

## INFLUENCE OF SUPERSTRUCTURE VIBRATION MODE ON SEISMICALLY INDUCED FORCES ALONG PILE

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### ABSTRACT

A series of shaking table tests of model piled rafts in dry sand have been carried out. In the experiments, two-storey flexible model superstructures were placed on the model piled raft. Shaking table tests of the combined structure model were carried out. In this paper, induced forces along pile (shear forces and bending moments) during the shaking table tests are presented. Influences of superstructure vibration mode on seismically induced forces along pile are discussed. A traditional seismic design method of a foundation, in which dynamic loads acting on the foundation are modelled by an equivalent static horizontal load and moment, is carried out, in order to predict the maximum seismically induced bending moments and shear forces in the pile.

Keywords: piled raft, superstructure, shaking table test, static analysis, bending moment

### INTRODUCTION

Piled raft foundation has been widely recognized as economical and rational foundation when subjected to vertical load since the load is transferred to both the raft and the piles. Some guidelines for design of piled raft foundation subjected to vertical load have been presented (e.g. Randolph 1994, Katzenbach and Moormann 2001, Poulos 2001).

In highly seismic areas such as Japan, estimation of the behaviour of piled raft foundation subjected to horizontal loading or seismic loading becomes a vital issue in seismic design of a piled raft foundation. Horikoshi et al. (2003a, b) investigated correlation between the behaviours of model piled rafts in dry sand during shaking and static horizontal loading using centrifuge modelling. Kitiyodom et al. (2002) investigated the effect of use of batter piles in piled rafts against horizontal loading. In the above model tests, superstructure on the raft was not explicitly modelled.

Matsumoto et al. (2004a, b) carried out static horizontal load tests and shaking tests of model piled raft in dry sand, in which rigid superstructures having the same mass but different heights of gravity centre were placed on the model raft. The results of their experiments showed that the height of gravity centre of the whole structure consisted of the superstructure and the piled raft has a great influence on the behaviours of the whole structure during shaking. When applying the piled raft to foundation of a building, the flexibility of superstructure (building) may be rather flexible, compared with bridge piers for example. Hence a series of shaking tests of model piled rafts with flexible superstructures on them were carried out in this paper. The test set-up used in this paper is fundamentally the same as that used in Matsumoto et al. (2004a, b), except for the flexibility of superstructure models.

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Many pile failures during earthquakes have occurred due to the inadequacy of pile to withstand large induced moment and shear. The pile designer needs to know approximately what the maximum seismically induced internal moment and shear of the pile would be. In a traditional seismic design method of a foundation, dynamic loads acting on the foundation are modelled by an equivalent static horizontal load and moment. In this paper, the analyses of model tests were conducted using a computer program PRAB (Kitiyodom and Matsumoto 2002, 2003; Kitiyodom et al. 2005) in order to predict the maximum seismically induced bending moments and shear forces in the pile. In the analyses soil parameters were estimated from the triaxial test results of the sand used for the model ground (Matsumoto et al. 2004a).

## TEST DESCRIPTION

### Model foundation and model superstructure

Figure 1 shows the model raft and the model pile. The square model raft, with a breadth of 80 mm, was made of an aluminium plate with a thickness of 25 mm. The mass of the model raft was 0.4 kg. In order to increase the friction at the raft base, the base was roughened. The interface frictional angle between the raft base and the model ground was 30.5 degrees, i.e., the coefficient of frictional angle was 0.59.

Aluminium pipes with an outer diameter of 10 mm, an inner diameter of 8 mm and a length of 170 mm were used for the model piles. Each pile toe was capped with a thin aluminium plate. Young's modulus,  $E_p$ , and Poisson's ratio,  $\nu_p$ , were determined from bending tests of the model piles. Each pile was instrumented with foil strain gauges along the pile shaft as shown in Figure 1(b) in order to obtain the distribution of the axial forces, the shear forces and the bending moments of the pile. The geometrical and mechanical properties of the model pile are listed in Table 1, together with the properties of a corresponding prototype pile when the scaling factor,  $\lambda$ , is taken as 50.

