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Shaking table test study on dynamic behavior of micropiles in loose sand

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ABSTRACT

Micropiles are small-diameter piles installed in soil. Due to wide application of micropiles in seismically active areas, investigation of their behavior during earthquake is of great significance. In this study, shaking table tests were conducted on a small-scale physical model of micropiles consisting 16 vertical micropiles embedded in loose sand fill and subjected to harmonic sine waves. Influence of amplitude of input excitations, presence of a single degree of freedom superstructure and variation of concentrated mass of this model superstructure on the dynamic response of micropiles system were examined. Response of physical model to the base excitation was investigated in terms of the horizontal acceleration at different locations of physical model and also bending moment generated along two instrumented micropiles during the experiment. Increase in the amplitude of input wave and cyclic nature of shaking resulted in densification of underlying soil and modification of soil-micropile stiffness, which accordingly reduced dynamic amplification and shifted fundamental frequency of vibration of micropile cap. However, presence of superstructure and increase in its concentrated mass resulted in a shift of fundamental frequency the other way. There was a maximum bending moment induced by vibrations in the mid-length of model micropiles which increased with augmentation of amplitude of input wave. Inertial effect of superstructure resulted in significant elevation of bending moment in the vicinity of micropile head, and also caused bending moment in the corner micropile to exceed bending moment in center micropile.

1. Introduction

Owing to wide application of pile systems for foundation support and also foundation repair purposes, they have gained significance in building codes and numerous researches have attempted to examine their performance under different conditions including static and dynamic loadings. Since the most commonly encountered dynamic loads on a pile–soil–structure system are those due to earthquakes [1], earthquake loading is considered to play a major role in design of pile foundations and also needs to be considered in the studies focusing on pile systems.

Micropile is a small diameter (typically less than 300 mm) pile, which is constructed by drilling a borehole, placing reinforcement and grouting the drill hole [2]. High capacity steel reinforcements are used as the principal load bearing element in micropiles. Taking advantage of the friction generated along the shaft of micropile, the applied load is transferred from the grout to the surrounding ground. Owing to their small diameters, the end bearing capacity is insignificant and usually neglected in micropile systems [3].

Micropiles present significant advantages including flexibility, ductility, capacity to resist axial and lateral loads and ease of installation in access-restrictive environments and almost all ground conditions with minimal disturbance and noise [4–8]. They confine the soil and create an in situ coherent composite reinforced soil system with remarkably well engineering behavior such as reduction in soil movement [9,10]. In addition, micropiles are very flexible due to their slenderness and ductile steel core and so they can follow shock-induced ground displacements while remaining integrated with soil [3,11]. This makes micropiles a popular option for foundation of structures in seismic prone areas. Field observations after seismic events such as the 1989 Loma Prieta and 1995 Kobe earthquakes also reveal advantages of using micropiles as foundation elements since there is a higher resistance to seismic loads in inclined and small diameter piles as compared to large diameter vertical reinforced concrete piles [12,13].

Owing to the abovementioned advantages, micropiles have been increasingly used as foundation support of new structures and also seismic retrofitting of existing structures. Seismic retrofit of 92/280 I/C foundations in San Francisco Bay Area, California by micropile groups [14] and improving the stability of a minaret exposed to seismic hazards in the city of Mosul in Iraq by micropile network [15] are some examples of using micropiles for the latter purpose. As a result, improved understanding on the performance of micropiles under seismic

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loading conditions is of great significance for their proper design and construction.

Throughout recent decades, several researchers have attempted to investigate seismic response of micropile systems and examine the influencing parameters. However, theoretical and numerical methods were used in the majority of these studies. Micropile systems, particularly inclined ones, were proved to be effective when applied in seismic retrofitting projects and also remediation purposes [6,9,12,16–22]. This can be mainly attributed to their flexible and ductile behavior which provides them with a strain compatibility with the surrounding soil and the ability to follow the free field movements during a seismic excitation.

Results of numerical simulations conducted by Shahrour *et al.* [11] showed that presence of the superstructure induces significant inertial effect and large increase in the bending moments in the upper parts of the micropiles. This inertial effect depends mainly on the loading frequency with respect to the fundamental frequency of the soil layer and that of the superstructure. Also, in the same study, a positive group effect of micropile groups was observed, which leads to a reduction of bending moment and lateral displacement at the head of micropiles.

A number of studies investigated the parameters influencing the performance of micropiles during a seismic event. The peak amplitude of earthquake, configuration of micropile systems (number and inclination angle), slenderness ratio, predominant frequency and mass of superstructure and connection conditions of micropiles were found to have significant influence on seismic performance of micropiles [5,8,12,23–25]. The elastoplastic behavior of soil was also found to have a considerable effect on the soil-micropile-structure response to earthquake owing to the fact that plasticity of the soil causes a decrease in the dominant frequencies of the system as well as the inertial forces by reducing the transmission of energy to the superstructure [7,13].

