local experience and databases are available, AASHTO recommends calibrating the resistance factor using reliability analyses to produce an overall reliability level that is consistent with local practice.

Objective

The main objective of this research project is to calibrate the resistance factors for different pile design methods needed in LRFD design of driven piles based on the Louisiana pile load test (soil database) and the Louisiana Department of Transportation and Development (LADOTD) experience. The findings of this research effort will help Louisiana geotechnical engineers begin implementing the LRFD design methodology for the design of all driven piles in future Louisiana projects as mandated by AASHTO.

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Scope

To achieve the objectives of this study, reliability based analyses were performed on different design methods used by LADOTD for the estimation of axial load resistance of driven piles in soft Louisiana soils. Fifty-three precast-prestressed-concrete (PPC) piles that were loaded to failure were investigated in this study. Statistical analyses were conducted to evaluate different pile design methods including the static design method (α -method and Nordlund method), three different direct cone penetration test (CPT) design methods [Schmertmann method, De Ruiter and Beringen method, and Bustamante and Gianeselli (LCPC) method], and the Case Pile Wave Analysis Program (CAPWAP) method. The target reliability (β_T) of 2.33 was selected. In addition, reliability analyses based on First Order Second Moment (FOSM) method, First Order Reliability Method (FORM) and Monte Carlo (MC) simulation method were conducted to calibrate resistance factors (ϕ) for different pile design methods.

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Methodology

The pile load test database used for the calibration of different pile design methods was established by conducting an extensive search in LADOTD's project files. Only PPC piles that have been tested to failure and that include adequate soil information were included in this study. A total of 53 pile load tests met this criterion. The data on the selected pile load test reports were compiled. The information and data regarding the project, soil stratification and properties, pile characteristics, load test data, CPT profiles, dynamic test data, etc. were processed and transferred from each load test report to tables, forms, and graphs.

The measured ultimate pile resistance (R_m) of all investigated piles was interpreted from the load-deformation curve using the Davisson method for piles with a size less than 24 inches and the modified Davisson method proposed by Kyfor et al. for piles exceeding a size of 24 inches. The estimated pile capacities (R_P) were determined using the static method based upon the soil conditions where soil borings are available. Whenever CPT soundings are available, the pile capacities were also calculated using three CPT design methods: Schmertmann (1978), the Laboratoire Central des Ponts et Chaussees (LCPC) (Bustamante and Gianeselli, 1982), and De Ruiter and Beringen, (1979), as well as the average of the three CPT methods. Dynamically determined pile capacities using CAPWAP [end of driving (EOD) and beginning of restrike (BOR)] were also estimated. The mean, standard deviation, and coefficient of variation of the resistance bias factor (λ), which is measured to the predicted pile capacity ratio (R_m/R_P), was calculated for different design methods. The histogram and normal and log-normal distribution of (R_m/R_P) of the static method, three CPT methods, the average of three CPT methods, and the dynamic measurement with signal matching analysis (CAPWAP) were plotted. Figure 1 presents the histogram and probability density function (PDF) of λ□ for the static method.

Reliability analyses were conducted and resistance factors (ϕ) for all pile design methods were calibrated at a dead load to live load ratio, $Q_D/Q_L = 3$. The resistance factors for various reliability indices (β) were determined for different pile design methods. Resistance factors obtained by the advanced methods (FORM and MC simulation methods) were relatively close and generally higher than resistance factors obtained from FOSM. Figure 2 presents resistance factors determined static method at different reliability indexes (β).

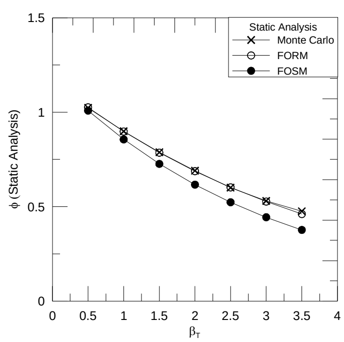

Figure 1
Histogram and PDF of resistance bias factors (static method)

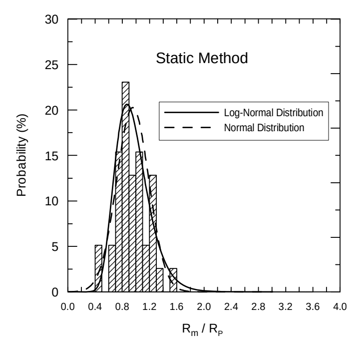

Figure 2
Resistance factors for different reliability indexes (static method)

Conclusions

This study presents a reliability-based evaluation of different design methods for predicting the ultimate axial resistance of piles driven into Louisiana soils. Based on the results of this study, statistical analyses showed that the static method over-predicted the pile resistance by 12 percent. Among the three direct CPT design methods, the De Ruiter-Beringen method was the most consistent method with the lowest coefficient of variation (COV). Dynamic analysis methods (CAPWAP-EOD and 14 days BOR) showed under-predication of pile resistance with a setup factor of 2.9. In addition, reliability analyses based on FOSM, FORM, and the Monte Carlo simulation were conducted to calibrate resistance factors (ϕ) for different Louisiana pile design methods. The results of reliability analyses at a target reliability, $\beta_T = 2.33$, showed that the De Ruiter-Beringen method has the highest resistance factor [$\phi_{De\text{-}Ruiter} = 0.66$ (FOSM), 0.74 (FORM), and 0.73 (MC simulation)], while the Schmertmann method showed the lowest resistance factor [$\phi_{Schm} = 0.44$ (FOSM), 0.48 (FORM), and 0.49 (MC simulation)], which is lower than the AASHTO recommended value of 0.5.

Recommendations

It is highly recommended that LADOTD engineers begin implementing resistance factors (ϕ) for the different pile design methods for all future state projects; select a few projects to demonstrate the cost benefit study and comparison between the LRFD and traditional ASD designs, and continue collecting pile load 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.