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Pile Stability Analysis in Soft or Loose Soils: Guidance on Foundation Design Assumptions with Respect to Loose or Soft Soil Effects on Pile Lateral Capacity and Stability

Introduction

The lateral capacity of pile foundations supporting bridge piers depends on the pile group configuration. Single pile rows and piles crossing soft clay, organic soil, or very loose sand are particularly vulnerable to failures. Piles may reach a limit state due to excessive lateral deflection under design loads, and they can be susceptible to buckling instability when subjected to both vertical and lateral bridge loads with very little lateral support provided by the weak, compliant soil in the vicinity of the pile cap.

The design of laterally loaded piles has traditionally been done using the *p-y* method. Since commonly used p-y curves have been derived empirically using data obtained either from a limited number of lateral pile load tests or from in situ test data, the p-y method's accuracy in predicting the response of pile groups is limited.

The interactions between piles in a group can be quantified by using either the concept of the p-multiplier or the concept of pile efficiency. The research on p-multipliers has not accounted for the effects of load eccentricity, deflection level, soil profile, and pile group configuration. In addition, research considering the use of the pile efficiency concept for laterally loaded pile groups is limited.

The critical bucking load of a partially embedded pile can be calculated using the Euler column formula by converting the pile into an equivalent fixed-end Bernoulli beam. The length of the equivalent Bernoulli beam is determined by summing up the free length of the pile above the ground and the depth to fixity. AASHTO only provides equations for the calculation of the depth to fixity for sand and clay, which were derived with certain simplifying assumptions. AASHTO also uses the term depth to fixity to refer to the distance from the pile head to a zero-deflection point for a laterally loaded pile. These two different definitions for the depth to fixity concept are a source of confusion when performing buckling stability analysis for laterally loaded piles.

In this study, we performed a series of three-dimensional (3D) finite element (FE) analyses for single piles and piles groups, with pile diameters ranging from 0.36 m (14.17 inches) to 1.0 m (39.37 inches), pile lengths ranging from 10 m (32.81 ft) to 20 m (65.62 ft), uniform and multilayered soil profiles, lateral load eccentricity ranging from 0 m to 10 m (32.81 ft), combined axial and lateral loads, three different pile group configurations (1×5, 2×5, and 3×5), pile spacings ranging from 3 to 5 times the pile diameter, two different load directions (strong direction and weak direction), and two different pile cap types (free-standing and soil-supported pile caps). From the simulation results, we proposed new sets of *p-y* curves for sand and NC clay, respectively, and new sets of p-multipliers and equations for the pile efficiency. Moreover, we proposed general design guidelines for laterally loaded pile groups in soft soils by identifying critical conditions to avoid and by clarifying the definitions of depth to fixity.

Findings

Based on the results of the FE analyses performed for laterally loaded single piles, we evaluated the effects of several design factors on the lateral responses of the piles and the *p-y* curves. We proposed new p-y curves for sand and clay that are a function of intrinsic soil variables and state variables to realistically reflect the 3D soil-pile interaction process. Based on the results of the FE analyses performed for laterally loaded pile groups, the effects of several design factors on the lateral responses of the piles in pile groups were evaluated. We proposed new values of p-multipliers that consider the different positions of the individual piles within the group in loose and dense sand and under different load eccentricities with free-standing and soil-supported pile caps. We also developed equations for pile efficiency that consider load eccentricity, position of the individual piles in the group, and pile spacing.

One of our main findings is that the lateral load eccentricity (which can be represented by an equivalent moment acting on the head of the piles) has significant impact on the lateral capacities of single piles and pile groups. The moment applied on the pile group is not fully absorbed by axial loads on the individual piles in the group. Part of the moment applied to the cap of a pile group is transferred to the individual piles as moments in the group, further weakening their response to lateral loading.

By using the proposed *p-y* curves, p-multipliers, and pile efficiencies, we proposed two design approaches for lateral capacity estimation of pile groups: *p-y* analysis using p-multipliers and *p-y* analysis using pile efficiencies. When piles and the superstructure are analyzed as a whole, simultaneously the p-multiplier method can be used to estimate the lateral capacity of the piles. Otherwise, the estimation can be unconservative due to lack of information about loads and moments distribution within pile group. Unlike the p-multiplier method, the pile efficiency method does not require information on the loads and moments at the heads of the individual piles in the pile group because it already implicitly considers it.

From the design examples following our proposed design approaches, we found that single-row pile groups under certain condition could be too vulnerable to carry the service load.

We reviewed and clarified the two definitions of depth to fixity and showed that the estimated values of depths to fixity are different depending on the definition selected. We also calculated the depth to fixity and the buckling load resulting from the results of the *p-y* analysis with the proposed *p-y* curves and found that the critical buckling load calculated from the *p-y* method was generally less than that calculated using the AASHTO method. However, the calculated buckling load was generally considerably greater (3 to 135 times greater) than the axial service load expected to be added to the pile head, regardless of the methods used, indicating that buckling is unlikely to be a critical limit state.

Implementation

Based on our findings, we propose implementation of the following items for laterally loaded piles in weak soils.

1. Single-row pile group loaded laterally in weak soil profiles (with a top layer thickness greater than 5 times the pile diameter and a representative SPT blow count less than 7) should be avoided if loaded in the weak direction.
2. With the new *p-y* curves developed in this project, *p-y* analysis can be performed by using any commercially available software (e.g., PYGMY or LPile) to obtain accurate estimates of the load-deflection responses of single piles.
3. Two methods for pile group lateral capacity estimation are proposed: (1) *p-y* analysis with p-multipliers and (2) *p-y* analysis with pile efficiencies. The method using p-multipliers can be used with the *p-y* curves and the p-multipliers proposed in this study when the moments and loads distributions within the pile group are known. However, in most cases, when these distributions are unknown, the second method, which uses pile efficiencies, can be used with the proposed *p-y* curves and the proposed pile efficiency equations.
4. There are two different definitions of depth to fixity. One is the difference in length between the free length of the pile above ground and the length of a fixed-ended beam required to have the same deflection at its top as that at the top of the pile. Another one is the depth to the final zero-deflection point. To prevent confusion, it is desirable that design flow processes at INDOT clarify which of the two definitions should be used. The calculated depth to fixity and the critical buckling load can vary significantly. However, the buckling loads calculated following either AASHTO (2020) or the procedures proposed in this report are much greater than the axial service loads on the piles. This means that buckling is unlikely to be a critical limit state in most cases.

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