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CENTRIFUGE MODEL TESTS ON GROUP PILES IN LIQUEFIABLE AND NON-LIUEFIABLE GROUND

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SUMMARY

Model tests are performed on group piles in liquefiable and non-liquefiable ground using a geotechnical centrifuge with a 2.5 m arm length at the Disaster Prevention Research Institute, Kyoto University. The objective of this study is to obtain an overview on how behavior of a soil-pile system is affected by difference in the fundamental conditions, such as single or group pile condition, or under static or dynamic condition (i.e. shaking table tests). Results of the model tests indicate that (1) larger residual displacements of a soil-pile system are expected during dynamic loading for the same level of inertia force, and (2) group pile effects are observed in liquefied ground.

INTRODUCTION

Pile behavior under seismic loading has a long history of research and the relevant literatures are abundant (e.g. Finn [1]). Through the history of research, common understanding has been gradually formed among researchers and design engineers in that (1) pile behavior under seismic loading is different from that under static loading for the same level of external load, and (2) group pile effects are also observed during the seismic loading condition. However, interpretation of these research results in design practice, including those with respect to the very fundamental issue, still differs from one practice to another. For example, depending on the design practice, the p-y curve or coefficient of subgrade reaction for use in pseudo-static seismic design is either stiffer or softer than that for static loading condition (e.g. API [2], Japan Road Association [3]). The coefficient of subgrade reaction in liquefiable ground for use in design differs from one practice to another (e.g. Japan Road Association [3]; Architectural Institute of Japan [4]). In view of this variety in the current state of practice, there is a need to demonstrate which design practice fits better to the actual performance of pile under seismic loading. In particular, in stead of studying the static and dynamic behaviors by separate groups of specialists, a comparative study on the static and dynamic behavior of piles may be necessary to resolve these issues.

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With this ultimate objective in mind, the authors performed a series of centrifuge model tests on group piles to obtain an overview of how the behavior of a soil-pile system is affected by the difference in fundamental conditions, such as single or group pile condition, or under static and dynamic condition (i.e. shaking table tests). The paper presents the results of the initial series of the model tests and tentative conclusions, which could be useful to identify the high priority areas in the subsequent test program scheduled in the near future.

The test results are presented in terms of prototype unless otherwise stated.

EXPERIMENTAL SETUP

Geotechnical centrifuge, soil container, and shaking table

Model tests on group piles in liquefiable and non-liquefiable ground were performed using a geotechnical centrifuge with a 2.5 m arm length, maximum capacity of 24 G-ton, at the Disaster Prevention Research Institute, Kyoto University. The centrifugal accelerations used were 20g for static tests and 40g for dynamic tests. Both cases corresponded to the same prototype. Inner dimensions of a rigid container were 0.5 m (L) x 0.15 m (W) x 0.3 m (H) for static tests and 0.4 m (L) x 0.1 m (W) x 0.28 m (H) for dynamic tests. In the static test, load was applied to a pile head through a worm and bevel gear and an electric motor attached to the rigid container. In the dynamic test, the rigid container was put on a shaking table with maximum force capacity 14.7kN, maximum acceleration 10g, maximum amplitude ±2.5mm, in model scale.

Material properties of soil, fluid, and piles

The model ground was made of Silica sand #7 with the physical properties shown in Table 1 and the particle size distribution curve shown in Figure 1. Saturated model ground was made with a viscous fluid using Metolose (Type: SM-25 Shin-Etsu Chemical Co.) dissolved into lukewarm water for properly simulating pore water pressure dissipation during and after shaking. Metolose is water-soluble cellulose made of organic material. Since Metolose is sensitive to temperature change, viscosity was measured by viscometer in room temperature before poring sands to achieve the specified viscosity (40cSt for 40g centrifugal acceleration).

Brass tubes were used for model piles with dimensions shown in Table 2. In this table, prototype refers to the piles used in the in-situ full-scale tests performed by Rollins [5].

Table 1 Physical properties of Silica sand #7

Dry unit weight γd(kN/m^3)	14.0
Maximum void ratio	1.2
Minimum void ratio	0.70
Average diameter D_{50}(mm)	0.13
Coefficient of uniformity Uc	1.9
Friction angle (degree)	43.0

