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Research Paper

Estimation of load-sharing ratios for piled rafts in sands that includes interaction effects

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ABSTRACT

A key design component for piled rafts is the proportion of load carried by the raft and piles, as both contribute to the load-carrying behavior of piled rafts. The analysis in the present study of the load-sharing behavior of piled rafts embedded in sands includes consideration of the pile–raft interaction effect. For this purpose, 3D finite element analyses were performed for various foundation and soil conditions. Due to the interactions between raft and piles, the load-carrying capacities of the raft and piles, once combined into a piled raft, become different from those of unpiled rafts and group piles. As pile spacing increased, the load proportion of piles became higher. Based on the results from finite element analyses, a normalized load-sharing model was proposed that introduced the load capacity interaction factor β. Values of β were evaluated, and a design equation was proposed. The values of β decreased logarithmically with increasing settlement, showing a marked decrease within the initial settlement range. Case examples were introduced to confirm the validity of the proposed method. Reasonably close agreement was observed between measured and calculated load-sharing behaviors.

1. Introduction

A piled raft is a combined foundation type that was developed to utilize the load-carrying capabilities of both rafts and piles. Due to its combined nature and interactions between the raft and piles, the estimation of load capacity for piled rafts is not straightforward and requires the consideration of various design parameters, including foundation configuration, soil condition and interaction effects. As rafts and piles both contribute to the load-carrying behavior of piled rafts, a key design component is the proportion of the load carried by each part [3,16]. The load proportion is often expressed as the load-sharing ratio, defined as the load carried by piles divided by the total load imposed on the piled raft.

The load–settlement curves of the raft and piles are both nonlinear and given in different settlement scales due to different foundation sizes. The load capacity of piles with smaller diameters is mobilized earlier at smaller settlements than in larger rafts, implying that the load-sharing ratio changes with settlement. The proportion of load carried by piles decreases with increasing settlement as the load-carrying capacity of raft is mobilized progressively and reaches the ultimate state at much larger settlement levels. Most previous investigations have specified the load-sharing ratio as a function of foundation geometry, stiffness and soil compressibility [7,9,16]. A load-sharing model was proposed to consider the settlement-dependent variation [10] but was limited to cases in clays where the effect of interactions between the raft and piles is not significant.

The interactions of piled rafts occur due to the overlapped stress and displacement fields of the raft and piles upon loading. In clays, the interaction effect is relatively small [8,16]. For sandy soils, the effect of pile–raft interactions is significant, markedly affecting the overall load-carrying behavior of piled rafts [5,11,13]. Due to the effect of the pile–raft interactions, the load-carrying capacities of rafts and piles, once combined into a piled raft, become different from those of unpiled rafts and group piles; these capacities are difficult to quantify. As the load-sharing behavior of piled rafts is directly related to the load-carrying capacities mobilized by the raft and piles, the interaction effect should be an important design consideration and must be properly considered for the estimation of the load-carrying capacity of piled rafts.

In the present study, a load-sharing model is proposed for piled rafts embedded in sands by considering settlement-dependent variation and interaction effects. For this purpose, 3D finite element analyses were performed for various foundation and soil

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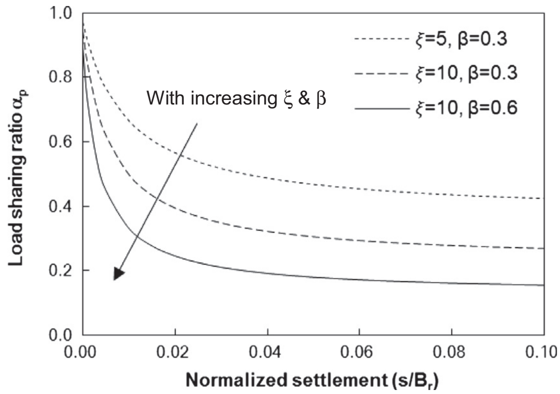

Fig. 1. Normalized load-sharing curves with different values of ξ and β.

conditions. Based on the results from these analyses, the load-carrying behavior of piled rafts under various conditions is analyzed, and a normalized load-sharing model is proposed that introduces a pile–raft interaction factor. A design equation is presented that can be used to estimate the load-carrying capacity of piled rafts at different settlement and performance levels. Case examples are selected from the literature and used to check the validity of the proposed load-sharing model.

2. Load-carrying behavior of piled rafts

2.1. Load-sharing ratio

The estimation of the load-carrying capacity of piled rafts is complex due to uncertain aspects associated with the load-sharing behavior and interaction effects that vary with settlement. If a load imposed on a piled raft is carried by both raft and piles, the load-carrying capacity of the piled raft can be decomposed into those of the raft and piles, given as follows:

$$Q_{pr} = Q_r + Q_p \tag{1}$$

where Q_{pr} is the load-carrying capacity of the piled raft and Q_r and Q_p is the load-carrying capacities of the raft and piles. In terms of the load capacities of an unpiled raft and group piles, Eq. (1) can be rewritten as:

$$Q_{pr} = \eta_r \cdot Q_{ur} + \eta_p \cdot Q_{gp} = \eta_r \cdot Q_{ur} + \eta_p \cdot (\chi_g \cdot \Sigma Q_{sp}) \tag{2}$$

where Q_{ur} and Q_{gp} is the load capacities of unpiled raft and group piles; η_r and η_p the load capacity efficiency factors for raft and piles = Q_r/Q_{ur} and Q_p/Q_{gp}; χ_g the pile group effect factor; and Q_{sp} is the load capacity of a single pile. Factors η_r and η_p represent changes in the load-carrying capacities of a raft and piles when combined into a piled raft due to interactions between the two components.

