6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Shaking Table Tests of Piled Raft and Pile Group Foundations in Dry Sand

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ABSTRACT

Traditional design concept of pile group is still adopted predominantly for the foundations of several buildings in Japan, one of highly seismic areas in the world, even though they are piled rafts in reality. This situation may be attributed to the limited knowledge about behaviour of piled rafts subjected to vertical and dynamic loads. Hence, in this study, a series of shaking table tests on 3-pile piled raft and pile group models were carried out in dry sand under the combination of vertical loading and dynamic loading. The input motion was sinusoidal wave with a frequency of 20 Hz and amplitude of 4 m/s^2, measured at the bottom of the box. The results showed that, although there are some similarities on the behaviours of the piled raft and the pile group under dynamic loading, the differences are more considerable in horizontal load-horizontal displacement behaviour, settlement and acceleration responses. Horizontal displacement and settlement during shaking are suppressed in the piled raft model compared to the pile group model, showing superiority of the piled raft.

Introduction

Piled foundations are widely used in the world. However, the effect of combination combined loads on piled foundations especially under dynamic loading has not been fully understood. Experimental studies on piled rafts supported by end bearing piles were carried out by many researchers such as Murano et al. (1997), Tokimatsu et al. (2005) and Ishizaki et al. (2012). Moreover, Horikoshi et al. (2003) and Matsumoto et al. (2004) carried out shaking table tests on piled rafts with friction piles at centrifugal field and 1-g field, respectively. These experimental works show the advantages of piled rafts over pile groups during shaking. However, influence of vertical load on the raft from a super-structure was explicitly modelled in these experimental researches. Although design of piled raft foundations have been adopted for foundations of several buildings in Japan, one of highly seismic areas (Yamashita et al. (2011), Yamashita (2012), Yamashita et al. (2012)), traditional design concept of pile group is still adopted predominantly even though piled foundations are piled raft foundations in reality. As the raft effect is not taken into account in the traditional design approach, the results do not reflect the actual behaviour of piled raft. This situation may be attributed to the limited knowledge about behaviour of piled rafts subjected to combination of vertical load and shaking (dynamic load)

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A series of load tests which included static and dynamic loading of different model foundations, such as single pile, capped pile, pile group, raft alone and piled raft, were carried out in this research to investigate the behaviour of piled rafts in dry sand in more detail. The static loading test results are presented in Unsever et al. (2014) and Unsever et al. (2015). In this paper, pile group and piled raft behaviours under the combination of vertical loading and dynamic loading are compared. For this purpose, shaking table tests on 3-pile pile group (PG hereafter) and 3-pile piled raft (PR hereafter) with friction piles (which was confirmed by the test results, where the piles' bases shared 25-30% of the total pile load) were carried out under sinusoidal waves.

It may be appropriate to mention again that the purposes of this study are to demonstrate and discuss the differences of the behaviours between the piled raft and pile group under the same conditions, and to show some possible advantages of the piled raft. The authors do not intend to apply the experimental results in 1-g environment to practical problems directly.

Experiment Setup

Model Foundation and Model Ground

A schematic illustration of the shaking table test is shown in Figure 1. The soil container was a laminar box with dimensions of 800 mm (in *x*-direction) × 500 mm (in *y*-direction) and a depth of 530 mm. It consists of 10 rings each having a height of 50 mm. The model ground was dry Silica sand #6 with a relative density, D_r, of 70 %, where the properties are summarised in Table 1. Note that the internal friction angle, ϕ', was estimated from CD triaxial test results. In the figure, LDT-1 and LDT-2 are laser displacement transducers to measure horizontal displacements and LDT-R and LDT-L measure vertical displacements.

