

Experiments of Piled Raft Models subjected to Static Vertical and Horizontal Loads

Background

Piled raft foundations have been widely recognized as one of the most economical foundation systems since Burland et al. (1977) presented the concept of '**settlement reducers**'.

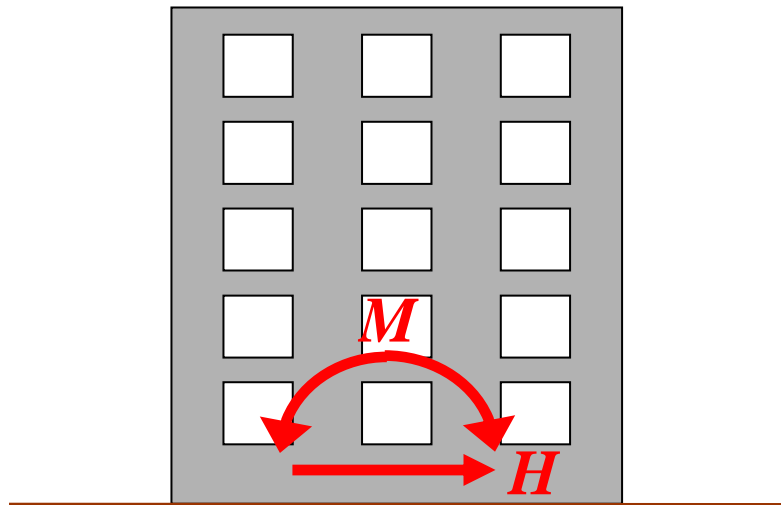
Some design concepts and their applications have been reported.

Although a number of works on the settlement of piled raft foundations have been reported, the detailed behavior of the piled raft foundations subjected to horizontal loads still has not been well clarified.

Establishment of a seismic design concept for piled raft foundations is necessary especially in highly seismic areas such as Japan.

A design approach of a foundation subjected to an earthquake

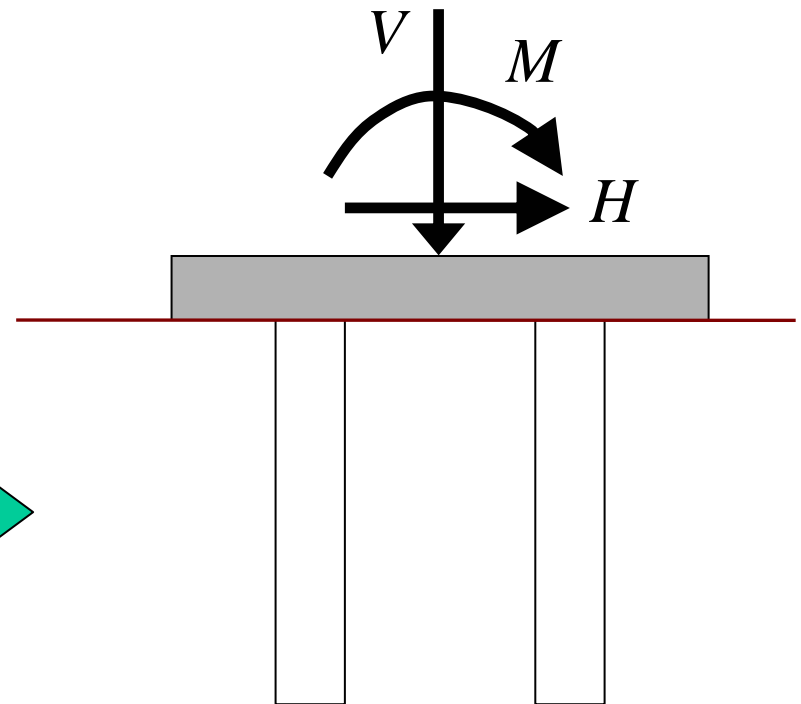
Approximate Equivalent Static Approach



Dynamic Analysis



Equivalent Forces



Static Deformation Analysis

Experiments of Piled Raft Models subjected to Static Vertical and Horizontal Loads

Background

Establishment of a seismic design concept for piled raft foundations is necessary especially in highly seismic areas such as Japan.



Estimation of deformation and load distribution of piled raft foundations subjected to general loadings is needed.

Experiments of Piled Raft Models subjected to Static Vertical and Horizontal Loads

Part 1: Centrifuge modelling of vertical and horizontal load tests of piled rafts in dry sand

Joint research of Kanazawa University and Taisei Corporation

Part 2: Vertical and horizontal load tests of model piled rafts with different pile head connection conditions at 1-g field

Joint research of Kanazawa University, Ando Corp., Hazama Corp., Nishimatsu Corp. and Sumitomo-Mitsui Corp.

Part 1: Centrifuge modelling of vertical and horizontal load tests of piled rafts in dry sand

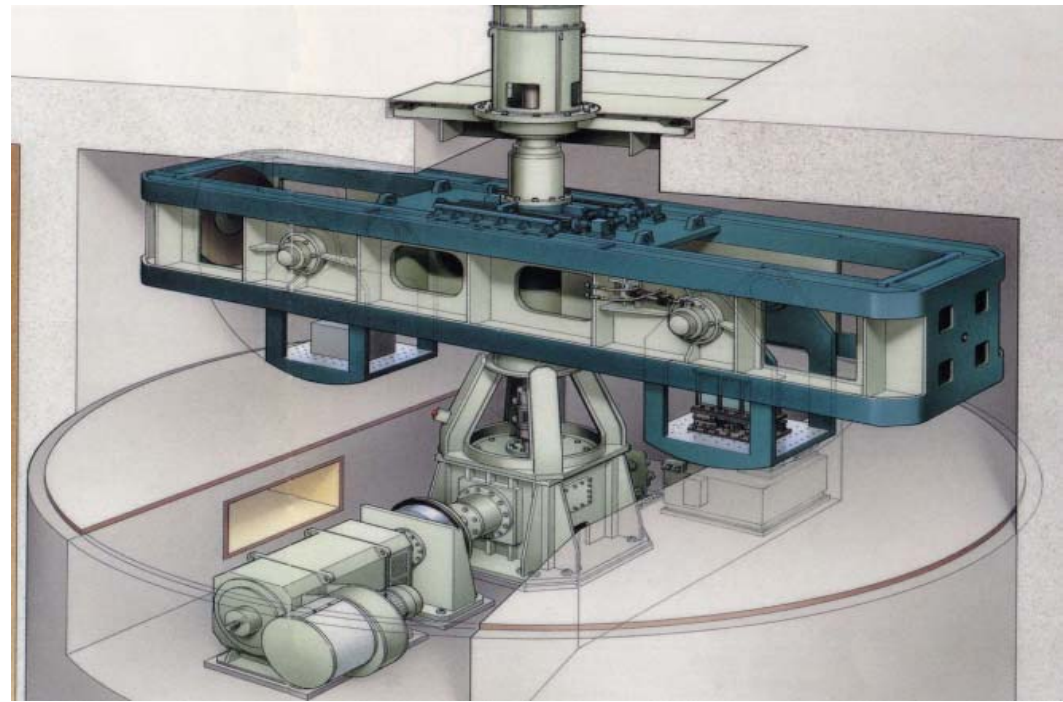
REFERENCE

Horikoshi, K., Matsumoto, T., Hashizume, Y., Watanabe, T. and Fukuyama, H. (2003): **Performance of piled raft foundations subjected to static vertical loading and horizontal loading**, *Int. Journal of Physical Modelling in Geotechnics* 2: 37-50.

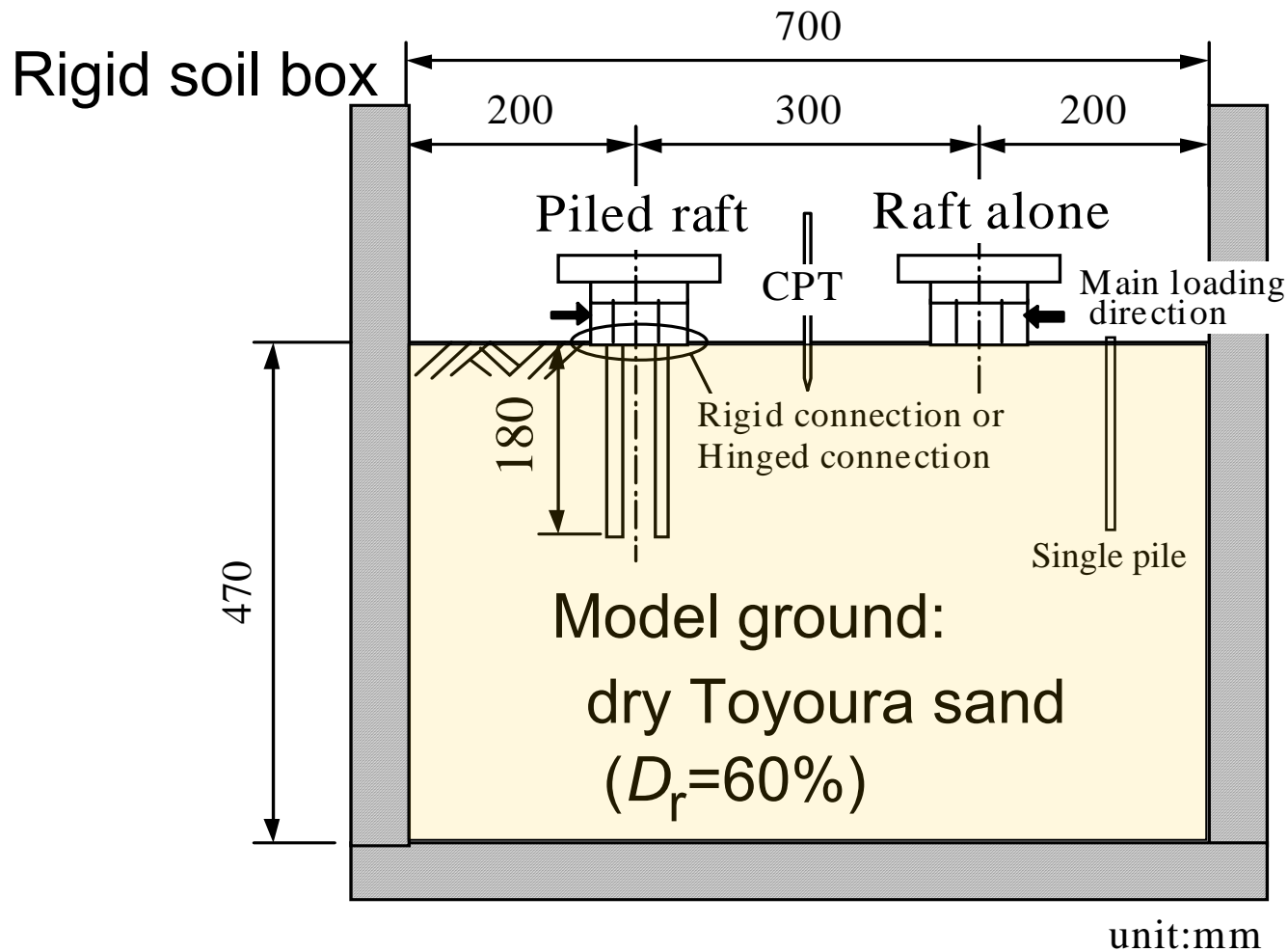
Centrifuge Device

Research Institute of
Taisei Corporation

Arm length
6.90 m
Max revolutions
260 r.p.m
Max centrifugal acceleration
200 G
Max load capacity
400 kg
Loading space
L1000 × B900 × H1000 mm



Centrifuge package used in static tests



Vertical and horizontal load tests on

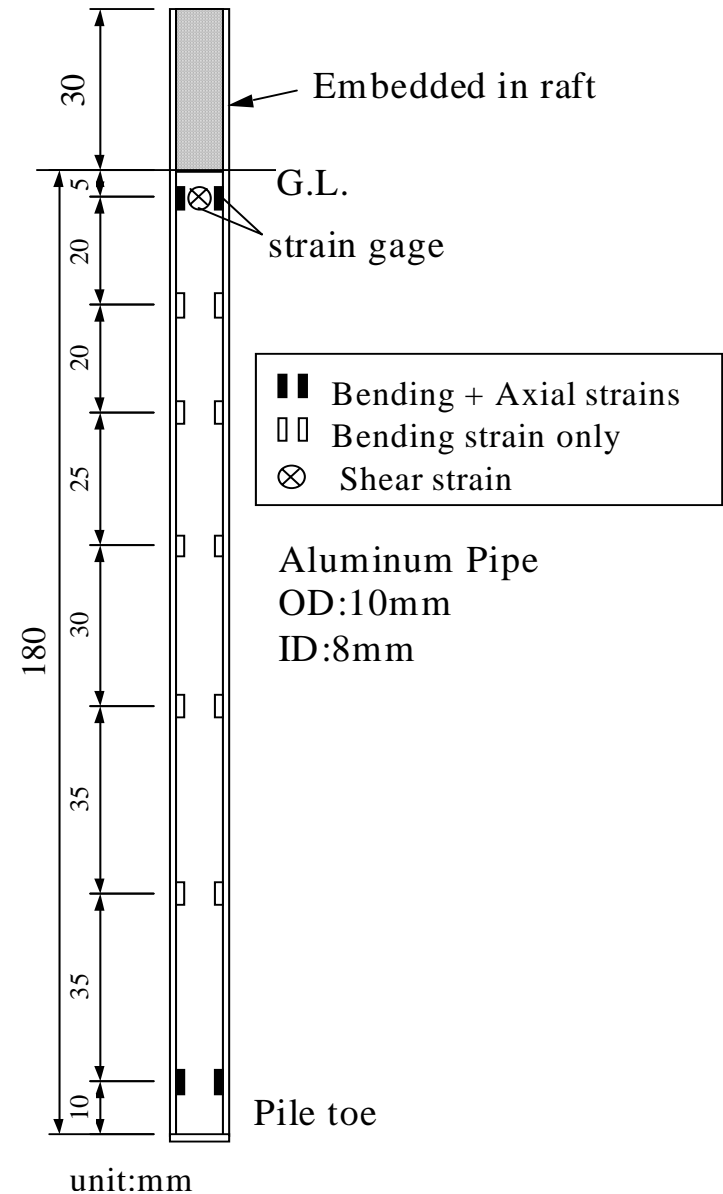
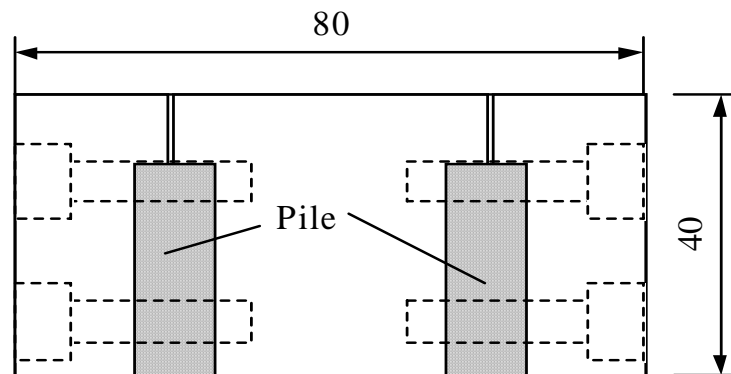
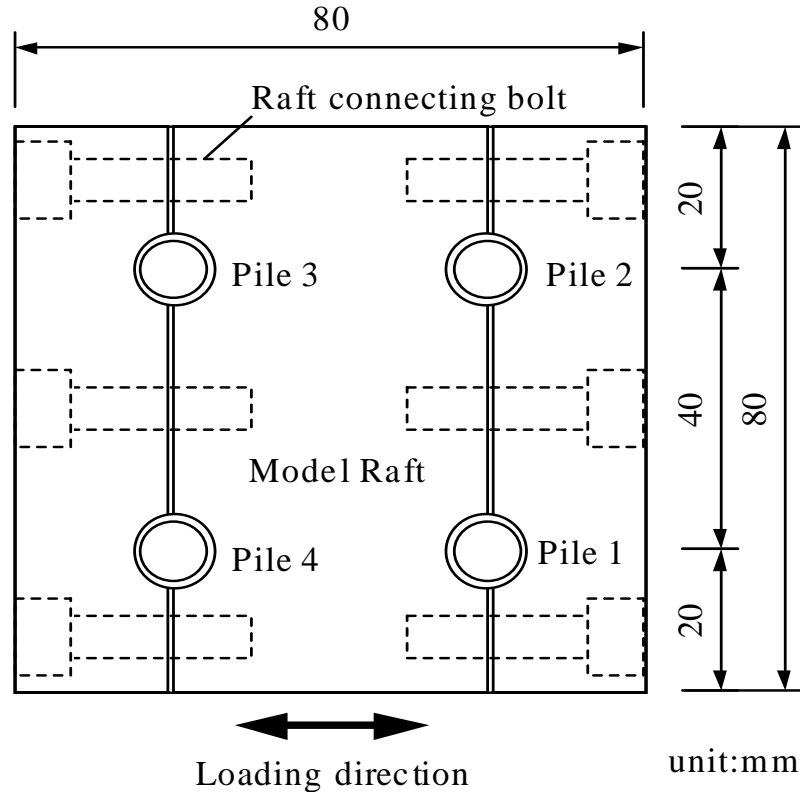
- Single piles
- Raft alone
- Piled rafts

Centrifugal acceleration = 50 G

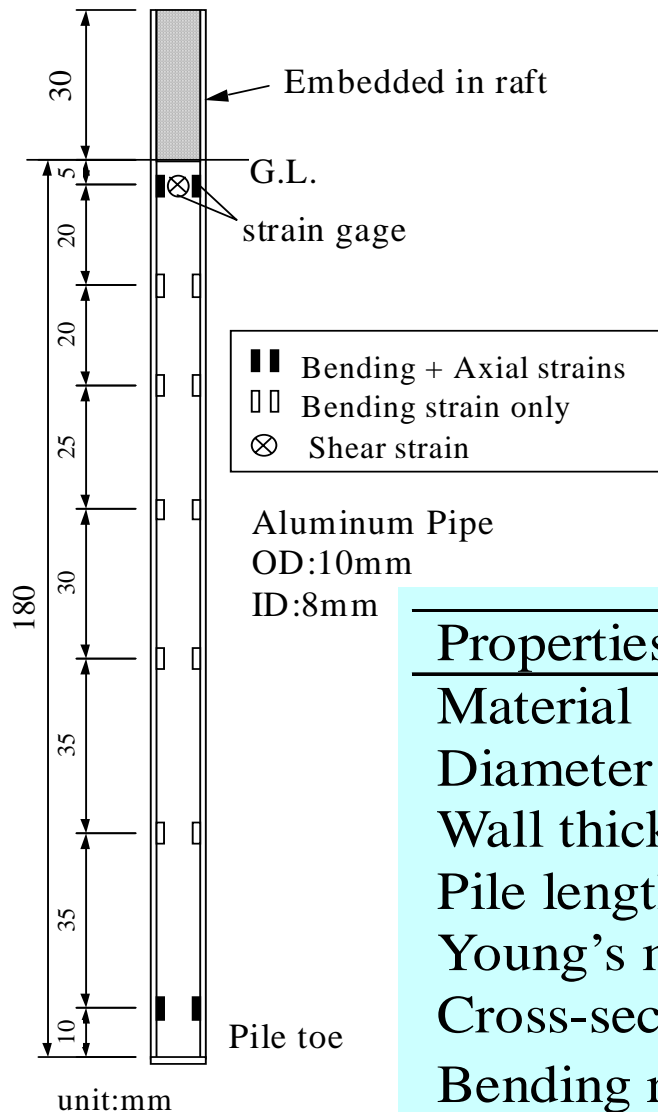
Properties of Toyoura sand

Properties	Value
Density of soil particle, ρ_s (t/m ³)	2.661
Mean grain size, D_{50} (mm)	0.162
Maximum dry density, ρ_{dmax} (t/m ³)	1.654
Minimum dry density, ρ_{dmin} (t/m ³)	1.349

Model piled raft for rigid pile head connection



Geometrical and mechanical properties of model pile in model and prototype scales

