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DYNAMIC RESPONSES OF MODEL PILE IN SATURATED SAND IN SHAKING TABLE TESTS

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ABSTRACT

For the study of the soil-structure interaction in a saturated sand under one- and two-dimensional shakings, shaking table tests on a model pile in the large biaxial laminar shear box filled with clean sand were conducted at the National Center for Research on Earthquake Engineering (NCREE), Taiwan. The model pile made of aluminum alloy was used in the shaking table tests. The pile tip was fixed at the bottom of the shear box to simulate the condition of a pile foundation embedded in a firm stratum. The pile head was mounted with various numbers of steel disks. The input shakings included sinusoidal and recorded earthquake accelerations. Strain gauges and accelerometers were placed on the pile surface to obtain the bending strains and accelerations of the pile under shaking. The responses of the model pile and the soil-pile interactions under shakings for liquefied and non-liquefied soil conditions were evaluated according to the measured data. The behavior of the pile foundation was affected by the relation among the dynamic characteristics of the pile and the surrounding soil, and the mass on the pile head.

Keywords: pile, shaking table test, liquefaction, soil-pile interaction

INTRODUCTION

Pile foundations have suffered extensive damage in saturated sand in many large earthquakes such as the 1964 Niigata Earthquake, the 1989 Loma Prieta Earthquake, the 1995 Kobe Earthquake and the 1999 Chi-Chi Earthquake. Previous studies on soil-pile interactions were conducted in order to understand the mechanism of the dynamic loading on the piles (soil-pile interaction) and their responses under earthquake loading. Lateral loading tests in the field or in the laboratory and shaking table tests on model piles within soil specimens, under either 1 g or centrifugal condition, have been used to investigate the pile behaviors and soil-pile interaction in saturated soil (e.g. Ashford et al., 2006, Dobry & Abdoun, 2001, Tokimatsu et al., 2005). The results of these studies, including bending moments along the piles, pore water pressure variation around the piles and failure mechanisms, can provide information on performance criteria for aseismic design of structures with pile foundations.

However, there are still uncertainties concerning the soil-pile interaction, including (1) the influence of the superstructure; (2) the effect of the dynamic characteristics and their correlations of the pile and the free-field soil; and (3) variations of responses of the surrounding soil and soil-pile system, especially during soil liquefaction. In addition, most studies on soil-pile interaction are tested and analyzed as one dimensional problem. In this study, a large biaxial laminar shear box developed at the National Center for Research on Earthquake Engineering (NCREE) as the soil container and an instrumented aluminum model pile was installed inside the shear box filled with saturated sand. Besides lateral loading tests on the model piles, the biaxial shear box with the model pile in a saturated sand specimen was placed on the shaking

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table at NCREE and tested under one- and multi-directional sinusoidal and recorded earthquake shakings. The responses of the model pile and soil-structure interaction under various testing conditions were studied.

MODEL PILE AND SAND SPECIMEN

The model pile was made of an aluminum alloy pipe, with a length of 1600 mm, an outer diameter of 101.6 mm, a wall thickness of 3 mm and a flexural rigidity, EI = 77.62 kN·m^2. Strain gauges and mini-accelerometers were placed at different locations to respectively measure bending strains and accelerations along the model pile. The pile was fixed at the bottom of the shear box to simulate the condition of a pile foundation embedded in rock or within a firm soil stratum. Up to 6 steel disks of mass were fixed to the top of the model pile to simulate the superstructure of different mass. Each steel disk of mass weighs 37.10 kg. The model pile with instrumentation inside the shear box was set up before preparation of the sand specimen, as shown in Figure 1.