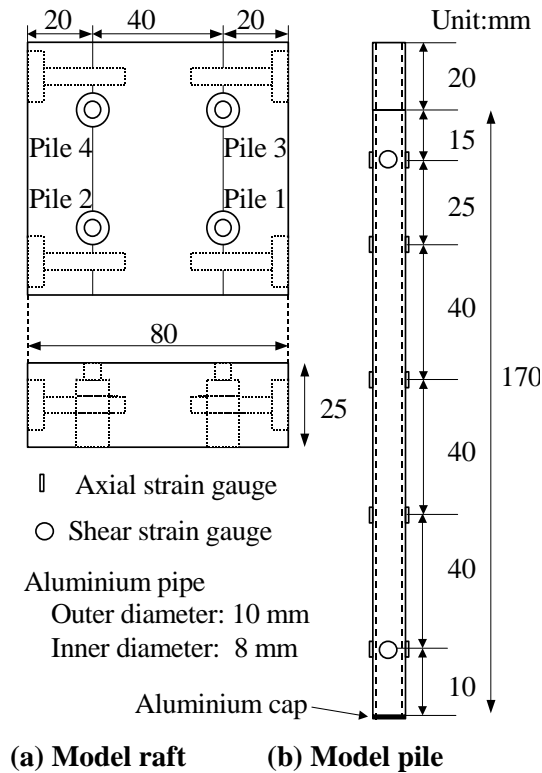


Figure 1. Model piled raft

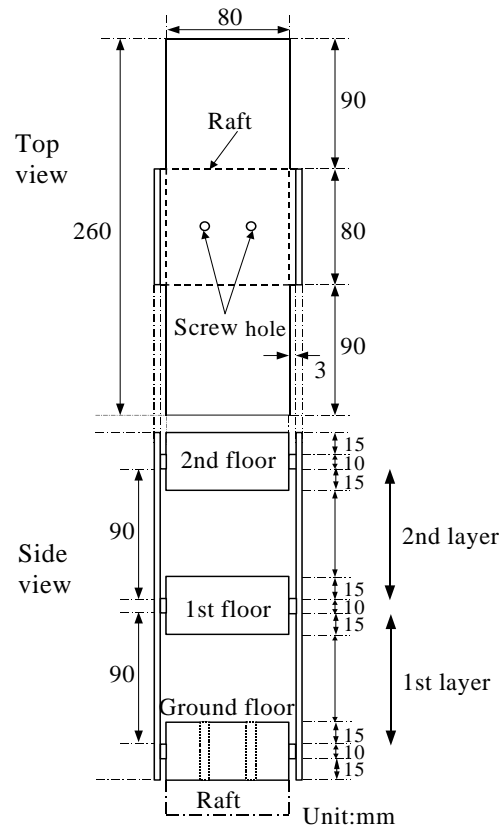


Figure 2. Flexible superstructure model

**Table 1. Properties of model pile**

Property	Model	Prototype ( $\lambda = 50$ )
Outer diameter (mm)	10	500
Wall thickness (mm)	1	50
Length (mm)	170	8500
Cross sectional area (mm <sup>2</sup> )	28.3	70685.8
Young's modulus (GPa)	67.1	3354
Poisson's ratio	0.345	0.345
Longitudinal rigidity (GN)	$1.90 \times 10^{-3}$	33.53
Bending rigidity (GNm <sup>2</sup> )	$1.94 \times 10^{-7}$	0.859

**Table 2. Properties of model superstructure**

Property	Value
Wall thickness (mm)	2
Total mass (kg)	21.6
Horizontal stiffness of each layer (kN/m)	$1.89 \times 10^2$
Young's modulus of wall material (kPa)	$8.39 \times 10^7$
Primary resonant frequency (Hz)	14.2
Secondary resonant frequency (Hz)	37.1
Damping ratio	0.0104

Four model piles were connected to the model raft with a pile spacing of 40 mm. The head of each pile was rigidly connected to the raft.

Figure 2 shows the model superstructure that was placed on the model raft. The two-layer bent type model superstructure consists of three masses and two sidewalls. Each mass, designated as base floor, 1<sup>st</sup> and 2<sup>nd</sup> floor, is made of brass and has a mass of 7 kg. The sidewall is made of brass and has a thickness of 2 mm. The total mass of the model is 21.6 kg.

Static horizontal load test of the superstructure model was carried out in order to estimate the horizontal stiffness of the 1<sup>st</sup> layer and the 2<sup>nd</sup> layer. Horizontal load was applied to the 2<sup>nd</sup> floor and the horizontal displacements of the 1<sup>st</sup> floor and the 2<sup>nd</sup> floor were measured by means of two laser displacement transducers. From the measured relationships between the horizontal load and the horizontal displacements, the horizontal stiffness of the 1<sup>st</sup> layer and the 2<sup>nd</sup> layer are identical with  $1.89 \times 10^2$  kN/m. From the beam theory, Young's modulus of the wall material was estimated as  $8.39 \times 10^7$  kPa. The primary and secondary resonant frequencies of the superstructure model were estimated from the theory of vibration. Free vibration test of the superstructure model was also carried out to estimate the damping factor of the superstructure model alone. The results of the above tests are summarized in Table 2.

#### **Model ground, test set-up and test procedure**

Dry Toyoura sand was used for the model ground throughout. The sand was poured into a laminar soil box having a width of 510 mm, a height of 310 mm and a depth of 210 mm (Figure 3). Physical properties of the sand are summarised in Table 3. Triaxial tests of the sand have been conducted by Matsumoto et al. (2004a) and it was confirmed that the shear modulus of the sand is proportional to the square root of confining pressure. Hence, the similitude for 1-g model test proposed by Iai (1989) as shown in Table 4 could be applied to the model tests in this paper.

Figure 3 shows an illustration of the final stage of the test set-up just before starting shaking. First, the model foundation consisting of the model raft and the model piles was set near the centre of the soil box with a special rig. Then, dry Toyoura sand was poured into the box and was shaken by small amplitudes to have a relative density,  $D_r$ , of about 95 %. After the completion of preparation of the model ground, a superstructure model was placed on the raft and connected to the raft by bolting.

**Table 3. Properties of Toyoura sand**

Property	Value
Relative density (%)	95
Maximum density ( $\text{t/m}^3$ )	1.65
Minimum density ( $\text{t/m}^3$ )	1.35
Density of soil particle ( $\text{t/m}^3$ )	2.66
Mean grain size (mm)	0.162
Internal friction angle (deg.)	45

**Table 4. Similitude for model tests (after Iai 1989)**

Item	Prototype/model
Length (size)	$\lambda$
Density	1
Stress	$\lambda$
Strain	$\lambda^{1/2}$
Shear modulus	$\lambda^{1/2}$
Time	$\lambda^{3/4}$
Frequency	$1/\lambda^{3/4}$
Displacement	$\lambda^{3/2}$
Velocity	$\lambda^{3/4}$
Acceleration	1
Bending rigidity	$\lambda^{9/2}$
Longitudinal rigidity	$\lambda^{5/2}$