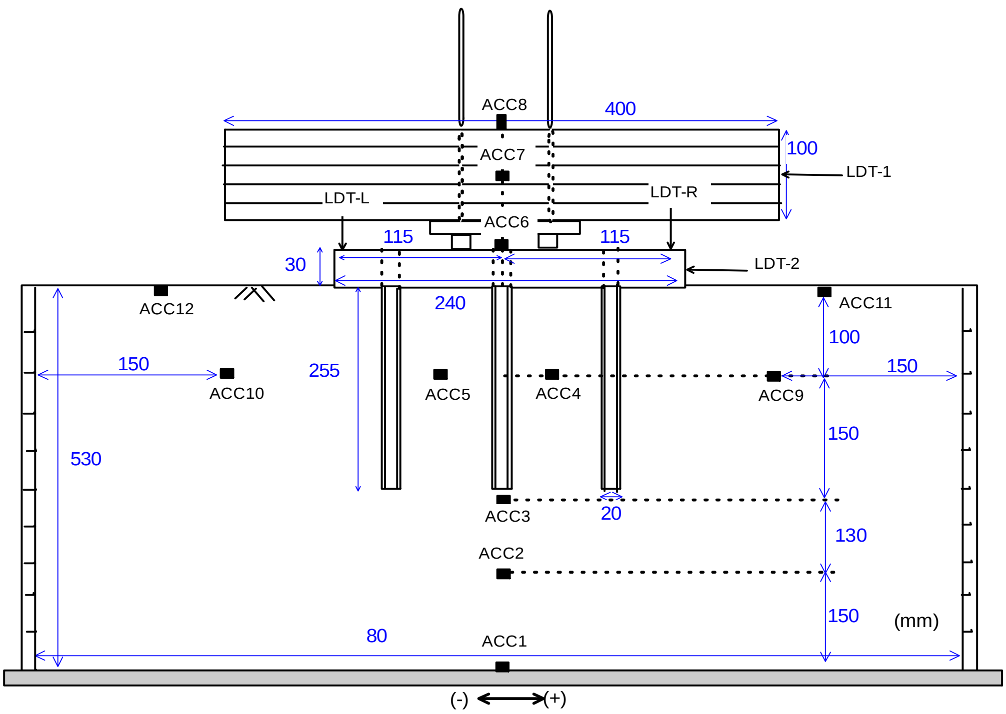

Figure 1. Input motion measured at the bottom of the laminar box for PR and PG.

Table 1. Properties of model ground.

Item	Value
Density of soil particles, ρ_s (t/m^3)	2.66
Maximum dry density, ρ_{dmax} (t/m^3)	1.542
Minimum dry density, ρ_{dmin} (t/m^3)	1.280
Maximum void ratio, e_{max}	1.079
Minimum void ratio, e_{min}	0.725
Median grain size, D_{50}	0.423
Coefficient of uniformity, C_u	1.880
Internal friction angle, ϕ'	43.2

Piled foundation dimensions were decided by considering the limitations of the size of laminar box and boundary effects. Figure 2 indicates the model foundation that was used for both pile group (PG) and piled raft (PR) with the details of the single pile. The piles were made of aluminium hollow tubes, where the properties are summarised in Table 2. The effective pile length was 255 mm since the top 30 mm was embedded in the raft. Tip of each pile was closed with a cap which had a thickness of 5 mm. Each pile was instrumented with strain gauges at a total of 6 levels to obtain axial forces, bending moments and shear forces induced in the pile during loading tests. Note that, as described in Unsever et. al. (2014), using a scale ratio of 30 between the prototype and the model, a concrete pile having 0.6 m diameter and 7.65 m length could be considered in this study, according to a similitude rule proposed by Iai (1989).

Piled raft (PR) or pile group (PG) model was composed of three model piles and a rectangular raft of stainless steel having dimensions of 240 × 80 mm with a thickness of 30 mm (Figure 2). Piles were rigidly connected to the raft and centre-to-centre pile spacing, *s*, was 80 mm, 4 times the pile diameter, where D = 20 mm (s/D = 4). The bottom of the raft and the outer surface of the piles were covered with the silica sand particles to obtain frictional surface between the raft and the ground and the piles and the ground as well. The same model foundation was used for both cases of PR and PG, however 20 mm space was provided between the raft base and the model ground surface for the pile group (PG) case to eliminate the raft effect.