Figure 1. The instrumented aluminum pipe inside the shear box with one steel disk of mass on its top

Clean fine silica sand (G_s = 2.65, D_{50} = 0.30 mm) from Vietnam was used in this study for the sand specimen inside the laminar shear box. This sand has been used in the shaking table tests for liquefaction studies at NCREE, Taiwan (Ueng et al., 2006). The representative grain size distribution of the sand is shown in Figure 2. The maximum and minimum void ratios are 0.882 and 0.609, respectively, according to ASTM D4253 Method 1B (wet method) and ASTM D4254 Method A. The sand specimen was prepared using the wet sedimentation method after placement of the model pile and instruments in the shear box. The sand was rained down into the shear box filled with water to a pre-calculated depth. The size of the sand specimen is 1.880 m × 1.880 m in plane and about 1.40 m in height before shaking tests. Details of biaxial laminar shear box and the sand specimen preparation were described in Ueng et al. (2006).

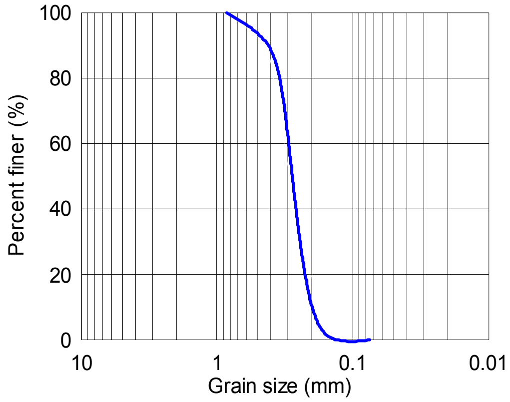


Figure 2. Grain size distribution of Vietnam sand

INSTRUMENTATION

Two linear displacement transducers (LDTs) were set up to measure X- and Y-displacements of the pile top. They were mounted to the reference frames outside the shaking table. The waterproof resistance-type strain gauges were placed on the pile surface to measure the bending strains of the model pile. There are 10 different depths with a 15-cm spacing along the pile axis as shown in Figure 3. At each depth, two pairs of strain gauges were attached on opposite sides of the pile in X- and Y-directions. Vertical acceleration arrays along the pile were also installed on the model pile in X- and Y-directions for acceleration measurements. In addition, in order to observe the build-up and dissipation of the pore water pressures and accelerations in the sand specimen (near field and far field), mini-piezometers and mini-accelerometers were installed inside the box at different locations and depths (Figure 3).

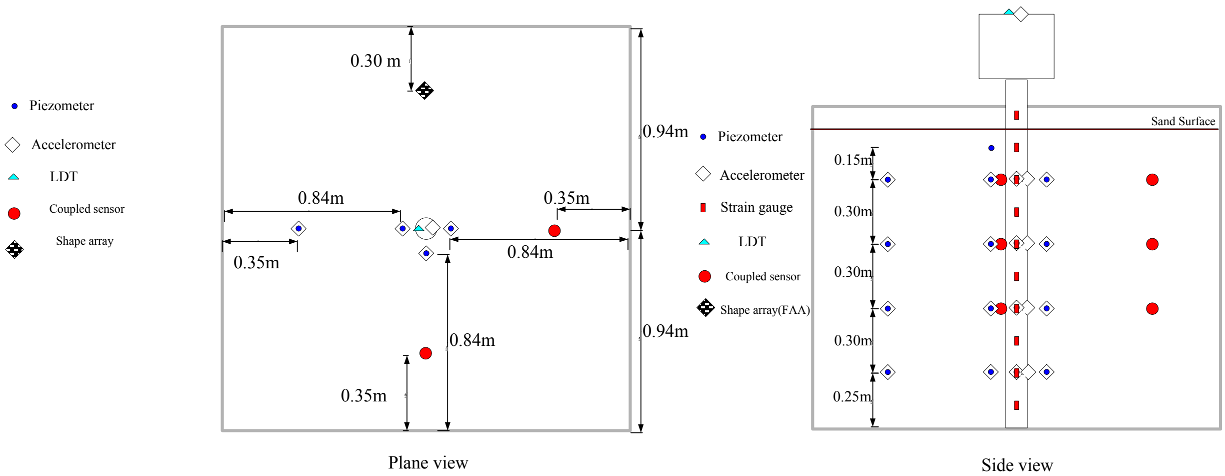


Figure 3. Instrumentation on the model pile and within the sand specimen

The responses of 15 layers of inner and outer frames at different depths of the laminar shear box were also recorded to evaluate the ground motion and liquefaction depth of the sand specimen using linear displacement transducers and accelerometers. Figure 4 shows the layout of the instrumentation on the shear box.