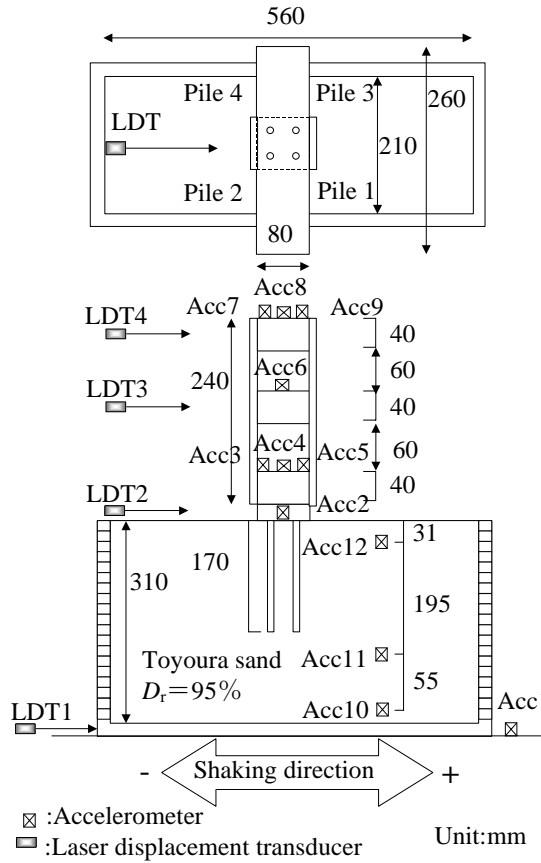
Horizontal accelerations of the shaking table, the model ground and the superstructure, vertical accelerations of the base floor and the 2<sup>nd</sup> floor of the superstructure were measured by accelerometers (Acc1 to Acc12). Horizontal displacements of the bottom of the soil box and each floor of the superstructure were measured by means of laser displacement transducers (LDT1 to LDT4).

Sinusoidal horizontal acceleration wave having peak amplitude of  $1 \text{ m/s}^2$  were applied to the base of the soil box in a series of shaking tests of a whole structure model. The input frequency,  $f$ , was varied from 2 Hz to 75 Hz.

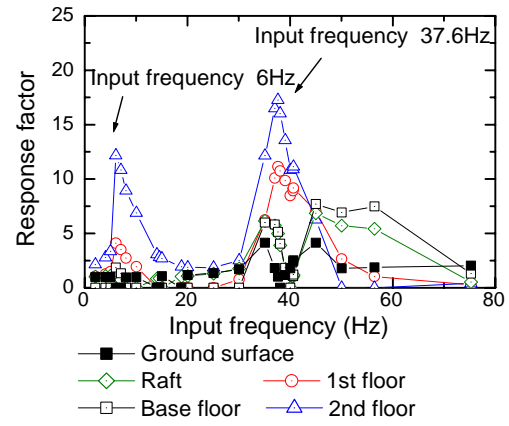
## TEST RESULTS

The response factors measured at different locations of the superstructures are shown in Figure 4. Here, the response factor is defined as the ratio of the peak response horizontal acceleration to the peak input acceleration. The 5 types of response factors at the ground surface, the raft, base floor, 1<sup>st</sup> floor and 2<sup>nd</sup> floor are shown in the figure. Judging from the measured transfer functions, the primary and secondary resonant frequencies of the whole structure model in dry sand are 6 Hz and 37.6 Hz, respectively. The natural frequency of the model ground was estimated as 42 Hz from the shaking tests of the model ground alone. Hereafter, the behaviours of the model at the primary and secondary resonant frequencies are presented.

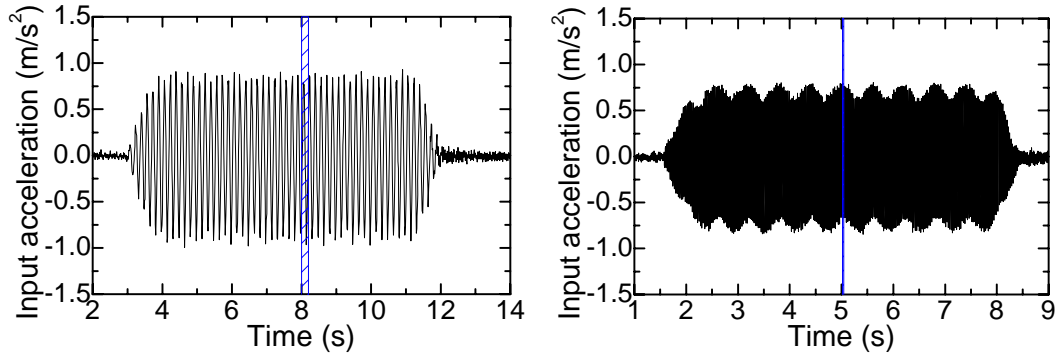
Figure 5 shows the time history of the input accelerations measured in each shaking table test. Figure 6 shows the input accelerations (Acc. 1), the horizontal acceleration responses of the base floor (Acc. 4), 1<sup>st</sup> floor (Acc. 6) and 2<sup>nd</sup> floor (Acc. 8) during a cycle of loading indicated by the shaded area in Figure 5 where steady-state input and response accelerations were observed. During the shaking test at  $f = 6$  Hz (Figure 6a), amplitude of the horizontal acceleration is the largest at the 2<sup>nd</sup> floor, the second largest at the 1<sup>st</sup> floor and the smallest at the base floor. The figure shows that time shift between the response accelerations at each floor is very small, showing that the superstructure vibrates in a primary mode. During the shaking test at  $f = 37.6$  Hz (Figure 6b), in contrast, there is time shift between the response accelerations at base floor, 1<sup>st</sup> floor and 2<sup>nd</sup> floor, showing that the superstructure vibrates in a secondary mode.