Experimental data obtained from full-scale field studies as well as small-scale laboratory studies can play a crucial role in calibrating the numerical or theoretical models adopted to investigate a soil-micropile dynamic interaction problem [26]. In the past decades, a number of field studies have investigated the performance of deep foundations under dynamic horizontal excitations [26–34]. However, further field studies on pile foundations, particularly micropile systems, are required since effective execution techniques in construction and real soil deposit configuration are of great significance in their dynamic lateral behavior.

There were a few experimental laboratory studies focusing on seismic performance of micropile systems. Centrifugal model experiments conducted at Rensselaer Polytechnic Institute on a model micropile system indicated to a positive group effect increasing with number of micropiles and the inclination angle [35]. Moreover, a number of shaking table experiments were performed on micropile model in the University of Canterbury, which showed that micropile followed the motion of the soil at weak base shakings (< 0.25 g)[36].

Due to limited experimental data on soil-micropile-superstructure interaction in the literature, further experimental studies are required to elucidate the response of micropile systems to dynamic excitations. Hence, a series of shaking table experiments were designed and carried out in the Hong Kong Polytechnic University to study the response of a small-scale physical model of micropiles to harmonic input waves. The study aimed at monitoring the response of physical model to a base shaking in terms of acceleration response, distribution of dynamic bending moment induced in the model micropiles and also the spatial variation of bending moment in the group of micropiles.

This paper presents the results of a number of these tests with a focus on understanding the influence of amplitude of input harmonic wave as well as presence and mass of model superstructure on the dynamic behavior of micropile groups. The inertial effect of the superstructure and also variations of bending moment induced in the micropile group due to the dynamic excitations are examined in this study. Results of this experimental study can shed insights onto future endeavors of future numerical studies. In the first part of the paper, the small-scale physical model prepared for this study and the experimental program is described. Next, the results of shaking table experiments are presented and then discussed to probe the effect of each of the variables considered for this part of study.

Table 1
Characteristics of the shaking table in the Hong Kong Polytechnic University.

Property	Value
Plan dimensions	3 m × 3 m
Maximum allowable load at 1 g horizontal acceleration	10 t
Maximum overturning moment	10 t-m
Working frequency range	1–50 Hz

2. Shaking table experiments

2.1. Physical model

Reduced scale model experiments including centrifuge and 1 g shaking table tests are useful measures of studying different problems in geotechnical earthquake engineering. They provide the opportunity to simulate complex systems under controlled conditions and enhance the understanding of the soil-foundation-structure interactions. Design of a small scale physical model is governed by the principles of dimensionless analysis and similitude laws proposed for centrifuge and 1 g shaking table testing environments [37].

In this study, a series of 1 g shaking table experiments were conducted on a small scale physical model of micropile systems using the uniaxial shaking table facility in The Hong Kong Polytechnic University (PolyU). Table 1 presents the characteristics of this facility. The shaking table is driven by a closed-loop, servo-controlled hydraulic actuator with an MTS controller. It can reproduce motions with displacement, velocity and acceleration control according to the frequency range considered for the study [1].

Behavior of soil container under seismic excitation plays a major role in shaking table experiments since it significantly affects the soil-foundation-structure interaction. As a result, in such studies, it is ideal to use a container that not only confines the soil but simulates the free field soil response during a seismic excitation. In this study, a laminar soil container was used that can allow the soil to deform in simple shear and thus reproduce the free field shaking response with minimal boundary effects. The laminar soil container was fabricated using 15 rectangular steel frames, which were made by welding hollow sections of 50 mm × 50 mm × 3 mm. As depicted in Figs. 1 and 2, the internal dimensions and height of the laminar soil container were 1.4 m, 0.9 m and 0.75 m, respectively. In order to construct the laminar soil container, the first rectangular frame was welded to the bottom steel plate and then the remaining frames were mounted on it. It should be mentioned that 1-mm-thick Teflon layers were glued to the contact surface of the frames in order to reduce the friction and allow two adjacent frames to easily slide on each other. A three dimensional steel frame with cross bracing was set up outside the laminar container to prevent excessive translational movements of the container and also provide a reference for measuring lateral displacements at different levels (Fig. 1).

The soil used in this investigation was poorly graded (SP) river sand imported from China, which was suitable for repeated testing with little degradation. According to the scaling laws for shaking table experiments, the density of sand fill in the physical model is equal to the density of soil mass in the prototype. Hence, air pluviation method was used to prepare the soil deposit for this study, which gave reproducible average sand deposit densities with a minimum variation. For this purpose, soil was poured into the laminar container at a constant height of almost 100 mm above the soil surface to prepare a sand fill of low