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Assessment of load sharing behavior for micropiled rafts installed with inclined condition

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ABSTRACT

As a combined foundation, micropiled rafts under compressive loads show the load-sharing behavior between raft and micropiles. The load carrying and sharing behaviors of micropiled rafts installed with inclined condition would become further complicated as a result of the coupled influences of group and inclined configurations. In this study, the 3D finite element analyses were performed to investigate the load carrying and sharing behaviors of inclined micropiled rafts. Changes in foundation configurations, including micropile inclination angle and spacing, were considered in the analyses. The load carrying capacity of micropiled rafts varied with the inclination angle of micropiles and the proportion of load carried by inclined micropiles was larger than for vertically installed condition. The values of the load sharing ratio α_p for the inclined condition were obtained and analyzed. The normalized load-sharing model for inclined micropiled rafts was proposed with the modified load capacity interaction factor and design equations as a function of micropile configuration and inclination angle. Case studies were selected from the literature and adopted to compare with the calculated results using the proposed method. The calculated results were in reasonable agreement with measured load sharing ratios.

1. Introduction

A micropile is a drilled and grouted deep foundation with a diameter typically smaller than 300 mm, where a steel bar is introduced as reinforcement. Since first introduced in the 1950s, micropiles have been widely adopted for various geotechnical applications such as reinforcing existing structures, reducing settlement, enhancing seismic performance, and serving as the main foundation component [1–6]. Due to the smaller-diameter characteristics of micropiles, the frictional resistance is the main source of the load carrying capacity whereas the end bearing capacity is regarded as minor and not usually taken into account in design.

Micropiles are in general installed as a group where a cap or raft is introduced, placed on the top of group micropile heads. As a combined foundation, micropiled rafts exhibit load sharing phenomenon between raft and micropiles, often expressed by the load-sharing ratio [4,7]. The load sharing behavior of the combined foundation should be properly characterized and considered in design for more effective utilization of the load carrying capabilities of individual foundation components. The load carrying capacity of smaller-diameter micropiles is mobilized earlier than the larger-sized raft, leading to settlement-dependent load sharing behavior. It is noted that the majority of previous investigations on the load sharing behavior of combined foundations were carried out mainly for piled-raft foundations [7,8].

If micropiles were installed in an inclined configuration, the load sharing behavior would become further complicated as the load carrying capacity of micropiled rafts varies with micropile inclination [3,4]. The effect of micropile inclination on the load carrying capacity has been investigated by several authors, showing improved load carrying capability of inclined micropiles [3,4,9–13]. The load sharing behavior of micropiled rafts, on the other hand, was rarely addressed because micropiles have been adopted mainly for underpinning or reinforcing existing structures in most cases installed vertically. For more enhanced and optimized design of micropiled rafts with fully utilized load carrying capabilities of raft and micropiles, the load sharing phenomenon should be clearly identified.

In this study, the load response and load sharing behavior of micropiled rafts installed with inclined piles are investigated considering changes in foundation configurations and soil conditions. The 3D finite element analyses were performed to simulate vertically loaded micropiled rafts, focusing on the effect of micropile inclination on the load carrying and load sharing behaviors. Based on results from the finite element analyses, a load-sharing model, which can quantify the portion of load carried by micropiles, is proposed. Model parameters for the

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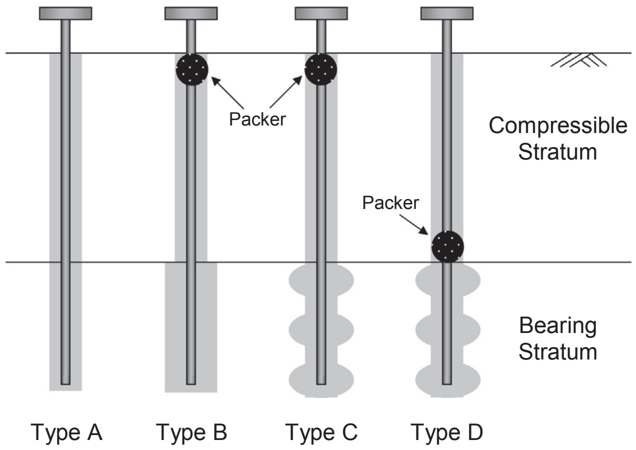

Fig. 1. Type of micropile foundation.

proposed method were evaluated and design equations applicable in practice were presented. Case examples were selected from the literature and used to compare measured and estimated load sharing ratios.

2. Load response of micropile foundation

2.1. Load carrying capacity

According to the installation method, micropiles can be classified into Types A to D as described in Fig. 1. Type-A micropiles are formed by the gravity grouting with a water-cement ratio of around 0.45–0.5. For Type-B micropiles, the pressurized grouting is applied with the injection pressure of 0.5–1.0 MPa. The pressurized grouting is also applied for Types-C and -D micropiles whereas a post grouting procedure is additionally introduced for hydraulic fracturing and injecting into the ground. The load carrying capacities of Types-C and -D micropiles are dependent on the timing and intensity of injection pressure [2,14]. For Type D, the packer position for the pressure grouting is located lower, close to the bearing stratum, and higher injection pressure is applied to form a stronger and harder bond zone.

