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Soil-pile-structure kinematic and inertial interaction observed in geotechnical centrifuge experiments

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ABSTRACT

This paper reports the results of a series of centrifuge tests examining dynamic responses of single and 3×3 grouped piles embedded in sand and supporting SDOF and 2DOF structures. A total of 7 model tests were conducted with the centrifugal acceleration of 40 *g*. Each model was subjected to 12 sinusoidal waves with constant acceleration amplitude and varying frequencies. The results of the tests indicate that pile-head motion is dominated by two sequential frequencies: a lower frequency (f_{SSI}) where pile-head motion is substantially maximized and a higher one (f_{pSSI}) where the response is minimized with respect to free field surface motion. These results confirm recent published numerical results on single piles supporting SDOF structures and generalize their findings to grouped piles supporting SDOF and 2DOF structures. The results show also strong mobilized kinematic interaction effect generating significant pile bending when the ground is excited at its resonant frequency. On the other hand, structural vibrations tend to impose large bending moments as the excitation frequency approaches the natural frequency of the coupled soil-pile-structure system. Distribution of pile bending moments in the group is found to be a function of the pile position and the excitation frequency. In contrast to inner piles having the greatest kinematic bending moments, outer piles have a more pronounced inertial ones.

1. Introduction

Single and grouped piles are widely used in the foundations of many civil structures such as bridges and buildings. During earthquakes, piles undergo stresses stemming from both the vibration of the surrounding soil (kinematic interaction) and that of the superstructure (inertial interaction). Evaluating these interactions is an important issue in the seismic design of piled buildings, highway-bridges, overcrossings and ramps, several of which experienced considerable damage in the 1994 Northridge earthquake, the 1995 Hyogo-Ken Nanbu earthquake, and the 2011 Tohoku Pacific Earthquake [1,2].

Post-earthquake field investigations [3–5], well documented centrifuge and shaking table tests [6–9], and numerical simulations of piled structures [10–13] have clearly highlighted the impact of soil-pile-structure interaction on the dynamic characteristics of the structure and the seismic motion imposed at its base [10]. Such effects may be present in some degree for every structure and is what has been recognized by the modern seismic codes, such as Eurocode8 [14] that specify conditions where soil-pile-structure interaction should be accounted for in the seismic design of foundations and superstructures. These specifications are set based on a variety of numerical and analytical methods that utilize either simplified multi-step method that uncouple the structure and foundation portions, commonly referred to in literature as kinematic-inertial decomposition method (substructure approach) [15–17], or a direct analysis of the coupled soil-pile-structure system in a single step [18–20]. Several comprehensive reviews on the subject have been published, among others, by Novak [21], Pender [22], and Gazetas and Mylonakis [23]. The single-step approach gives a direct and often more convenient estimation of the seismic response of soil-pile-structure systems since inertial and kinematic effects are simultaneously modeled. However, it is very complex and requires huge computational load and resources, and consequently it is rarely performed in engineering practice [10]. On the contrary, the multi-step approach has been extensively implemented in professional engineering and research practices in lieu of the direct approach. A key limitation of the multi-step approach is that it refers to linear or moderately nonlinear response of the coupled soil-pile-structure system. In reality, the soil, the soil-pile interface and often the structure

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respond nonlinearly during an earthquake. Accordingly, either high-quality laboratory tests or case history data are required to validate the results from the substructure approach. The advantage of laboratory testing compared to field testing lies in its ability to define the site conditions and structural systems that can be in turn tested under controlled-intensity earthquake motions [24]. In addition, it provides relatively rapid, precise and detailed analyses of factors affecting the soil-pile-structure behavior under earthquake events. A powerful laboratory device for soil-pile-structure interaction testing is the geotechnical centrifuge since it allows the researcher to monitor the simultaneous seismic response of the soil, pile foundation, and structure [6,7].

At present, it seems that certain aspects of soil-pile-structure interaction require further evidence based on well-documented experimental data such as: (i) the identification of characteristic frequencies dominating pile group response in coupled soil-pile group-structure systems; (ii) the relative contributions of kinematic and inertial interaction to the dynamic bending of a pile as part of a pile group; (iii) pile-soil-pile interaction under kinematic and inertial loading as affected by the frequency content of input motion. These three aspects of soil-pile-structure interaction are discussed in this paper based on a comprehensive set of centrifuge test data, which consist of end-bearing single and 3×3grouped piles embedded in dry sand layer and supporting single (SDOF) and two (2DOF) degree of freedom structures.