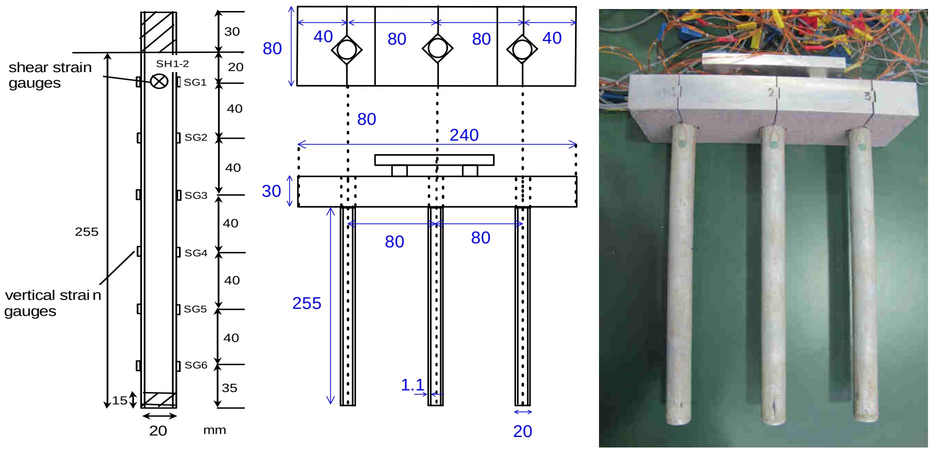

Figure 2. Model foundations.

Table 2. Properties of the model pile.

Outer diameter, D (mm)	20.00
Wall thickness, t (mm)	1.1
Length, L (mm)	255
Cross sectional area, A (mm2)	65.31
2nd moment of area, I (mm4)	2926.2
Young's modulus, E (N/mm2)	64000
Poisson's ratio, υ	0.31

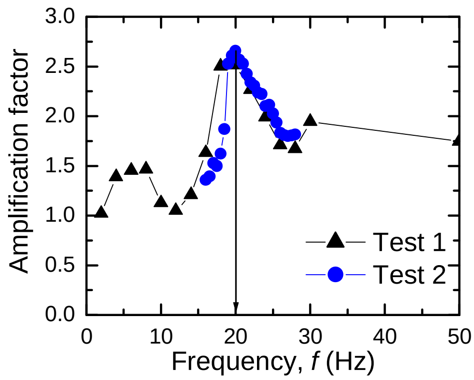

Figure 3. Results of sweep tests for the model ground without foundation

Test procedure and instrumentation

First, several shaking table tests were performed on the model ground alone condition (without model foundation) in order to estimate the resonant frequency of the ground. The ratio of the measured accelerations at the ground surface to the acceleration at the bottom of the box gives amplification factor of the input motion through the ground. It is known that, at resonant frequency this amplification becomes maximum. From the first test series, the resonant frequency of the model ground was found to be between 16 - 28 Hz (Figure 3). Then, to determine the resonant frequency, f_n, of the model ground more specifically, test series were conducted with a small interval, 0.5 Hz. After the second test series, the resonant frequency was estimated as 20 Hz for this model ground (Figure 3). Therefore, it was decided to perform piled raft and pile group tests under 20 Hz frequency.

Procedures for each separate shaking test are summarised below:

1) Prepare the model ground by layers (10 layers of 50 mm and one layer of 30 mm) in order to control the density of the model ground. Place (pour) 6 soil layers (which makes totally 280 mm height) one by one and compact the soil by tamping until an intended relative density.
2) Fix the model foundation on the box by the help of clamps and rods.

3) Place (pour) 5 more soil layers of soil until 530 mm or 510 mm height of the model ground is obtained for PR and PG, respectively. (Note that, during the preparation of the model ground, 12 accelerometers were set at proper locations in the model ground.)
4) Set the laser displacement meters and accelerometers (on the model foundation).
5) Place mass plates (weights) one by one on top of the raft to apply vertical load until the desired loading level is reached. Then, fix the plates to the raft by bolting. (The total amount of vertical load was 497 N, which corresponded to a half of the yield vertical load, for the tests.)
6) Apply the sinusoidal input wave (which had a frequency of 20 Hz and 4 m/s^2 amplitude.)

Test Results

Acceleration

Figure 4 shows the input motion of PR and PG tests. It can be said that the input wave is similar for both tests. Therefore, it is reasonable to compare the results of both tests.

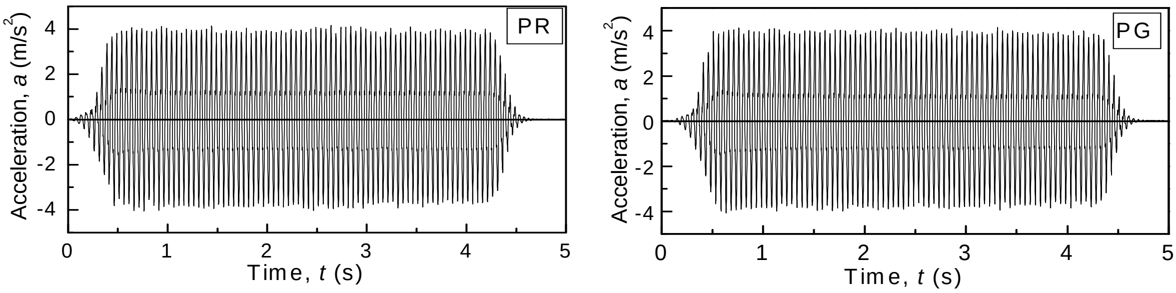

Figure 4. Input motion measured at the bottom of the laminar box for PR and PG.