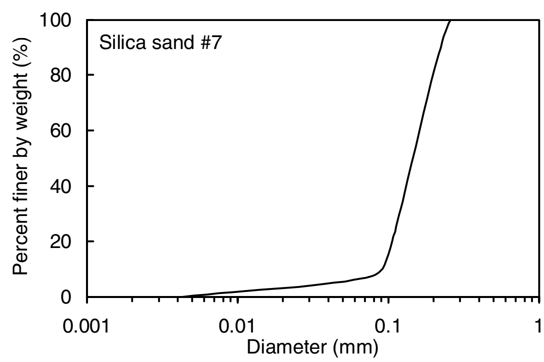

Figure 1 Particle size distribution of Silica sand #7

Test programs

A total of six centrifuge tests was performed as shown in Table 3. Two of them (Test Nos. 1 and 2) were static lateral loading tests and the rest of four cases (Test Nos. 3 through 6) were dynamic tests. These static and dynamic tests were performed for single or group pile condition, with dry or

Table 2 Dimensions and material properties of piles

(a) For static tests

	Brass tube		Prototype	
	Model scale	Prototype scale	Target	Unit
Length	0.5	10	10	m
Outer diameter	15	300	305	mm
Wall thickness	1	20	9.5	mm
Young's modulus (E)	100.5	100.5	200	Gpa
2nd moment of area (I)	1083	1.73×10^8	9.64×10^7	mm^4
Bending stiffness (EI)	108.9	1.74×10^7	1.93×10^7	$MN\text{-}mm^2$

(b) For dynamic tests

	Brass tube		Prototype	
	Model scale	Prototype scale	Target	Units
Length	0.25	10	10	m
Outer diameter	7	280	305	mm
Wall thickness	0.9	36	9.5	mm
Young's modulus (E)	101	101	200	GPa
2nd momemt of area (I)	82	2.1×10^8	9.64×10^7	mm^4
Bending stiffness (EI)	8.2	2.11×10^7	1.93×10^7	$MN\text{-}mm^2$

Table 3 Test cases

Test No.	Loading	Pile setup	Soil deposit	Centrifugal Acc.	Relative density (%)
1	Static	Single	Dry	20g	70
2	Static	Group	Dry	20g	65
3	Dynamic	Single	Dry	40g	68
4	Dynamic	Single	Sat	40g	40
5	Dynamic	Group	Dry	40g	83
6	Dynamic	Group	Sat	40g	37

saturated ground condition as shown in Table 3.

Typical cross sections of model tests are shown in Figure 2. As shown in this figure, group piles were lined up 3 by 3 with a spacing of 3 times a pile diameter. The pile head was set in rotation free to simulate the prototype, and the pile end was set in rotation fixed at the bottom of container using a stainless plate 16 and 8mm thick (in model scale) for static and dynamic tests.

For static tests as shown in Figure 2(a), loading height was 0.4 m from the ground surface. Lateral load was applied to piles through small bits attached to stainless bars attached to a lattice work. Loading rate was about 1mm/min in model scale. Dry sand deposit was prepared by air pluviation.

For dynamic tests, a weight made of brass plate was attached at the pile head with free rotation condition in order to simulate the inertia force applied on piles. One brass plate (0.80 kg in model scale) was used for single pile test (Test Nos. 3 and 4) and a stack of four plates (2.75 kg in model scale) was used for group pile tests (Test Nos. 5 and 6). As shown in Figure 2(b), in order to put these plates at the specific height, i.e., 0.4m from the ground surface, a short bar was laterally attached on each pile to keep plates on top of it. Holes of a plate were made larger than the pile diameter except the bottom plate, where the hole size was tapered off to exactly fit to the pile as shown by broken lines in this figure. Dry sand deposit was prepared by air pluviation. Saturated sand deposit was prepared through dispersion of sands with small spoons into deaired Metolose fluid filled in the container. The input acceleration was a sinusoidal wave of 1Hz, 20 cycles with an amplitude of 0.25g.