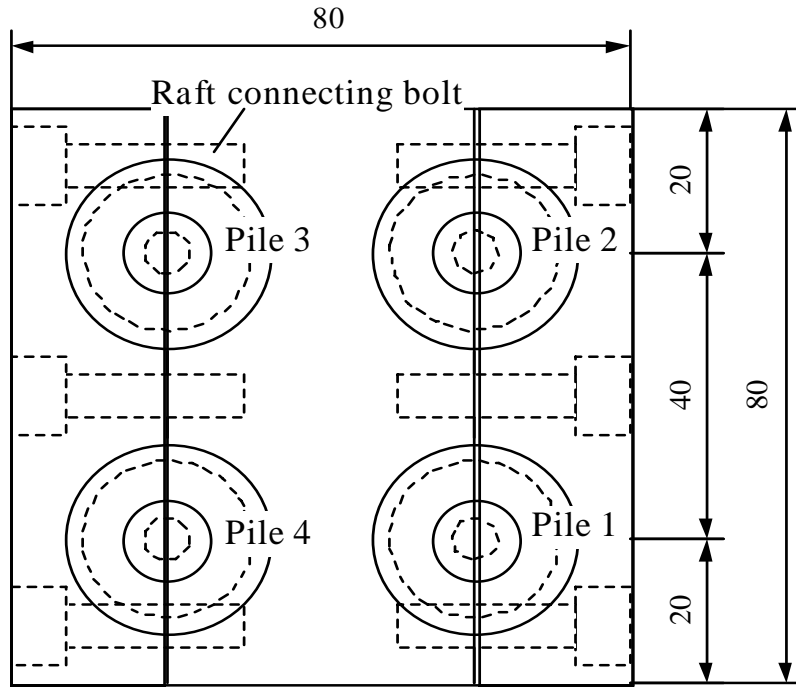


Centrifugal acceleration = 50 G

Properties of the model pile and the corresponding prototype pile

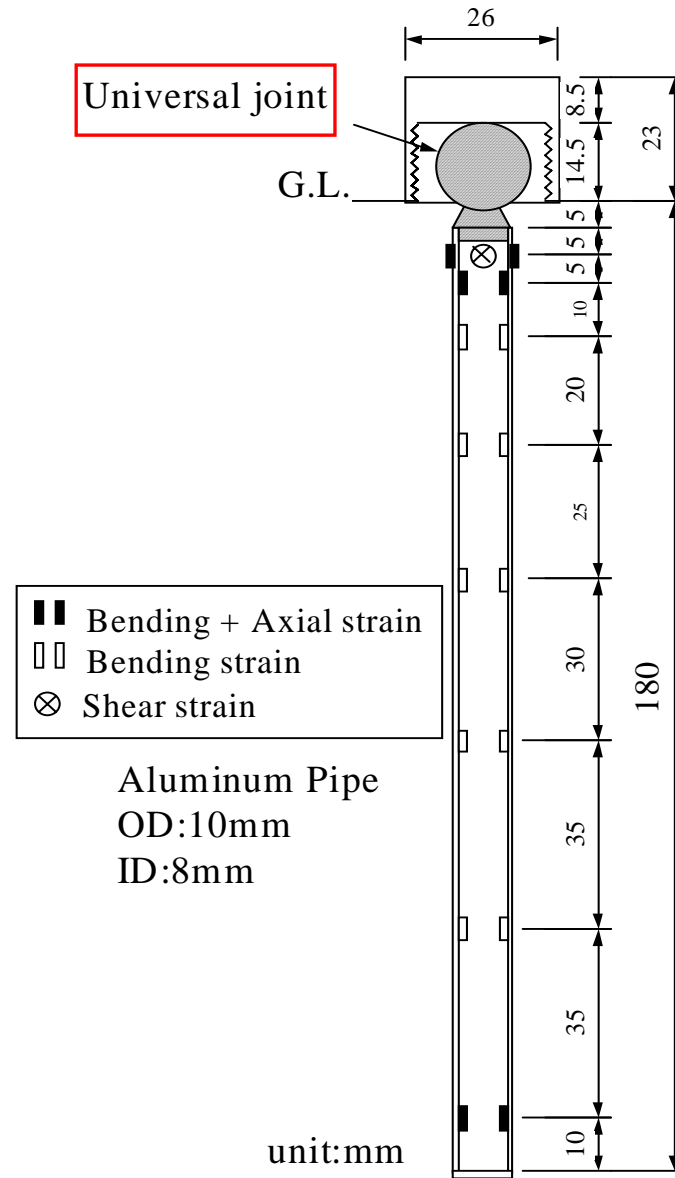
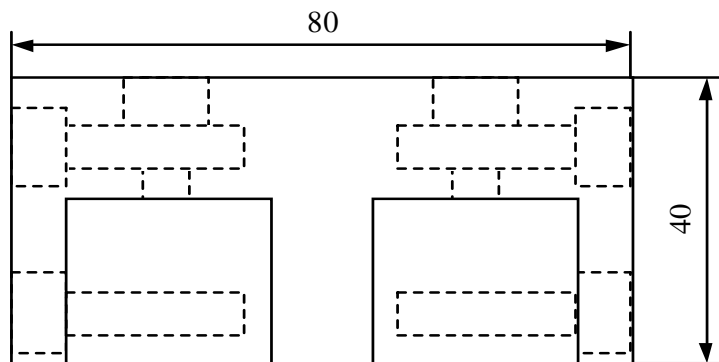
Properties	Centrifuge model	Prototype
Material	Aluminum	Concrete
Diameter	10 mm	500 mm
Wall thickness	1 mm	Solid
Pile length, L_p	180 mm	9.0 m
Young's modulus, E_p	71 GN/m ²	41.7GN/m ²
Cross-sectional rigidity, $E_p A_p$	2.0×10^{-3} GN	5.0 GN
Bending rigidity, $E_p I_p$	2.0×10^{-8} GNm ²	0.13 GNm ²

Model piled raft for hinged pile head connection



Loading direction

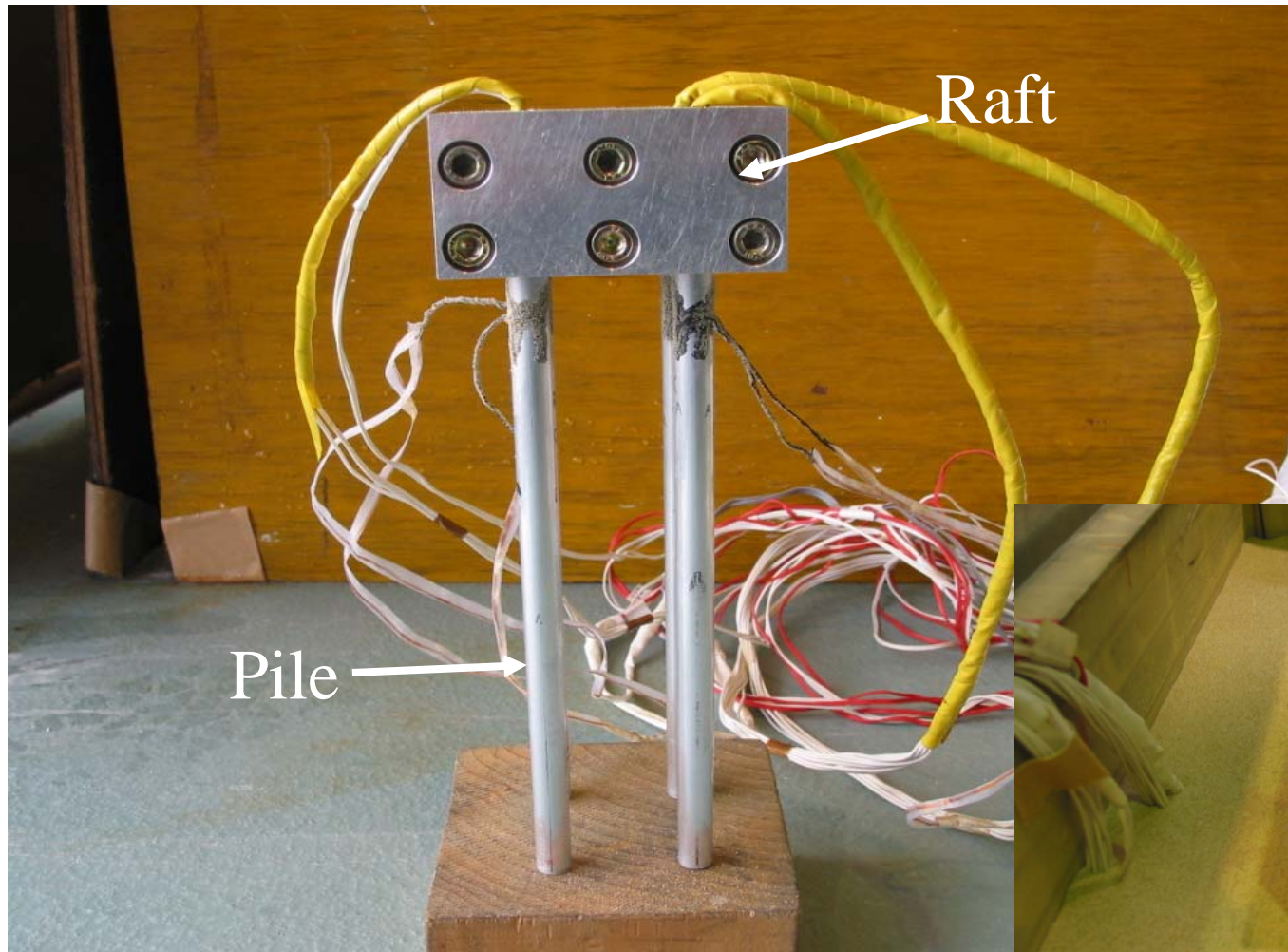
unit:mm



Universal joint used for hinged pile head connection model



Piled raft model

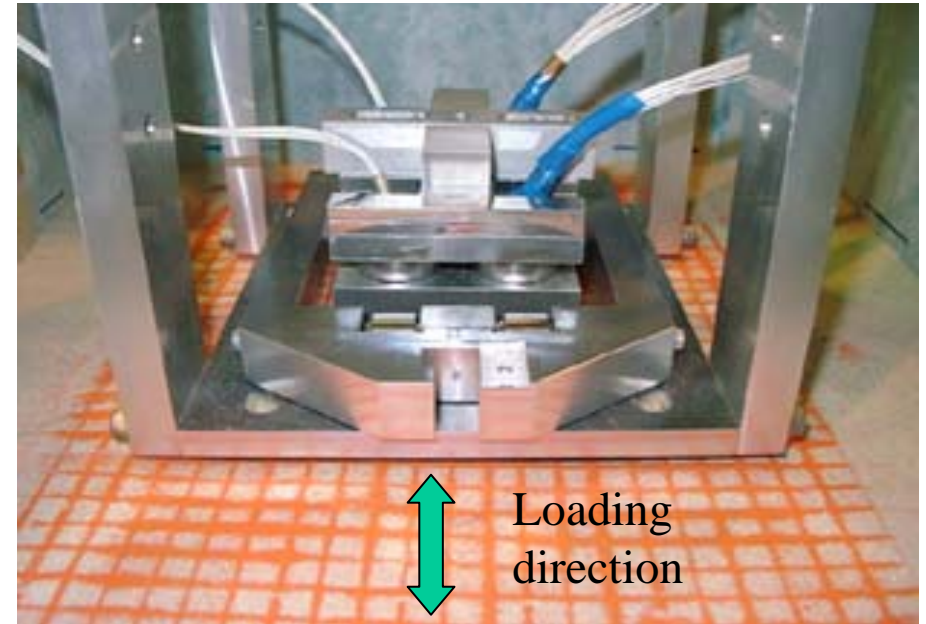
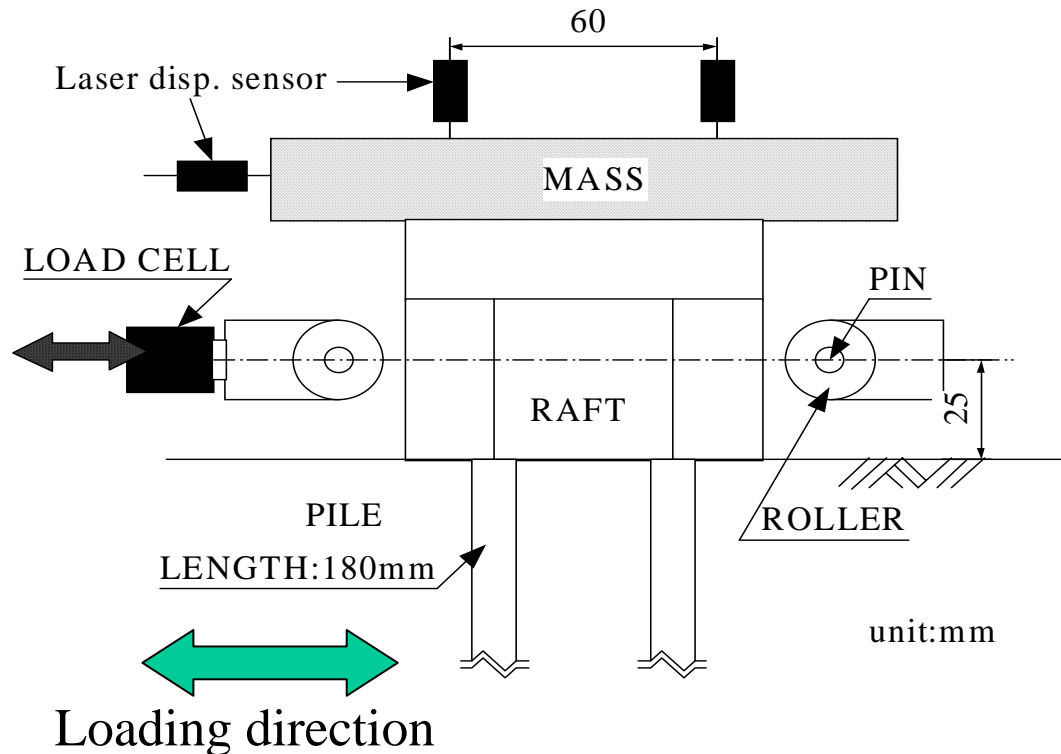


Experimental cases and their conditions

Model Type	Loading direction	
	Vertical loading	Horizontal loading
Single Pile	$L_p = 120, 180, 200 \text{ mm}$	$L_p = 180 \text{ mm}$
Raft (alone)	$B = 80, 120 \text{ mm}$ $M_r = 0.36 \text{ kg}$	$B = 80 \text{ mm}$ $M_r = 4.69 \text{ kg}$
Piled Raft	$L_p = 180 \text{ mm}$ $B = 80 \text{ mm}, 120 \text{ mm}$ $M_r = 0.90 \text{ kg}$	$L_p = 180 \text{ mm}$ $B = 80 \text{ mm}$ $M_r = 4.69 \text{ kg}$ Rigid or hinged pile head conditions

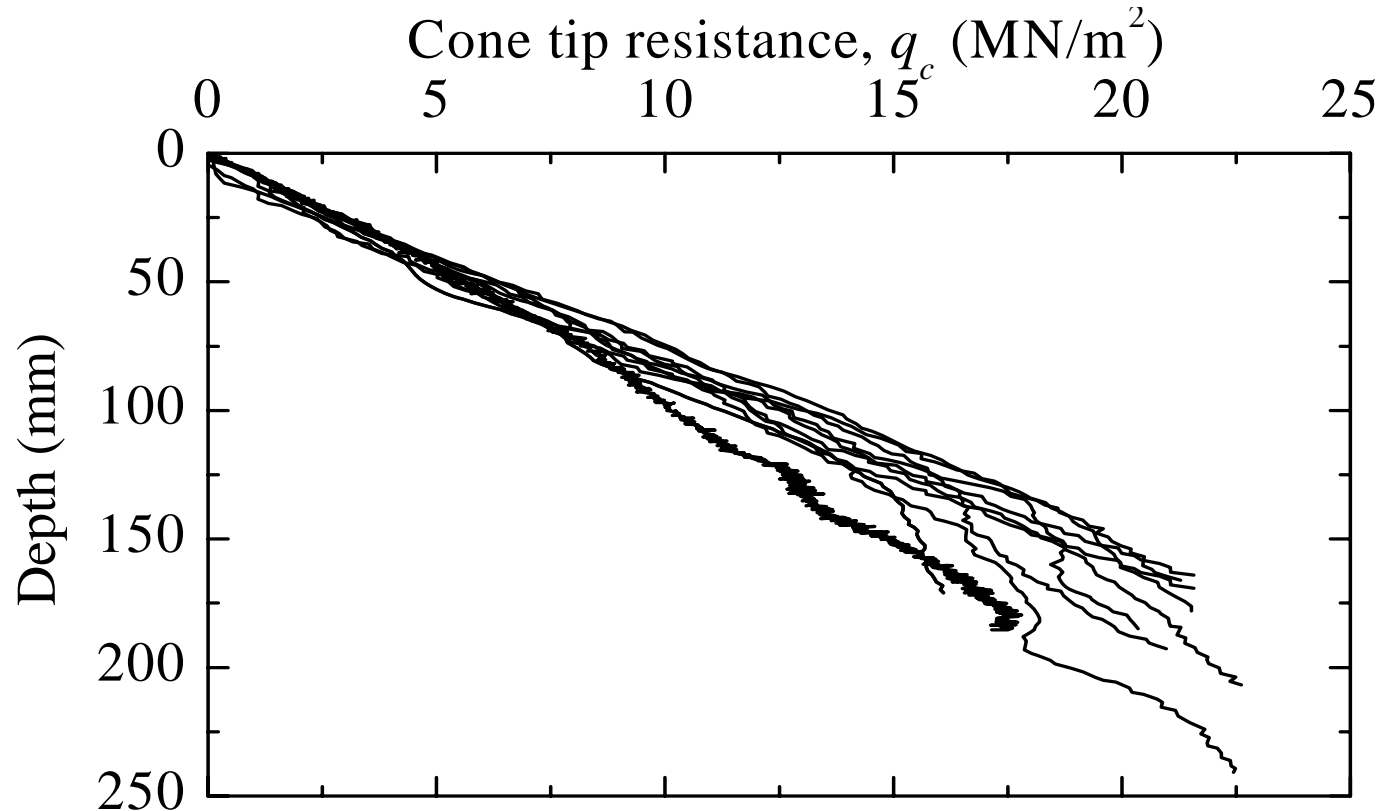
L_p : Pile length, B : Square raft width, M_r : Mass of raft

Horizontal loading device



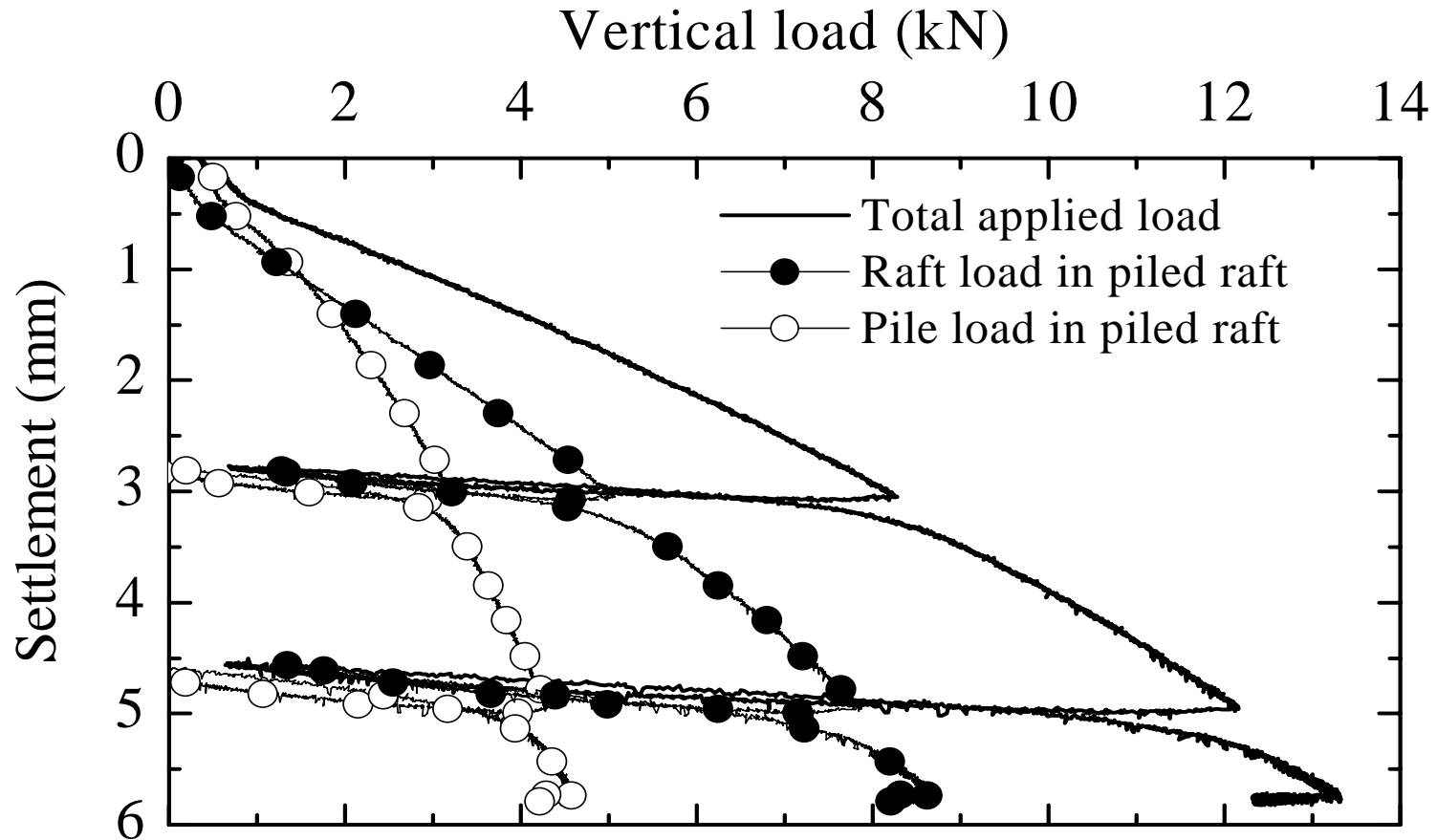
Capability to load cyclically
Loading rate 0.1 mm/min.
Horizontal load measured by load cell

Profiles of cone tip resistance

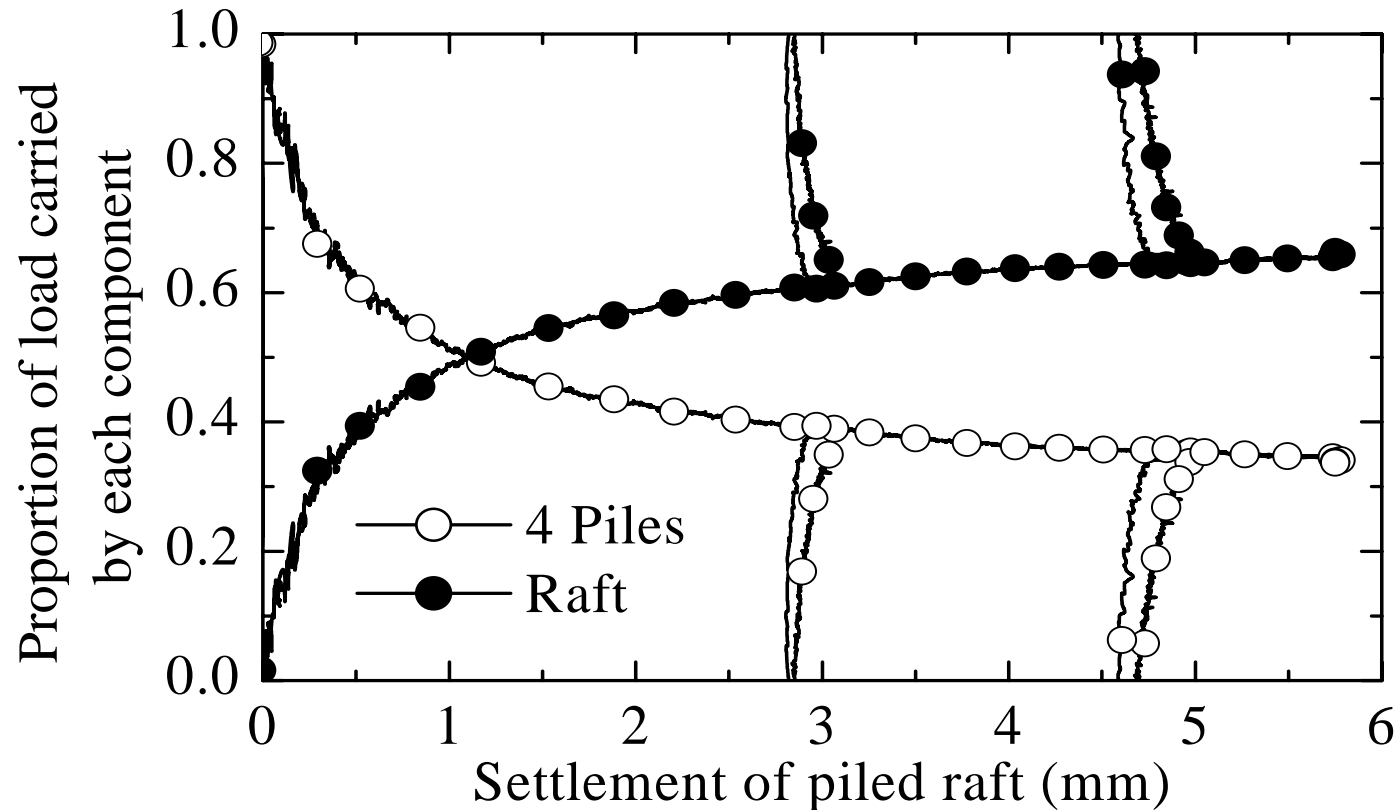


Soil conditions in tests were uniform.

