Shaking table tests on model piles in liquefiable sand

Essai sur table vibrante de pieux modèles dans du sable liquéfiable

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ABSTRACT
For the study of the soil-pile interaction in a liquefiable soil under earthquake shakings, lateral load tests and shaking table tests on two model piles, one of stainless steel and another of aluminum alloy, in the large biaxial laminar shear box filled with saturated sand were conducted at the National Center for Research on Earthquake Engineering (NCREE), Taiwan. The pile tip was fixed at the bottom of the laminar shear box to simulate the condition of the pile foundation embedded in a firm stratum. Strain gauges and accelerometers were placed on the pile surface to obtain the pile behaviors during shaking. The near- and far-field soil responses, including pore pressure changes, accelerations, and settlements were also measured using mini piezometers, accelerometers and displacement sensors. Lateral load tests from the reaction wall and one- and multi-directional shaking table tests were performed on the model piles in the shear box with and without soil. The test results from the lateral load tests and shaking table tests were analyzed and compared. The responses of the model pile and the soil-pile interactions under shakings for liquefied and non-liquefied soil conditions were evaluated. The performance of the pile foundation was affected by the relation among the dynamic characteristics of the pile and the surrounding soil, and the mass of the superstructure.

RÉSUMÉ
Pour l'étude de l’interaction sol-pieu dans un sol liquéfiable soumis à des secousses sismiques, des essais de chargement latéral et des essais sur table vibrante ont été réalisés au National Center for Research on Earthquake Engineering (NCREE) de Taïwan sur deux pieux modèles, l'un en acier inoxydable et l’autre en alliage d'aluminium, à l’aide d’une grande boîte de cisaillement bi-axial laminaire remplie de sable saturé. La pointe du pieu a été fixée au fond de la boîte de cisaillement laminaire pour simuler l'état des fondations de pieux enfouis dans une couche ferme. Les jauges de contrainte et les accéléromètres ont été placés sur la surface du pieu pour obtenir le comportement du pieu au cours des secousses. Les réponses du sol en champ proche et lointain, y compris les variations de pression interstitielle, les accélérations et les tassements, ont également été mesurées à l'aide de mini-piézomètres, d'accéléromètres et de capteurs de déplacement. Des essais de chargement latéral du mur de réaction et des essais monodirectionnels et multidirectionnels sur table vibrante ont été effectués sur des pieux modèles dans la boîte de cisaillement laminaire avec et sans sol. Les résultats des essais de chargement latéral et des essais sur table vibrante ont été analysés et comparés. La réponse du pieu modèle et l’interaction sol-pieu lors de secousses dans des conditions de sol liquéfié et non liquéfié ont été évaluées. Les performances de la fondation du pieu ont été affectées par la relation entre les caractéristiques dynamiques du pieu et le sol environnant, et la masse de la superstructure.

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

1 INTRODUCTION

In the previous large earthquakes, such as 1964 Japan Niigata Earthquake, 1989 US Loma Prieta Earthquake, 1995 Japan Kobe Earthquake and 1999 Taiwan Chi-Chi Earthquake, there are many cases of pile foundation failures due to soil liquefaction, which caused loss of soil supports for the piles or induced lateral spreading. Therefore, many studies on soil-pile interactions for pile foundations in a liquefiable stratum were conducted recently in order to understand the mechanism of the dynamic loading on the piles (soil-pile interaction) and their responses under earthquake loading. The results of these studies provide the bases for aseismic design criteria for structures with pile foundations.

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 conditions, have been used to investigate the pile behaviors and soil-pile interaction in liquefiable soils (e.g., Ashford et al., 2006; Dobry & Abdoun, 2001; Tokimatsu et al., 2005). This research used the large biaxial laminar shear box developed at NCREE as the soil container and the instrumented model pile was installed inside the shear box filled with saturated sand. Lateral load tests and shaking table tests were then conducted at NCREE. The soil and pile responses and their interaction under these types of shakings were studied including the inertial and kinematic actions on the model pile.