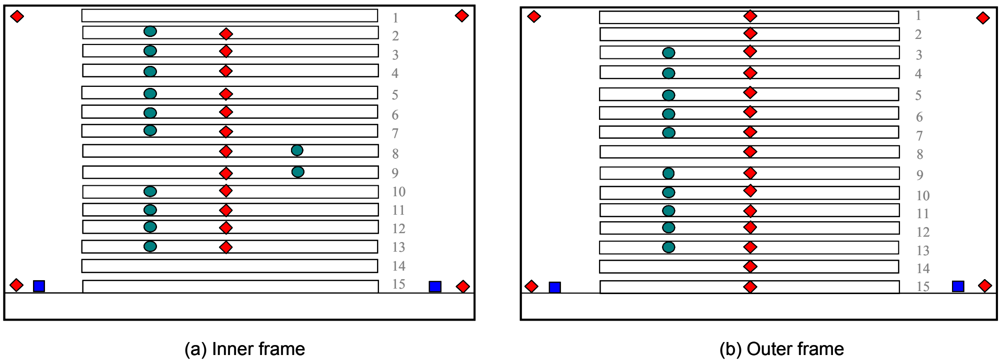


Figure 4. Instrumentation on inner and outer frames of the shear box

SHAKING TABLE TESTS

Shaking table tests were first conducted on the model pile without the sand specimen in order to evaluate the dynamic characteristics of the model pile itself. Sinusoidal and white noise accelerations with amplitudes from 0.03 to 0.075 g were applied in X and/or Y directions. In the two-dimensional (multidirectional) sinusoidal shaking, there is a 90° phase difference between the input acceleration in X and Y directions, i.e., a circular or ellipse motion was applied. The model pile within the saturated sand specimen was then tested under one- and multi-directional sinusoidal (1-24 Hz) and recorded accelerations during Chi-Chi Earthquake and Kobe Earthquake with amplitudes ranging from 0.03 to 0.25 g. White noise accelerations with amplitude of 0.03 g were also applied in both X- and Y-directions to investigate the dynamic behaviors of the model piles within soil and the sand specimen. Figure 5 shows a picture of shaking table test on the model pile with 6 steel disks of mass on its top. The height of the sand surface after each shaking test was measure to compute the settlement and density of the sand specimen. Soil samples were taken using short thin-walled cylinders at different depths and locations after completion of the shaking tests to obtain the densities of the sand specimen.

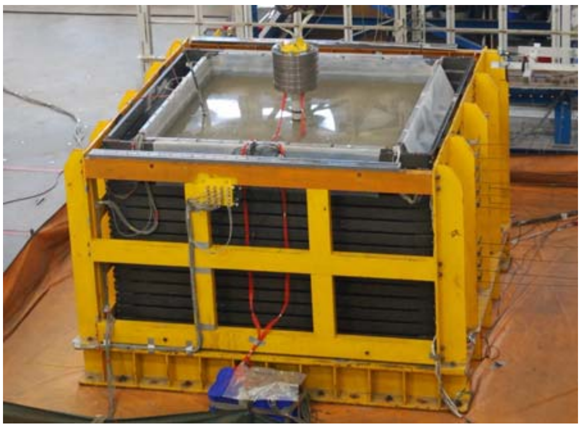


Figure 5. A model pile with 6 steel disks of mass on its top in the saturated sand specimen on the shaking table

TEST RESULT

Dynamic characteristics of the model pile

Shaking table tests on the model pile without sand specimen were conducted to evaluate the dynamic characteristics of the model pile itself. We consider the behavior of model pile on the shaking table as a single-degree viscously damped system. The amplification curve was obtained from the Fourier spectral ratio of the measured acceleration of the pile top to that of the input motion. The predominant frequency of the model pile with 6 steel disks of mass on its top was identified at about 2.07 Hz as shown in Fig. 6. Table 1 lists the predominant frequencies of the model pile according to the test data. The average damping ratio of the model piles is about 1.4 % according to observations of the free vibration of the piles after the end of the input motions.