According to de Sanctis and Mandolini [16], η_r varies as a function of raft and pile geometry conditions, indicating that values of η_r equal to 0 and 1 represent conditions of block failure of piles and unpiled–raft failure, respectively. For piled rafts embedded in undrained clays, the load capacity efficiency factor η_p for piles was suggested to be equal to 1 for practical purposes. For sands, the values of η_p can be smaller or greater than 1 depending on the type or magnitude of interactions that occur between raft and piles [5,13]. If loading on a piled raft results in increased confining stress within underlying soil near piles, η_p would be greater than 1 due to increases in pile skin friction [13]. Factor η_p can be smaller than 1 when downward movements of the raft reduce relative displacements between soil and the pile shaft, resulting in decreased pile skin frictions [5].

Due to the combined nature of piled rafts, the load-sharing behavior is a unique feature of piled rafts that can be distinguished from other types of foundations. The load-sharing behavior of piled rafts can be described using the load-sharing ratio, which represents the ratio of load carried by the piles to the total load imposed on the piled raft and is defined as follows:

$$\alpha_p = \frac{Q_p}{Q_{pr}} = 1 - \frac{Q_r}{Q_{pr}} \tag{3}$$

where α_p is the load-sharing ratio; Q_{pr} the load imposed on the piled raft; and Q_r and Q_p is the loads carried by the raft and piles. An example of α_p correlation was reported by Clancy and Randolph [3], who proposed an equation for α_p as a function of raft and pile stiffness, given as follows:

$$\alpha_p = 1 - \frac{(1 - i_{rp})k_r}{k_p + (1 - 2i_{rp})k_r} \tag{4}$$

where k_r and k_p is the stiffnesses of the raft and piles from load–settlement curves and i_{rp} is the raft–pile interaction factor. Eq. (4) indicates that α_p decreases as the raft stiffness k_r increases or the pile stiffness k_p decreases. Horikoshi and Randolph [7] suggested that α_p decreases with increasing load but decreases less as the number of piles increases. Higher raft stiffness and increasing load level both represent conditions of a higher load portion carried by the raft. Eq. (4) is also an elastic-based solution and thus produces a constant α_p value.

2.2. Normalized load-sharing model

Due to differences in the load responses of the raft and piles, the load-sharing behavior of piled rafts varies with settlement. Considering the settlement-dependent load-sharing behavior and load capacity ratio, Lee et al. [10] proposed the following normalized load-sharing model:

$$\alpha_p = \frac{1}{(\beta \cdot \xi) \cdot \left[\frac{a_p \cdot \lambda_B + b_p \cdot (s/B_r)}{a_r + b_r \cdot (s/B_r)}\right] + 1} \tag{5}$$

where α_p is the load-sharing ratio; β the load capacity interaction factor; ξ the load capacity ratio; a_r, b_r, a_p and b_p the model parameters; s the settlement; B_r and B_p the raft width and pile diameter; and λ_B is the foundation size ratio = B_p/B_r. The model parameters a_r, b_r, a_p, and b_p are equal to 0.02, 0.8, 0.01, and 0.9, respectively, and represent the functional properties of the normalized non-linear load–settlement curves for the raft and piles.

The load sharing model of Eq. (5) was established based on the normalized load–settlement relationships of raft and piles for which load and settlement were normalized with ultimate load capacity and foundation geometry (i.e., B_p and B_r), respectively. As the ultimate load capacity and foundation geometry represent the local soil condition and characteristics of foundation, the process of normalization itself reflects the effect of soil and foundation conditions indicating the uniqueness of the model parameters. Akbas and Kulhawy [1] and Dithinde et al. [4] also showed the uniqueness of the model parameters of the normalized load–settlement relationships for raft and piles, respectively.

The load capacity ratio ξ in Eq. (5) represents the ratio of raft to pile load capacities and is defined as follows:

$$\xi = \frac{Q_{ur,u}}{Q_{gp,u}} = \frac{Q_{ur,u}}{\chi_g \sum Q_{sp,u}} \tag{6}$$

where $Q_{ur,u}$, $Q_{gp,u}$, and $Q_{sp,u}$ is the ultimate load capacities of unpiled raft, group piles, and a single pile and χ_g is the pile group effect factor. The load capacity interaction factor β in Eq. (5) represents changes in the load-carrying capacities of a raft and piles when