Load-settlement relationships obtained from vertical loading test of piled raft

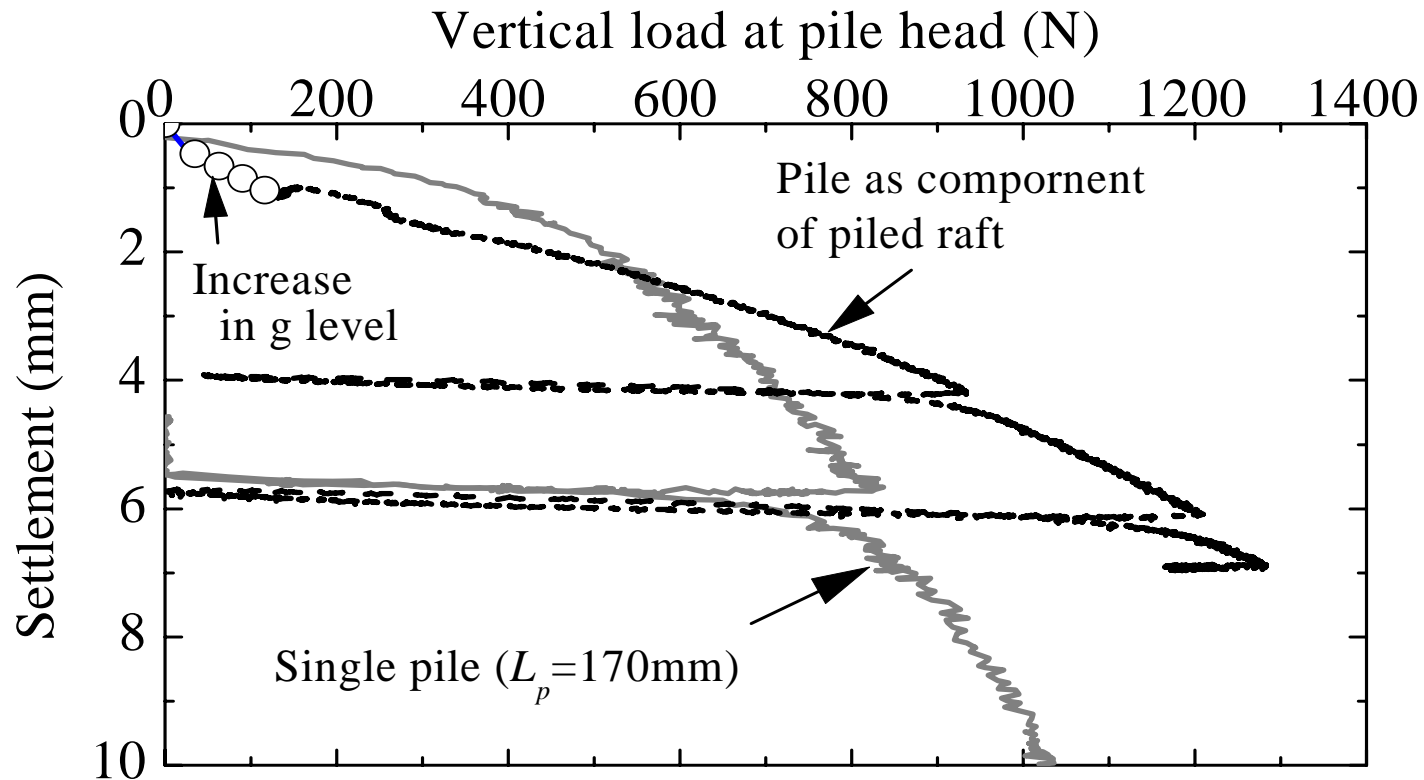


Proportion of vertical load carried by each component



- Piles carry much load when settlements are small.
- Proportion of load carried by the piles decreases with increasing settlement of the piled raft, thus proportion of raft load increases.

Behaviors of a pile in piled raft and isolated single pile

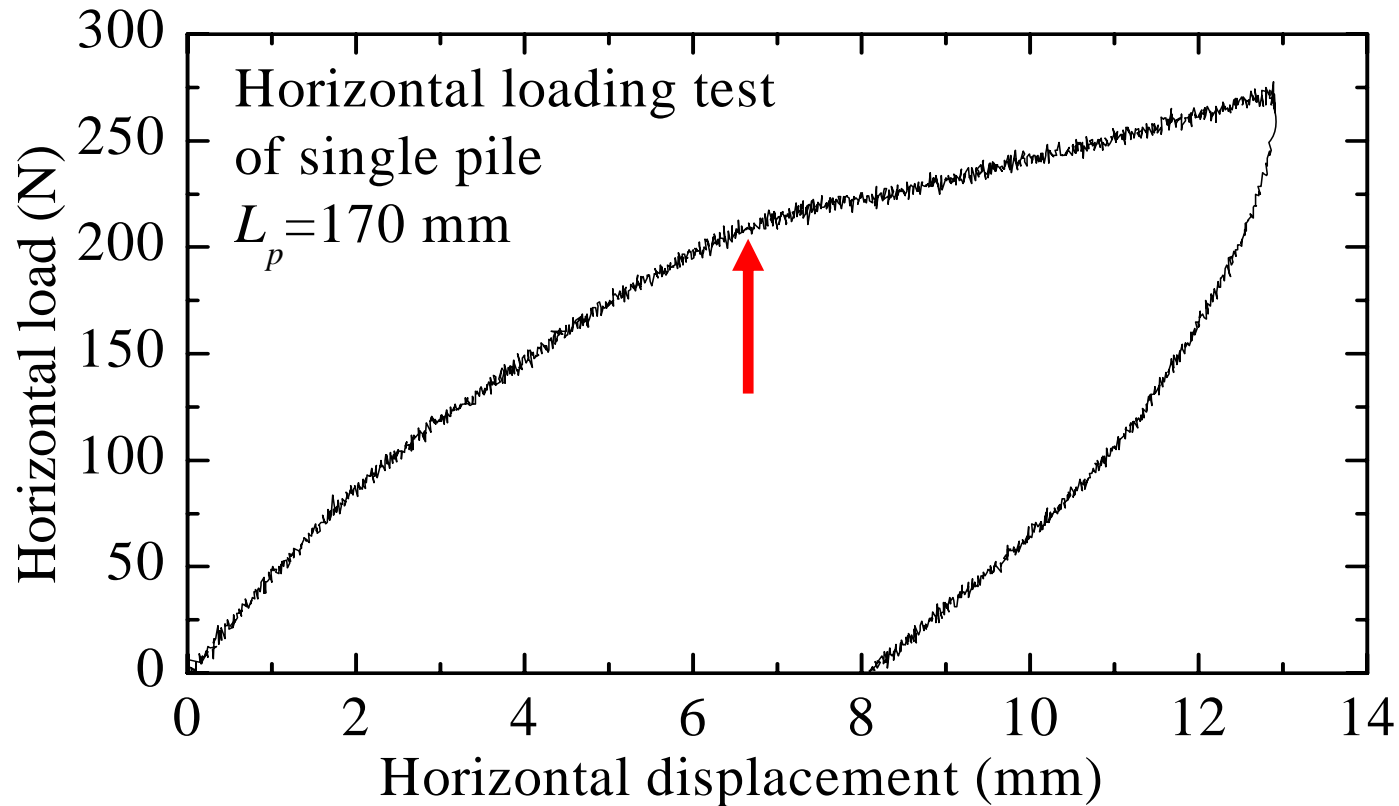


Resistance of a pile in the piled raft increases, compared to the corresponding single pile.



Effects of load transfer to the soil from the raft base.

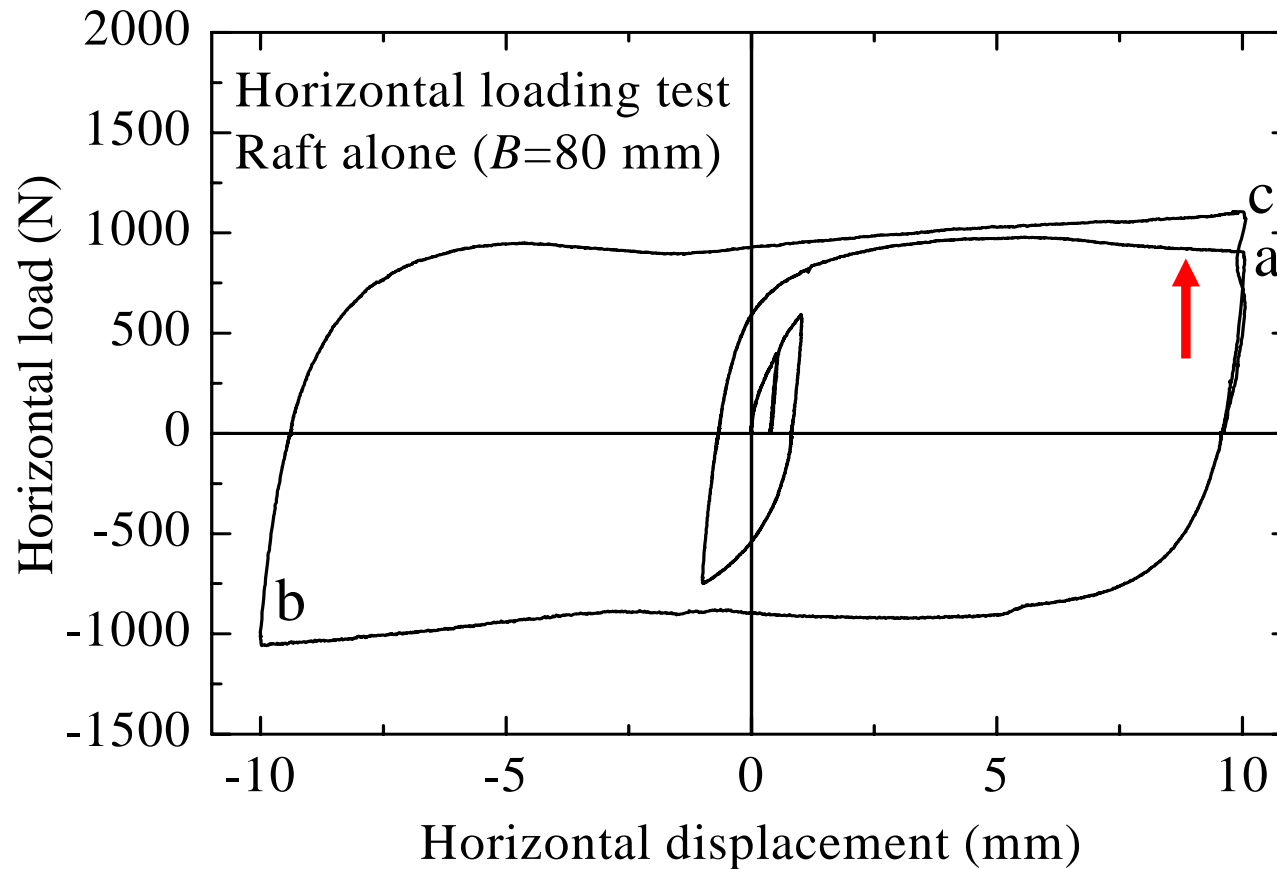
Horizontal load-displacement relationship of single pile



Bending yielding of the pile body did not occur.

⇒ Yielding of the soil occurred.

Horizontal load-displacement relationship of raft alone



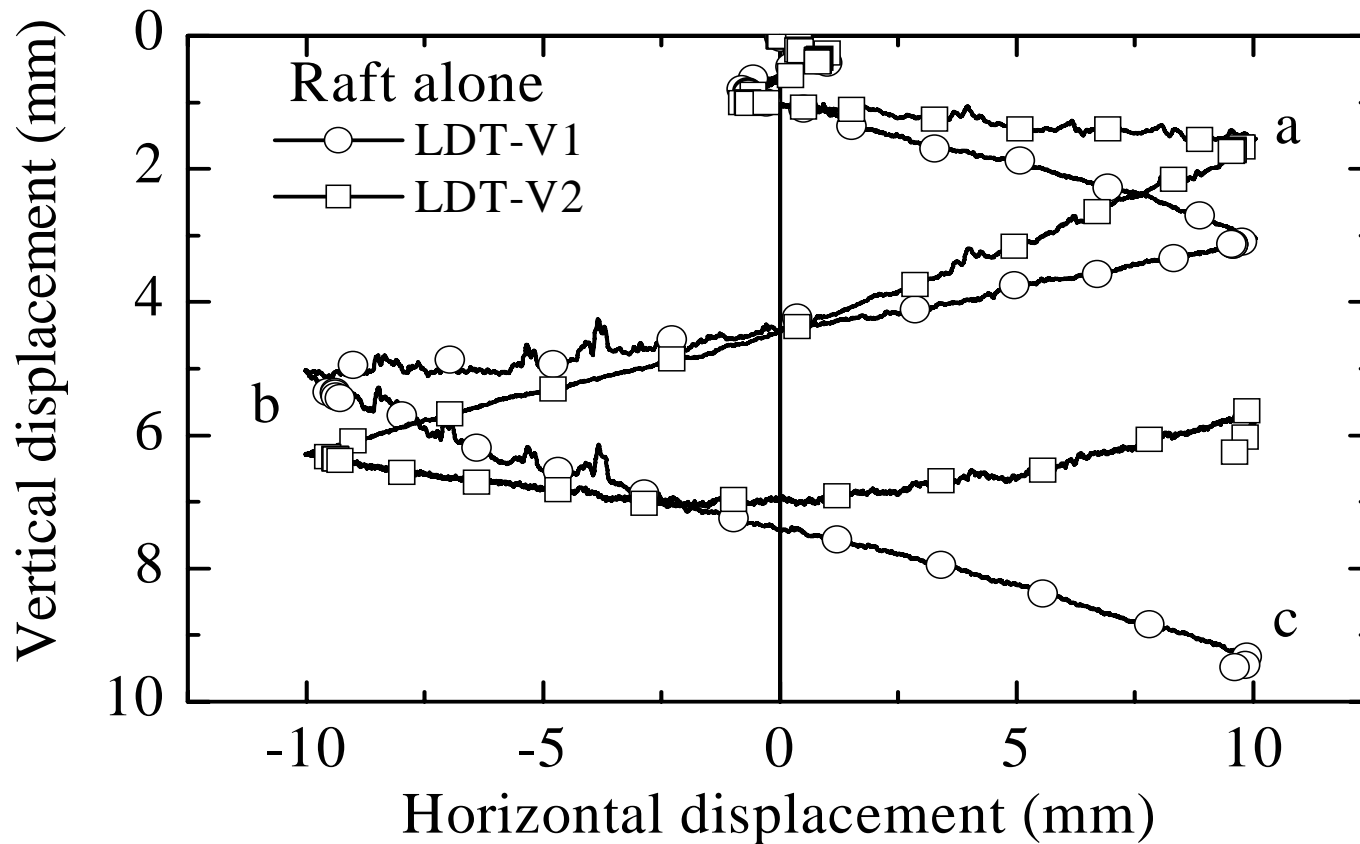
expressed in
prototype scale

Raft weight at 50 G = 2298 N

Peak horizontal resistance = 973N

⇒ Coefficient of friction between the raft base and the soil = $973/2298$
= 0.423

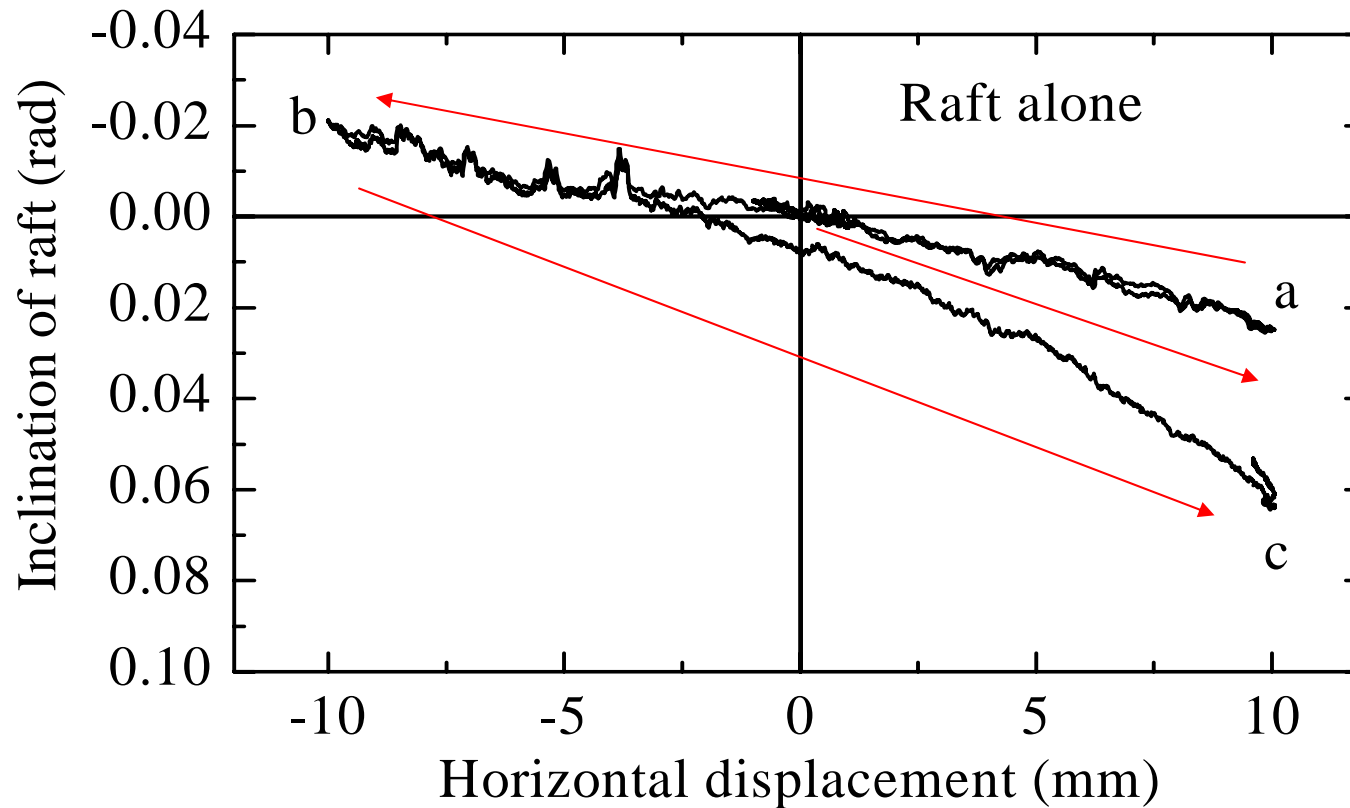
Vertical displacements of model raft during horizontal loading



expressed in
prototype scale

Rate of increase in settlement increased when the direction of horizontal displacement reversed.

