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Load and Resistance Factor Design of Bridge Foundations Accounting for Pile Group–Soil Interaction

Introduction

Pile group foundations are used in most foundation solutions for transportation structures. Traditionally, design of pile group foundations has been performed in the United States using working stress design (WSD), which uses a single value factor for safety to account for the uncertainties in pile design. A method that would enable designs to reflect uncertainties in a more precise manner and be associated with a target probability of failure would be advantageous with respect to WSD. Recognizing this, the Federal Highway Administration (FHWA) mandated that load and resistance factor design (LRFD) be used for designing the foundations of all bridge structures initiated after September 2007. In LRFD, load variability is reflected in load factors applied by multiplication to the loads the foundations must carry, and resistance variability is reflected in resistance factors applied by multiplication to the foundation resistances. If load and resistance factors are determined using reliability analysis, it is possible to link them to a probability of failure. In order to develop a comprehensive and reliable LRFD pile design framework, it is necessary to have clear, detailed, and accurate understandings of the mechanism of resistance development in pile groups. This report contains a number of analyses that provide insights into pile group response that were not previously available. It then uses these analyses to develop a first iteration of an LRFD design framework for pile groups.

Findings

To evaluate the axial load response of single piles and pile groups, finite element (FE) simulations are performed with advanced, two-surface plasticity constitutive

models for soils. The finite element simulations are realistic not only because of the use of realistic soil models, but also because they enable behavior that would be observed in reality. For example, mesh configurations are such that the FE analyses can capture the highly localized deformation (formation of shear bands) along the pile shafts and near the pile bases.

Analyses for single piles successfully capture the development (initial build up, softening, and achievement of critical/residual states) of shear stresses in the soil. The analyses shed light on the relationships between the global response of the pile-soil system (development of shaft and base resistances) and the behavior of local soil elements and shear band formation. The analyses provide insight into the effect of embedment depth into stiff bearing layers on axially loaded nondisplacement piles in sand and clay. The obtained resistances show good agreement with Purdue design equations for nondisplacement piles installed in sand and clay.

Based on the simulation results for pile groups, we found that group effects are almost negligible for small pile groups (1×2, 1×3, and 2×2 pile groups) due to intense localization of deformation along the pile shafts. In contrast, individual piles at different locations (center, corner, or side) in a large pile group (e.g., 4×4) respond differently to the axial load applied on top of the pile group. Mechanisms of pile-soil-pile interactions in pile groups are revealed by correlating the change of local state variables (e.g., stresses, void ratio, and pore pressure) to the resistance mobilization in individual piles. Due to these group interactions, pile efficiencies (defined as the ratio between the resistance developed by an individual pile in a group to the resistance that it would develop as a single pile)

are different for different individual piles in a pile group. Since the mechanisms of the resistance mobilization, as well as the group interactions, are different along the pile shafts and near the pile bases, the pile efficiencies for shaft and base resistances are considered separately. It is found that pile efficiencies depend on the soil profile, pile spacing, pile group configuration, pile head settlement, position of pile in the group (center, corner, or side), pile diameter, and embedment length. Additional analyses are required to reliably assess the impact of these factors on the pile efficiencies for large pile groups (larger than 4×4).

As part of a validation effort for design equations presented in the report, a closed-ended pipe pile was carefully instrumented with two types (electrical-resistance and vibrating-wire) of strain gauges, driven in a sandy soil profile and load tested (both static and dynamic) in Marshall County, Indiana. The test results were interpreted in terms of load-settlement response, residual loads, development of shaft and base resistance, and set-up effects. The measured pile bearing capacities, along with the test results of two other case histories, were used to validate the new Purdue pile design method, which was improved in this report to take shaft degradation effects into account for displacement piles in sand. Very good agreement was found between the measured and estimated resistances.

Rigorous reliability analyses were performed using Monte Carlo simulations based on the new Purdue pile design equations to produce different resistance factors for shaft and base resistances, respectively. We considered single piles, both nondisplacement and displacement piles, in sand and clay with practical ranges of soil properties, soil profiles, pile dimensions, various ratios between live loads and dead loads, and different

target probability of failures. The optimal resistance factors determined using the reliability analyses were then adjusted to values that could be used with the load factors suggested by AASHTO. Calculated equivalent factors of safety also provided a general sense of how the same design methods would be used in WSD. We recommend that the resistance factors for single piles be used for small pile groups due to the negligible group effect in small pile groups. For large pile groups, further research is required to quantify uncertainties and variabilities related to the group effects and soil profiles.

Implementation

Single pile and pile group design examples show that the proposed pile design methods are straightforward and easy to implement in simple spreadsheet programs. While much work remains to be done in this topic, the report advances considerably the understanding of both single and pile group load response and how they should be designed for transportation infrastructures. Further studies are required to understand and quantify the effects of pile driving on the soil surrounding the piles as a function of pile diameter and pile length and how changes in soil density and state due to pile installation affect the pile group interaction factors.

Recommended Citation for Report

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