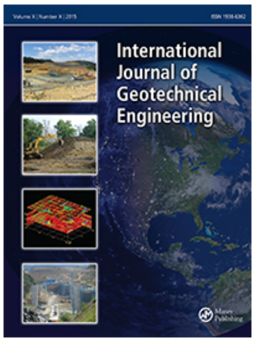

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Behaviours of batter-pile foundations subjected to combination of vertical load and cyclic horizontal loading

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ABSTRACT

In this research, a numerical study through three-dimensional finite element method is carried out to investigate the behaviours of pile foundations including piled raft and pile group subjected to a combination of vertical load and cyclic horizontal loading. Three-pile pile foundation models (with or without batter piles) and six-pile pile foundation models (with or without batter piles), which were used in the experiments by the authors, are considered in the numerical analyses. The foundations work as pile group foundations if the raft base is not in contact with the ground surface, while they are piled rafts if the raft base is in contact with the ground surface. The foundations are modelled as linear elastic. Interface elements are employed to simulate the slippage between the foundations and the soil. In this study, the hypoplastic model, an incrementally non-linear constitutive model, is used to model the ground. The numerical results are compared with the corresponding results from the experiments carried out by the authors. The mechanisms of the resistance and the reduction of displacement and inclination of the piled raft with batter piles were clarified. The piled raft with batter piles is the optimum foundation type to minimize the inclination induced by cyclic horizontal loading.

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KEYWORDS
Piled raft; pile group; batter pile; numerical analysis; cyclic loading

Introduction

Pile foundations including pile group and piled raft foundations are usually applied to structures subjected to large horizontal load, such as high-rise buildings, bridges, wind-turbine towers and offshore structures. In practical conditions, these pile foundations carry not only vertical loads caused by deadweight of the superstructures but also horizontal loads such as wind load, water wave loads and/or earthquakes, etc. Horizontal loads acting on these structures caused by winds and/or water waves can be considered as cyclic load. Hence, the foundations are subjected to a combination of vertical load and cyclic horizontal load. Cyclic loading with large amplitudes in short term and cyclic loading with small amplitudes in long term may be design concern.

Matsumoto et al. (2010) carried out experimental and analytical studies on the behaviour of pile group and piled raft models subjected to static vertical loading and static cyclic horizontal loading in dry sand, to investigate the influence of various pile head connection conditions between the raft and the piles on the response of the model foundations. Four different conditions of pile head connection called rigid, semi-rigid, semi-hinged and hinged were considered in this research. The results showed that the influence of pile head connection condition on the behaviour of the pile foundations under vertical load alone was not significant. However, in cyclic horizontal load tests, the horizontal stiffness of the piled raft foundations, rotation of the raft and the load proportion carried by the raft decreased with reduction in rigidity of pile head connection.

Unsever et al. (2014) conducted static cyclic horizontal load tests on pile foundation models without batter piles in a dry sand ground at the 1 g gravitational field to investigate the behaviour of the foundations under static cyclic horizontal load. The dead weight of the superstructure was also considered by applying a vertical load before applying horizontal load. The results indicated advantages of piled raft over pile group under cyclic horizontal loading.

Hussien et al. (2014) investigated numerically the influence of vertical loads on the lateral response of pile groups in a sandy soil. Two-dimensional finite element analyses focussing on the five piles in the middle row of a 3 × 5 pile group were conducted. Apart from the analyses of the pile group, analyses of free-head and capped single piles were also performed for comparison. Two types of loading were considered in the study such as pure lateral loading without vertical load and a combination of vertical and horizontal loads. It was found from the numerical results that vertical loads had an influence on increasing the confining pressure of the sand surrounding the piles, increasing of the lateral pile resistance.

A conventional method to increase the horizontal resistance is the use of batter piles in addition to vertical piles. Steel pipe piles and pre-stressed reinforced concrete piles are usually used for pile foundations having batter piles. Escoffier et al. (2008) studied the effects of batter piles on the performance of pile group through centrifuge modelling. They compared the response of two simplified pile groups as follows: 1 × 2 vertical pile group and 1 × 2 pile group with one batter pile. Two tip conditions as floating pile and end-bearing pile were considered in the study. The static cyclic load tests were

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conducted on the floating pile groups while the dynamic tests were performed on end-bearing pile groups. The results from the static tests showed that the pile group with batter pile has larger horizontal resistance compared with that of the pile group with vertical piles alone. The results of the dynamic tests indicated that the battered pile group is stiffer than the pile group with vertical piles alone and the batter pile reduces the translational movement of the pile cap.