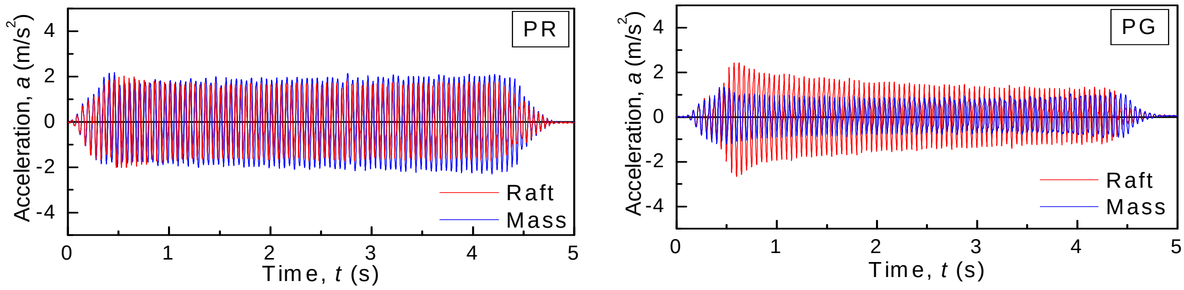

Figure 5. Measured acceleration at the raft and at the midpoint of the mass for PR and PG.

Figure 5 presents the measured accelerations at the top of the raft and at the midpoint of the mass for both cases. For PR test, the responses measured at the raft and the mass have amplitude of 2 m/s^2 in average and they are almost the same, which means that they behave as one element during the test. In contrast for PG test, the amplitude of the wave that measured at the mass is considerably smaller than that of the raft in PG test. It is also interesting to note that the horizontal acceleration of the raft of PG attenuates with time after the peak acceleration is reached. If the results are compared with the input motion, it is seen that for PR model, the acceleration amplitudes of the raft and the mass are being about half of the input motion. However, for PG model the acceleration response of the raft is about half of the input motion and twice of the mass amplitude.

Horizontal load-displacement relation

The horizontal load-displacement behaviours of the piled raft and pile group under the shaking are given in Figure 6. The horizontal load was calculated simply by multiplying the mass of the weight plates with the acceleration measured on the mass. Horizontal displacement was derived from the measured acceleration on the raft. Maximum horizontal displacements of the raft for PR and PG are ± 0.10 mm and ± 0.15 mm, respectively, showing a superiority of PR for suppressing horizontal displacement over PG. It is seen from Figure 6 that the load-displacement relation is almost linear for the initial part of the response where the amplitude of the acceleration increases to the steady value, thereafter the response becomes a steady loop for the steady sinusoidal input motion. Moreover, the maximum horizontal load on the PG raft (about 50 N) is half of the PR raft (110 N), due to the smaller acceleration of the mass (weight plates) in PG (see Fig. 5).

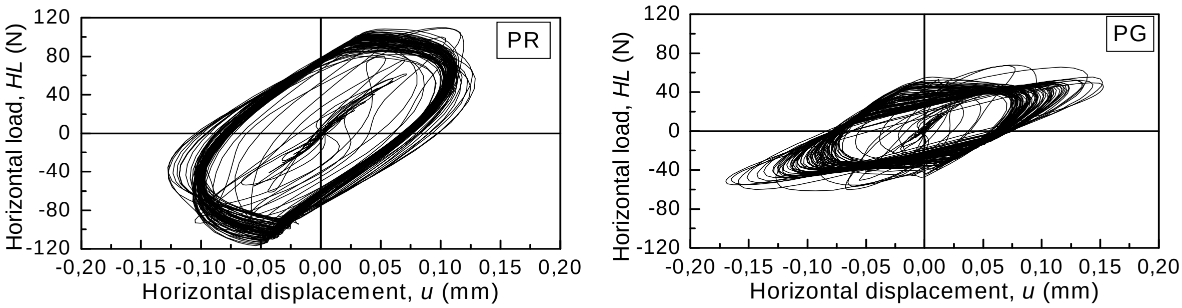

Figure 6. Horizontal load-displacement relationship of PR and PG.