2 MODEL PILES AND SAND SPECEMEN

Two different types of model piles were used in the shaking table tests. One was made of a stainless steel pipe, 1.50 m in length, with an outer diameter of 101.6 mm, a wall thickness of 3 mm and a flexural rigidity, EI, of 186.05 kN-m^2; the other was made of an aluminum alloy pipe, 1.60 m in length, with the same diameter and wall thickness and EI = 77.62 kN-m^2. The pile was fixed at the bottom of the shear box to simulate the condition of a pile foundation embedded in the rock or within a firm soil stratum. A rigid steel adapter for application of lateral force was fixed to the top of the steel pile, while up to 6 disks of masses were fixed to the top of the aluminum pile to simulate various conditions of the superstructure. Each disk of mass weighs about 37.10 kg. Displacements, bending moments and

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M. Hamza et al. (Eds.)

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accelerations were measured at different locations along the pile. The model pile with instrumentation was set up before preparation of the sand specimen, as shown in Figure 1.

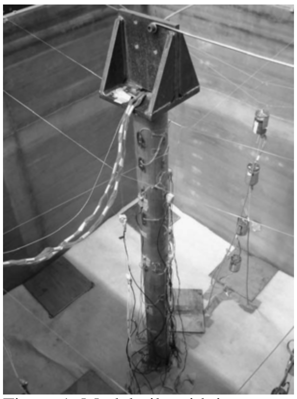


Figure 1. Model pile with instrumentation

Clean fine silica sand from Vietnam was used for the sand specimen inside the laminar shear box. The maximum and minimum void ratios are 0.887~0.912 and 0.569~0.610, respectively. The sand specimen was prepared using the wet sedimentation method after the 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, as shown in Fig. 2. The size of sand specimen is 1.880 m × 1.880 m in plane and about 1.40 m in height before shaking tests. Details of the sand specimen preparation and the mechanism of the biaxial laminar shear box were described in Ueng et al. (2006).

3 LATERAL LOAD TESTS

The lateral load tests on the steel model pile with and without sand were performed under static and cyclic loading by an actuator fixed on the reaction wall at NRCEE (Fig. 2). The input motions of cyclic loading included sinusoidal waves with amplitudes ranging from 1 mm to 5 mm and frequencies of 0.5 Hz, 1 Hz and 2 Hz. The dial gages, strain gages and piezometers were installed at various locations to measure the responses of pile and soil under different loading conditions. The height of the sand surface after each loading test was measured to calculate the settlement and density of the sand specimen.

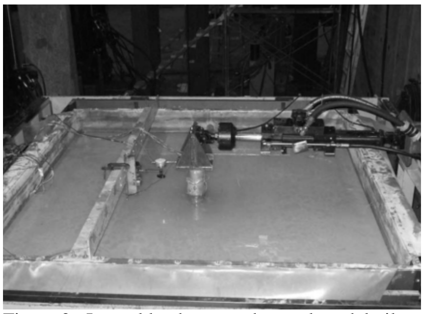


Figure 2. Lateral load test on the steel model pile

4 SHAKING TABLE TESTS

Shaking table tests were first conducted on each model pile without sand specimen to evaluate the dynamic behavior of the pile itself. Sinusoidal and white noise accelerations with amplitudes from 0.03 to 0.075 g were applied in X- and Y-directions. The model pile within the saturated sand specimen was then tested under one- and multi-directional sinusoidal (1~24 Hz) and recorded earthquake accelerations with amplitudes ranging from 0.03 to 0.15 g. White noise accelerations were also applied in both X- and Y-directions to investigate the behaviors of the model pile and the sand specimen of various soil densities at different occasions during shaking tests. Figure 3 shows a shaking table test of the aluminum model pile in the sand specimen.