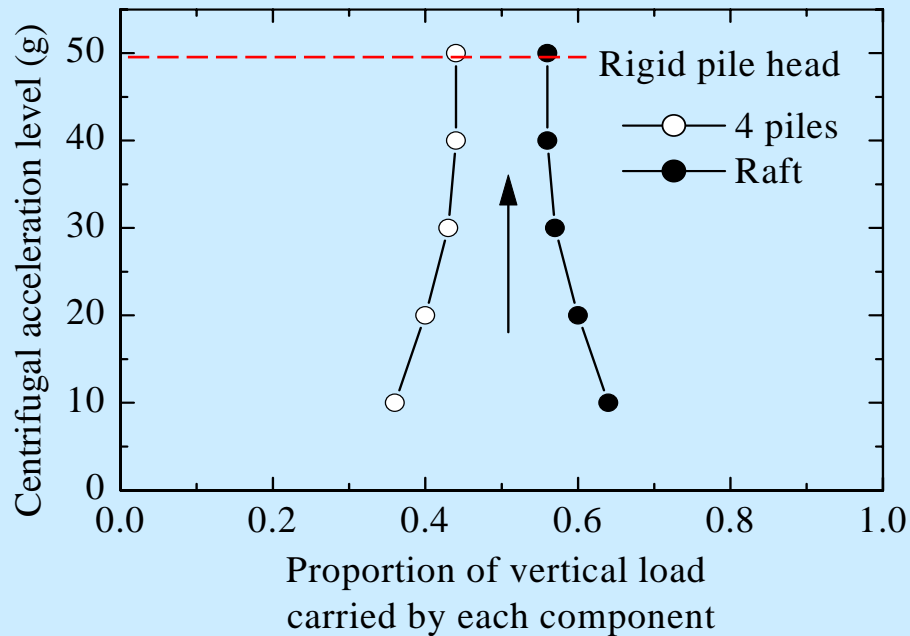
Inclination of model raft during horizontal loading



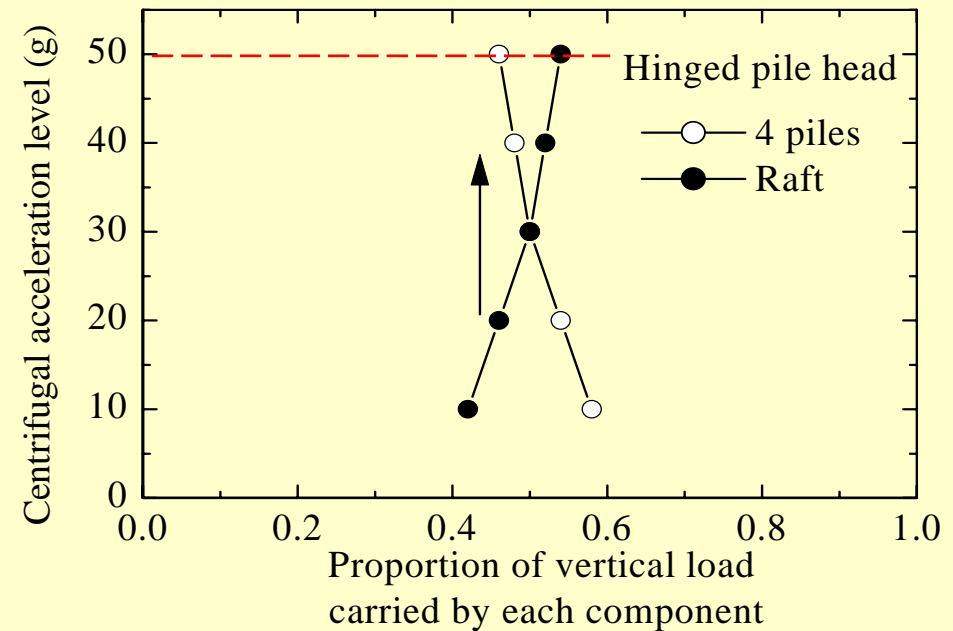
- Almost linear relationship between the tilting of the raft and the horizontal displacement was observed.

Piled Raft Models

Proportions of vertical load carried by raft and piles during the stage of increasing centrifugal acceleration level to 50 G



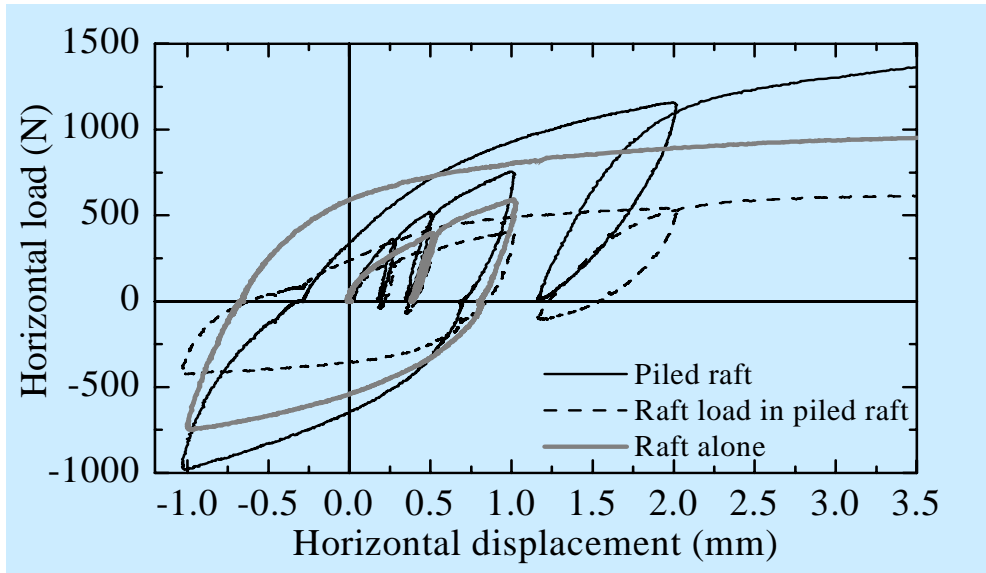
Rigid pile head connection



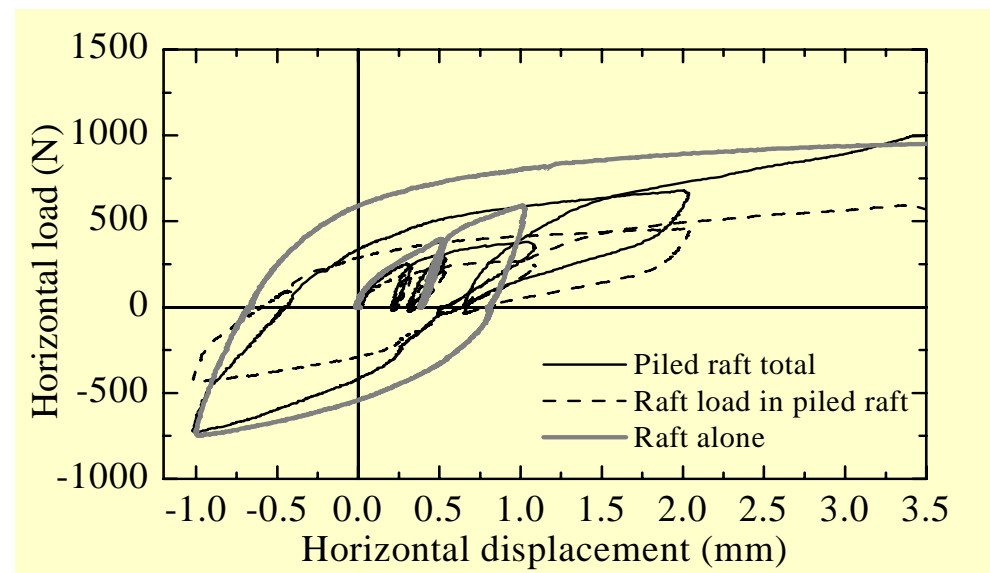
Hinged pile head connection

At centrifugal acceleration of 50 G, load proportions of the piles and the raft are about 50% and 50% in both models.

Horizontal load-displacement relationship of piled rafts

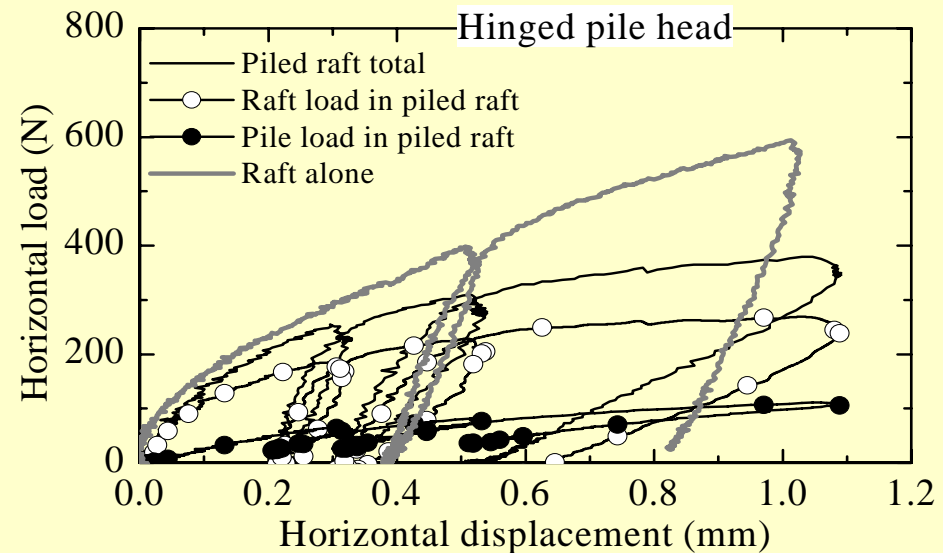
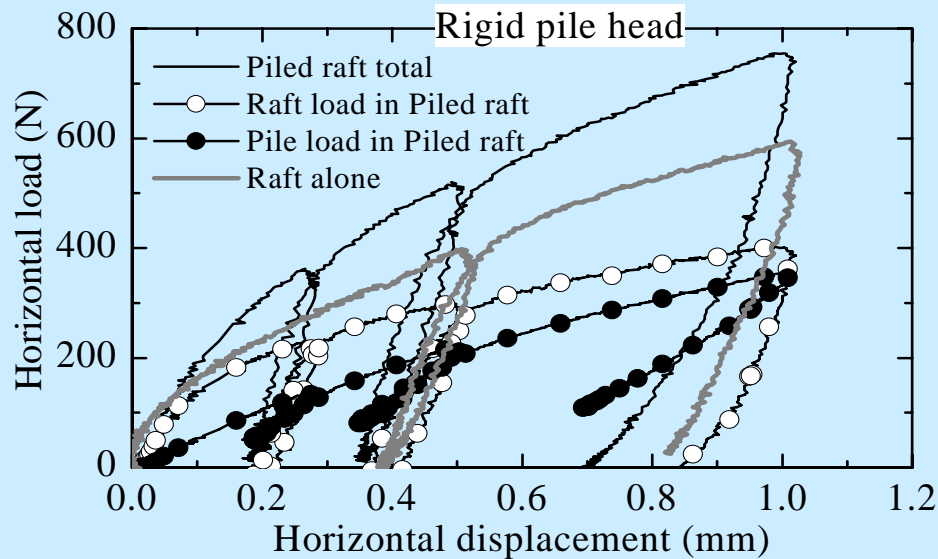


Rigid pile head connection



Hinged pile head connection

Horizontal load-displacement relationship of piled rafts (initial parts enlarged)



Piled raft with rigid pile head connection:

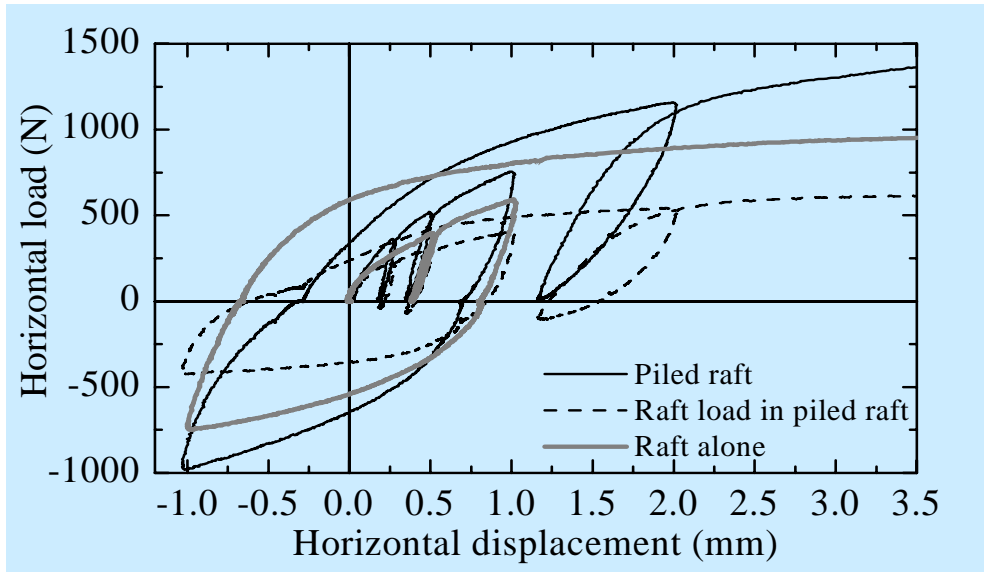
Horizontal load in the pile raft $>$ Horizontal load of the raft alone

Piled raft with hinged pile head connection:

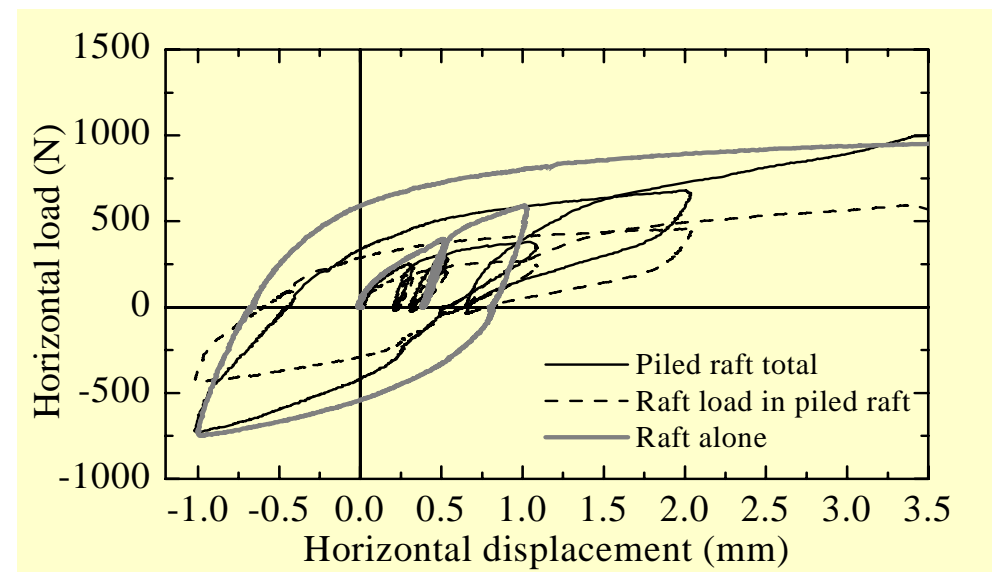
Horizontal load in the pile raft $<$ Horizontal load of the raft alone

Pile load is less in the piled raft with hinged pile head connection.

Horizontal load-displacement relationship of piled rafts



Rigid pile head connection



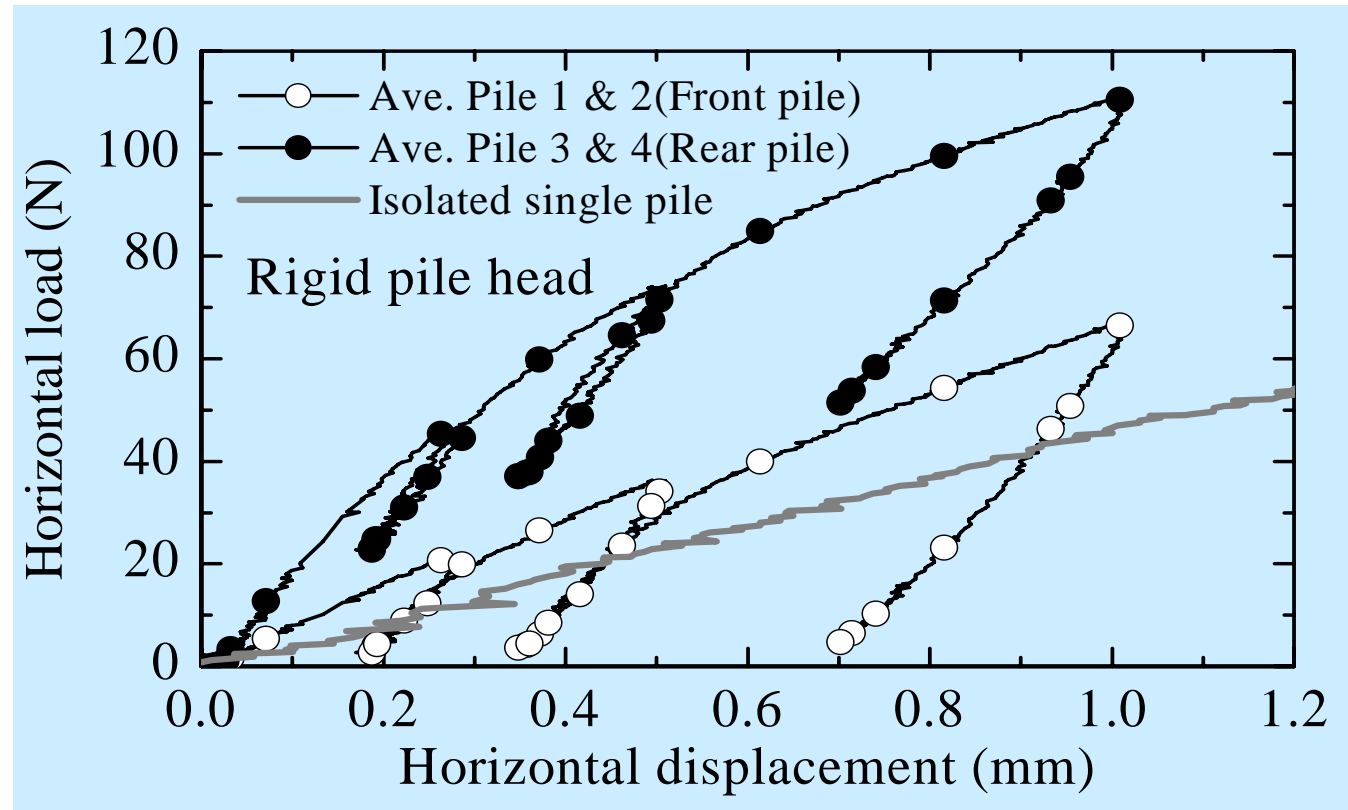
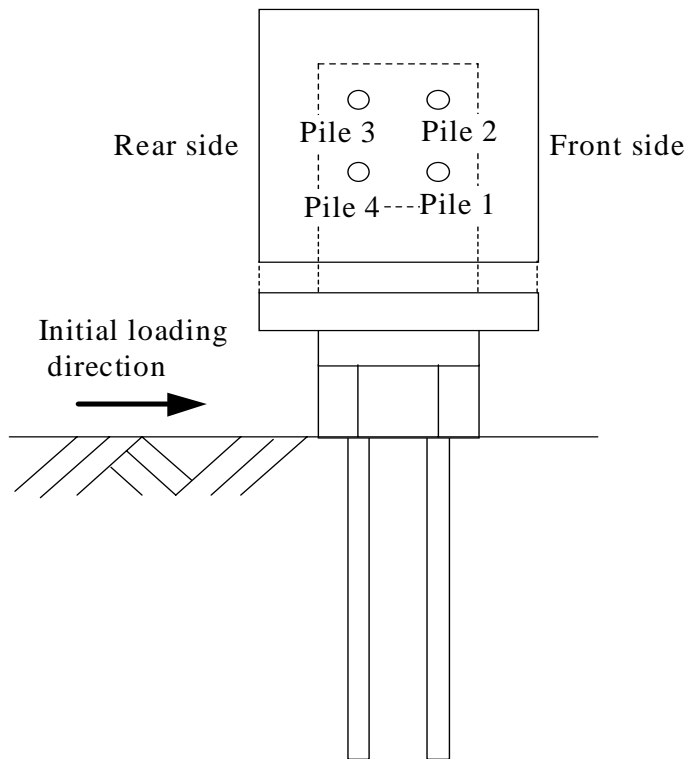
Hinged pile head connection

Measured and estimated raft resistance in the piled rafts

	Raft resistance (N)	
	Measured value	Estimated value
Rigid piled head connection	586 (0.83)	710
Hinged piled head connection	552 (0.95)	584

The value in () shows the ratio: Measured/Estimated

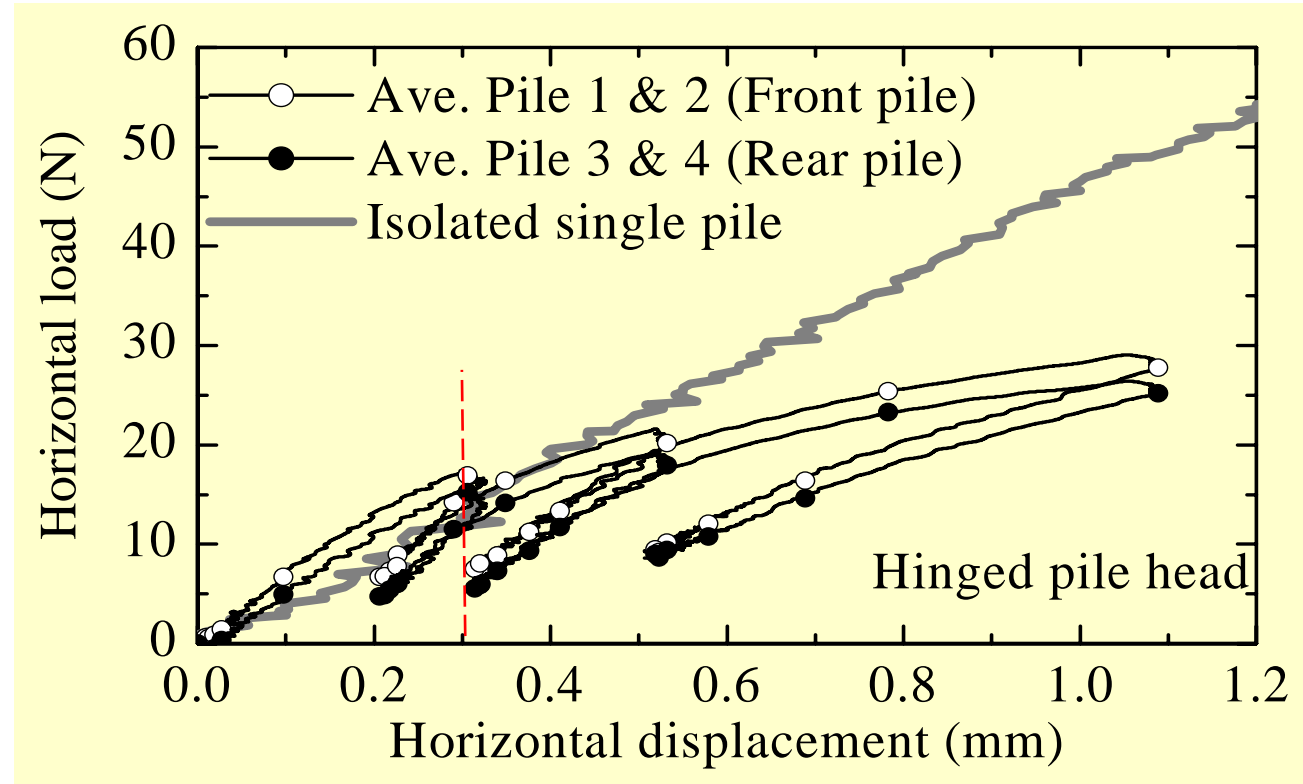
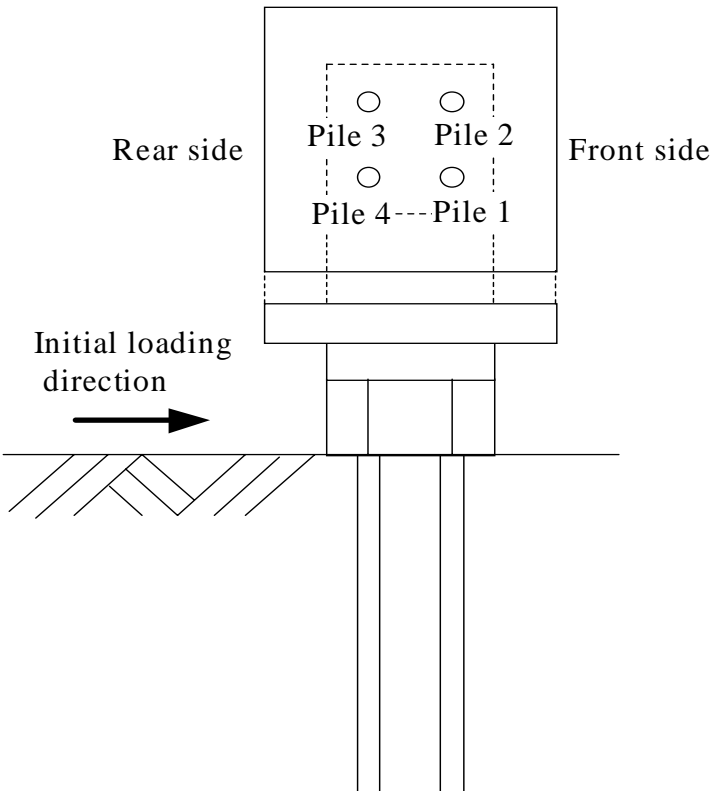
Horizontal load-displacement relationships of piles in rigid pile head connection model, together with that of single pile