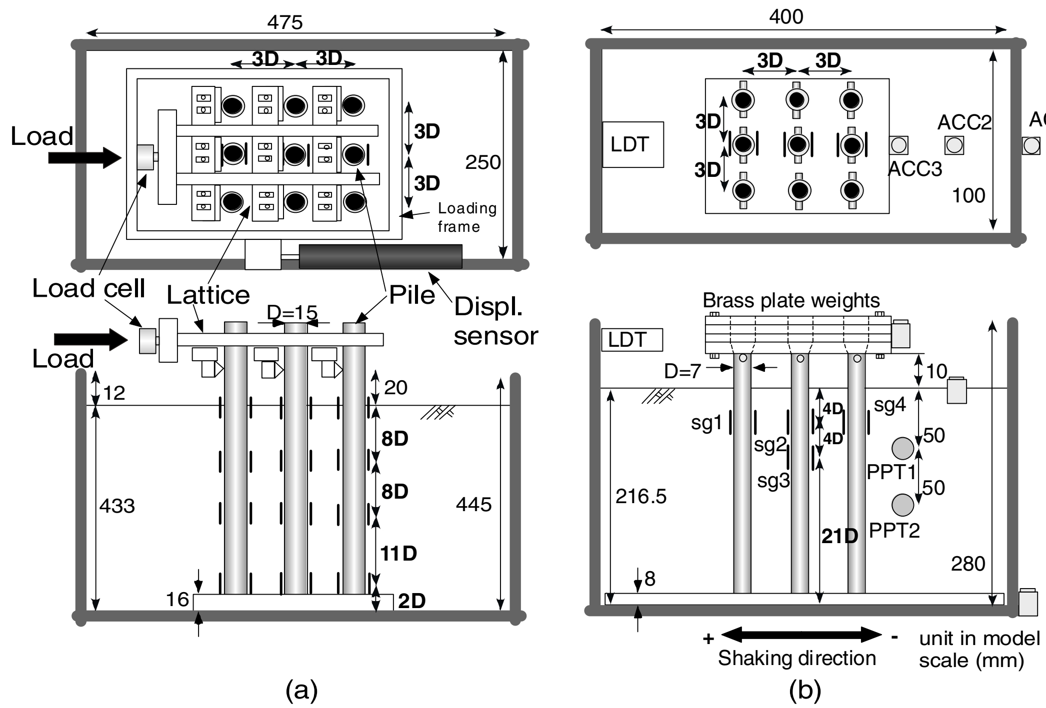

Figure 2 Cross section of model for (a) static test (Test No.2) and (b) dynamic test (Test No.6), Unit is in model scale

Instrumentation

In a series of tests in the present study, displacement and bending moments of piles, and applied load were measured for static tests. Acceleration and excess pore water pressures were also measured in the dynamic tests. Locations of instruments are shown in Figure 2. A displacement transducer of strain gauge type was used in static tests, whereas a laser displacement sensor was used for dynamic tests. Accelerometers of strain gauge type and pore pressure transducers of semi-conductor type were used in dynamic tests. Inertia force at the pile head was computed by multiplying the mass of the brass plates with the acceleration at the pile head.

STATIC VS DYNAMIC MODEL TESTS

Load – displacement curves of piles measured during static model tests (Test No. 1 and 2) are shown in Figure 3. Average load per pile was derived by dividing the total load by the number of piles. Unloading curve of single pile is not plotted for clarity in comparison. As shown in this figure, group pile carries 70 % of the load carried by single pile at the same level of displacement. This is attributed to the group pile effect that is caused by overlapping failure zones, or shadowing of stress zones (e.g. Rollins [5]).

Measured responses of group pile during dynamic test in dry sand deposit (Test No.5) are shown in Figures 4 and 5. From the results of the dynamic test, a load-displacement curve is obtained by assuming that the load is defined as inertia force applied at the pile head as shown by thin solid lines in Figure 6.

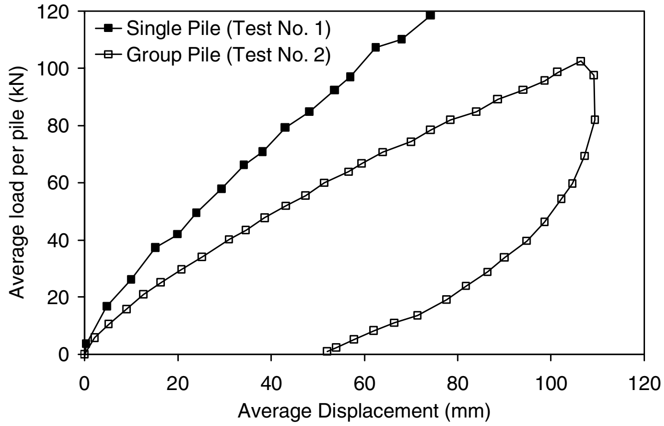

Figure 3 Measured load-displacement curves of single and group piles during static tests

