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Research Paper

Analyzing load response and load sharing behavior of piled rafts installed with driven piles in sands

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ABSTRACT

In this study, the load carrying behavior of piled rafts embedded in sand were investigated using the 3-D finite element analysis. Focus was given on piled rafts installed with driven piles. Various foundation and soil conditions were considered in the analyses. To simulate driven piles, the soil influence zone around driven pile was set where the relative density and lateral stress were increased to reflect the changes in soil condition and stress state due to pile driving. For both bored- and driven-pile cases, the values of load sharing ratio showed non-linear variation with settlement. The load sharing ratios for driven piles were higher than for bored piles within a certain settlement range. With further increasing settlement, however, the values of load sharing ratio for driven piles became similar to those of bored piles with limited variation. This indicates that load-sharing model can be applied for both cases to estimate the load capacity of piled rafts.

1. Introduction

Piled rafts are a combined foundation type of raft and piles, often adopted when large amounts of settlements are expected or additional bearing capacity is required. The raft part of piled raft is in contact with soil surface sharing loads from superstructure with piles at a certain load sharing ratio. If the load carrying capability of the raft part were not taken into account, the design of piled rafts would become conservative and may be uneconomical. Various efforts have been involved to enhance the design techniques of piled rafts considering more efficiently the load carrying capabilities of both piles and raft soil conditions [2,9,17,20,30,34,39,43].

The methods to analyze the mechanical behavior and load carrying capacity of piled rafts include simplified methods [5,33,34], semi-analytical methods [8,31,42] and more rigorous numerical methods such as the finite element analysis. Centrifuge model tests have also been often used as real-sized, full-scale structures can be simulated and stress states corresponding to field condition can be achieved [17,19]. As early developments, Liu et al. [25] and Phung and Long [27] investigated the interactions between raft and piles for piled rafts and showed how the load capacities of raft and piles become different from those of unpiled raft and group piles. Horikoshi and Randolph [19] and Conte et al. [10] both conducted centrifuge tests and analyzed the mechanical behavior of piled rafts focusing on the contribution of piles and raft for reducing settlement and increasing bearing capacity, respectively. Poulos [32] suggested the type of soils for the use of piled rafts and proposed a phased design methodology. Horikoshi and Randolph [19] presented the strategic placement of piles within raft to reduce differential settlements, which was further investigated later by Reul and Randolph [35].

Piles can be classified into non-displacement and displacement (driven) piles in terms of the installation method. The installation of displacement piles involves driving or jacking process that causes certain changes in soil condition and stress state affecting the load response and load carrying capacity of piles. It is difficult to quantify such changes and thus the design is often based on empirical correlations introducing certain modification factors [11,24]. For the same reason, most numerical analyses for piles do not consider changes in soil condition due to pile installation assuming that the soil condition remains the same, which is in fact only valid for non-displacement piles. For piled rafts, as different types of piles can be used, it is necessary to consider the effect of pile installation on the load carrying behavior of piled rafts.

In this study, piled rafts in sand were analyzed using the 3D finite element analysis focusing on the load response, load carrying and sharing behaviors of piled rafts installed with driven piles. Various pile and soil factors were considered in the analysis to investigate the effects of pile installation and significant geometry conditions. The results obtained for piled rafts with non-displacement and driven piles were compared, and the design application for evaluating the load carrying and load sharing behavior of both cases was examined.

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2. Load carrying behavior of piled rafts

2.1. Load carrying capacity

The estimation of the load carrying capacity of piled rafts is complex due to the load sharing phenomenon and interactions that occur between piles and raft upon loading. The load carrying capacity of piled raft can be decomposed into those of raft and piles, given as follows:

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

where Q_{pr} = load carrying capacity of piled raft; Q_r and Q_p = load carrying capacities of raft and pile components of piled raft. Q_r and Q_p in Eq. (1) differ from the load carrying capacities of unpiled raft and group piles because of the interactions between raft and piles when combined into piled raft. Fig. 1 shows the schematic view of load carrying mechanism and various piled-raft interactions [20]. Introducing the interaction effects shown in Fig 1, the load carrying capacity of piled rafts given by Eq. (1) can be rewritten in terms of the load capacities of unpiled raft and group piles as follows:

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

where Q_{ur} and Q_{gp} = the load capacities of the unpiled raft and group piles; η_r and η_p = the pile-to-raft and raft-to-pile interaction factors; χ_g = the pile-to-pile interaction factor; and Q_{sp} = the load capacity of single pile.