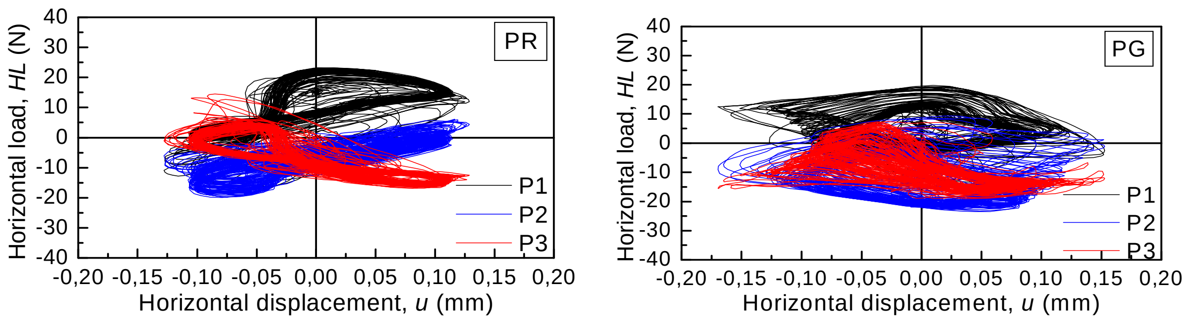

Figure 7. Horizontal load sharing of PR and PG.

Figure 7 shows the horizontal load carried by each pile during dynamic loading. It is seen that the edge piles (P1 and P3) carry almost the same amount of horizontal load for both cases, however the centre pile (P2) carries slightly larger load for PG case. Note that the total amount of load carried by PR is two times larger than the PG case, although the loads carried by piles are similar between PR and PG. This result shows that the raft base resistance is effectively mobilised in PR during dynamic loading.

Settlement and inclination

The settlement of the model foundations was measured at the top of raft by the help of two laser displacement transducers. Figure 8 shows the average of two measurements as the settlement of the raft took place during the shaking table tests for PR and PG. Before applying the input motion, there was a small settlement for both cases because of vertical loading by placing the weight plates. The settlement is slightly larger for PG test due to the space of 20 mm between the raft and the pile. At the end of dynamic loading, the final settlement of the piled raft was about 9 mm, whereas it was measured as 17 mm for PG, which is almost double of PR. It can be said that, reduced settlement amount is one of advantages of PR over PG.
Figure 9 indicates the inclination of the raft during the shaking test for PR and PG. As it is seen from the figure, the inclination of the rafts for both cases shows similar behaviour and similar amount. However, the slope of the inclination for PG test is slightly steeper than PR. Note that, positive inclination means clockwise rotation (Figure 10). Therefore, when the horizontal displacement is toward left side (which means negative horizontal loading), counter-clockwise rotation is observed.

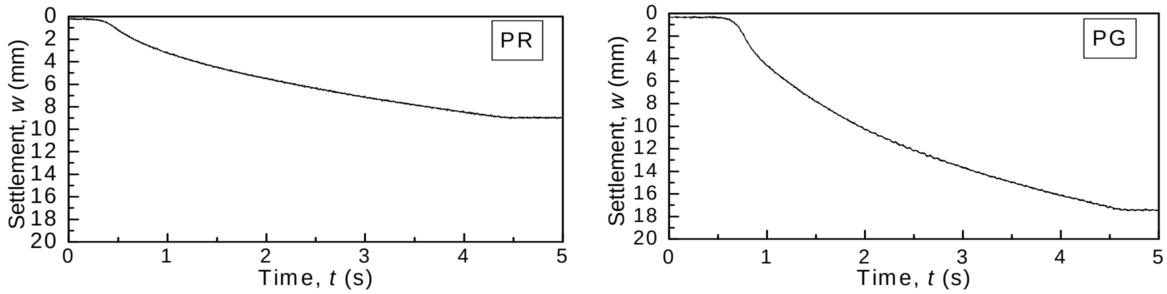

Figure 8. Settlement of the raft during loading for PR and PG.