The study is at an initial phase where an overview of the behavior of group pile is obtained through model tests on dense sand. The selected tested piles referred to typical hollow steel pipe piles with length, $L_p = 10$ m; diameter, $D_p = 0.4$; $L_p/D_p = 25$; and pile spacing to diameter ratio, $S/D_p = 4$. For the superstructures: we used combination of SDOF and 2DOF structures with different frequencies that are encountered in practice. In fact, pile foundations are primarily used in soft soils with dominant frequencies less than a few Hz and below resonant frequencies of structures on rigid bases. In the current study, a dry dense sand deposit is used, thereby aiming at the fundamental knowledge on the soil-pile group-structure interactions under seismic loading as a basis for further study including cases where soil is expected to liquefy. A total of 7 model tests including single and grouped piles cases were conducted with the centrifugal acceleration of 40 *g*. Each model was subjected at least to 12 sinusoidal waves with constant acceleration amplitude and varying frequencies. The results of the study are compared and presented in the form of dimensionless graphs, covering a wide range of excitation frequencies. The primary findings from this study are summarized as conclusions.

2. Centrifuge modeling

2.1. Centrifuge modeling principles

Geotechnical centrifuge modeling has been used over the past three decades to simulate dynamic and seismic events. Model similitude is an important issue in centrifuge experimentation using model scale models that are intended to capture the response of prototype scale [25–27]. During a centrifuge test, according to the scaling rules for n *g* centrifugal field, the gravity, frequency, and acceleration are to be increased by n times while the length and time are reduced by n. The stress and strain measured at model scale is the same as the stress and strain experienced by the prototype. Soil has stress-dependent strength, deformation, and volume change properties; therefore, the centrifuge is a useful tool for examining geotechnical earthquake engineering problems. Additional information on geotechnical centrifuge scaling laws can be found in Schofield [25,26]. All results presented in this study have been converted to prototype scale unless otherwise noted.

2.2. Centrifuge facility

The centrifuge tests were performed at the Disaster Prevention Research Institute, Kyoto University (DPRI-KU), Japan. The centrifuge facility has an in-flight platform radius of 2.5 m and a capacity of 24 *g*-tons. It is equipped with a one dimensional shake table (allowable displacement: ± 5 mm), which is operable under the centrifugal accelerations of up to 50 *g*. It has a single servo hydraulic actuator parallel to the rotation of the centrifuge arm, and it is controlled through a laptop personal computer (PC) on the centrifuge arm. The PC is fixed near the rotation axis of the centrifuge to minimize the centrifugal force acting on it. It is connected to a PC in the control room by a wireless LAN, and the data loggers attached on the arm are accessible from a PC in the control room through a wireless USB connection. A counterweight is loaded on other side of the arm to maintain balance during rotation [28]. In this study, all the tests were performed at a centrifugal acceleration of 40 *g* ($n = 40$).

2.3. Experimental-setup

Ground model was constructed with Silica sands No. 7. The physical properties of the sand are listed in Table 1, and the grain-size distribution curve is shown in Fig. 1. The soil is classified into “poorly graded sand (SP)”. The model ground was prepared in a strong container, which has nominal inner dimensions of $0.45 \times 0.15 \times 0.30$ m^3 with a glass wall on one side. The prototype scale depth of the model ground was 10 m. A total of 7 model tests, listed in Table 2, were performed. Schematics of experimental model tests No. 4 and 7 listed in Table 2 are provided in Fig. 2 (a) and 2(b), respectively. Fig. 2 includes important dimensions and the locations of selected instrumentation. Fig. 3 shows a plane view of the grouped pile arrangement and locations of instrumented piles. The pile group was lined up 3 by 3 with a spacing of 4 pile diameters from center to center in both directions. The tested pile had a 0.4 m outside diameter and wall thickness of 30 mm. The pile tips were set in motion fixed at the bottom of the container using a 10 mm thickness steel plate. The soil and structures were instrumented with accelerometers while piles were instrumented with accelerometers and strain gauges. These instruments recorded the seismic response of the soil, piles, and structures during test program. Detailed descriptions of the instrumentations can be found in [29].

Model piles and columns shown in Fig. 2(a) and 2(b) were made of steel tubes having the material properties listed in Table 3. Material properties and dimensions of square steel plates (Mass 1–4 shown in Fig. 2 and Table 2), used to model the structural masses, are listed in Table 4.

2.4. Model construction

The centrifuge model is normally prepared outside the centrifuge pit, and then transferred to the swinging platform. Each model was constructed very carefully so that all ground models were as identical to each other as possible. Piles were fixed in the model before the dry sand was placed, attempting to simulate a pile installed with minimal disturbance to the surrounding soil, as may be the case when a pile inserted into a pre-augered hole. The piles in the group are kept vertical in their positions using a guided plate as shown in Fig. 4. Dry silica sand was placed in the soil container using the air pluviation method [29]. Gaffer tape was used to supplementary fix the sensors in position as well as to fix the cables of the sensors to the back wall of the box to prevent unwanted influences on the sand deposit and movement of sensors. Single (Tests No. 3 and 6) or two (Tests No. 4 and 7) DOF structures were placed and fixed at pile-heads. The completed