Table 1. Predominant frequencies of the model pile

Mass on pile top	Aluminum pile
	Freq., Hz
No mass	21.40
1 steel disk	5.55
3 steel disks	3.11
6 steel disks	2.07

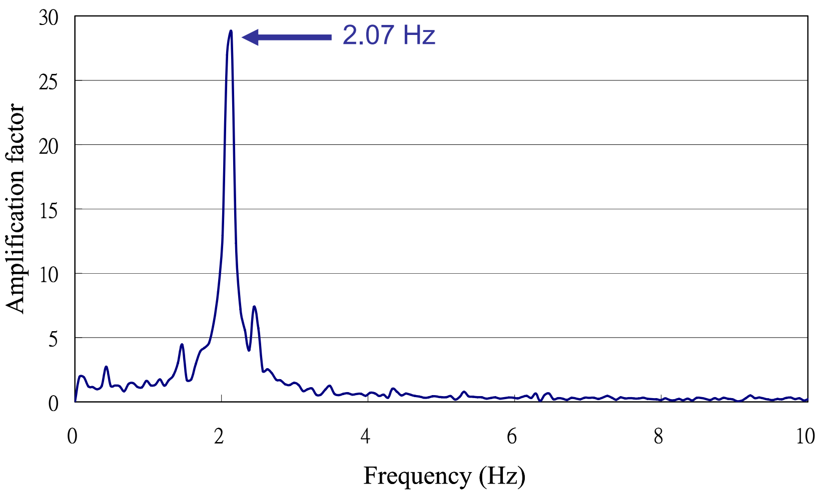


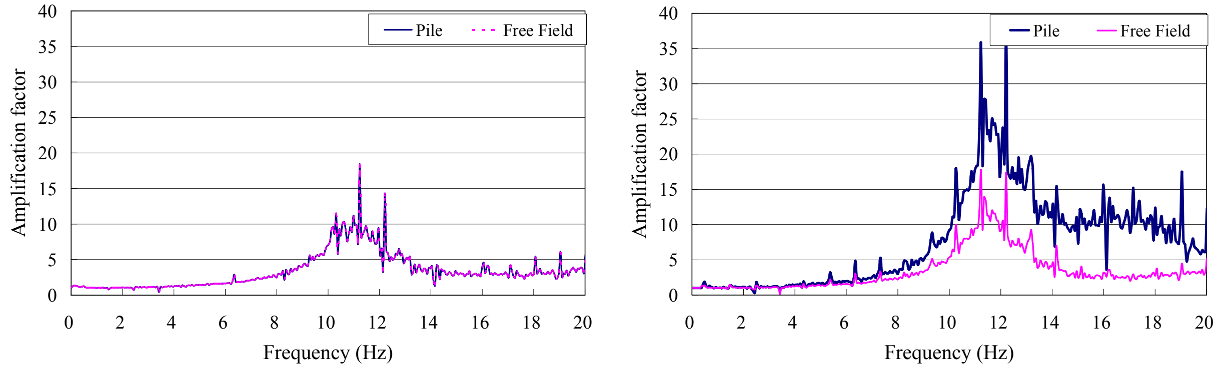
Figure 6. Amplification factor vs. frequency for the model pile

Dynamic characteristics of soil and soil-pile system under small amplitude of shakings