Horizontal loads of piles in pile raft >> horizontal load of single pile

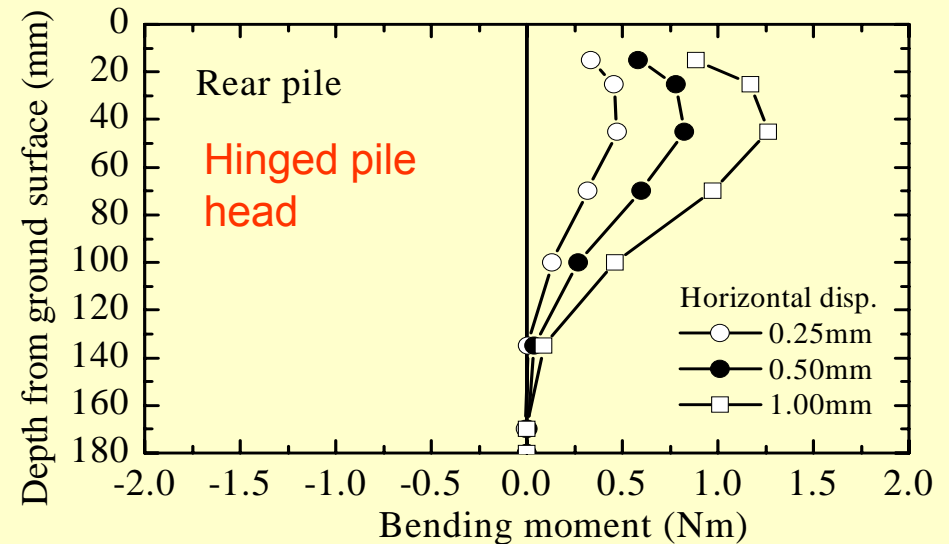
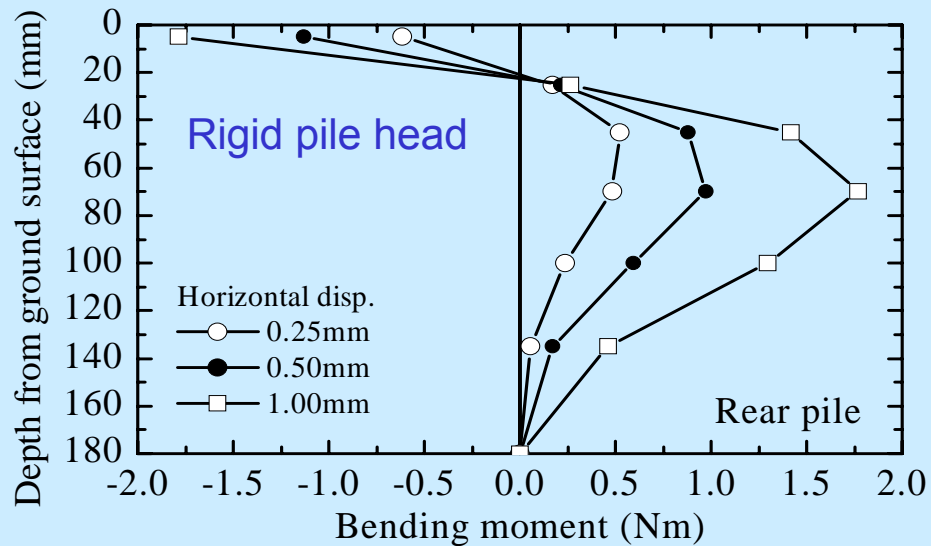
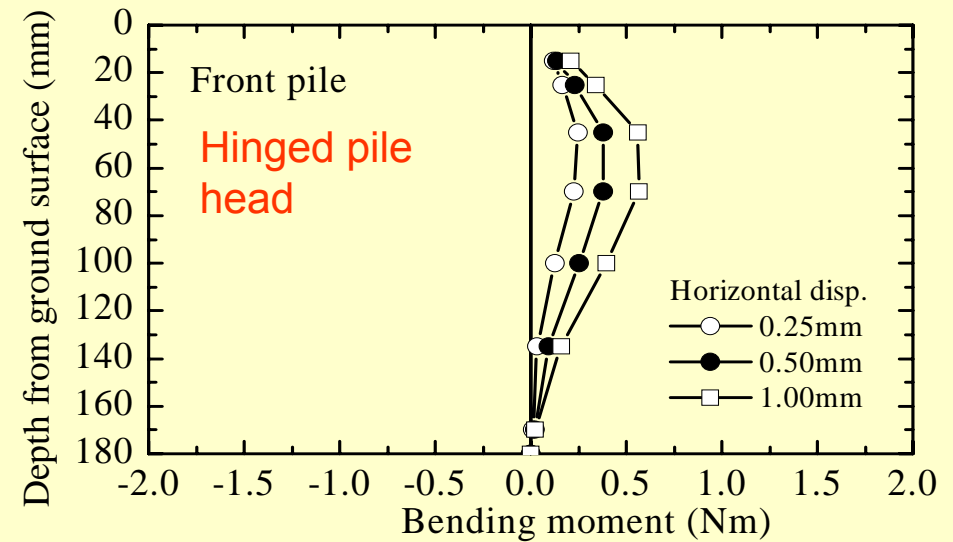
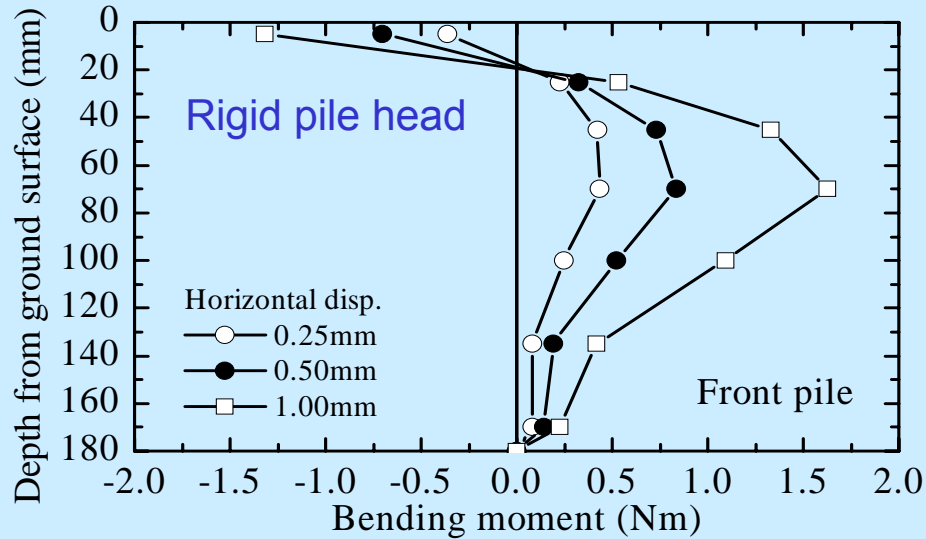
due to difference of the pile head conditions and stresses in the ground

Horizontal load-displacement relationships of piles in hinged pile head connection model, together with that of single pile

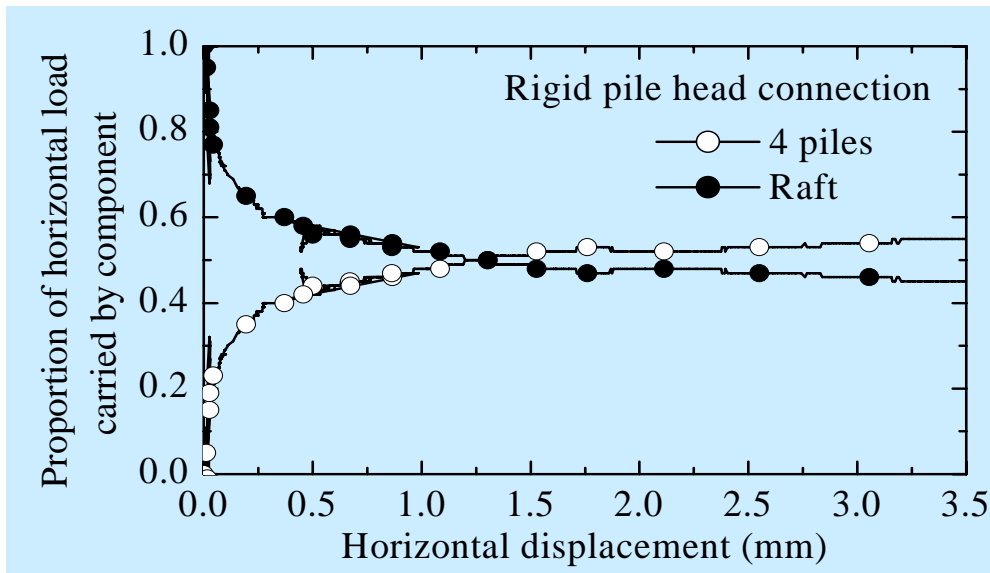


- The interaction between the piles and the raft base probably reduces the horizontal stiffness per pile in the piled raft.

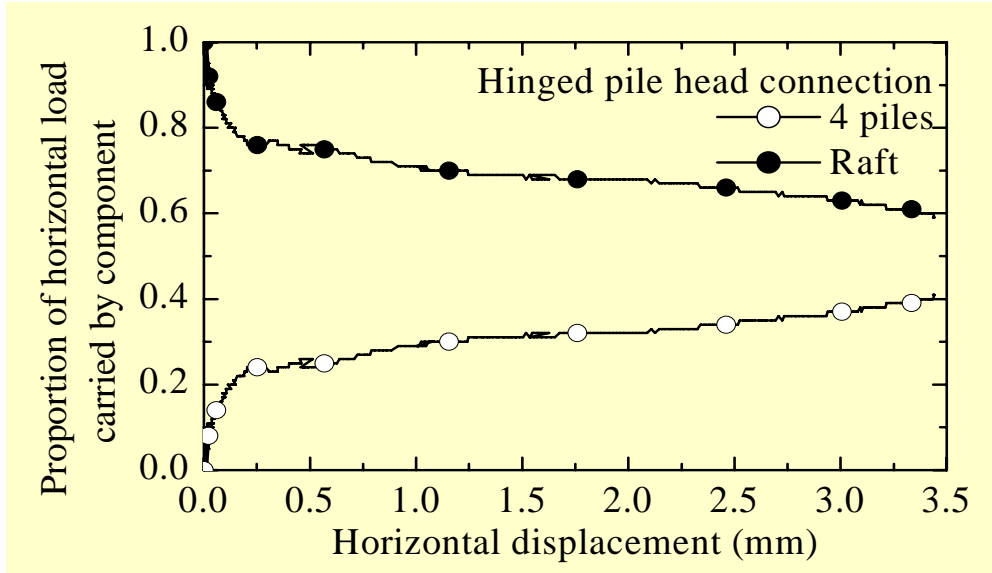
Distributions of bending moments down piles in the piled rafts



Proportions of horizontal load carried by each component



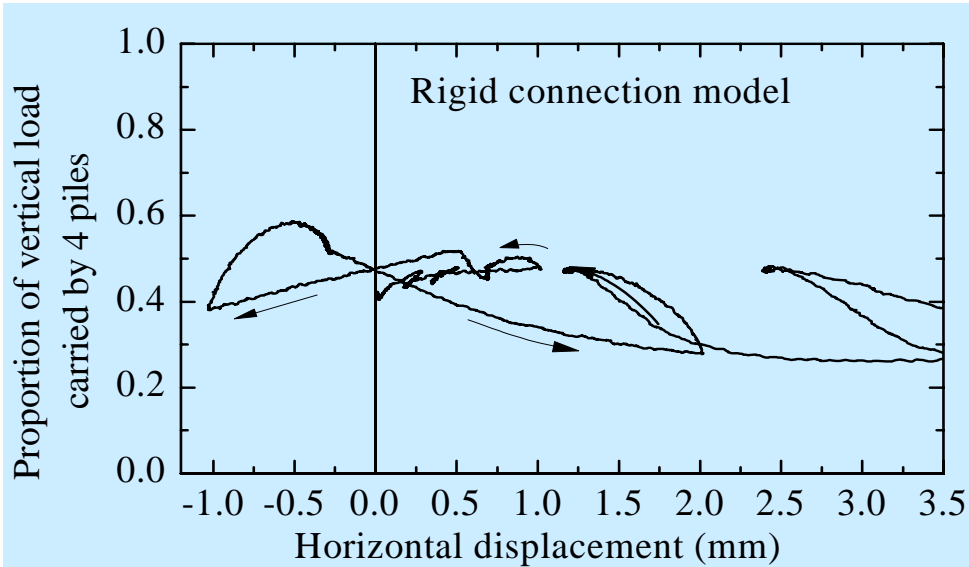
Rigid pile head connection



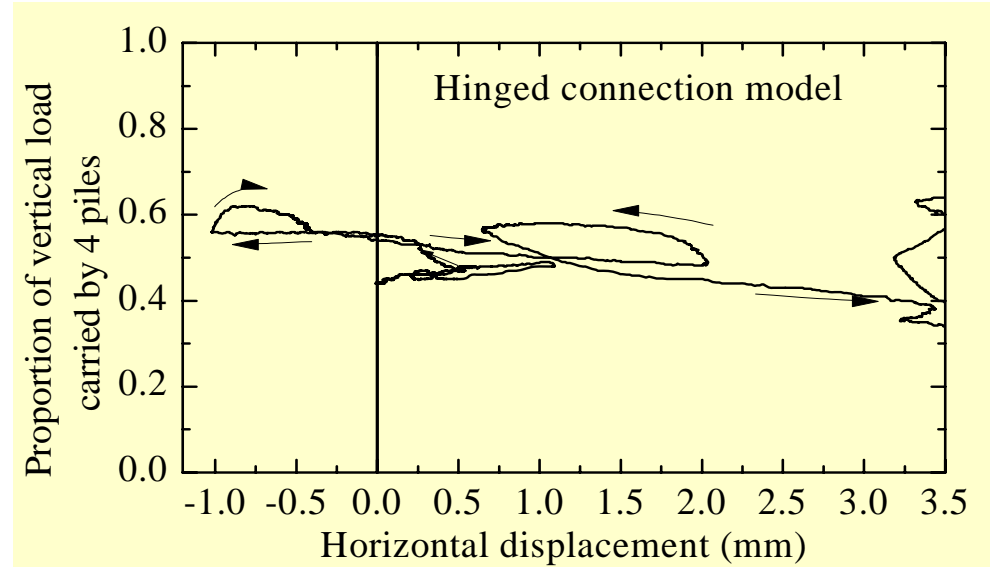
Hinged pile head connection

Raft = 'Horizontal displacement reducer'

Proportion of vertical load carried by piles



Rigid pile head connection

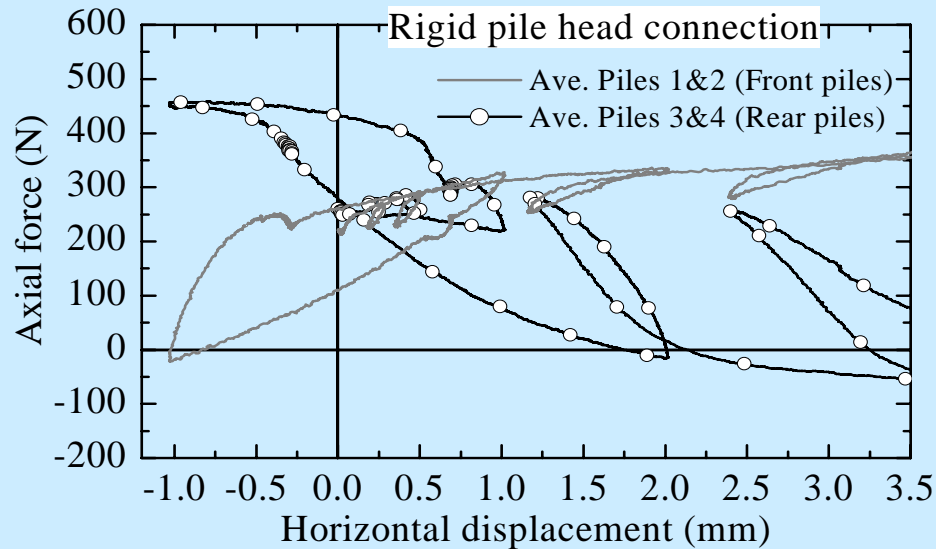


Hinged pile head connection

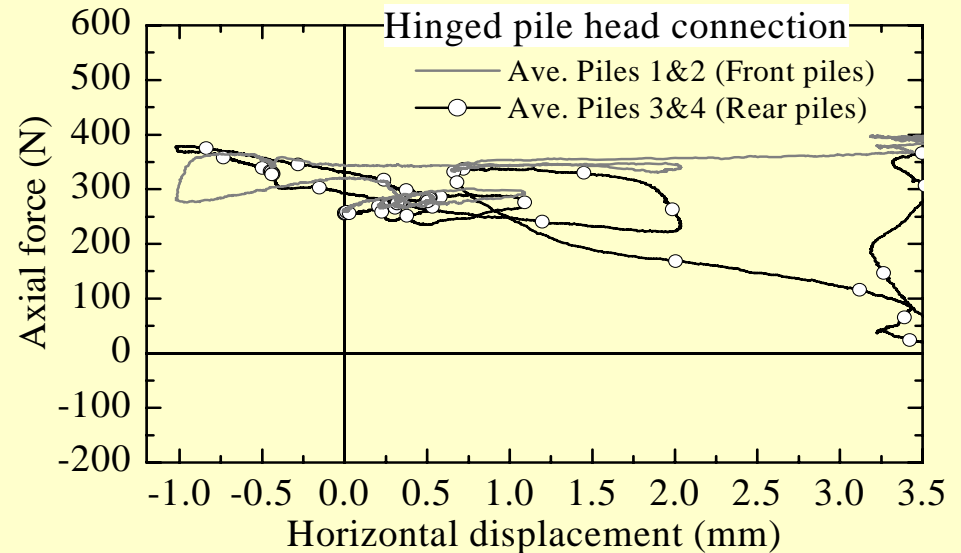
- Change in the vertical load proportion is smaller compared to the horizontal load proportion.

This tendency is clearer in the hinged pile head connection model.