**Figure 3. Test set-up for shaking table test**



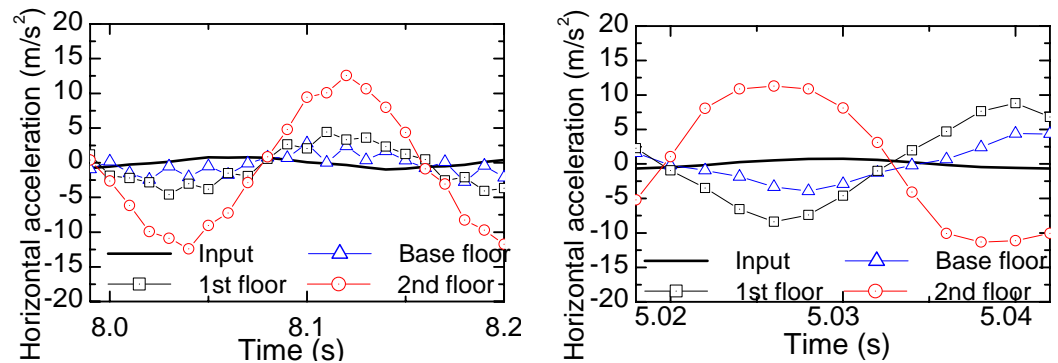
**Figure 4. Response factor**



**(a) Input frequency  $f = 6$  Hz**

**(b) Input frequency  $f = 37.6$  Hz**

**Figure 5. Input acceleration**



**(a) Input frequency  $f = 6$  Hz**

**(b) Input frequency  $f = 37.6$  Hz**

**Figure 6. Horizontal acceleration**

Figure 7 shows the proportion of the vertical load carried by the piles. The proportion of the vertical load carried by the piles prior to shaking was 85.5% at  $f = 6$  Hz and 81.7% at  $f = 37.6$  Hz. These proportions fluctuated during shaking and slightly increased to 86.2% and 83.2% at the end of shaking.

The horizontal loads acting on the model are shown in Figure 8. The total horizontal load acting on the superstructure was calculated as the sum of inertia forces of the base floor, 1<sup>st</sup> floor and 2<sup>nd</sup> floor. The inertia force of each floor was obtained as the product of the mass of the floor and the measured horizontal acceleration. The horizontal load carried by piles is the sum of shear forces at the heads of four piles. The horizontal load carried by the raft was obtained by subtracting the shear forces of the piles from the total horizontal load. The total horizontal load at  $f = 37.6$  Hz is only 1/5 of that at  $f = 6$  Hz. This reduction was caused by secondary vibration mode occurred in the former case, where directions of accelerations of the 1<sup>st</sup> floor and 2<sup>nd</sup> floor were opposite.

