Performance Based Design of Laterally Loaded Drilled Shafts

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**Project Background**

Reliability-based design of deep foundations, such as drilled shafts and driven piles, has become increasingly important due to the heightened awareness of the shortcomings of the conventional allowable stress design approach. The load and resistance factor design (LRFD) has been implemented by the American Association of State Highway Transportation Officials since 2007. Nevertheless, there are still many unsolved issues regarding the implementation of load and resistance factor design. For example, there is no generally accepted guidance on the statistical characterization of soil properties. Moreover, the serviceability limit check in LRFD is still deterministic. No uncertainties arising in soil properties, loads, and design criteria are taken into account in the current version of LRFD for the serviceability limit check. In current practice, the load factors and resistances are taken as unity, and deterministic models are applied to evaluate the displacements of geotechnical structures.

As a cost-effective solution for resisting large lateral loads, drilled shafts are widely used by the Ohio Department of Transportation to stabilize slopes in highway projects. In the analysis of drilled shafts subjected to axial and lateral loading, load transfer concepts have been widely applied. The t-z model is used to calculate the vertical movement of the pile at a given axial load. For axial loading, the axial soil-structure interaction is modeled as t-z curves and q-w curves, where t and q represent side shear on the shaft and the tip resistance at the toe, respectively; z and
w represent the vertical displacements of the shaft segment and the toe of the drilled shaft, respectively. The p-y method is used to calculate the lateral deflection of a laterally loaded pile. For lateral loading, the lateral soil-structure interaction is modeled as p-y curves, where p represents the soil reaction and y represents the lateral deflection. The capacity or the displacement calculated based on the load transfer methods has some variations as a result of various uncertainties. The main sources of uncertainties include the following:

- Soil properties;
- Concrete properties;
- Steel properties;
- External loads including axial and lateral loads; and
- Modeling of soil reactions to external loads.

In the load transfer methods, the soil properties are needed as input to construct the p-y curves, t-z curves and q-w curves. The strength and the stiffness of soil would directly influence the soil reactions that are represented by the load transfer curves. In addition, the properties of concrete and steel can influence the mechanical stiffness of the foundation system, thus affecting the capacity or the displacement of the system. The displacement of the foundation system is a response to the external loads. Hence, the variations in the external loads would cause some variations in the displacement. Finally, the soil reactions are represented by load transfer curves, which is a major assumption in the load transfer methodology. Thus, the accuracy of the load transfer curves would significantly affect the accuracy of the calculated capacity or displacement.

**Study Objectives**

The purpose of the research is to improve the reliability analysis of deep foundation design, so that the underlying risks in deep foundation design are properly accounted for. The objectives of this research include the following:

- To develop a fundamentally sound methodology of conducting reliability analysis for deep foundation design;
- To develop the associated computer programs of utilizing the methodology; and
- To develop the computational method for determining the soil variability model.

Because the calibration of the load and resistance factors in the LRFD framework invokes a number of assumptions or simplifications, the LRFD factors would inevitably have some limitations. Furthermore, the strategy of implementing the load and resistance factor independently of the stratum scenarios is problematic, as it is unable to achieve a uniform level of reliability for a diverse range of soil strata. Note that the re-calibrated LRFD factors would probably be unable to achieve a consistent level of safety, simply because the soil strata can vary significantly from one location to another. The limited amount of stratum cases in the calibration process cannot cover all possible scenarios. Therefore, re-calibration of the LRFD factors within the LRFD framework would be a meaningless exercise.
Description of Work

The purpose of this research is not to re-calibrate new load and resistance factors. Instead, the purpose is to develop a novel reliability-based design methodology. In order to accomplish the objectives, the scope of the research is defined as follows:

1. Conduct a literature review on the numerical methods for analyzing drilled shafts under axial and lateral loads, with a focus on state-of-the-art reliability methods;
2. Formulate Monte Carlo simulation–based methodology for reliability analysis that is applicable to both axially loaded and laterally loaded piles;
3. Develop a statistical method to characterize the variability of the uncertain parameters, particularly for soil properties; and
4. Conduct a comparative study on the developed methodology and the LRFD approach using real data.