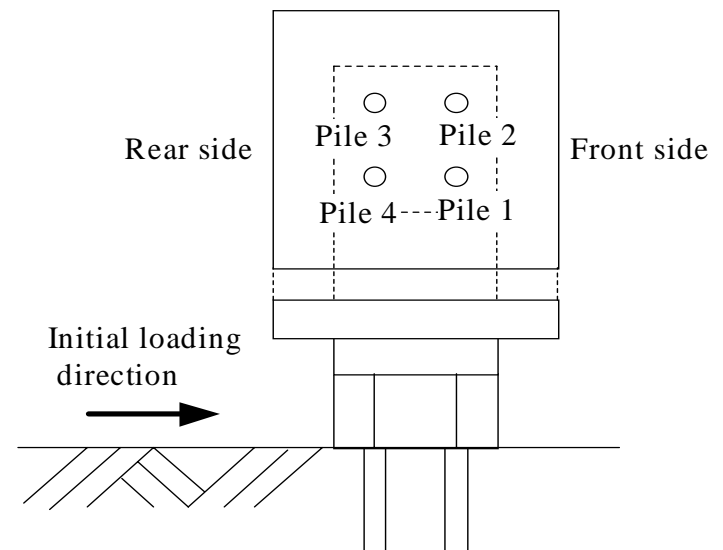
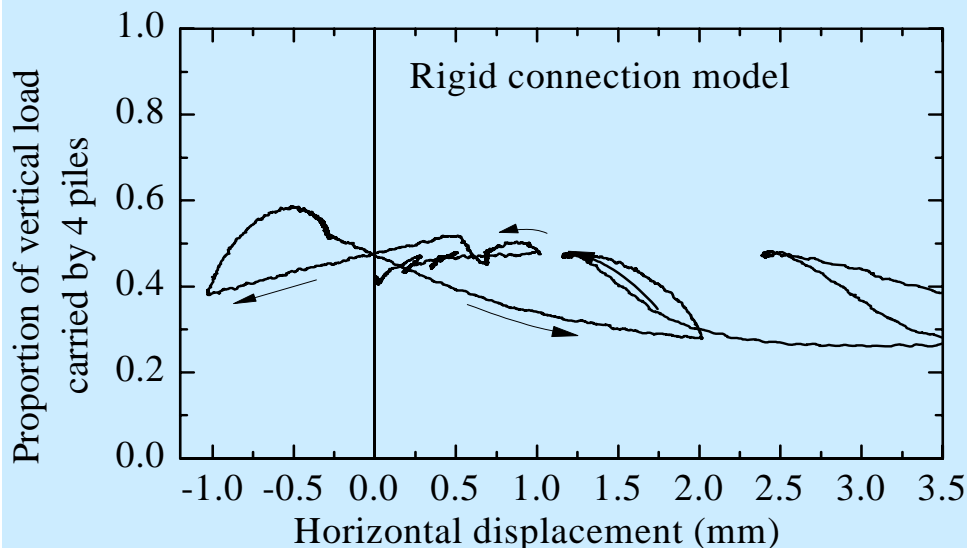
Vertical force at each pile head during horizontal loading



Rigid pile head connection



Hinged pile head connection



Summary of centrifuge tests

1. The stiffness and the ultimate resistance of the single pile in piled raft foundations are different from those observed in the loading test of the isolated single pile of the same size, due to the difference in the confining stress condition around the piles. Such difference should be considered in the evaluation of pile responses in piled raft designs.
2. The ultimate horizontal resistance of the piled raft with rigid pile head connection was much higher than that of the raft alone. Piles play important roles for increasing horizontal resistance of piled raft foundations. Ignoring the existence of piles in piled raft designs against horizontal loads may lead to conservative resistance.

Summary of centrifuge tests (Cont'd)

3. As far as the present centrifuge models are concerned, the initial horizontal stiffness of a piled raft is not always higher than that of a raft (alone), as the piles reduce the contact pressure between raft and soil and the stiffness of the upper soils. This behavior suggests the importance of the selection of the soil modulus in the design of piled raft foundations
4. The ultimate frictional resistance of the raft component in the piled raft was smaller (rigid pile head connection) or almost the same (hinged pile head connection) compared with the estimates from the raft vertical loads and the coefficient of the raft-soil friction. It is thought that the soil beneath the raft is constrained by the piles which may reduce the shear deformation of the upper soils, thus the mobilized shear stress at the interface become smaller. This constrained effect may be higher in the rigid pile head connection model.

Summary of centrifuge tests (Cont'd)

5. As for the proportion of the horizontal load carried by each component, the raft initially carried more load than the piles. With larger displacements, the piles carried more load than the raft in the piled raft with rigid pile head connection. In the piled raft with hinged pile head connection, the contribution of the piles was much smaller. Overall, however, the proportion is highly dependent on the piled raft displacement, and it is therefore important to consider such non-linear response in the designs.
6. The proportion of vertical load carried by the piles in a piled raft remains almost unchanged during horizontal loading, while the proportion of horizontal load carried by the piles increases as the horizontal displacement increases. Hinged pile head connection model gave smaller changes in the vertical load proportions of the raft and the piles.

Summary of centrifuge tests (Cont'd)

7. As far as the present centrifuge models are concerned, higher horizontal load was transferred to the rigid pile head connection model, which led to the higher initial horizontal stiffness compared to that of the hinged pile head connection model. On the other hand, bending moments of the piles were much smaller in the hinged connection model.

Part 2: Vertical and horizontal load tests of model piled rafts with different pile head connection conditions

H. Nemoto, *Ando Corporation*

H. Sakihama, *Ando Corporation*

M. Fujita, *Ando Corporation, Tokyo, Japan*

H. Mikami, *Sumitomo-Mitsui Construction Co., Ltd.*

N. Nishimura, *Sumitomo Mitsui Construction Co., Ltd.*

H. Hasei, *Sumitomo-Mitsui Construction Co., Ltd.*

H. Horii, *Hazama Corporation, Tokyo, Japan*

K. Yaegashi, *Hazama Corporation*

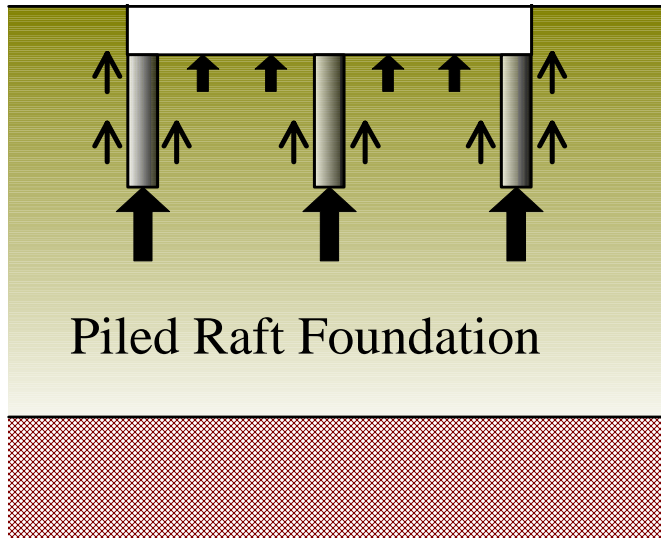
Y. Takeuchi, *Nishimatsu Construction Co., Ltd.*

T. Arai, *Nishimatsu Construction Co., Ltd.*

T. Matsumoto, *Kanazawa University*

P. Kitiyodom, *Kanazawa University*

Background



- The response of the piled raft is controlled by the load sharing between the raft and the piles, and the interactions between the raft, the piles and the soil.

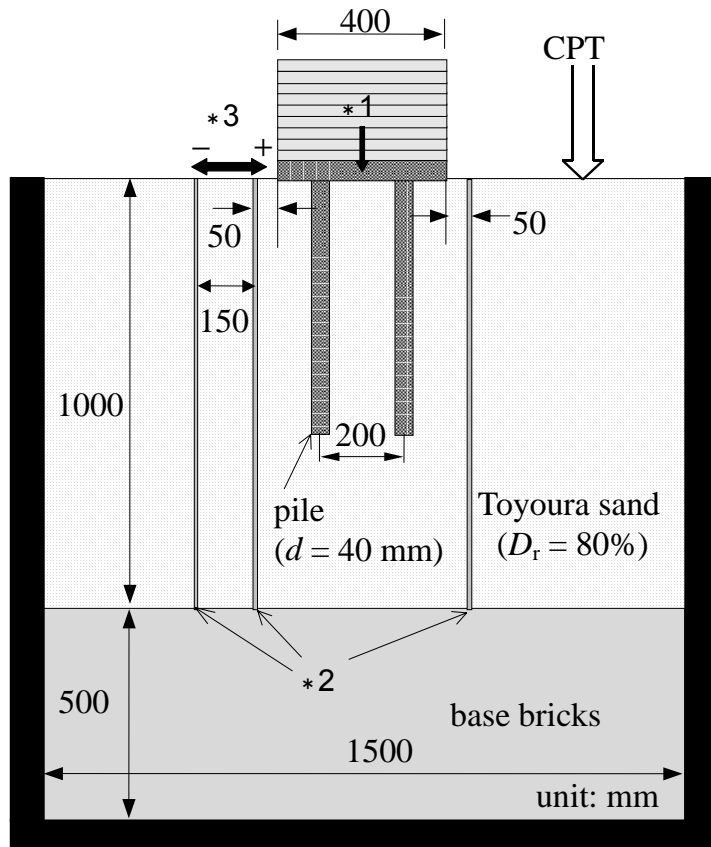
Usually, piles having uniform cross-section are rigidly connected to the raft.

Use of hinged or semi-rigid pile head connection conditions may reduce the bending moments of pile head sections in the piled raft subjected to vertical and horizontal loads.

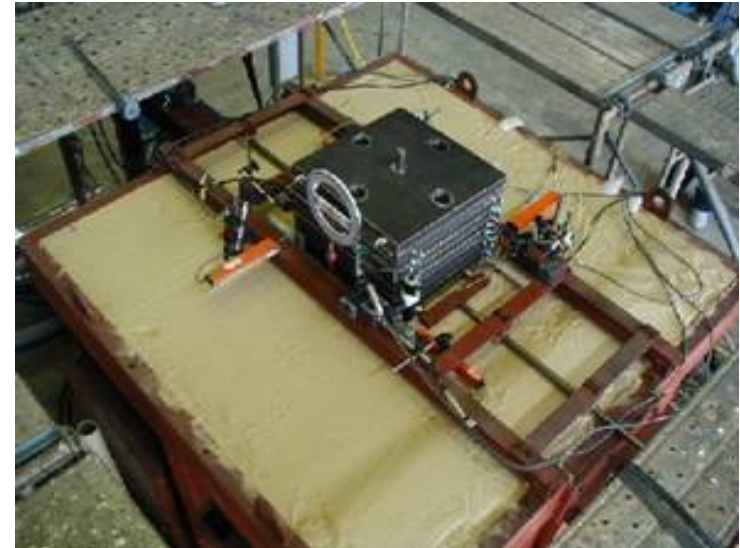
Objectives

Investigation of the influence of various pile head rotational connection conditions on the behaviour of model piled rafts in dry sand experimentally, and their analyses.

Test set-up



Model ground
dry Toyoura sand, $D_r = 80 \%$



Preparation of model foundation and model ground

Four model piles were set in the soil box prior to making the model ground



The sand was poured into the soil box and compacted by vibration.

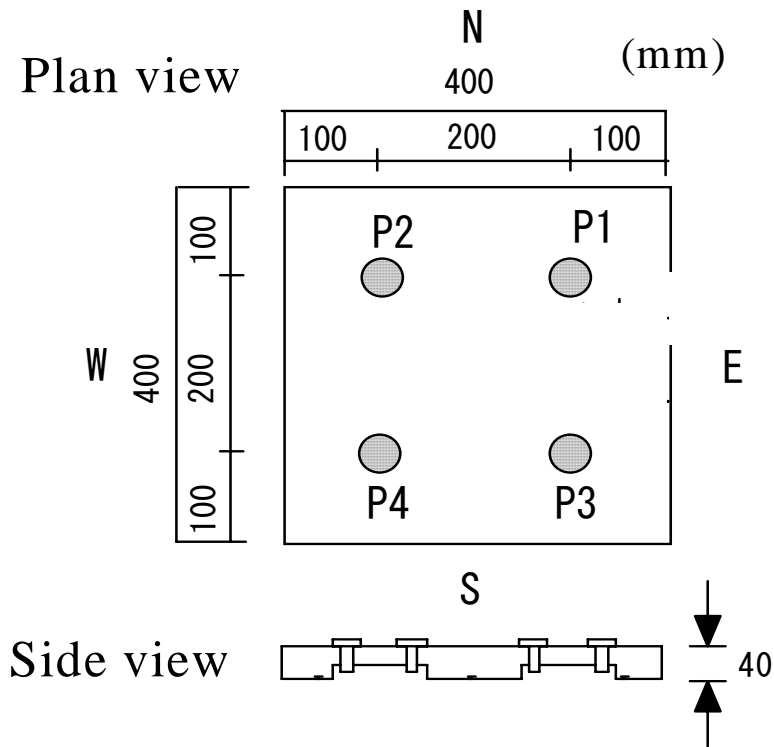
$$D_r = 80\%$$



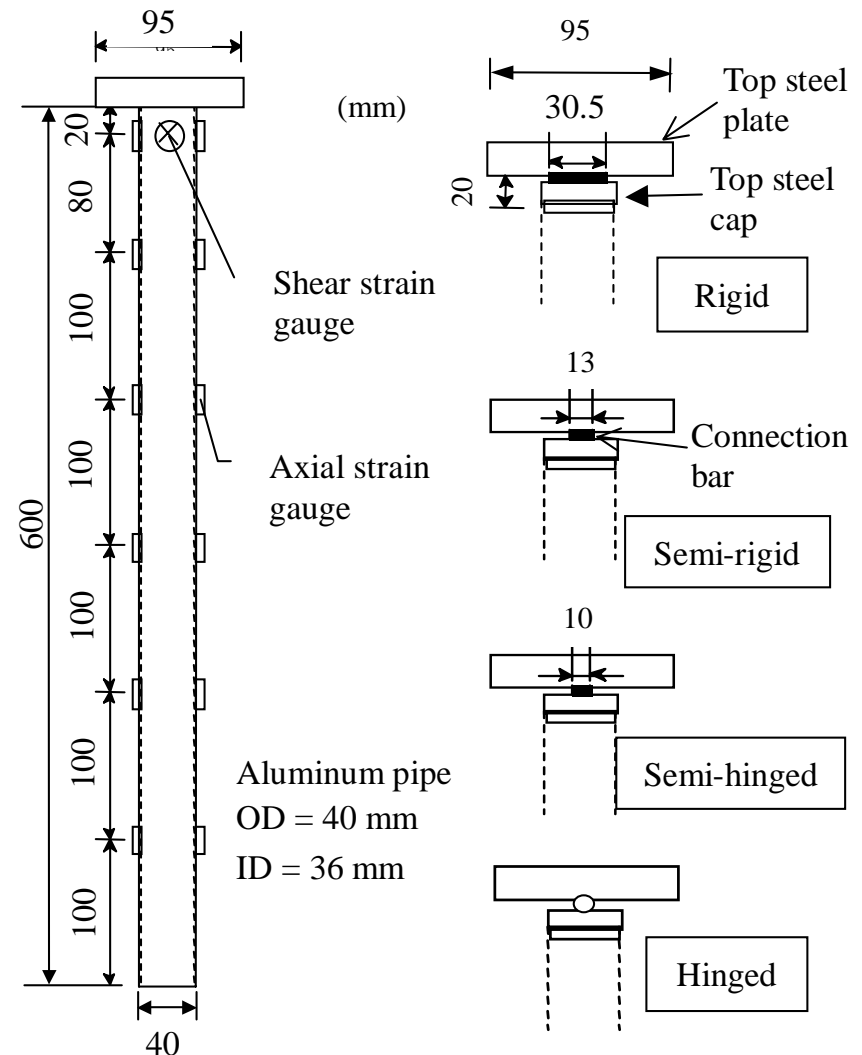
The model raft was placed on the model piles. Each pile was bolted to the raft.



Model raft and model piles



Model raft

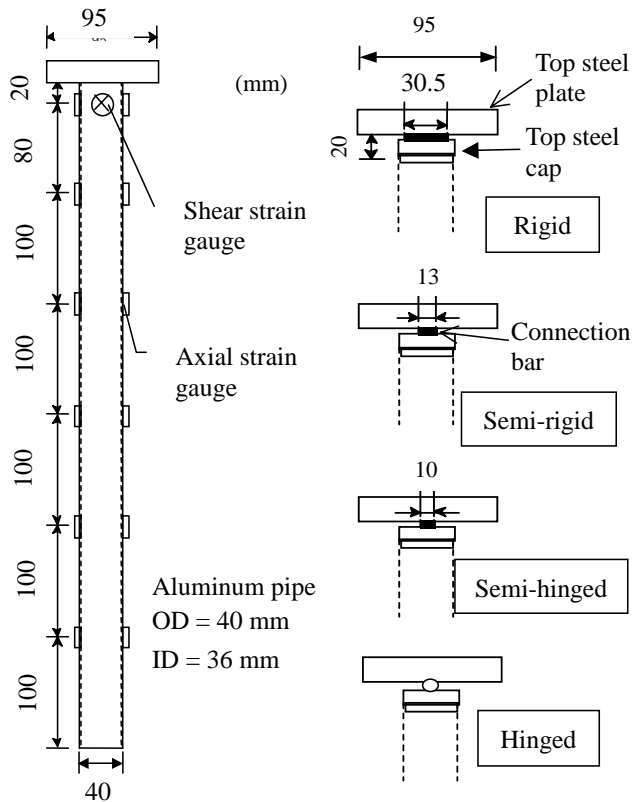


Model piles

4 types of pile head connection conditions

Test cases

Test cases and conditions



Test name	Type of foundation	Pile head connection condition
Case 1: Raft	Raft alone	-----
Case 2: PG-R	Pile Group	Rigid
Case 3: PG-H	Pile Group	Hinged
Case 4: PR-R	Piled Raft	Rigid
Case 5: PR-SR	Piled Raft	Semi-rigid
Case 6: PR-SH	Piled Raft	Semi-hinged
Case 7: PR-H	Piled Raft	Hinged



Hinged condition



Semi-hinged condition

Test cases

Test cases and conditions

Test name	Type of foundation	Pile head condition
Case 1: Raft	Raft alone	-----
Case 2: PG-R	Pile Group	Rigid
Case 3: PG-H	Pile Group	Hinged
Case 4: PR-R	Piled Raft	Rigid
Case 5: PR-SR	Piled Raft	Semi-rigid
Case 6: PR-SH	Piled Raft	Semi-hinged
Case 7: PR-H	Piled Raft	Hinged

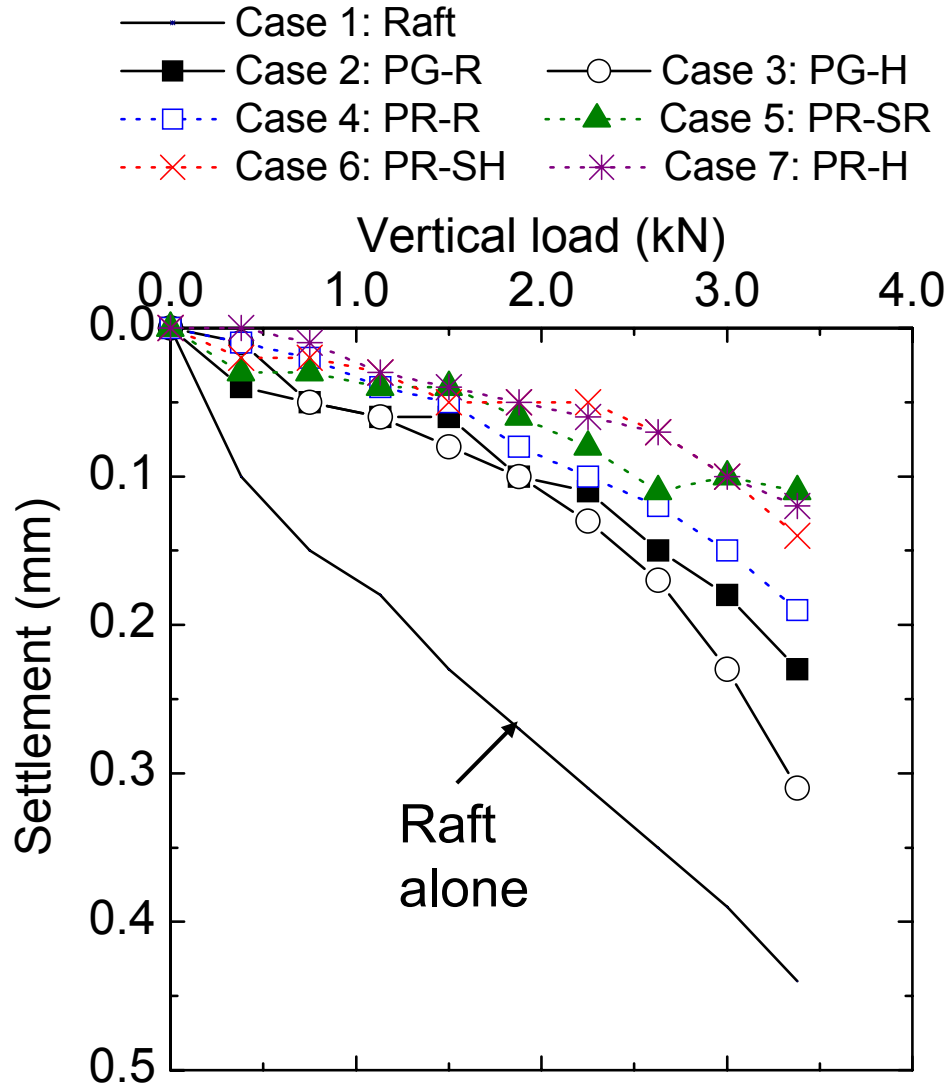


Vertical load was applied on the raft by weight of steel plates (0.376 kN each).

