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Seismic response of pile-raft-clay system subjected to a long-duration earthquake: centrifuge test and finite element analysis

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ABSTRACT

A series of seismic centrifuge model tests were performed to study the behavior of pile groups in soft kaolin clay. Several small-scale pile-raft models were fabricated, ranging from a 2×1 to a 4×3 pile group. Pile and raft were made of aluminum, rigidly connected each other at the pile head via a through bolt system. The excited long-duration ground motion of about 200 s strong motion was employed to represent a far-field earthquake arising from Sunda Subduction Trench. Experimental investigation into the influence of group size on both raft acceleration and pile bending moment response was conducted. It was found that both acceleration and pile bending moment response were influenced by stiffness-to-mass ratio of the pile-raft system; while pile spacing had no evident influence on acceleration response but significantly influenced the pile bending moment response. Besides, pile bending moment was also influenced by the row location of pile in the 4×3 pile group. Furthermore, by employing a hyperbolic-hysteretic soil constitutive model to model the kaolin clay, a series of three-dimensional finite element analyses were carried out to compare with the seismic centrifuge tests. Reasonably well comparisons between centrifuge test and numerical computed results were obtained, which suggest that the 3D finite element modelling procedure with a hyperbolic-hysteretic soil constitutive model can be extended to complement seismic centrifuge tests.

1. Introduction

The behavior of pile foundations under earthquake loading is an important factor affecting the performance of structures. Observations from past earthquakes have shown that piles in firm soils generally perform well, while those installed in soft or liquefiable soils are more susceptible to problems arising from ground amplification or excessive soil movements. A major problem associated with earthquakes in soft ground is the amplification of seismic-induced ground motion by soft soil layer(s) [61,72,8,89,7]. As a result, piles embedded in soft soils may be subjected to amplified loading even under small or moderate earthquakes. In particular, the stiffness degradation of soft clay during seismic loading can influence the natural frequency of the whole pile-soil-superstructure system [17,32,11], which makes the dynamic response of the entire system more complex. Furthermore, many studies have shown that the soil-structure (pile)-interaction (SSI) effect is quite significant to the dynamic response of foundation for structures built on soft soils rather than on stiff soils [4,43,76,77].

To examine the seismic soil-pile interaction, a number of previous experimental studies involving both centrifuge test and 1-g shaking table test were performed. However, most of the reported centrifuge tests (e.g. [12,27,1,2,30,13,22,95,36,47]) and shaking table tests (e.g. [63,64,92,93,90,31,23,68]) were focused on the dynamic interaction between pile and predominantly sandy soils, while the relevant studies involving soft clays are still relatively few. One significant work in this area was carried out by Meymand [62], who conducted a series of large scale 1*g* shaking table tests to study the seismic interaction of soft clay-pile-superstructure subjected to a strong earthquake with a peak acceleration of 0.45*g* and a short duration of 12 s. In his study, a large preload was applied to speed up the consolidation before the shaking test phase, which could give rise to difficulty in defining the soil stress state during test [62]. Besides, Banerjee [7] and Banerjee et al. [9] performed a series of centrifuge tests to study the dynamic response of pile-raft system in soft kaolin clay subjected to short-duration far-field ground motions. Ma [52] and Ma et al. [53] also performed a series of similar centrifuge tests, with the emphasis on much more flexible piles. In Banerjee's and Ma's work, pile spacings along the shaking direction were more than 10 times pile diameter, which is large enough to neglect the pile-to-pile effect. As a result, their test results were largely corresponding to the seismic response of single pile embedded in soft

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clay.

On the other hand, analytical methods such as beam-on-dynamic-Winkler-foundation model or dynamic p-y method (e.g. [57,70,32]) and pseudo-static method (e.g. [19,87,49]) are widely employed to account for pile-soil interaction. However, the accuracy of employing simplified methods is highly dependent on the input parameters which are often obtained from the back-calculation from the measured pile response. Meanwhile, numerical methods such as finite element analysis have been frequently used to investigate the pile-soil interaction. Some of the previous relevant studies involving finite element method were performed by Cai et al. [18], Lu [50], Cheng and Jeremic [24], Maiorano et al. [56] Banerjee [7], De Sanctis et al. [29] and Zhao [96].

In this study, a series of seismic centrifuge model tests were performed to study the behavior of pile groups embedded in soft kaolin clay subjected to a long-duration ground motion, with the focus on both acceleration and pile bending moment response. The centrifuge employs four different pile-raft systems, namely 2×1 sparse, 2×1 compact, 2×3 and 4×3 pile-raft systems. The influence of pile group configuration including pile spacing and stiffness-to-mass ratio of pile-raft system on acceleration and pile bending moment response was presented. For the 4×3 pile-raft system, the pile bending moment response was also found to be dependent on the pile location. Furthermore, by employing a hyperbolic-hysteretic soil constitutive model, a series of finite element analyses were carried out to compare well with the seismic centrifuge test results.