In order to investigate the effect of superstructure on soil-pile interaction prior to soil liquefaction, the dynamic characteristics of the soil stratum and soil-pile system were evaluated by white noise shaking with small amplitude. Table 2 lists the predominant frequencies of the soil and the soil-pile system for the model pile in soil of various relative densities. It can be seen that the density of sand specimen would increase after each shaking. In addition, for the model pile without mass and with one steel disk of mass, the predominant frequencies of both soil and the soil-pile system are almost the same and these frequencies increase with the relative density of the soil specimen. For the pile with 3 or 6 steel disks, the predominant frequency of soil-pile system is significantly lower than that of the soil specimen. Comparing the predominant frequencies of the model pile without and within soil specimen (Table 1 and Table 2, respectively), one can find that, except for the case without mass on the pile top, the predominant frequencies of the model pile in the soil specimen were higher than those without soil due to the constraint of the soil on the pile. For small inertia force from the superstructure (e.g. no mass or 1 steel disk of mass on the pile top), the pile responses were dominated by the kinematic force from the soil motion, but for large inertia force (e.g. 6 steel disks of mass on the pile top), the response of pile was mainly governed by the inertia force from the superstructure. Therefore, these observations suggest that the mass and inertia force induced by the superstructure play an important role on the soil-pile interaction.

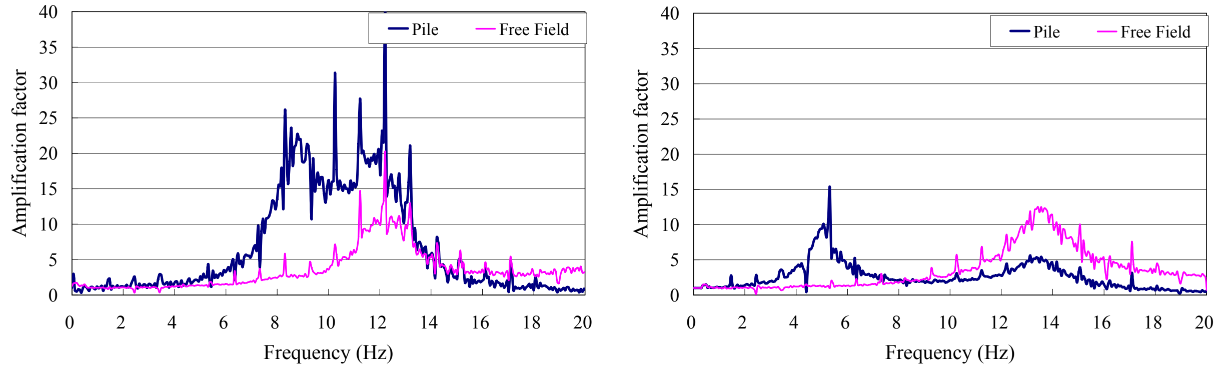
Table 2. Predominant frequencies of soil and soil-pile system for the aluminum pile in the soil specimen of different relative densities

Mass on pile top	Soil Freq., Hz	Soil-Pile Freq., Hz	Dr %
No mass	11.5	11.5	27.3
1 steel disk	11.5	11.5	38.1
1 steel disk	11.6	11.6	42.8
3 steel disks	12.0	8.70	42.9
3 steel disks	12.7	9.28	50.4
6 steel disks	13.7	4.87	70.2



(a) No mass on the pile top (Dr = 27.3 %)

(b) 1 steel disk on the pile top (Dr = 38.1 %)



(c) 3 steel disks on the pile top (Dr = 42.9 %)