The factors η_r and η_p represent changes in the load capacities of raft and piles in comparison to those of unpiled raft and group piles, respectively. For sandy soils, η_r is smaller than unity [13,30] while values close to unity for η_r were reported in the earlier works [25,27]. η_p can be, on the other hand, greater than unity if the pressure acting on raft produces increases in the confining stress within soil resulting in larger pile skin friction. η_p becomes smaller than unity if downward raft settlements reduce relative displacements between soil and pile shaft leading to decreases in pile skin friction.

2.2. Load sharing behavior

Loads imposed on piled raft are supported and shared by piles and raft at a certain load sharing ratio. The load sharing ratio indicates the ratio of load carried by piles to total load imposed on piled raft defined as follows:

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

where α_p = load sharing ratio; Q_{pr} = load imposed on piled raft; and Q_r and Q_p = loads carried by raft and piles. An example of α_p correlation can be found from Clancy and Randolph [8] who proposed an α_p equation varying 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 = stiffness of raft and piles from load–settlement curves and i_{rp} = raft-pile interaction factor. Horikoshi and Randolph [19] presented that α_p decreases with increasing load and less decreases as the number of piles increases.

The load sharing behavior of piled rafts varies with settlement due to the different load responses of raft and piles. To take into account the settlement-dependent and non-linear variation of the load sharing behavior, Lee et al. [22] proposed the normalized load sharing model given as follows:

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

where α_p = load sharing ratio; β = load capacity interaction factor; and ξ = load capacity ratio; a_r, b_r, a_p and b_p = load sharing model parameters; s = settlement; B_r and B_p = raft width and pile diameter; and λ_B = foundation size ratio of B_p/B_r. a_r, b_r, a_p, and b_p represent the characteristics of the normalized load–settlement curves of raft and piles, equal to 0.02, 0.8, 0.01, and 0.9, respectively [1,12,22].

The load capacity interaction factor β in Eq. (5) indicates the changes in the load carrying capacities of raft and piles when combined into piled raft. In clays, the piled-raft interaction effect is small and the value of β can be assumed equal to 1 [38]. For piled rafts in sands, however, the interaction effect is significant and β tends to be smaller than unity.

2.3. Effect of pile installation

Piles can be classified into non-displacement and displacement piles according to the installation method. Non-displacement piles are installed by drilling or excavating soils where concrete and reinforcement steel cages are placed forming a cast-in-place pile. Examples are bored piles and drilled shafts. The installation process of non-displacement piles does not disturb soil, in principle, and the soil condition remains unchanged [15,26]. In practice, however, drilling or excavating may also induce some disturbances within surrounding soils, in particular for larger-diameter piles, as there are more chances of strain occurrence toward inside and stress release [7,21]. Displacement piles are formed by driving or jacking a pile into ground causing certain displacements of soils with changes in soil condition. The changes in soil condition include increases in soil density and horizontal stress around pile shaft. This produces a stiffer load response when compared with non-displacement piles resulting in higher load carrying capacity. The difference of loads carried by non-displacement and displacement piles becomes less pronounced as settlement level increases. In fact, once the plunging state is reached at very large settlement level, the base resistance is theoretically the same for both pile types [11,16].

The interaction effect of piled rafts would also be affected by the pile installation method. Displacement piles are subject to higher interaction effects than non-displacements piles due to the densification of surrounding soils and increase in the lateral stress. The pile installation effect on the load response of piles was investigated by several authors [11,24]. Most of them were based on empirical correlations with experimental or numerical results. The empirical approach is largely due to the uncertain aspects of soil condition with installing process of displacement piles, which is difficult to consider numerically or analytically in a systematic way.

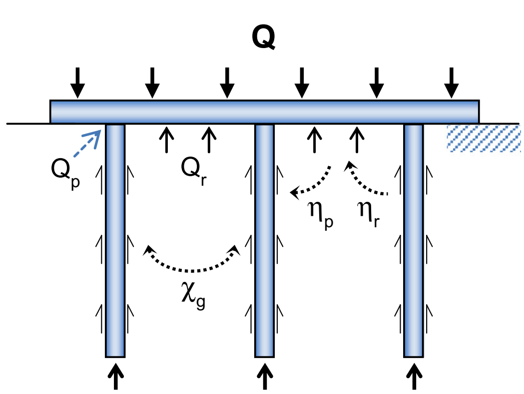

Fig. 1. Schematic view of various interactions for piled rafts [20].