9 plates → 3.384 kN

Test results

Vertical load - settlement relationship



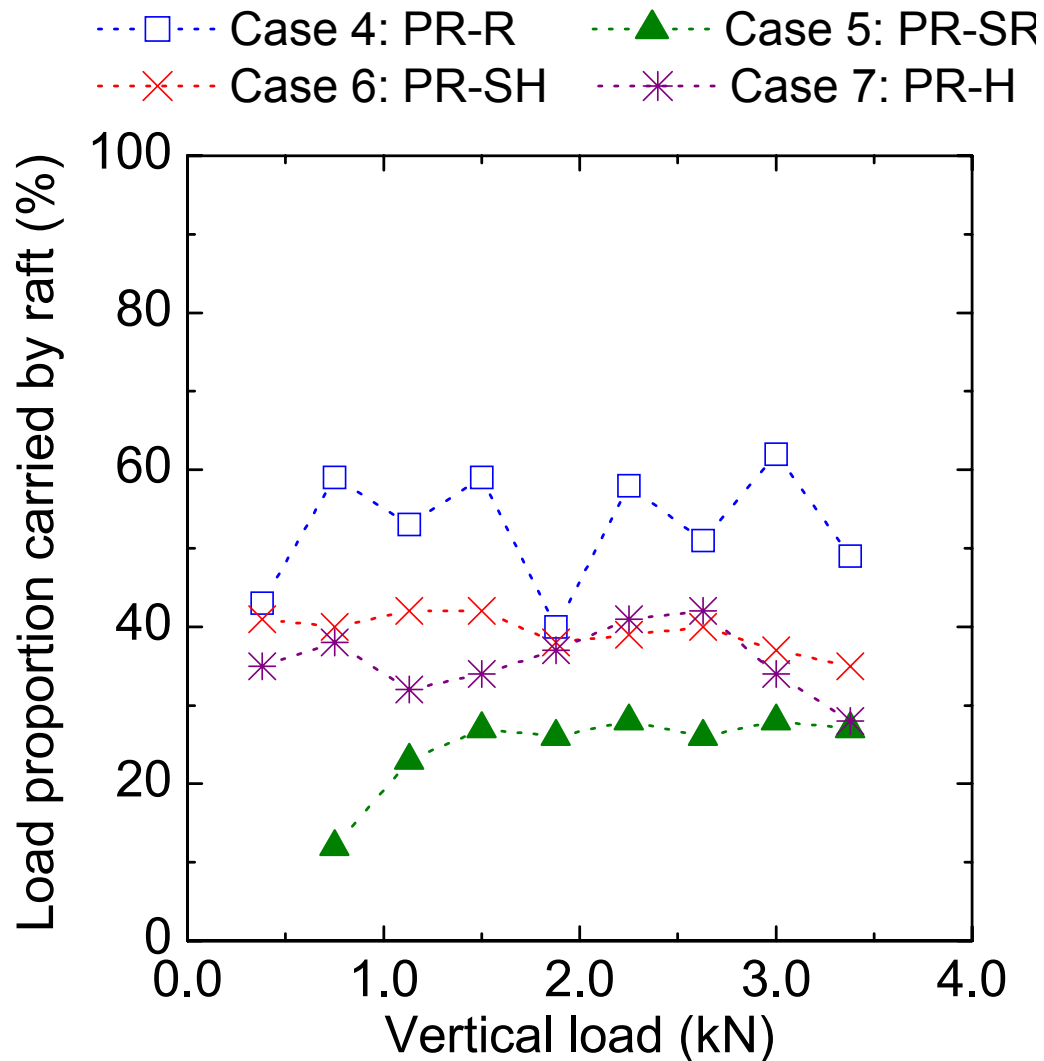
Settlement

piled raft < pile group < raft alone

Pile head connection condition has little influence on the settlement.

Test results

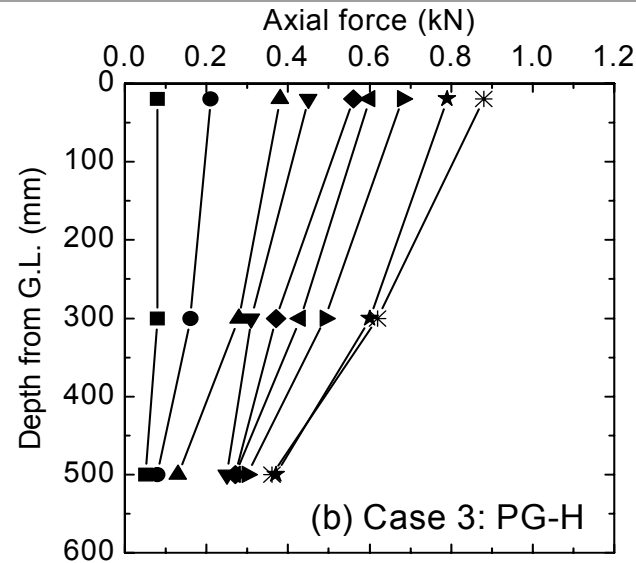
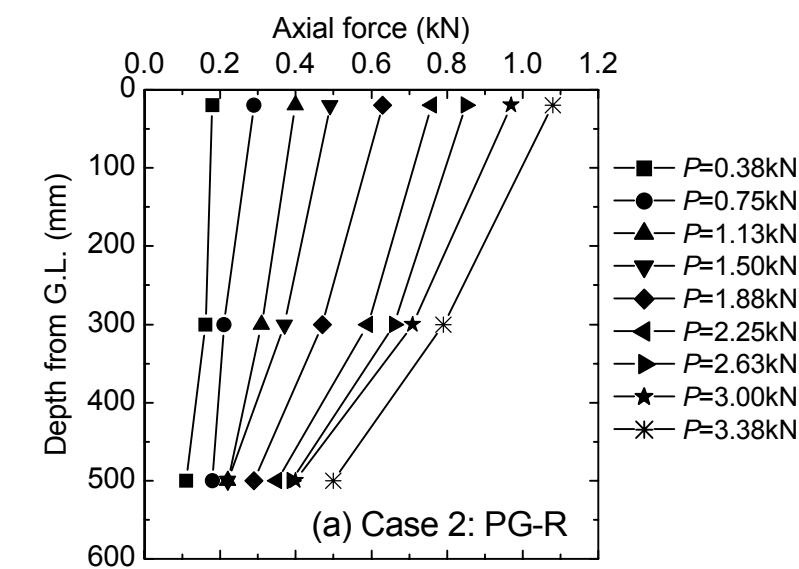
Vertical load – vertical load proportion relationship



The vertical load proportion is almost constant irrespective of the amplitude of the vertical load in all cases.

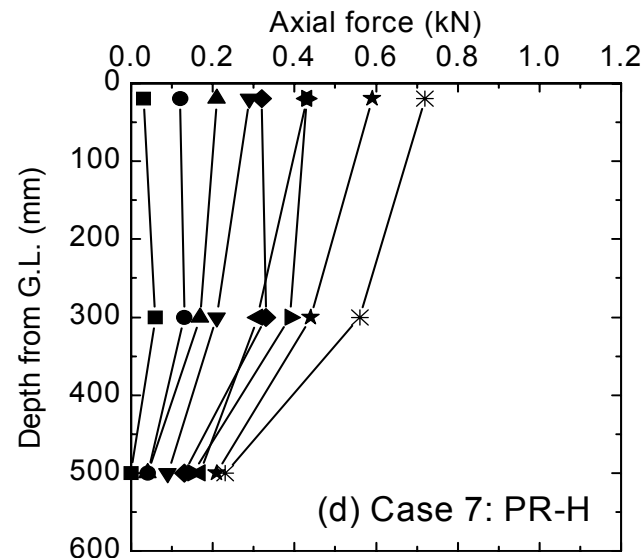
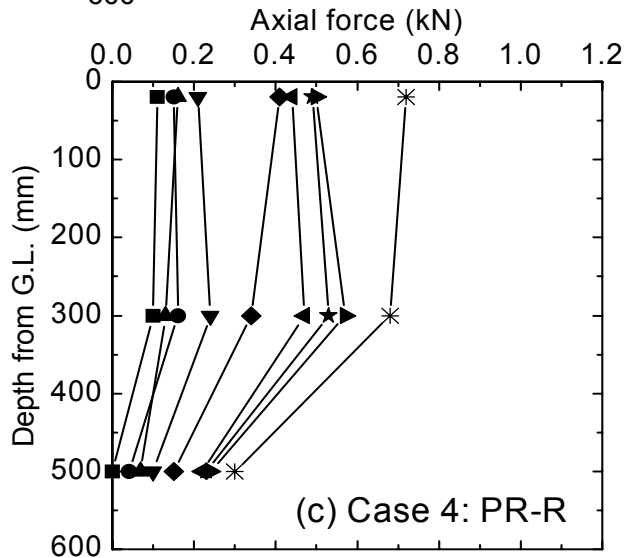
Test results

Change in axial force distribution in pile



Pile group

Axial force decreases almost linearly from the pile head to the pile base.



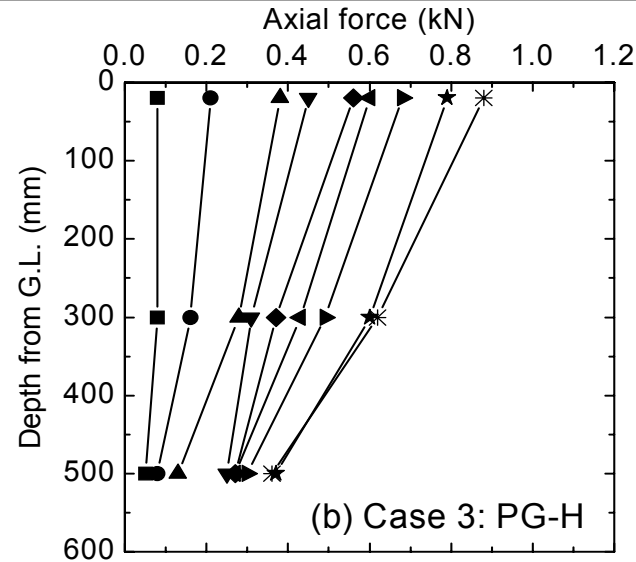
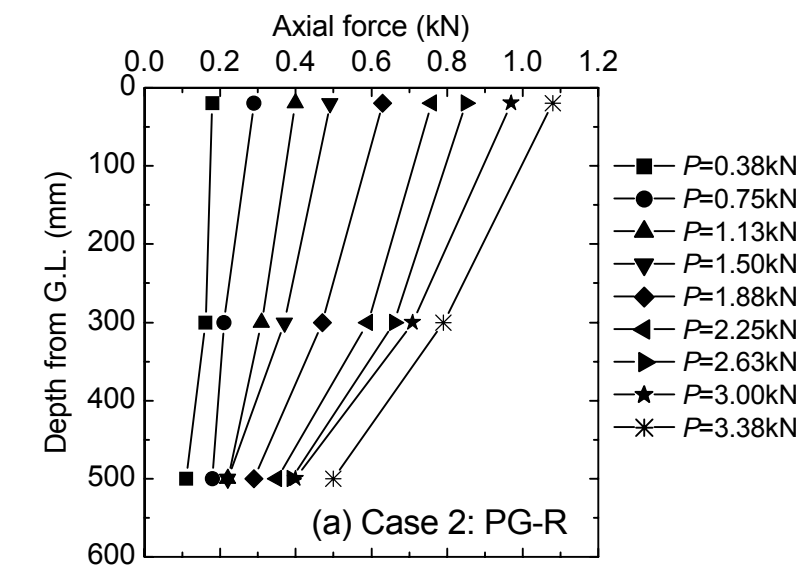
Piled raft

Axial force from the pile head to a depth of 300 mm is relatively constant for each vertical load.

Shaft resistance along the upper section of the piles in the piled raft is smaller than that in the pile group, due to interaction between the pile and the raft.

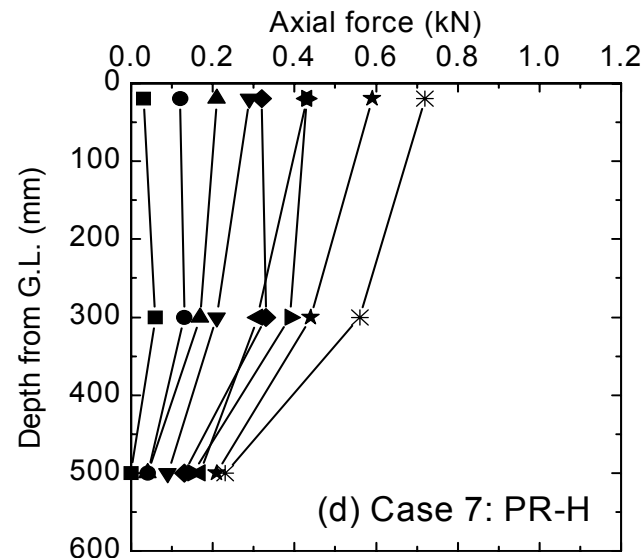
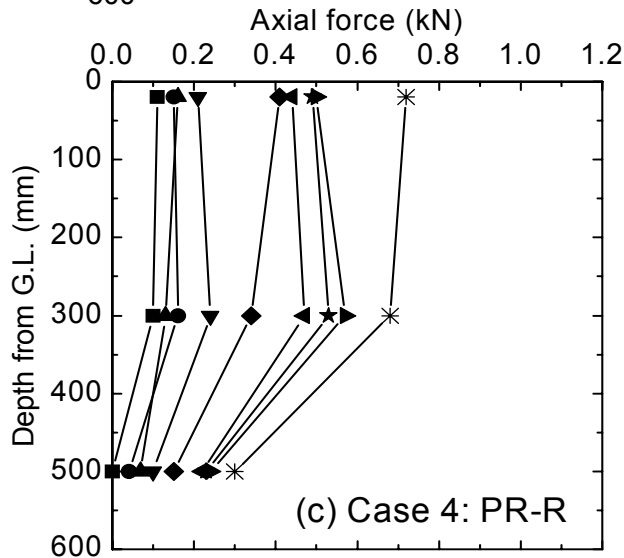
Test results

Change in axial force distribution in pile



Pile group

Axial force decreases almost linearly from the pile head to the pile base.



Piled raft

Axial force from the pile head to a depth of 300 mm is relatively constant for each vertical load.

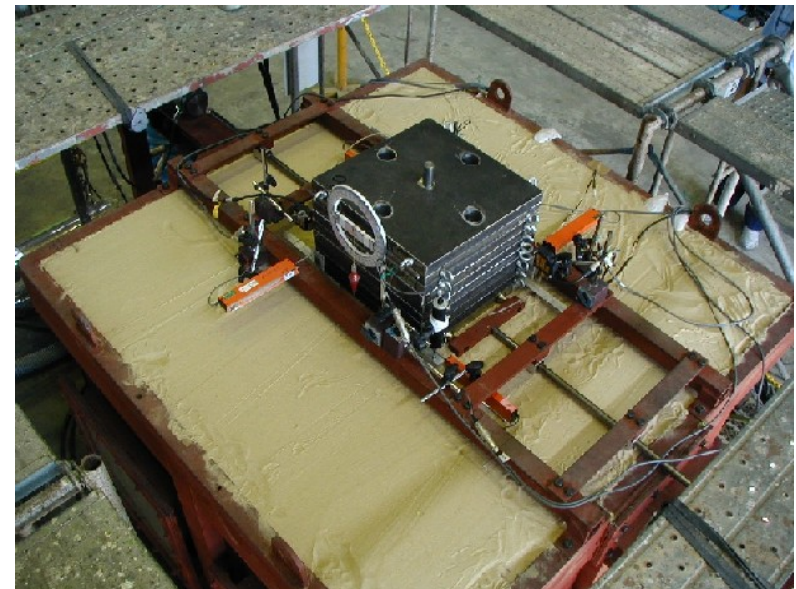
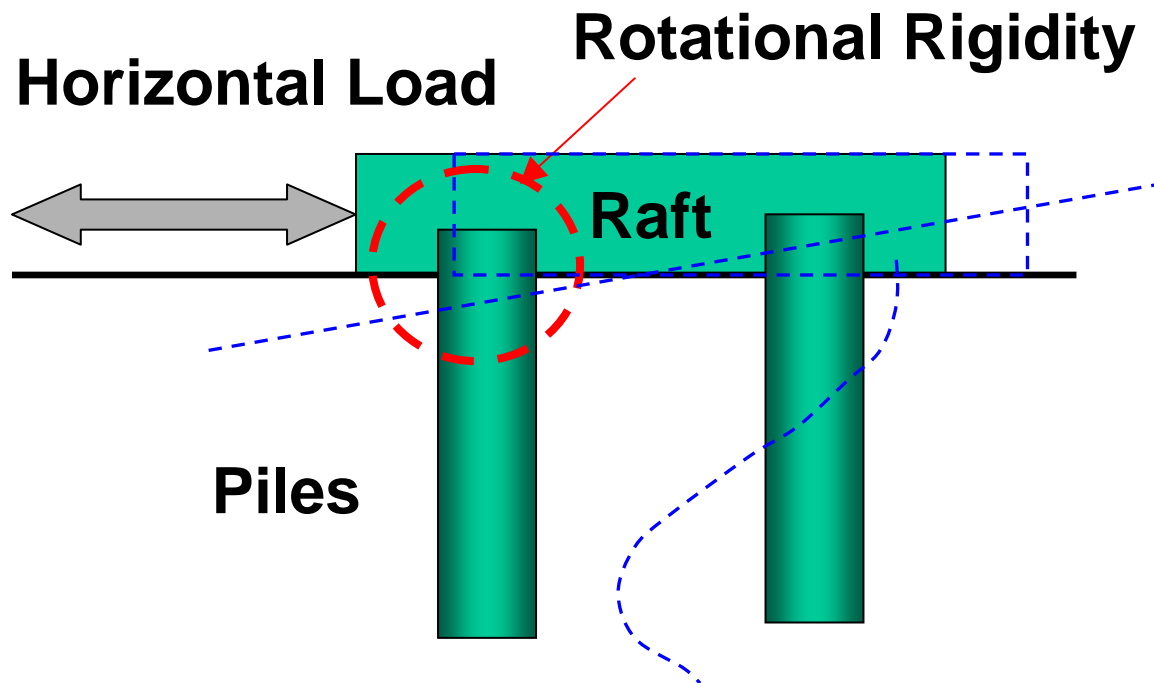
Influence of pile head connection condition is negligible in both pile group and piled raft.

Conclusions of vertical loading process

1. Vertical settlement stiffness of piled raft is larger than those of the pile group and the raft alone for small loads, and decreases to that of the raft alone as the vertical load increases.
2. Pile head connection condition has little influence on behaviours of the pile groups and the piled rafts subjected to vertical load alone.
3. Mobilized shaft resistance along the upper part of the pile in the piled raft is much smaller than that in the pile group, due to interaction between the raft and the piles through the ground.

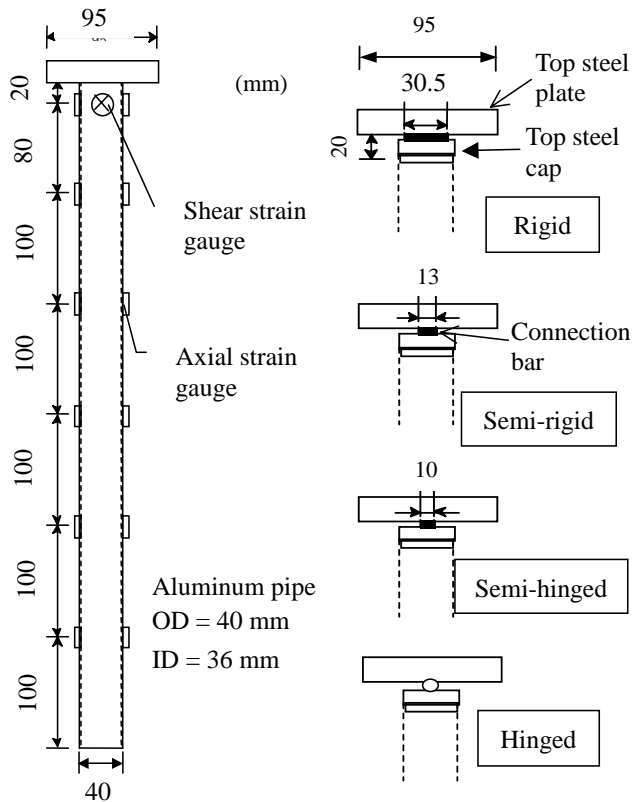
Objective of horizontal load tests

- Investigate the influence of rotational rigidity at the pile head connection on the behaviour of horizontally-loaded model piled rafts in sand.