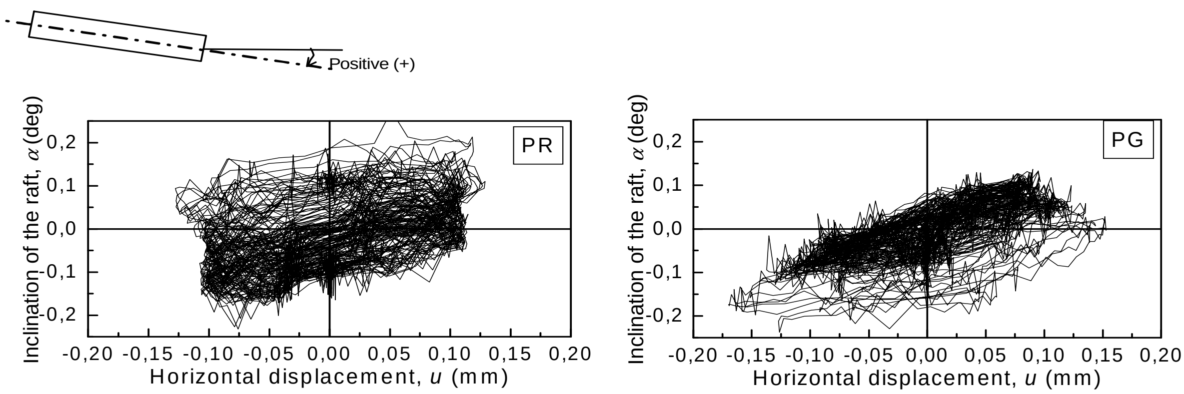

Figure 9. Inclination of the raft during loading for PR and PG.

Load sharing

Figure 10 shows the time history of the proportion of the horizontal load carried by 3 piles in PR model. Although it is not so stable, the trend is recognizable. It is seen that the percentage of horizontal load carried by 3 piles is between 20 % – 40 % of the total applied load. The proportion of vertical load carried by 3 piles is also given in Figure 11. Before applying the input motion, 70 % of the total applied vertical load was carried by 3 piles, however after the shaking, vertical load sharing dropped to 50 %. This result clearly shows an advantage of PR, in which the reduction of the vertical load of the piles is compensated by the raft and resulting in smaller settlement as presented in Fig. 8.

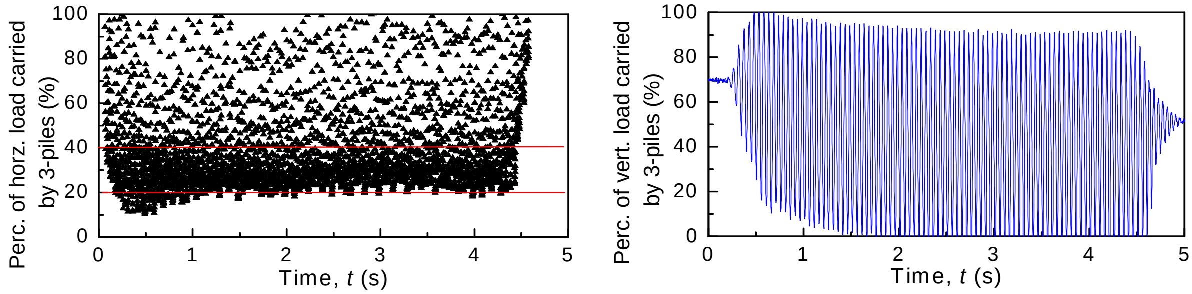

Figure 10. Percentage of horizontal and vertical load carried by 3 piles during shaking of PR.

Conclusions

In this particular paper, behaviours of piled raft and pile group in dry sand ground were compared under dynamic loading. For this purpose, shaking table tests with sinusoidal wave were carried out. Model piles were friction piles since their tips were not fixed to the bottom of the soil box. In order to take into account the superstructure effect on the foundation behaviour, vertical load was applied to the models prior to the start of dynamic loading.

Although the same acceleration was applied for both of the models, the measured horizontal load at the piled raft is almost two times larger than that of the pile group. Moreover, horizontal displacement of the piled group is larger than the piled raft due to the instability of pile group model. Another advantage of piled raft is the settlement amount, which is half of the pile group case. On the contrary, the inclination behaviours are very similar for both tests. Note that, similar behaviour was also observed from static cyclic horizontal load test of the piled raft and pile group (Unsever et al., 2014), which means that inertia effects are much more dominant than kinematic effects for this experimental condition. In addition, proportion of horizontal load carried by each component is nonlinear and dependent on the horizontal displacement, which was also pointed out at the study of Horikoshi et al. (2003). It is suggested that an appropriate combination of model tests and numerical analyses should be utilized in the design of prototype foundation structures.

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