2. Centrifuge experiments

The centrifuge tests in this study were carried out using the centrifuge facility at the National University of Singapore. The model gravitational acceleration is 50*g*, and all dimensions and results are presented in prototype scale unit unless otherwise stated. Fig. 1 shows the schematic layout of the centrifuge model. Each centrifuge sample has the dimensions of 25 m in length, 14.25 m in width and 16 m in height, contained in a laminar box. The Fig. 2 shows the plane layouts of 4 different pile-raft systems employed in centrifuge test. Rafts have a thickness of 1.2 m and piles have a diameter of 1 m. Piles in 2×1 sparse and compact pile groups are spaced at 9 and 3 times pile diameter (9 D versus 3 D) along the seismic shaking direction, respectively. Piles in 2×3 and 4×3 pile groups are spaced at 3 D and 2.75 D along and perpendicular to the shaking direction, respectively. Each instrumented pile was equipped with 9 equally spaced strain gauges along the pile shaft, with the uppermost and lowest strain gauges located at about 3 m and 13.4 m below pile head, respectively. Besides the 4 different pile-raft models, a pure kaolin clay model (without embedded pile-raft system) was employed to investigate the free-field acceleration response. A summary of centrifuge tests performed in this study is listed in Table 1. One issue of concern is whether the distance of the laminar box end walls along the shaking direction has a enough distance to minimize its influence on the test results. To this end, by employing a hyperbolic-hysteretic [7] soil constitutive model, Zhang [94] performed a series of three-dimensional (3D) finite element analyses to investigate the influence of boundary dimension on the raft acceleration and pile bending moment responses during the seismic centrifuge tests; the results suggest that the boundary effect of the laminar box on the computed raft acceleration and pile bending moment responses is relatively insignificant.

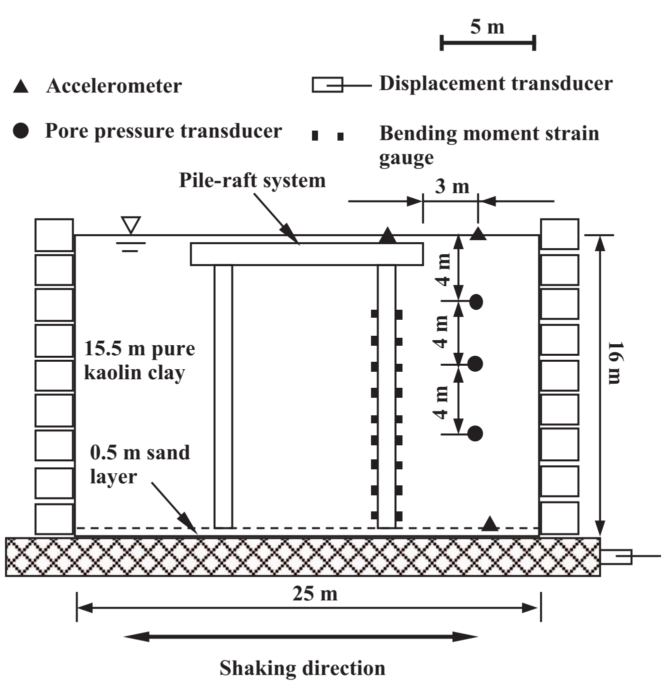

Fig. 1. Schematic layout of the centrifuge model (prototype unit scale, gravity level: 50*g*).

2.1. Sample preparation

The clay beds used in the centrifuge model tests were prepared using kaolin powder. The general properties of the kaolin clay are shown in Table 2. Kaolin powder was first mixed with water in a mass ratio of 1:1.2 to form the clay slurry. The completed slurry mixture was then subjected to both 1-g and 50-g consolidation processes to develop the required strength profile and stress history. 1-g consolidation was first carried out to pre-compress the clay beds, so as to reduce the time required for the subsequent in-flight consolidation. After 1-g consolidation, the sample was then subjected to in-flight centrifuge consolidation under 50*g* until the degree of consolidation along the entire depth was 90% or more, which is a process that typically requires at least 18 h of continuous spinning. Three pore pressure transducers (PPTs), embedded at 4 m, 8 m and 12 m below the clay surface respectively (Fig. 1), were employed to monitor the variation of pore water pressure of the soil sample during the 50-g consolidation. After consolidating for more than 18 h under 50-g to achieve an average consolidation degree of 90% or more, a T-bar test was performed to obtain the soil strength profile with depth using a jack-in velocity of 3 mm/s. This was followed by approximately another 3 h of 50-g consolidation to dissipate the excess pore water pressure induced by the T-bar disturbance. After that, the soil sample was subjected to the in-flight seismic shaking via the centrifuge shaker.

2.2. Excited ground motion at sample base

This study employed a far-field long-duration ground motion representative of far-field subduction event such as that generated along the Sunda subduction trench. As Fig. 3 shows, the peak amplitude is about 0.06*g*, and the dominant frequency is slightly less than 1 Hz, which is quite close to that of artificial earthquakes used by Balendra et al. [5] and Balendra and Li [6] to simulate the earthquake events triggered along Sunda Subduction Trench. As shown in Fig. 3(b), the response spectra of the measured base accelerations in different tests are quite comparable with each other, suggesting that the centrifuge shaking table can perform well to replicate the prescribed input ground motion in this study. As a result, hereafter, this study will not differentiate the input base accelerations from different tests unless otherwise stated.