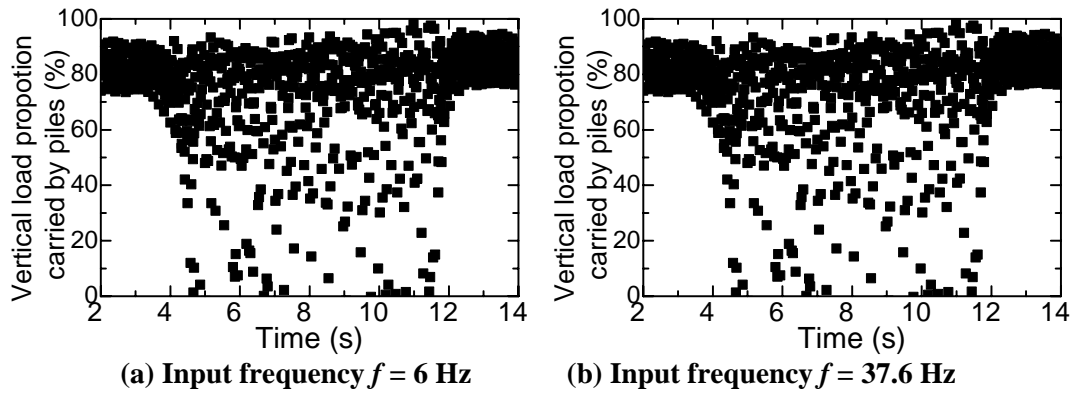


Figure 7. Proportion of vertical load carried by piles

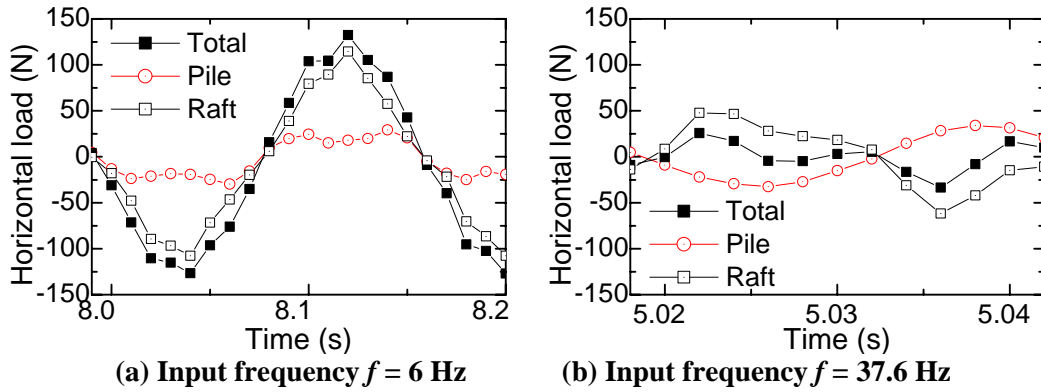


Figure 8. Horizontal loads carried by piles and raft

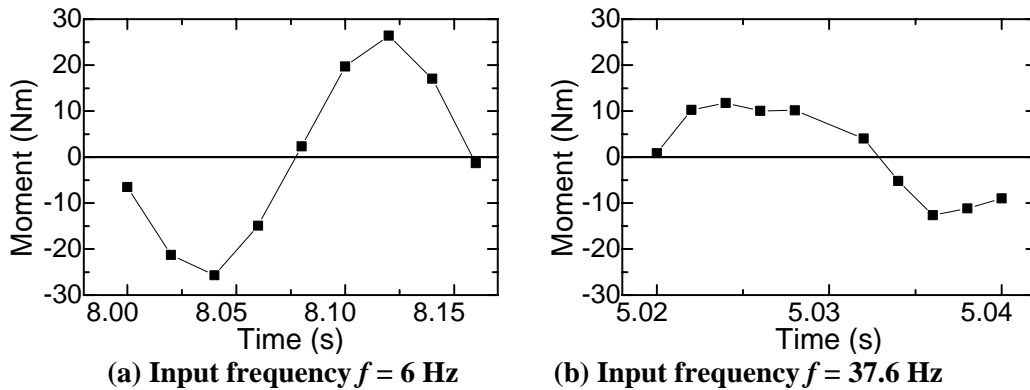


Figure 9. Overturning moment acting on model foundation

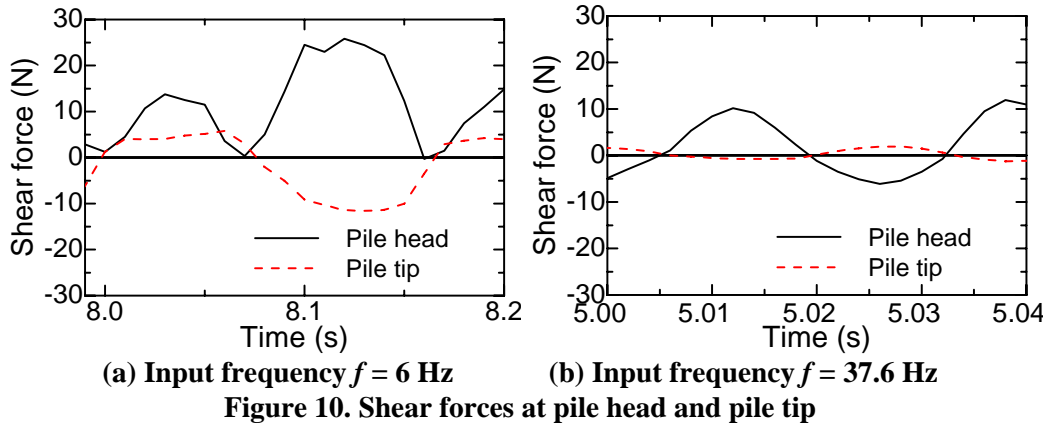
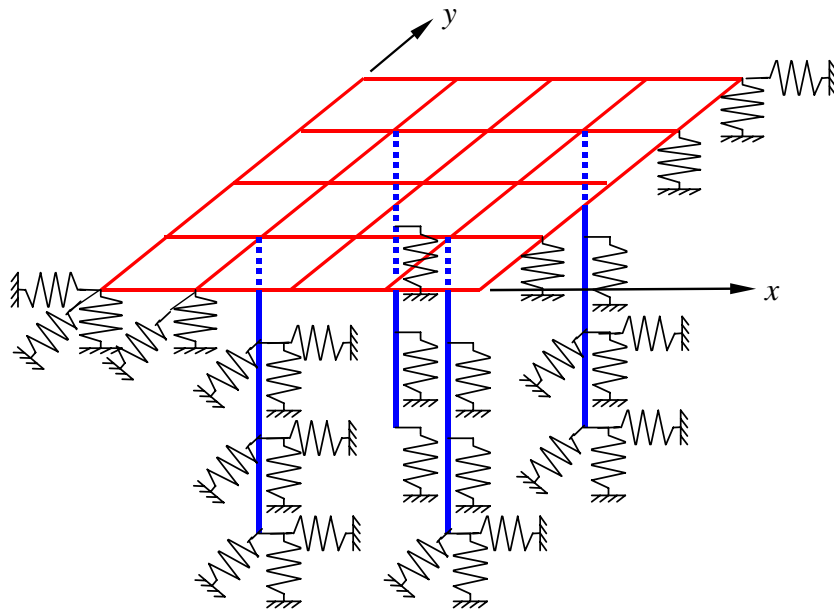


Figure 9 shows the overturning moment acting on the model foundation. The moment was obtained as the sum of the product of the horizontal load acting on each floor and the distance between the raft top surface and the centre of gravity of each floor. The overturning moment at  $f = 37.6$  Hz is about a half of that at  $f = 6$  Hz. Figure 10 shows the shear forces at the pile head and at the pile tip. The shear forces at  $f = 37.6$  Hz is 1/4 of that at  $f = 6$  Hz. This reduction is less than the reduction of the total horizontal load. This is caused by the effect of overturning moment. Hence, in the analysis not only the horizontal load but also the overturning moment should be considered, in order to predicted accurately the induced bending moments and shear forces in the pile.

## ANALYSES OF THE SHAKING TESTS

### Analysis method

In order to predict the maximum seismically induced bending moments and shear forces in the pile during the shaking tests, the static analyses were conducted using a computer program PRAB (Kitiyodom and Matsumoto 2002, 2003; Kitiyodom et al. 2005). In this program, a hybrid model is employed in which the flexible raft is modelled as thin plates, the piles as elastic beams, and the soil is treated as interactive springs (Figure 11).



**Figure 11. Plate-beam-spring modelling of a piled raft foundation**

Both the vertical and horizontal resistances of the piles as well as the raft base are incorporated into the model. The interactions between structural members, pile-soil-pile, pile-soil-raft and raft-soil-raft interactions are taken into account based on Mindlin's solutions for both vertical and horizontal forces. The considered soil profile may be homogeneous semi-infinite, arbitrarily layered and/or underlain by a rigid base stratum. The estimation of non-linear deformation of the foundations is calculated by employing the bi-linear (elastic-perfectly plastic) response of soil springs.