During every test, pile top displacements, strains and accelerations at different depths on the pile, and pore water pressures and accelerations in the sand specimen (near field and far field) were measured using displacement transducers, strain gages and accelerometers. Besides, the frame movements at different depths of the laminar shear box were also recorded to evaluate the responses and liquefaction of the sand specimen. Pore water pressures inside the sand specimen were measured continuously until sometime after the end of shaking to observe the generation and dissipation of the pore water pressures. The height of the sand surface after each test was obtained for the settlement and density of the sand specimen. Soil samples were taken using short thin-walled cylinders at different depths after completion of the shaking tests to obtain the densities of the sand specimen.

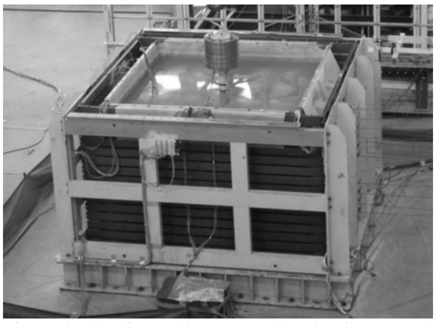


Figure 3. Shaking table test on the aluminum model pile in saturated sand

5 TEST RESULT ANALYSES

5.1 *Characteristics of model piles*

The flexural rigidity of the steel model pile was verified with the results of the lateral load tests on model pile without soil specimen. An additional equivalent rotational spring was considered to take into account the possible rotation at the pile tip at the bottom of the shear box. Shaking table tests on both model piles without sand specimen were conducted to evaluate the dynamic behaviors of the model piles themselves. The dynamic characteristics can be evaluated based on the forced vibration of white noise shaking. The amplification curve was derived from the Fourier spectral ratio of the measured accelerations of the pile top to those of the input motions. The predominant frequency of the steel pile was identified at around 13.62 Hz as shown in Figure 4 along with the results. Figure 5 also shows that the amplification factors from the sinusoidal shakings are in good agreement with amplification curve from the white noise shaking with small amplitude of acceleration. This predominant frequency was also verified with observations of free vibrations after the end of the input motions. Table 1 lists the predominant frequencies of the steel and aluminum model piles according to the test data. It was found that a single hinged-end beam with a rotational spring can well simulate the dynamic behaviors of the model pile in our tests.

Table 1. Predominant frequencies of the model piles without soil

Mass on pile top	Steel pile	Aluminum pile
	Freq., Hz	Freq., Hz
No mass	….	23.4
Rigid adapter	13.62	…
1 disk of mass	…	5.55
3 disks of masses	…	3.11
6 disks of masses	…	2.07*

* This frequency was obtained by numerical method.

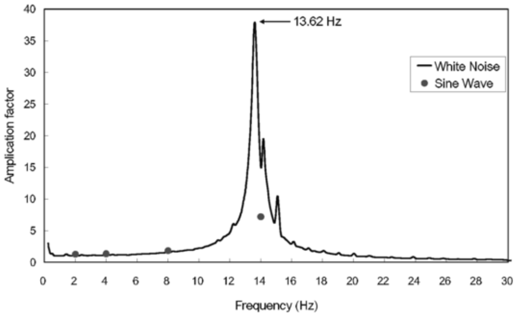


Figure 4. Amplification factor vs. frequency for the steel pile from forced vibrations

5.2 *Pile and soil responses in the lateral load tests*

A typical force-displacement relation for the pile top in a lateral load test on the steel model pile within the sand specimen is shown in Figure 5. The equivalent stiffness and damping ratio of the pile top motion were obtained based on the hysteresis force-displacement relation. The stiffness of pile top displacement decreases with increasing deflection and increases with frequency as shown in Figure 6a. The damping ratio of the model pile increases with increasing deflection and decreases with frequency as shown in Figure 6b. The p-y curves were also obtained based on the measured pile curvatures along the pile. The modulus of p-y curve increases with the pile depth, and increases with loading frequency. It was observed that the generated excess pore water pressure mainly occurred near the pile perimeter when the model pile subjected to lateral load. Positive excess pore water pressures were generated on the compression side of the pile, while on the extension side, negative excess pore water pressures were observed.