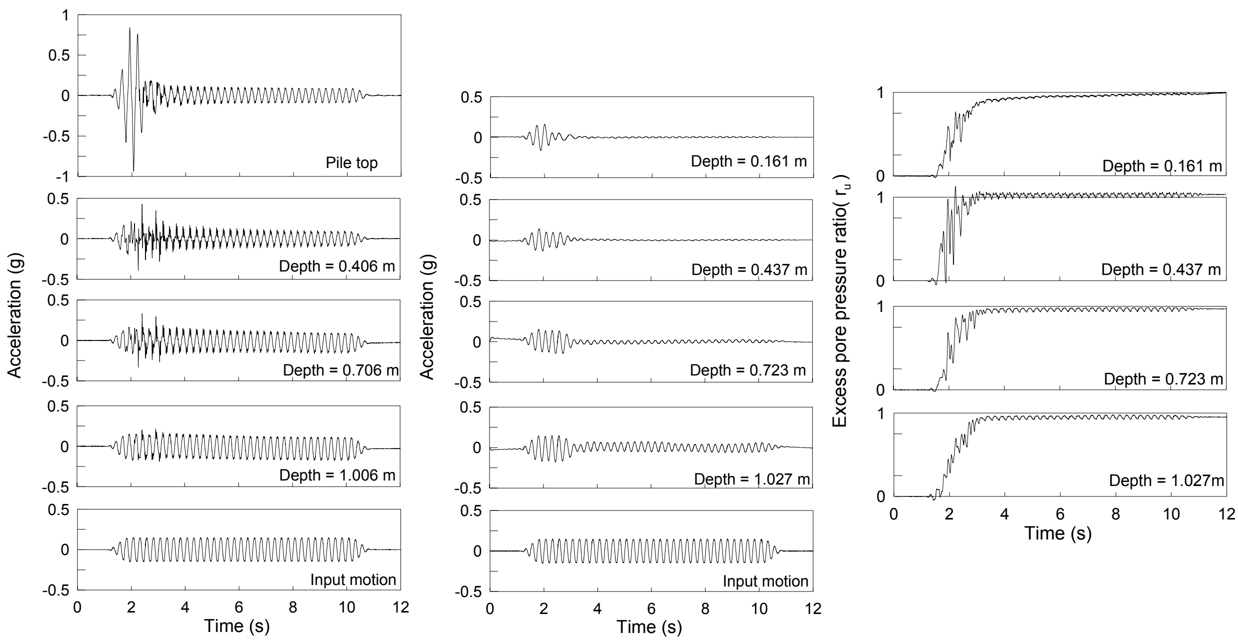
(d) 6 steel disks on the pile top (Dr = 70.2 %)

Figure 7. Amplification factor vs. frequency for free-field soil and the model pile with various mass on its top

Figure 7 shows the amplification curves of free-field soil and the model pile, with and without mass on the pile top, in sand specimen of various relative densities under white noise shakings with amplitude of 0.03 g. It can be seen that, for the model pile without mass, the amplification curves of both soil and the pile are almost the same. As the mass on the pile top increases, there is a tendency to have distinct peaks at two different frequencies for the amplification curve of the model pile. One is the predominant frequency of the soil-pile system and the other is the predominant frequency of the soil specimen. In the case of model pile with 6 steel disks of mass (Figure 7(d)), the inertia effect of the pile and the added mass appears more pronounced than the kinematic effect of the soil movement on the pile behavior under shaking. More tests and analyses are needed to further evaluate the relative importance of the kinematic and inertia effects on the soil-pile interaction and the pile performance during earthquakes.

Response of model pile in liquefiable soil

A shaking table test under one-dimensional sinusoidal acceleration with frequency of 4 Hz and amplitude of 0.15 g was conducted to study the pile response in a liquefied ground. Figure 8 shows the measured time histories of accelerations of the model pile with 6 steel disks of mass on its top, the free-field soil, and excess pore water pressure ratios (r_u) at various depths in the sand specimen with relative density of 68.6 %. It can be seen that the accelerations of pile and soil increase with height due to the upward shear wave propagation. The depth of liquefaction was determined based on the measured pore water pressures in the sand specimen and accelerometers on the frames (Ueng et al., 2010). In this shaking test, the sand specimen was fully liquefied at about 3.1 seconds. It was found that the maximum accelerations along the pile occurred just before liquefaction of the sand specimen. After liquefaction, the acceleration of the pile reduced and remained steady while the acceleration of the soil diminished. This phenomenon can be interpreted as that the stiffness of the soil almost vanished when the specimen was fully liquefied.



(a) Pile accelerations (b) Soil accelerations (c) Excess pore pressure ratios

Figure 8. Time histories of accelerations of the model pile and the free-field soil, and excess pore pressure ratios in the sand specimen

The amplification curve of the model pile top with 6 steel disks of mass during the post-liquefaction period was shown in Fig. 9. The predominant frequency of the model pile within liquefied soil was identified at around 2 Hz. Comparing this result with the predominant frequency of the model pile without soil specimen (Table 1 & Fig. 6), one can find that the predominant frequency of the model pile within liquefied soil was almost the same as that of model pile without soil specimen. This inferred that the stiffness of the soil almost vanished when soil liquefaction occurred. Further analysis of the soil reaction on the model pile is needed to verify the inference.