The analyses were conducted in the prototype scale assuming a scale factor  $\lambda = 50$  (Table 1). The model ground was modelled as a finite ground having a depth of 15.5 m. The ground was further divided into 20 layers to account for the increase in the shear modulus,  $G$ , with depth due to the increase in the confining pressure  $p$ . The shear modulus of each soil layer was estimated using the relation of Equation (1), which was obtained from the triaxial test results (Matsumoto et al. 2004a).

$$G = 29163 \left( \frac{P}{100} \right)^{0.5} \quad (\text{kPa}) \quad (1)$$

The Poisson's ratio of the ground was assumed as 0.3. In this particular paper, only elastic responses of soil and pile foundations are concerned. The soil, the pile and the raft were treated as elastic homogeneous materials in the analysis.

Dynamic loads acting on the foundation are modelled by the equivalent static horizontal load and the overturning moment. The equivalent forces acting on the foundation when the superstructure deformed in 1<sup>st</sup> vibration mode and 2<sup>nd</sup> vibration mode are shown in Figures 12 and 13, respectively.

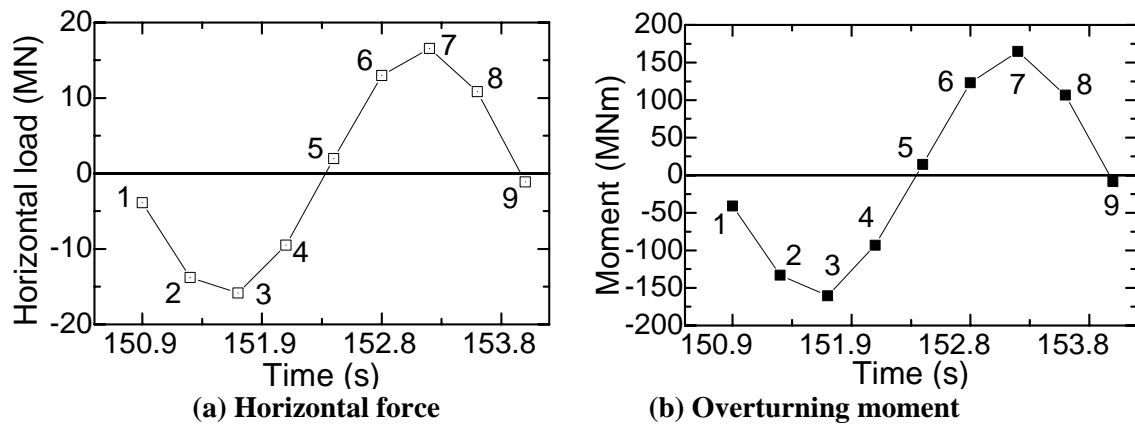


Figure 12. Equivalent forces acting on the foundation (1<sup>st</sup> vibration mode)

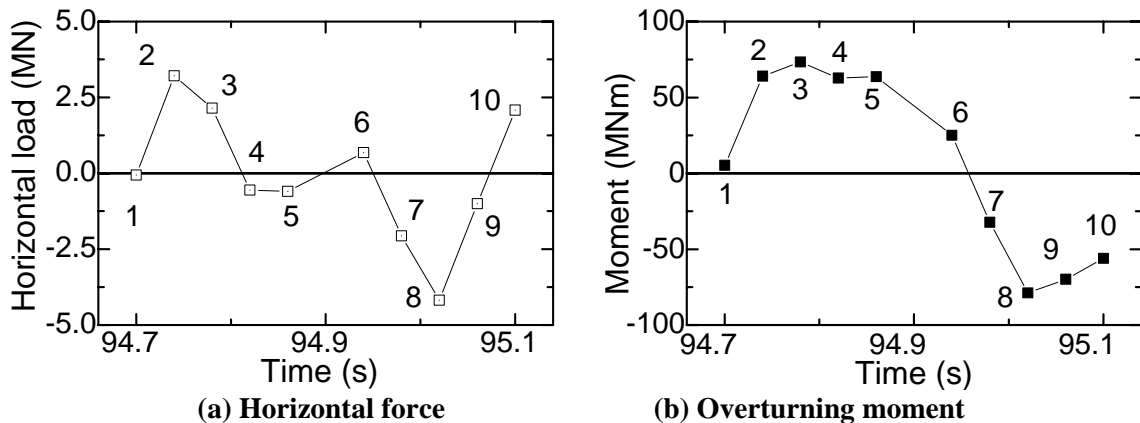


Figure 13. Equivalent forces acting on the foundation (2<sup>nd</sup> vibration mode)



## Analysis results

Figure 14 shows the comparisons between the calculated seismically induced shear forces and bending moments in the piles and the measured ones at the time instants 3 and 7 indicated in Figure 12 when the superstructure deformed in 1<sup>st</sup> vibration mode. It can be seen that the calculated results match very well with the measured one especially at the time when the pile acted as the front pile (pile 1 at time instant 7 and pile 2 at time instant 3).

Figure 15 shows the comparisons between the calculated seismically induced shear forces and bending moments in the piles and the measured values at the time instants 2 and 8 indicated in Figure 13 when the superstructure deformed in 2<sup>nd</sup> vibration mode. It can be seen from the figures that the analysis could not simulate the measurements well. This is thought to be due to the neglect of the kinematic effect in the analysis.

Figure 16 shows the distribution of horizontal ground movements during shaking. These horizontal ground movements were obtained by double integration of the measured horizontal acceleration (Acc10 to Acc12). It was found that when the superstructure exhibits the primary vibration mode, the ground also behaves in a primary vibration mode, and that when the superstructure exhibits the secondary vibration mode, the ground also behaves in a secondary vibration mode. In the latter case, it is thought that additional shear forces and bending moments in the piles due to kinematic effect (ground movements) occurred. Hence, kinematic effect should be taken into account in this case.

The analysis was carried out again for the 2<sup>nd</sup> vibration mode, taking into account the kinematic effect. Dynamic loads acting on the foundation were modelled by an equivalent static horizontal load, moment, as well as ground movement induced load. Figure 17 shows the assumed distribution of horizontal ground movements at time instant 8 used in the analysis.