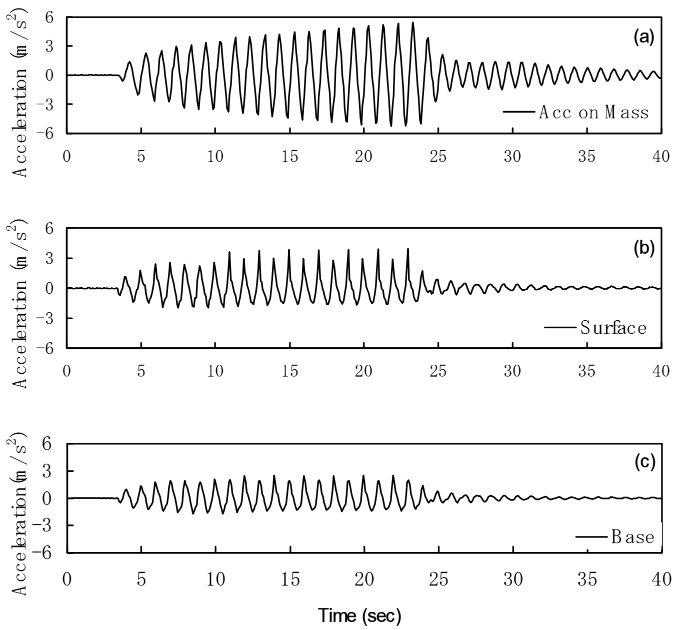

Figure 4 Measured accelerations of dynamic test of group pile in dry deposit (Test No.5);
(a) at pile head, (b) at model ground surface, and (c) input.

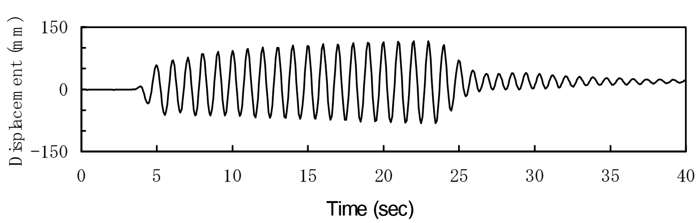

Figure 5 Measured displacement of pile head at dynamic test of group pile in dry deposit (Test No.5)

By combining the result shown in Figure 3 with the dynamic test results in Figure 6, static and dynamic load-displacement curves can be compared with each other. As shown in this figure, initial slope of the curves are similar to each other. However, as displacement increases, the residual displacement at the end of unloading (at the instance when the load becomes zero from the positive peak value) becomes larger for dynamic tests. There may be several reasons for this. One may be the non-linear behavior of sands in that reduction in equivalent shear modulus may be induced with increasing shear strain during shaking. Another may be the kinematic soil-structure interaction in that the pile is affected also by displacement of ground. These may be the priority areas that should be intensively studied in the subsequent study performed in the near future

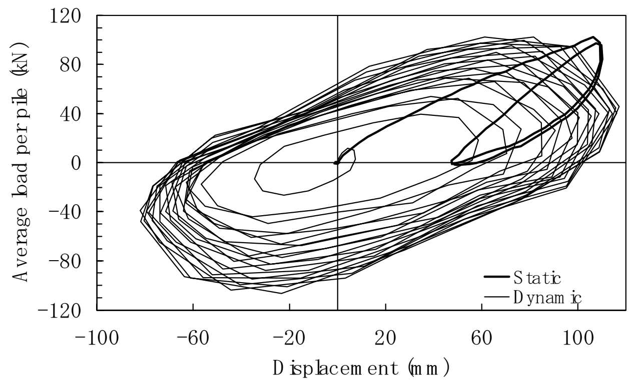

Figure 6 Static and dynamic load–displacement curves of group pile (Test Nos.2 & 5)

PILE RESPONSE IN LIQUEFIED GROUND

Measured responses of group pile during dynamic test in saturated sand deposit (Test No.6) are shown in Figures 7 through 9. From these results, a load-displacement curve is obtained as shown in Figure 10. In this figure, the curve from the single pile test in saturated ground (Test No.4) is also shown for comparison. The large loops shown this figure were formed before liquefaction in both single and group piles. As pore pressure builds up, the slopes of the curves become flat. It is evident that, even in a liquefied soil, the slope of the curve of group pile is smaller than that of single pile. This may be attributed to the group pile effect. Similar observation has begun to be made and reported in a literature (Kotani [6]).

CONCLUSIONS

The paper presents an initial set of the centrifuge model tests of on-going research project on group pile behavior in liquefiable ground. Results of the model tests indicate that (1) larger residual displacements of a soil-pile system are expected during dynamic loading for the same level of inertia force, and (2) group pile effects are observed in liquefied ground. These tentative conclusions indicate the priority areas in the subsequent study scheduled in the near future. In particular, the group pile effects and effects of non-linear dynamic soil-structure interaction will be the primary issues that should be studied in a systematic manner.