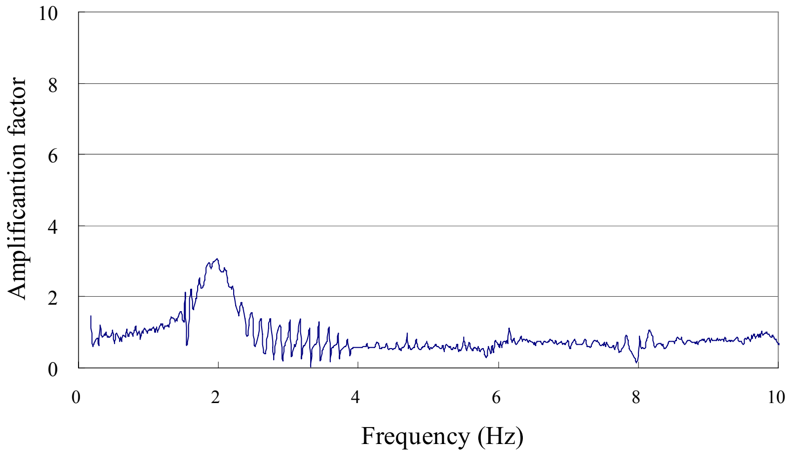


Figure 9. Amplification factor vs. frequency for model pile with 6 steel disks of mass after initial liquefaction

CONCLUSIONS

Shaking table tests were conducted on an aluminum model pile in the biaxial laminar shear box with and without saturated sand specimen. The displacements, strains and accelerations at different depths of the model pile were measured. Analyses of the dynamic behavior of the model pile and the pile-soil system during shaking tests were conducted based on the test results. It is concluded that the behavior of the model pile under shaking was affected by the soil specimen density, the dynamic characteristics of the pile and the surrounding soil, and the mass of the superstructure. Dynamic pile behavior was controlled by kinematic effect from ground motion and inertia effect from the superstructure. For a small inertia, the pile responses were dominated by the kinematic force, but for a large inertia, the responses of pile were mainly governed by the inertial force according to the amplification factor. In addition, the stiffness of the soil almost vanished when soil liquefaction occurred. Further tests and analyses of the test data will be performed to obtain more information on the soil-pile interaction, such as the relationship among soil reaction on the pile, pore water pressure generation, and pile displacements and their coupling.

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REFERENCES

Ashford, S. A., T. Juirnarongrit, T. Sugano and Hamada, M. (2006). "Soil–pile response to blast-induced lateral spreading I: Field Test," Geotechnical and Geo-environmental Engineering, Vol. 132, No.2, pp. 152-162.

Dobry, R. D. and Abdoun, T. (2001). "Recent studies on seismic centrifuge modeling of liquefaction and its effect on deep foundations," State-of-the-Art Report (SOAP3), Proceedings of 4th International Conference on Recent Advance in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, CA, 26-31 March, Vol. 2.

Tokimatsu, K., Suzuki, H. and Sato, M. (2005). "Effect of inertial and kinematic interaction on seismic behavior of pile with embedded foundations," Soil Dynamics and Earthquake Engineering, Vol. 25, No. 7-10, pp. 753-762.

Ueng, T. S., Wang, M. H., Chen, M. H., Chen, C. H. and Peng, L. H. (2006). "A large biaxial shear box for shaking table tests on saturated sand," Geotechnical Testing Journal, Vol. 29, No. 1, pp. 1-8.

Ueng, T. S., Wu, C. W., Cheng, H. W. and Chen, C.H. (2010). "Settlements of saturated clean sand deposits in shaking table tests," Soil Dynamics and Earthquake Engineering, Vol. 30, No. 1-2, pp. 50-60.