First of all, a literature review is conducted to identify the state-of-the-art methodologies pertaining to performance-based design of deep foundations. The numerical algorithms for analyzing piles under lateral loads and axial loads are reviewed. In particular, the uncertainties of the numerical algorithms are identified. Since the main objective of this research is to develop a mathematically sound methodology for conducting reliability analysis, the advantages and the disadvantages of the first order reliability method (FORM) and Monte Carlo simulation (MCS) are discussed.

In order to consider the spatial variability of soil properties, random field modeling is introduced in which a mean, a variance and a correlation function are needed. To account for the influence of soil spatial variability, Monte Carlo simulation is applied. Following the Monte Carlo simulation–based methodology, a series of computer codes are developed. With a large number of realizations of the displacements, statistical analysis can be conducted. Accordingly, feasible designs that achieve the target reliability index can be identified.

In an attempt to determine the soil variability model that can be used as input to the computer codes, a Bayesian approach is developed to model the spatial variability of the data from a standard penetration test. The objective of the approach is to have an estimate of the mean, the standard deviation, and the correlation length of a soil property, which are the parameters of interest in the Bayesian approach. The developed approach is applied to the data of a real-world project. Once the soil variability model is determined, the developed computer codes are used to conduct reliability analysis, and a feasible design is obtained. A comparative study between the feasible design and the design by the LRFD approach is conducted.

Research Findings and Conclusions

The conclusions from this study can be summarized as follows:

- Reliability Analysis of Piles under Axial And Lateral Loads
1. The spatial variability of soil properties, particularly the coefficient of variation and the correlation length of undrained shear strength for cohesive soils, could exert significant influences on the computed probability of failure for the specified performance criteria. The difference in the computed probability of failure caused by different correlation length of soil strength parameters such as undrained shear strength could be several orders of magnitude.

2. The proposed performance-based design approach provides a systematic procedure to consider various sources of uncertainties arising in the soil properties, the concrete properties, the steel properties, the computational model, and the applied loads.

3. Probabilistic approaches that do not take into consideration of the spatial variance of soil properties may potentially result in a foundation design that would not meet the performance criteria with the target reliability. It is demonstrated that the probability of failure is sensitive to correlation length, $\theta$. If $\theta$ is not considered in reliability assessment, the estimated probability of failure ($P_f$) would probably be biased. Therefore, considering correlation length is warranted in the reliability analysis of deep foundations. There is a strong incentive to use a reliability method that considers the correlation structure of soil properties for deep foundations.

The Importance Sampling Technique

1. The proposed importance sampling method gives the same unbiased estimate of the failure probability as the crude MCS method. Nevertheless, the proposed importance sampling method is much more efficient than the crude MCS method when evaluating a small $P_f$ (e.g., $P_f \leq 1/1000$). By drawing more samples from the region of interest, the proposed method will achieve a faster rate of convergence. With the same sample size, the estimate obtained by using the importance sampling method would have a much smaller coefficient of variation than the estimate obtained by the crude MCS method. It is recommended to use the importance sampling method in the evaluation of small $P_f$.

2. The probability of failure evaluated by the commonly used first order reliability method (FORM) may significantly deviate from those of Monte Carlo statistical methods, although the reliability index by FORM is close to those of Monte Carlo statistical methods. The differences in the failure probabilities between FORM and Monte Carlo statistical methods are primarily attributed to the approximation of the limit state function in the response surface method and the linear truncation of the limit state function in the FORM.

The Analysis Of The System Reliability

1. The failure probability of the system, $P_f$, is greater than any of the three component failure modes. Besides, $P_f$ is less than the summation of the failure probabilities of the three component failure modes. The failure probability of the system may be underestimated if multiple failure modes are not considered simultaneously.

2. It is recommended to use the system reliability if multiple failure modes exist. In the
current LRFD approach, different limit states are considered separately, which leads to overestimation in the reliability.

**Recommendations for Implementation of Research Findings**

The following recommendations are made for possible implementations:

1. The developed computer codes could be employed to conduct reliability analysis for piles under axial and lateral loads;
2. System reliability of a design should be considered, so that the final design can meet the reliability requirements;
3. The computational methods for site variability characterization can be applied to model the spatial variability of data of standard penetration test.