The load carrying capacity of an individual single micropile (SMP) can be evaluated based on the mobilized interface strength along the bond length given as the following relationship:

$$Q_{SMP} = \alpha_{bond}\cdot\pi\cdot D\cdot L_b \tag{1}$$

where Q_{SMP} = load capacity of SMP; α_{bond} = grout-to-soil bond strength; D = drill-hole diameter; and L_b = bond length. The bond strength α_{bond}, as the main resistance component of micropiles, can be obtained using the interface frictional resistance on the micropile surface and the effective stress along the embedded depth of micropiles given as follows:

$$\alpha_{bond} = \chi\cdot\sigma'_{vz} \tag{2}$$

$$\chi = K\cdot\tan\phi' \tag{3}$$

where χ = coefficient of interface friction and σ'_{vz} = effective stress at depth z; K = lateral earth pressure ratio and ϕ' = internal friction angle. K depends on the stress state in soil around micropiles and thus the type of grouting method. For Type-B micropiles with the pressurized grouting, K would be higher than for Type-A micropiles with the gravity grouting, close to the passive stress state in the range of 4–7.

When combined with a cap or raft, a micropiled raft (MPR) is similar to a piled raft in that raft and micropiles can be both regarded as load carrying components. Following the design concept for piled rafts [15], the load capacity of micropiled rafts can be written as:

$$Q_{MPR} = \eta_{UR}\cdot Q_{raft} + \eta_G\cdot Q_{GMP} \tag{4}$$

where Q_{MPR}, Q_{raft} and Q_{GMP} = load capacities of MPR, raft and group micropiles (GMP) and η_{UR} and η_G = micropile-to-raft and raft-to-micropile interaction effect factors. As a simpler form, a unified interaction factor combining the effects of raft and micropiles were proposed given as follows [3,4]:

$$Q_{MPR} = \eta_{MPR}\cdot(Q_{raft} + Q_{GMP}) \tag{5}$$

where η_{MPR} = MPR interaction effect factor. It was observed that η_{MPR} is lower than unity from the initial to a certain settlement level of around 10% raft width (s/B = 0.1) beyond which it becomes higher than unity [4].

A micropile can be installed with an inclined condition, as an effective option in improving the load carrying capability [3,4,9]. Sharma et al. [9] conducted model load tests using inclined micropiles with the inclination angle of 15° and confirmed an increase in the load carrying capacity. Tsukada et al. [3] and Kyung et al. [4] reported marked improvement in the load carrying capacity of micropiles for the inclination angle of 15° to 30°.

2.2. Load sharing behavior

The load sharing behavior is a unique feature of combined foundations including piled rafts and micropiled rafts that can be distinguished from other types of foundations. As for conventional piled rafts, the load sharing behavior of micropiled rafts can be described using the load sharing ratio that represents the ratio of load carried by micropiles to the total load imposed on a micropiled raft given as follows:

$$\alpha_p = \frac{Q_{MP,MPR}}{Q_{MPR}} \tag{6}$$

where α_p = load sharing ratio; $Q_{MP,MPR}$ = load carried by micropiles of micropiled raft; and Q_{MPR} = total load on a micropiled raft. For piled rafts, an example of α_p correlation can be found from Clancy and Randolph [7] who proposed α_p as a function of raft and pile stiffness:

$$\alpha_p = 1-\frac{(1-i_{rp})k_r}{k_p + (1-2i_{rp})k_r} \tag{7}$$

where k_r and k_p = stiffness of raft and piles from load-settlement curves and i_{rp} = raft-pile interaction factor. Eq. (7) indicates that α_p decreases as the raft stiffness k_r increases and the pile stiffness k_p decreases.

Due to the different load responses of raft and micropiles, the load sharing behavior of micropiled rafts varies with settlement [16]. Considering the settlement-dependent load sharing behavior of piled rafts and micropiled rafts, the following normalized load sharing model (NLSM) by Lee et al. [16] can be introduced for characterizing the load sharing behavior of micropiled rafts:

$$\alpha_p = \frac{1}{(\beta\cdot\xi)\cdot\left[\frac{a_p\lambda_B + b_p(s/B_r)}{a_r + b_r(s/B_r)}\right] + 1} \tag{8}$$

where α_p = load sharing ratio; β = load capacity interaction factor; and ξ = unpiled raft-to-vertical group micropiles (GMP) load capacity ratio; a_r, b_r, a_p and b_p = model parameters; s = settlement; B_r and B_p = raft width and pile diameter; and $\lambda_B = B_p/B_r$. The model parameters a_r, b_r, a_p, and b_p represent non-dimensional normalized values, equal to 0.02, 0.8, 0.01, and 0.9 [16–18]. Note that the normalized load sharing model of Eq. (8) was established and valid for the vertically installed condition and thus modification is necessary for the inclined condition.

3. Numerical analysis of micropiled rafts

3.1. Finite element modeling

A 3D finite element (FE) analysis was performed to analyze the load sharing behavior of micropiled rafts with inclined piles. Various foundation and soil conditions with changes in the relative density (D_R),