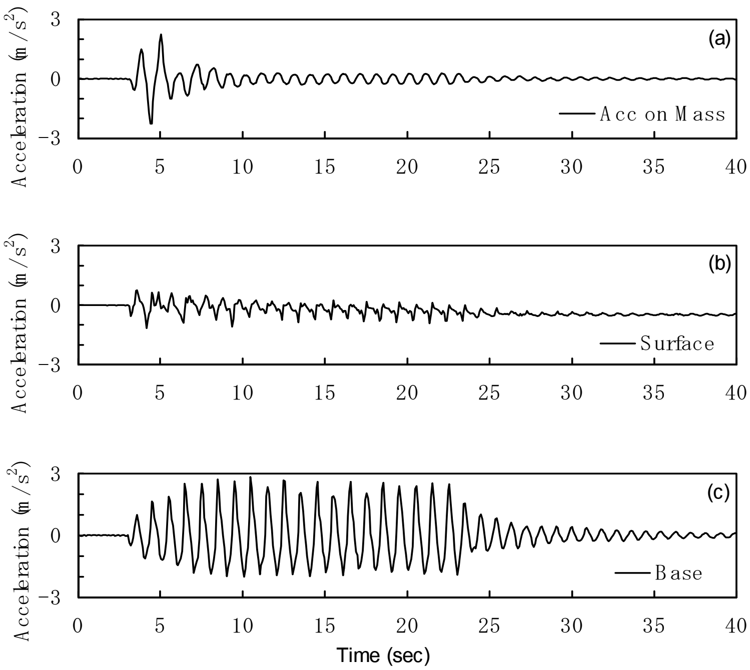

Figure 7 Measured accelerations of dynamic test of group pile in saturated sand deposit (Test No.6); (a) at pile head, (b) at model ground surface, and (c) input.

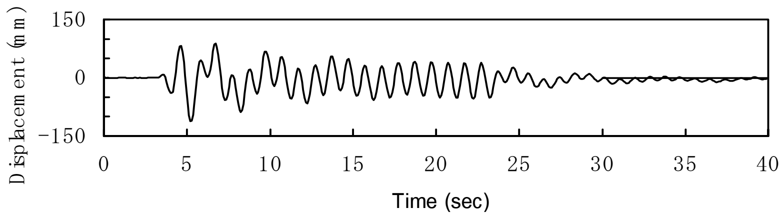

Figure 8 Measured displacement of pile head at dynamic test of group pile in saturated deposit (Test No.6)

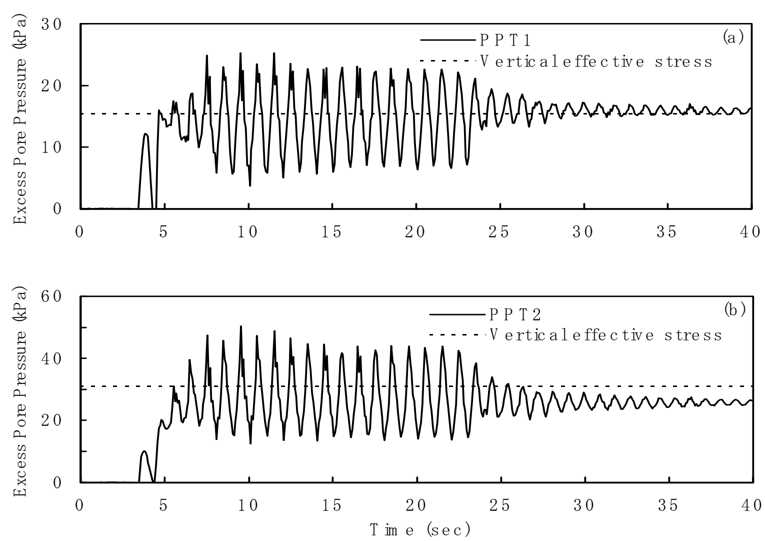

Figure 9 Measured excess pore water pressures at group pile test (Test No.6); (a) GL-2m, (b) GL-4m

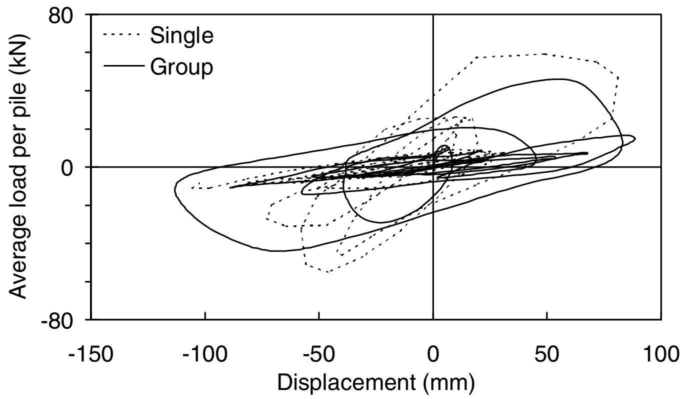

Figure 10 Measured load–displacement curve of group pile at dynamic test in saturated deposit (Test Nos.4 & 6)

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