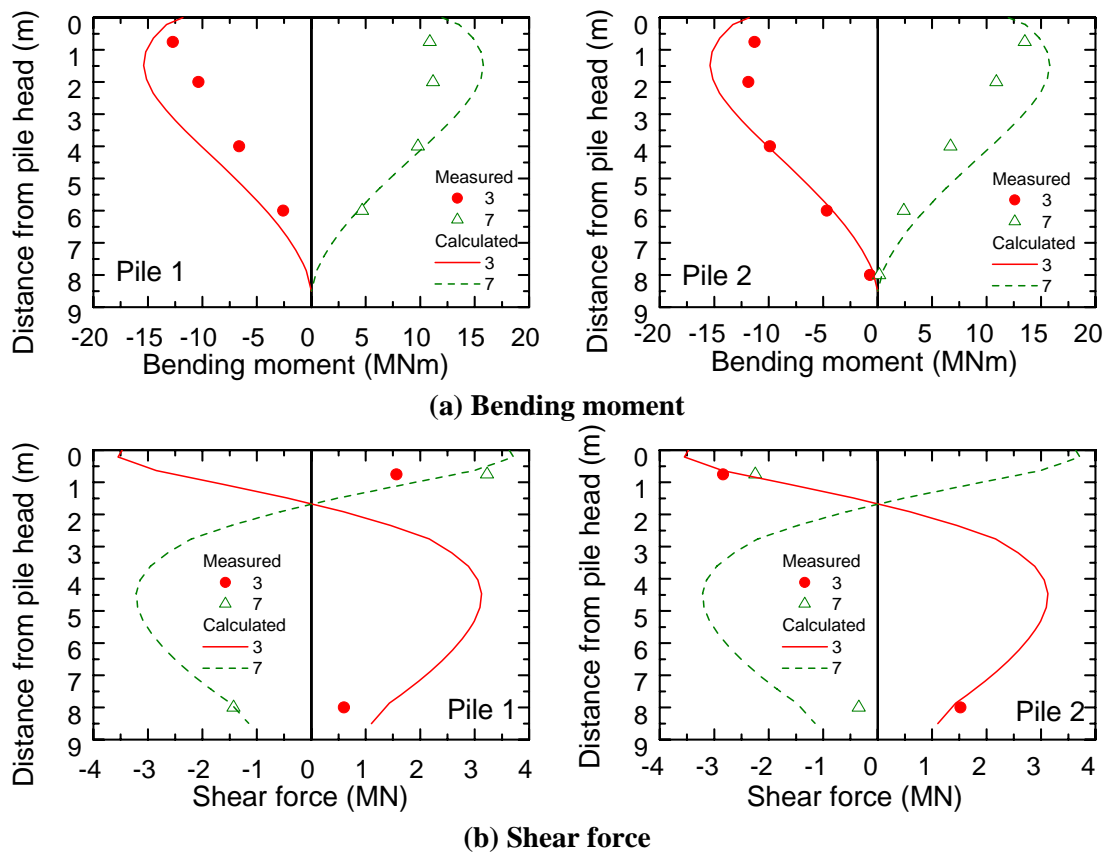
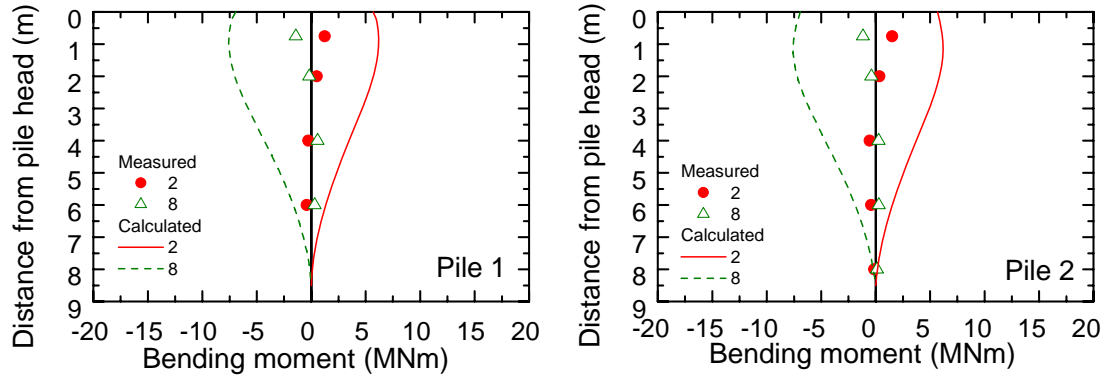
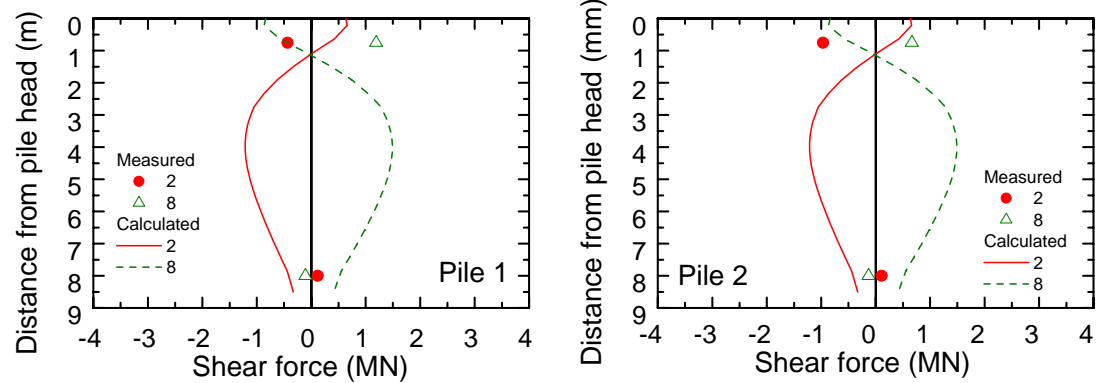


