

# JOINT TRANSPORTATION RESEARCH PROGRAM

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## Development of Load and Resistance Factor Design for Ultimate and Serviceability Limit States of Transportation Structure Foundations

### Introduction

Pile foundations are used in most foundation solutions for transportation structures. Design of pile foundation solutions can best be pursued by clearly defining limit states and then configuring the piles in such a way as to prevent the attainment of these limit states. There are three approaches to do this; in order of complexity, they are: working stress design (WSD), load and resistance factor design (LRFD), and reliability-based design (RBD). All three approaches account in some way for the fact that foundation engineering problems are not deterministic, and most, if not all, variables in the problem are random or have a random component. In this report, we develop LRFD methodology for ultimate limit states related to the application of axial load on single piles. Both displacement and nondisplacement piles are considered; likewise, sands and clays are the two soil types we have considered.

We have developed our LRFD design methods using reliability analysis and the specific technique of Monte Carlo simulations. The principles that we have adhered to in doing so are:

1. Recognize that resistance factors are inseparable from the design method for which they are developed and that "one size fits all" does not work with LRFD.
2. Perform careful, detailed, specific evaluation of the uncertainties in variables and relationships entering the design calculations. With respect to these evaluations, "one size fits all" does not work either. Attempts to find universal coefficients of variation for a given soil property, regardless of the method used to estimate it, for example, negates the benefits of LRFD.
3. Use to the maximum extent possible theories that are both realistic and rigorous, for it will be easier and more logical to account for variability of the theoretical method and its variables if this requirement is met.
4. Probabilities of failure must balance the need for safety with the impracticality or cost of attempting to

reduce them too far.

We have taken load factors as given by AASHTO. This means that resistance factors calculated in the course of the reliability analyses are then adjusted to match the specified load factors. The methods of design we have determined resistance factors for have been developed and refined both in the course of the current research and in previous research at Purdue University.

### Findings

The approach we have followed to develop ultimate limit state design check methods has proven to be effective. Resistances calculated using design equations compare well with experiments performed under controlled conditions and better-quality field experiments. Calculations of equivalent factors of safety also show that the resistance factors arrived at appear reasonable for the probabilities of failure assumed in calculations. For example, for foundations based on one drilled shaft supporting one column, where redundancies resulting for use of pile groups are not a factor, a probability of failure between one pile in one thousand and one pile in ten thousand should be targeted. Equivalent factors of safety resulting from this level of risk appear reasonable in light of the experience accumulated over the years with WSD and the use of rigorous methods for all but one case in this report: that of piles driven in sand, where reliance on empirical considerations is still necessary.

The final result of the research done and reported here is a set of design equation or inequalities with accompanying resistance factors for use with AASHTO load factors for single nondisplacement (bored) or displacement (driven) piles installed in sand or clay.

## **Implementation Recommendations**

Implementation of this research requires that the design methods be used in projects in which enough testing during and after pile installation is done so that any required adjustments or questions may be addressed in further research. This testing must include not only dynamic but also static pile load tests. Every effort to use instrumented piles in the static tests should be made. High-quality characterization of the soil before pile design and installation should also be done.

## **References**

Salgado, R., S. I. Woo, and D. Kim. Development of Load and Resistance Factor Design for Ultimate and Serviceability Limit States of Transportation Structure Foundations. Publication FHWA/IN/JTRP-2011/03. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2011. doi: 10.5703/1288284314618

