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A new expression for determining the bending stiffness of circular micropile groups

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ABSTRACT

Increased bending stiffness and decreased foundation rotation are two main factors which reduce the rocking motion of foundation. A micropile group in circular arrangement is an innovative technique for reducing the rocking motion of the foundation. In this paper, the effects of several parameters were numerically investigated on the rocking stiffness of circular micropile group foundations. The finite difference software FLAC3D was used to model the foundation, soil, and the structure. The micropiles used in this study varied in the diameter, but had similar length. A total of seven records were selected to cover a wide range of frequency content, duration and amplitude. The results from the numerical simulation were compared and verified against those obtained from an alternative numerical method as well as a set of experimental test results. The model was then used for parametric studies and the effects of relevant parameters were investigated. The results showed that slenderness, inclination angle and distance ratio of a micropile group are main factors which increase the soil stiffness and control the seismic motion of high-rise buildings. Based on the results, a new expression was proposed that can be used to determine the optimal moment of inertia of circular micropile groups. The proposed expression revealed that the primary factors which reduce the effective period of the buildings are the number, diameter, and injection pressure of micropiles in a circular micropile group. Using the proposed relationship, it was found that using circular micropile groups can reduce the destructive seismic effects (i.e. drift demand) in high-rise buildings by up to 60%.

1. Introduction

Building structures can be constructed on shallow foundation systems with acceptable settlement behavior. However, the construction of high-rise building structures with shallow foundations placed on soft sites can increase foundation settlement. Seismic motions can also increase roof displacement of high-rise structures, leading to an increase of bending moments in the base. If the site is soft, the soil is not able to withstand large bending moments, and the settlement enlarges in the corners of the foundation. The increase of bending stiffness and the decrease of the foundation rotation are two important factors which amplify rocking stiffness of foundation and reduce the effective period of the structures. Rocking motions have an essential role in rising the effective period of structures, such that more than 90% of the changes in the structural period correspond to the rocking motion of the foundation [1].

Micropiles are small piles whose application in soft soils can reduce the motions and increase the bending stiffness of foundations. Inclined micropiles increase the system plasticity against bending moments caused by high-rise buildings. The bearing capacity of micropile foundation, with regard to the seismic motion and the type of soil in the site, can incorporate an impact factor larger than one. Also, the type of soil and the surrounding environment of the micropiles can severely affect their operational efficiency [2]. Besides, circular micropile groups influence the seismic behavior of the high-rise structures. Because of the circular shape of micropile groups, as well as the inclination angle of micropiles, the application of circular micropile groups can increase the bending stiffness of the foundation. In this regard, the high-pressure injection of micropile additionally increases the soil stiffness, which consequently decreases foundation rotations.

Al-Hussaini and Ahmad [3] reported that the rows of piles can be effective as wave barriers. Mylonakis et al. [4] developed a substructuring method for the seismic analysis of bridge piers founded on vertical piles and pile groups in multi-layered soil. The results illustrated the potential errors from ignoring the radiation damping generated from the oscillating piles and the

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rotational component of motion at the head of the single pile or the pile-group cap. Takashi et al. [5] conducted laboratory tests and field tests for micropile systems to confirm feasibility and efficiency of a micropile system for seismic retrofit of foundations in Japan. Doshi et al. [6] proposed a new method, multi-helix micropile method, to retrofit the foundations. In this method, a small steel pipe pile was used with helical plates screwed into the ground without disturbing the surrounding soil. Shu et al. [7] proposed a state-dependent constitutive model for sand formulated within the critical-state framework and its implementation into the FLAC3D program. The proposed model captures the stress path dependent behavior of sand over a wide range of densities and confining pressures based on a unique set of parameters. According to their proposed model, numerical simulation of a micropile subjected to the vertical loading showed that the total resistance of the pile would be a function of the "in situ state" of soil. Turan et al. [8] investigated the vibration screening efficiency of an inclined secant micropile wall positioned as an active vibration barrier. Various parameters such as barrier depth, inclination, barrier distance and load excitation frequency were studied. The results showed that the effectiveness of the barrier boosts as its depth increases. It also revealed that the orientation of the inclined barrier towards or against vibration source is a fundamental design issue. Ghorbani et al. [9] using the parametric analysis, investigated the effects of the earthquake characteristics, soil properties, superstructure and micropiles' cap and micropiles' structure on the seismic performance of micropiles. The results showed that bearing capacity of circular micropile group is a function of number, length, inclination angle, and diameter of the micropile. This capacity varies in different densities and seismic motions. Previous studies have mostly been done on micropile groups with no contact between foundation and soil or even a regular contact surface between micropile foundation and soil.