Figure 14. Seismically induced moment and shear force in the piles (1<sup>st</sup> vibration mode)

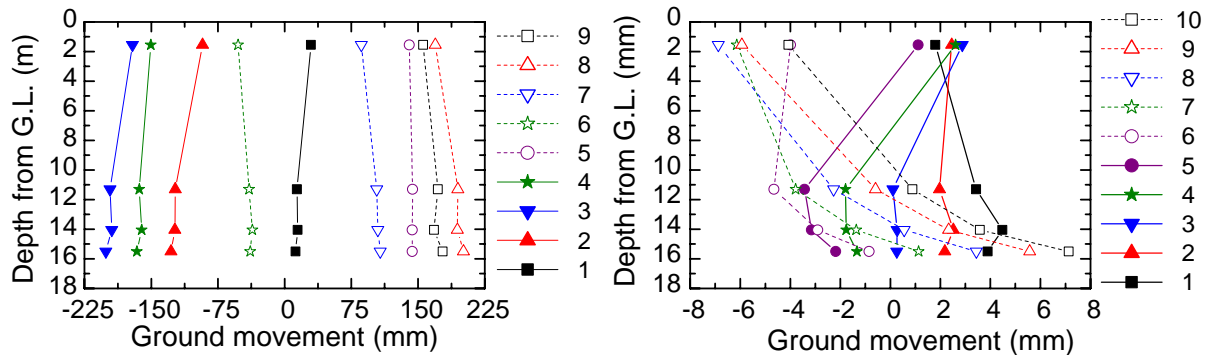


(a) Bending moment



(b) Shear force

Figure 15. Seismically induced moment and shear force in the piles (2<sup>nd</sup> vibration mode)



(a) 1<sup>st</sup> vibration mode

(b) 2<sup>nd</sup> vibration mode

Figure 16. Distribution of ground movements with depth

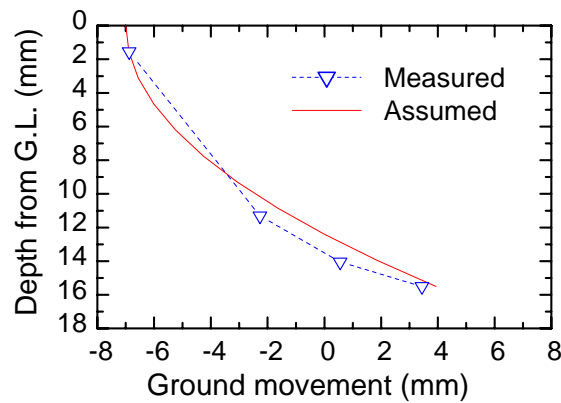
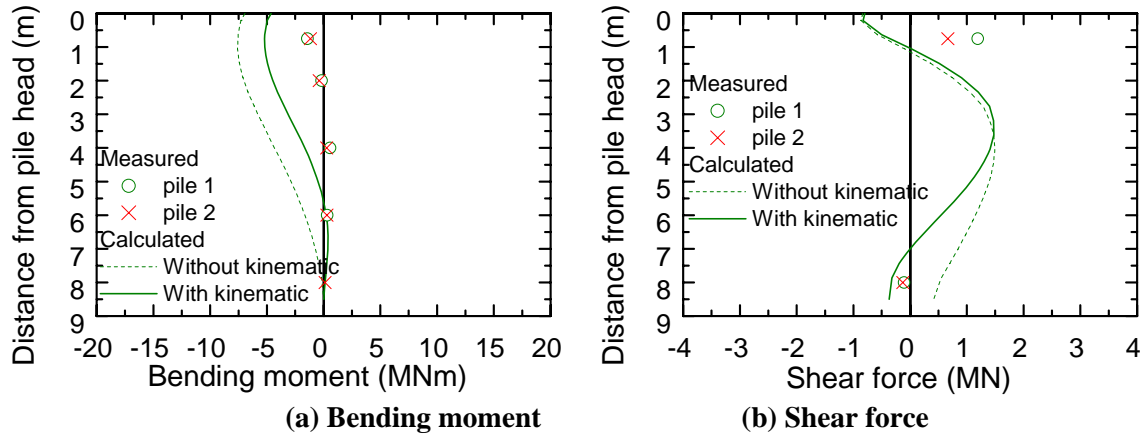


Figure 17. Free-field ground movement used in the analysis (time instant 8)



**Figure 18. Seismically induced bending moment and shear force in the piles**

Figure 18 shows again the comparisons between the calculated seismically induced shear forces and bending moments in the piles and the measured ones at the time instant 8 when the superstructure deformed in 2<sup>nd</sup> vibration mode. It can be seen that the calculated results with kinematic effect are closer to the measured values.

It can be seen from above measured results that magnitudes of bending moments and shear forces along the piles when superstructure exhibits the secondary vibration mode were about a half of the case when superstructure exhibits the primary vibration mode. These observed results were well simulated by the analyses.

### CONCLUDING REMARKS

In this paper, a series of shaking tests of model piled rafts with flexible superstructures on them have been carried out, in order to provide information on the influence of the flexibility of the superstructure on the whole structure. Main findings from the results of the model tests and the analyses are as follows:

- 1) For an input acceleration equal to the primary natural frequency of the superstructure, relatively large bending moments and shear forces were induced in the piles. In this case, even though the kinematic effect was neglected in the analysis, the calculated shear forces and bending moments match well with the measured values. That is, inertia force of the superstructure was dominant in this case.
- 2) For an input acceleration equal to the secondary natural frequency of the superstructure, magnitudes of bending moments and shear forces along the piles were about a half of the case of input acceleration equal to the primary natural frequency. In this case, the measured shear forces and bending moments were not predicted well from the analyses without the kinematic effect. The kinematic effect (ground movement) should be taken into account in this case.

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