Test cases

Test cases and conditions



Test name	Type of foundation	Pile head connection condition
Case 1: Raft	Raft alone	-----
Case 2: PG-R	Pile Group	Rigid
Case 3: PG-H	Pile Group	Hinged
Case 4: PR-R	Piled Raft	Rigid
Case 5: PR-SR	Piled Raft	Semi-rigid
Case 6: PR-SH	Piled Raft	Semi-hinged
Case 7: PR-H	Piled Raft	Hinged



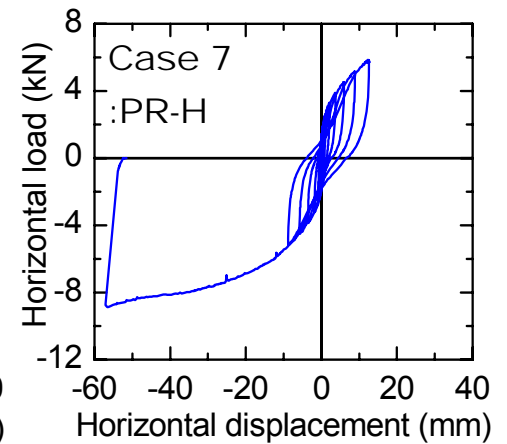
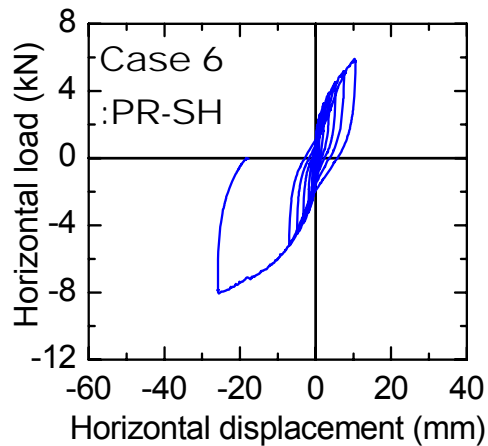
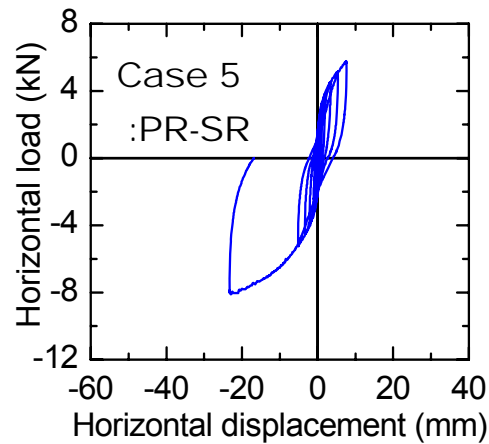
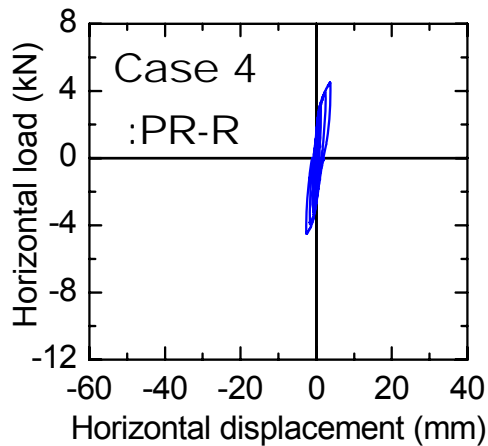
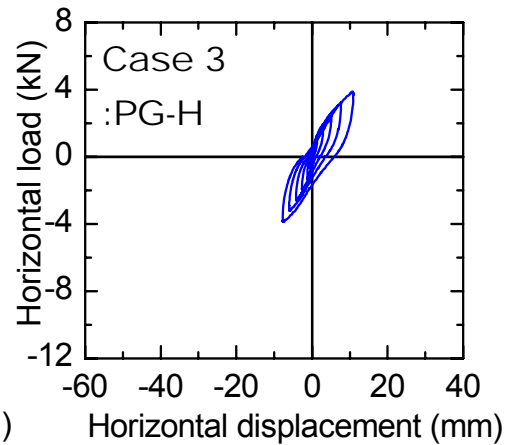
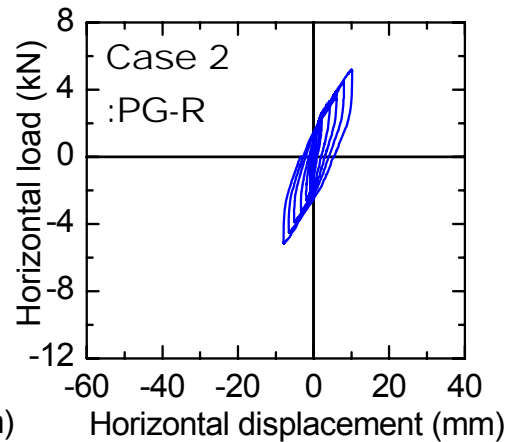
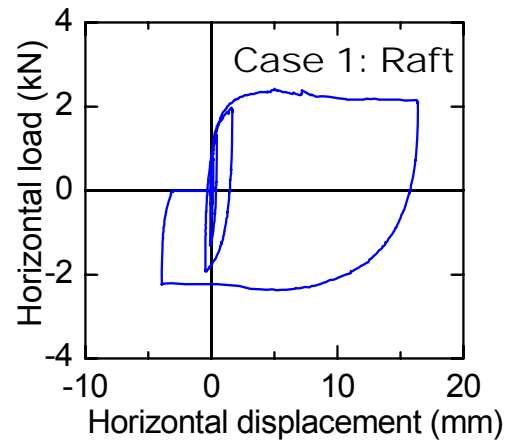
Hinged condition



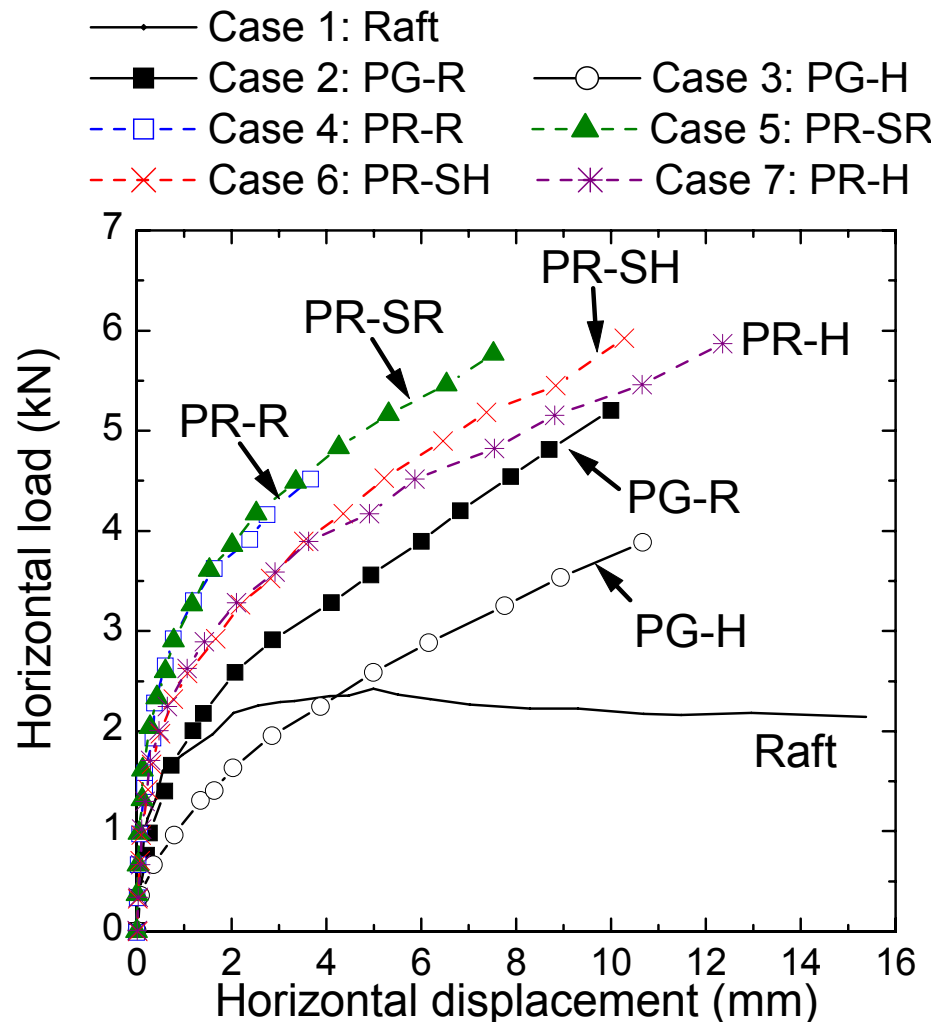
Semi-hinged condition

Test results

Horizontal load vs horizontal displacement



Horizontal load vs horizontal displacement at maximum load in each cycle



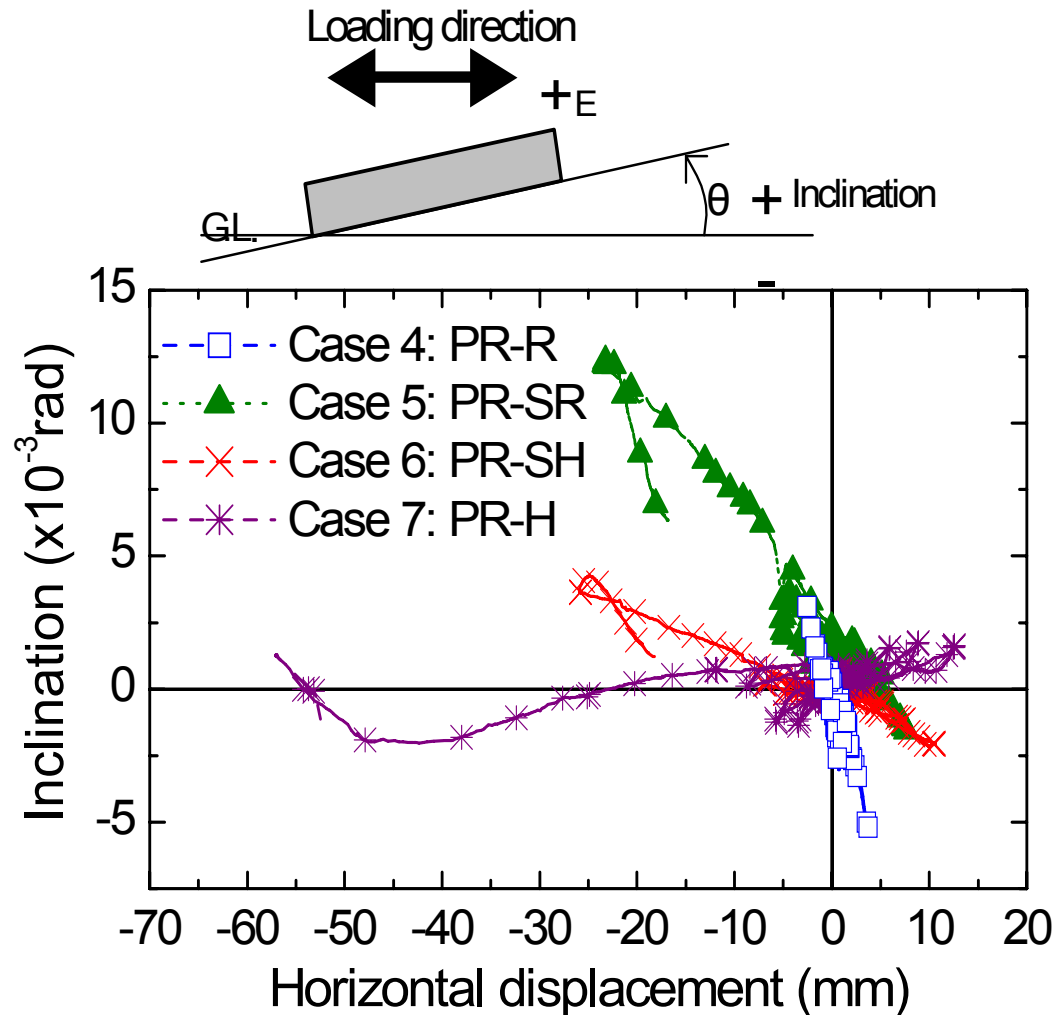
Horizontal stiffness

Piled raft > Pile group

Horizontal resistance at a given horizontal displacement is the largest in the piled raft with rigid pile head connection.

The raft acts as 'horizontal displacement reducer'.

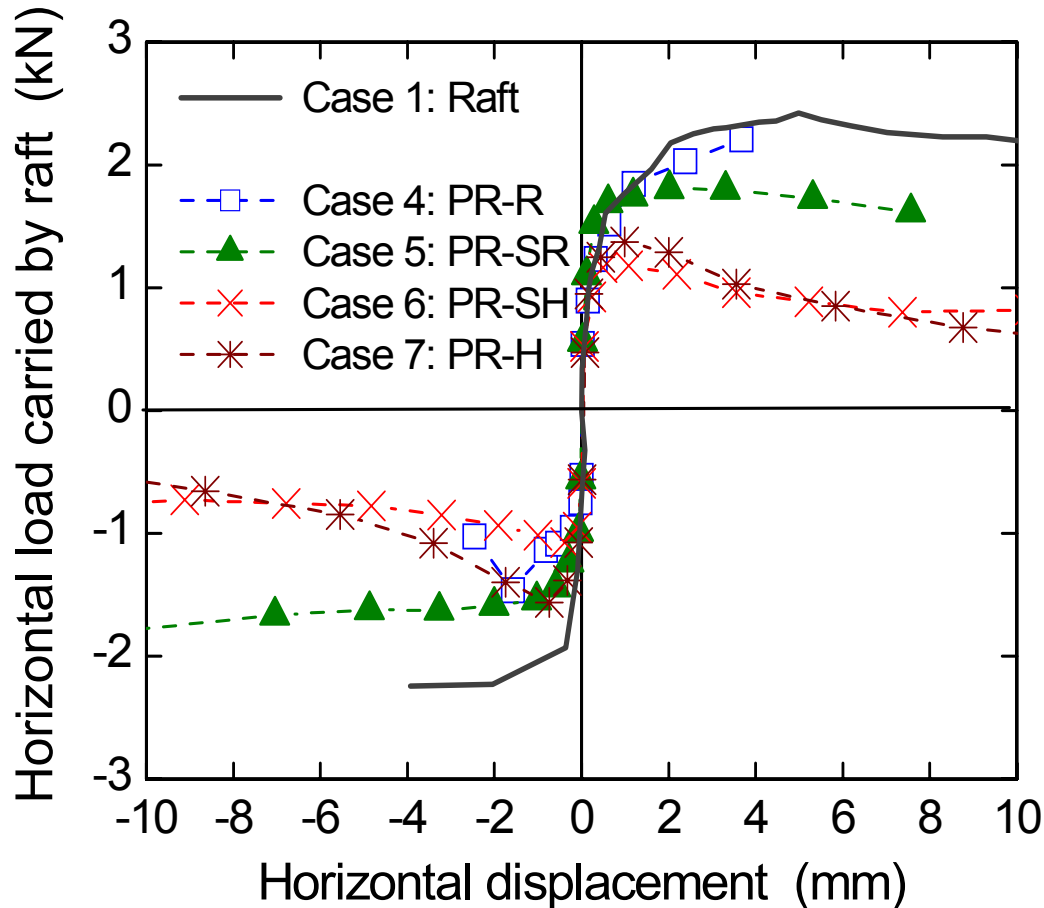
Raft Inclination vs horizontal displacement



Rotation of the raft decreases, as the pile head connection rigidity reduces.

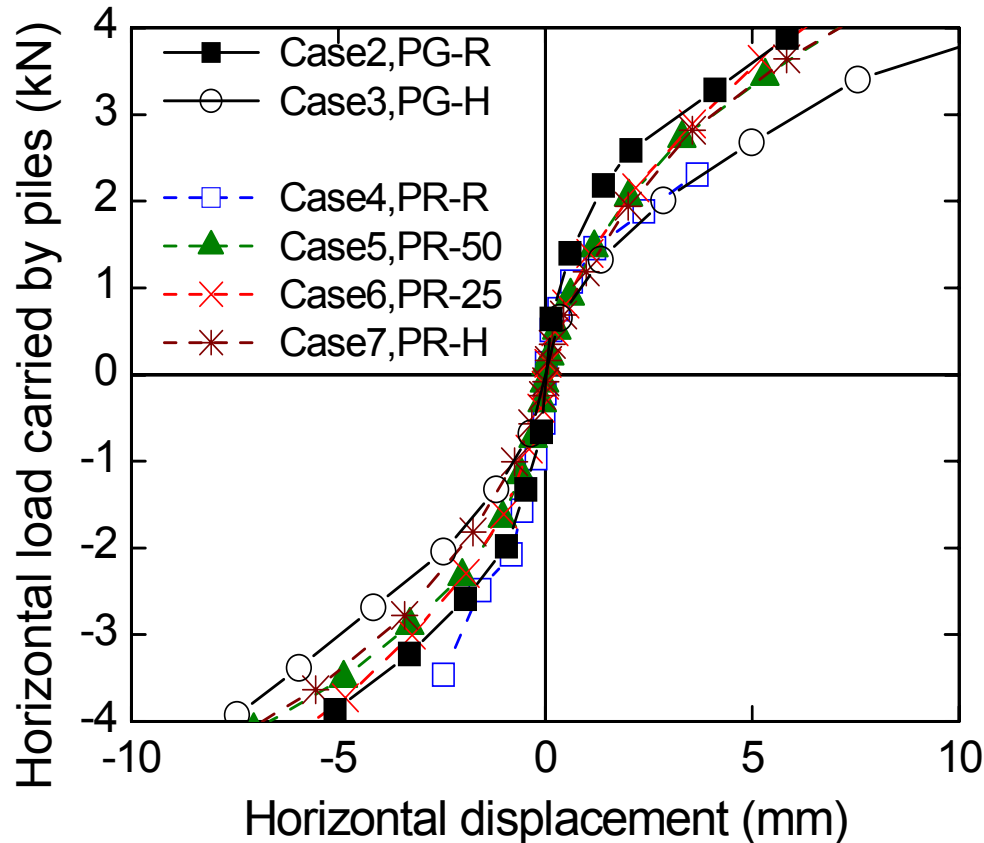
Rotation in the piled raft with hinged connection (case 7) is very small, even when large horizontal displacement occurs.

Load carried by raft vs horizontal displacement

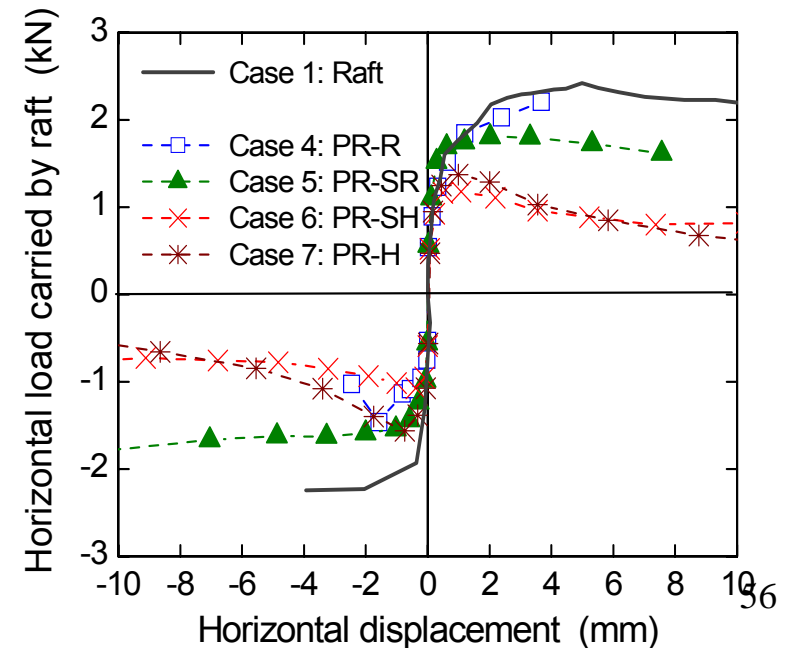


Horizontal load carried by the raft at a given horizontal displacement becomes lower as the pile head connection rigidity becomes lower.

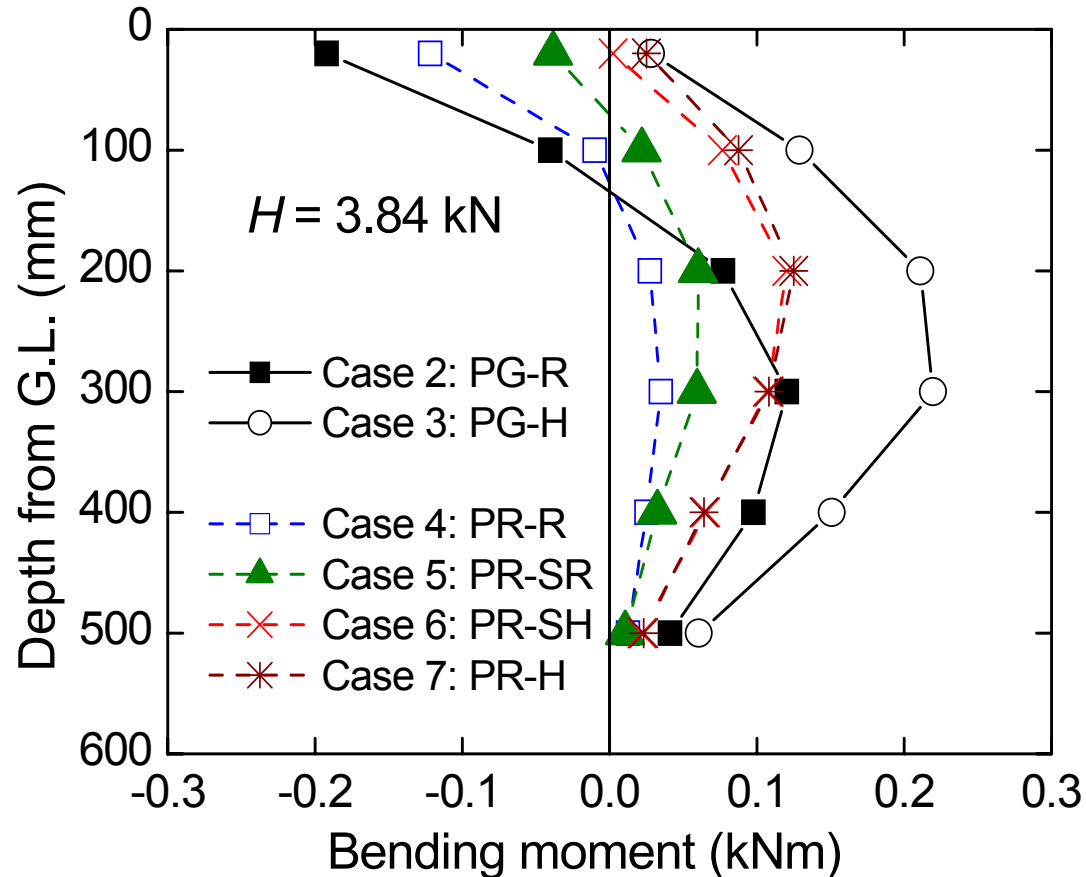
Load carried by pile vs horizontal displacement



The horizontal load carried by the piles in the piled raft is not affected so much by the pile head connection rigidity, compare to the case of load carried by the raft.



Distributions of bending moments in pile (at $P_h = 3.84$ kN)



Bending moments in piles in the piled raft (PR) are reduced, compared with those in the pile group (PG).

This result clearly may indicate an advantage of the piled raft to reduce possibility of pile failure by bending.

Conclusions of horizontal loading process

1. Horizontal stiffness of a piled raft is larger than that of a pile group having the same configuration as the piled raft, because the raft acts effectively as 'horizontal displacement reducer'.
2. Bending moments in piles in the piled raft are reduced, compared with those in the pile group.
3. In the case of piled raft, rotation of the raft decreases, as the pile head connection rigidity becomes lower, although the horizontal stiffness becomes lower.
4. Horizontal load proportion carried by the raft becomes lower as the pile head connection rigidity becomes lower.
5. The horizontal load carried by the piles in the piled raft is not influenced so much by the pile head connection rigidity, whereas the horizontal load carried by the raft is influenced by the pile head connection rigidity.

Main findings and suggestions from piled raft subjected to vertical and horizontal loads

- Piled rafts are effective against horizontal loading also.

Raft in piled raft acts as 'horizontal displacement reducer'.

- Rotation rigidity at the head of piles has a great influence on behaviour of a piled raft.

Smaller pile head rotation rigidity → smaller horizontal stiffness
smaller bending moments in piles, smaller inclination of the raft,
smaller changes in axial forces in piles

- Horizontal loading induces vertical responses of the foundation as well as horizontal responses.



Simplified 3-dimensional deformation analysis method of piled rafts will be of great use in design of piled rafts.