Main contributions of this paper include 1) studying the effect of foundation rocking stiffness variation caused by the application of circular micropile groups, 2) studying and presenting the main parameters which influence the type of site condition and the performance of a circular micropile group and 3) proposing a relationship for calculating the optimal bending stiffness of a circular micropile group. Therefore, in this paper, the methodology is initially explained in detail (Section 2). Thereby, geometry of the applied model, the micropile model, and the applied ground motion database are explained, and the experimental results are discussed based on the input database. In Section 3, characteristics of the regular foundation are examined, and in Section 4, the effects of circular micropile groups are studied on some parameters such as bearing capacity, modulus of subgrade reaction, and rotation of the foundation. Section 5 presents a new expression which provides a further insight into the understanding of the moment of inertia of a circular micropile group and provides a better estimation of the bending stiffness of micropile groups under the various ground motions.

2. Methodology

2.1. Geometry of the model

2.1.1. Soil and foundation model

In this study, the finite difference software FLAC3D is used to model the foundation, soil, and the structure. The selected structure includes a column with 3.55 s period on rigid base and the equivalent mass of a 23-storey building. The participating mass in seismic calculations is 5920 t, which is distributed uniformly throughout the bar column. The foundation with the dimensions of $10 \times 10 \times 1\ m^3$ is on soft soil. The mechanical properties of soil and foundation are presented in Table 1. The static settlement of the structure is 29 mm and, considering the applied static load, the subgrade reaction modulus is $2.01 \times 10^7\ N/m^3$.

The minimum distance between the center of the structure and the model borders should be three to four times larger than the foundation radius in horizontal direction and two to three times larger than the foundation radius in vertical direction [10]. This value for rectangular foundations is shown in Eqs. (1) and (2).

$$X \text{ or } Y \text{ direction } \geq 2 \times (3 \sim 4)\left(rh = \sqrt{\frac{B \times L}{\pi}}\right) \quad (1)$$

$$Z \text{ direction } \geq 2 \times (2 \sim 3)\left(rz = \sqrt{\frac{B \times L}{\pi}}\right) \quad (2)$$

Due to the large dimensions of the circular micropile group and its orientation beneath the foundation, the dimensions of the model are set to $100 \times 100 \times 50\ m^3$. In addition, such dimensions prevent seismic wave distortions. The numerical model is shown in Fig. 1.

2.1.2. Micropile model

The diameter of micropiles used in this study varies in a range of 100, 150, and 200 mm with the length of 10 m. Dimensional ratios of the piles (L/D) are 100, 67 and 50, respectively. The property of grout, reinforcement rebars and steel sheath of the micropiles are shown in Tables 2–4.

Table 1
Mechanical properties of soil and foundation.

	Soil	Foundation
Density, P (kg/m^3)	1900	2500
Poisson ratio, N (dimensionless)	0.45	0.25
Modulus of elasticity, E (Pa)	1.68E+08	2.22E+10
Friction angle, Φ (deg.)	19	–
Cohesion, C (Pa)	1.80E+04	–
Tensile strength, T (Pa)	5.00E+04	–

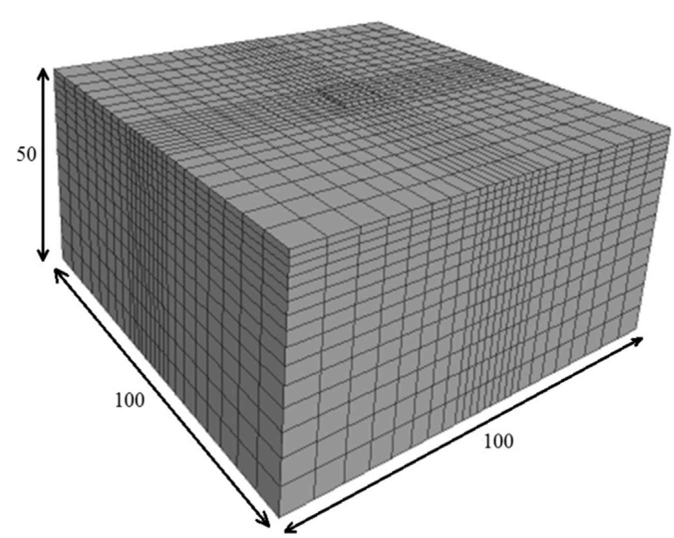

Fig. 1. Soil and foundation model (unit: m).