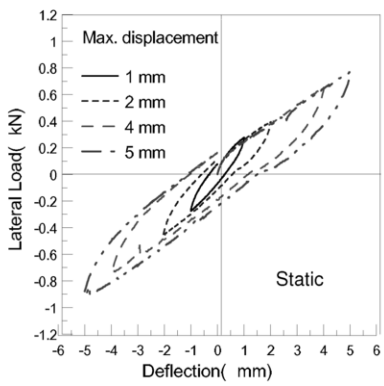


Figure 5. Force-displacement relation for the pile top in lateral load tests on the steel model pile in sand specimen

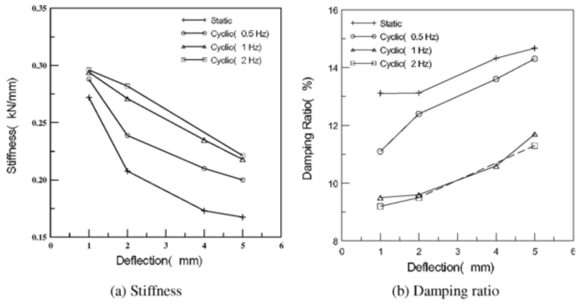


Figure 6. Stiffness and damping ratio of the pile top displacement under cyclic lateral loadings of various frequencies

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

Figure 7 shows the amplification factors for the steel pile top and the free-field ground surface under the white noise accelerations and sinusoidal vibrations of various frequencies with amplitude of 0.03 g. It is found that the predominant frequencies of both free-field soil and the pile in soil are nearly the same with a value of about 11.5 Hz. Table 2 lists the predominant frequencies of soil and the pile in soil specimens of different densities for the case of the steel model pile. It can be seen that the predominant frequencies of soil and the pile in soil are almost the same and these frequencies increase with relative density of the soil specimen. This infers that the kinematic effect from the soil motion dominates the pile response because of the small inertia force from the superstructure.

Table 3 lists the predominant frequencies of soil and the aluminum pile in soil of various relative densities. It can be seen that, for the model pile without mass and with one disk of mass, the predominant frequencies of both soil and the pile are almost the same and these frequencies increase with the relative density of the soil specimen. For the pile with 6 disks of masses, the predominant frequency of the pile in soil is significantly lower than that of the free-field soil. Comparing the predominant frequencies of the aluminum pile without and with soil specimen (Table 1 & Table 3), 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 soil on the pile. The lower predominant frequency of the model pile without mass in the soil specimen might be attributed to the kinematic effect from the soil motion, which has a lower frequency, dominates the pile response because of the small inertia force from the superstructure. Therefore, these observations suggest that the mass and inertia force induced by the superstructure can have an important effect on the soil-pile interaction.

Table 2. The predominant frequencies of soil and soil-pile system for the steel pile in different soil relative densities, Dr

Density of soil	Predominant frequency , Hz	
Dr, %	Soil	Pile in soil
37.13	11.5	11.5
50.78	12.5	12.38
70.58	12.9	12.9

Table 3. Predominant frequencies of soil and soil-pile system for the aluminum pile in the soil specimen of different relative densities, Dr

Density of soil,	Mass on pile top	Predominant frequency, Hz	
Dr, %		Soil	Pile in soil
7.5	No mass	10.49	10.49
30.6	No mass	11.68	11.7
31.7	1 disk of mass	11.8	11.7
40.5	1 disk of mass	11.8	11.7
56.6	6 disks of masses	13.1	4.88
65.4	6 disks of masses	13.2	5.1

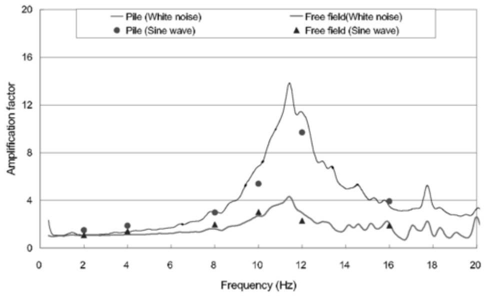
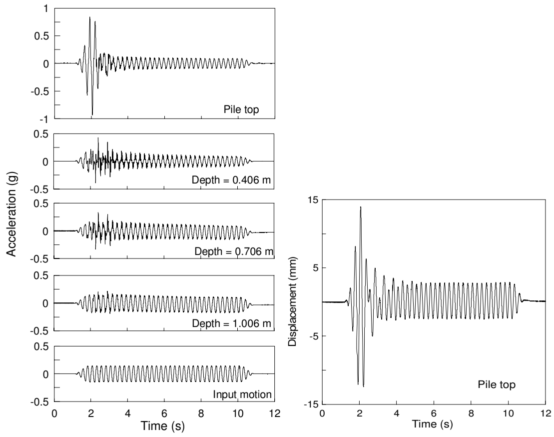


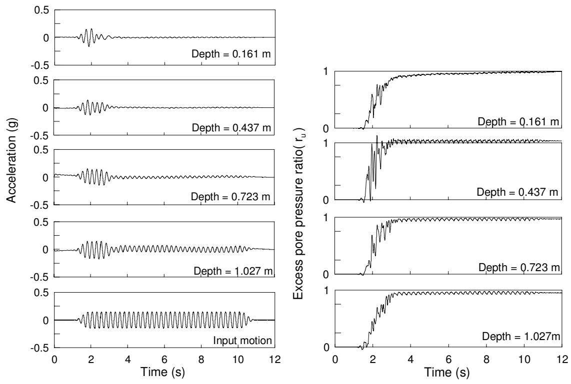
Figure 7. Amplification factors versus frequency for free-field soil and steel pile in soil (Dr = 37.13 %)

5.4 *Response of model piles in liquefiable soil*

Figure 8 showed the measured time histories of accelerations and displacements of the aluminum pile with 6 masses on its top and accelerations of the free-field soil, and excess pore water pressure ratios (r_u) at various depths in the specimen during one-dimensional sinusoidal shaking with frequency of 4 Hz and amplitude of 0.15 g, respectively. The depth of liquefaction was determined based on the measurements of mini-piezometers in the sand specimen and accelerometers on the inner frames (Ueng et al. 2008). In this shaking, the sand specimen was fully liquefied. It was found that the maximum accelerations along the pile occurred before liquefaction of the sand specimen. After liquefaction, the accelerations of the pile reduced and remain steady while the accelerations of the soil diminished. This phenomenon can be interpreted as that the stiffness of the soil almost vanished when the specimen was fully liquefied. The reason might be attributed to the lower predominant frequency of the aluminum pile with masses because of the lack of soil constraint. These results suggest that the acceleration and displacement of the pile with a mass may decrease due to soil liquefaction, but the stability of the pile-structure system should depend on the depth of liquefaction, the conditions of superstructure and the load capacity of the pile foundation.



(a) Pile accelerations (b) Pile top displacement



(c) Soil accelerations (d) Excess pore pressure ratios

Figure 8. Time histories of accelerations of the aluminium pile and the far-field soil, pile top displacement and excess pore pressure ratios in the sand specimen (Dr = 64.7 %)

6 CONCLUSIONS

Lateral load tests and shaking table tests were conducted on a steel and an aluminum model piles in the biaxial laminar shear box with and without saturated sand. The displacements, strains and accelerations at different depths of the model pile were measured. It was found that the behavior of the model piles under shaking was affected by the soil specimen density, the dynamic characteristics of the piles and the surrounding soil, and the mass of the superstructure. Further tests and analyses of the test data will be performed to understand the soil-pile interaction, such as the relationship of ground reaction on the pile, and pore water pressure generation versus pile displacements (p-y curve) and their coupling.

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