Gerolymos et al. (2008) investigated numerically with three-dimensional finite element models the seismic behaviour of pile groups with batter piles. In this research, there are three configurations of pile groups considered as follows:

1. A two-pile pile group consists of one vertical pile and one batter pile at 25° with respect to vertical direction;
2. A two-pile pile group consists of two symmetrically batter piles at 25° with respect to vertical direction;
3. A two-pile pile group consists of two vertical piles.

Both hinged and fixed-head conditions of piles were considered in the analyses to examine the influence of pile-to-cap connection on the performance of the foundation. The results showed that the pile groups with batter piles have larger horizontal stiffness than the pile group with only vertical piles.

A number of other studies on behaviour of inclined piles (batter piles) were reported by Sadek and Isam (2004), Isam, Hassan, and Mhamed (2012), Goit and Saitoh (2013). However, the researches only investigated the behaviours of pile groups with batter piles or single batter piles.

Recently, applications of piled raft foundations to buildings are increasing in the world to reduce average and/or differential settlement. Experimental and numerical studies on behaviours of piled raft foundations have been carried out, e.g. Small and Zhang (2002), Poulos, Small, and Chow (2011), Yamashita, Yamada, and Hamada (2011), Nguyen, Kim, and Jo (2013), Patil, Vasanwala, and Solanki (2016), Sinha and Hanna (2016), Watcharasawe, Kitiyodom, and Jongpradist (2017), Bhaduri and Choudhury (2019), Hoang and Matsumoto (2020).

Unsever, Matsumoto, and Ozkan (2015) carried out numerical analyses of load tests on model foundations in dry sand. A series of vertical and horizontal load tests on a three-pile piled raft model and its component (raft and pile) alone were conducted in a dry sand ground at the 1 g field. After that, simulations of the model tests were carried out through an FEM software PLAXIS 3D to get a deeper insight into the mechanisms of the piled raft foundation. The hardening soil model was used for modelling the sand. The simulations of the vertical load tests obtained reasonable agreements with the experimental results. Although the numerical calculations of the horizontal loading of the piled raft did not obtain a good simulation of the measured results quantitatively, the trends of the experimental results were reasonably simulated. It was derived that the behaviour of the piled raft foundation is not a mere summation of the raft and the piles, but considerably affected by the interactions in the foundation system.

Vu et al. (2018) carried out vertical and horizontal load tests on pile group and piled raft foundation models with and without batter piles in a dry sand ground, at 1 g gravitational field. Finite-element analyses of the piled raft models in the case of horizontal load tests were conducted and the results were compared with the experimental results to confirm the experimental results and to obtain a deeper insight into the resistance mechanism of the foundations. The results indicated that the foundations with batter piles have advantages over the foundations with vertical piles alone in aspects of resistance and settlement reduction.

Although batter piles have been used in structures subjected large horizontal load, as a design recommendation in design standards, understanding on the mechanism of batter pile foundations under cyclic horizontal loading is still limited. Few research on the behaviours of piled raft having batter piles subjected to a combination of vertical load and cyclic horizontal load is reported. Hence, in this study, the behaviours of batter-pile foundations subjected to a combination of vertical load and cyclic horizontal load are investigated through both the experimental and numerical results. Both types of long and short piles are targets in our research. The authors think that concepts of ‘short pile’ or ‘long pile’ are not so important, load-deformation analyses are used in design process. In this particular study, the model pile is categorized into ‘short’ pile.

Also, the shortage of cyclic soil models for long-term cyclic conditions (and their computational complexity) was a motivation of this research.

Description of the experiments

Pile foundation models

Three-pile pile foundation models and six-pile pile foundation models (with or without batter piles) were used in the experiments, as shown in Figure 1. The foundations work as pile group foundations (3PG, 3BPG, 6PG and 6BPG) if the raft base is not in contact with the ground surface, while they are piled rafts (3PR, 3BPR, 6PR and 6BPR) if the raft base is in contact with the ground surface. In the case of pile group, a gap of 20 mm is set between the raft base and the ground surface before the start of loading.

The rectangular rafts were made of duralumin with the dimensions as shown in Figure 1, and can be regarded as rigid. The sand particles were adhered to the raft base surface to increase the friction between the raft and the ground during cyclic horizontal loading.

The model pile was a close-ended aluminium pipe having a total length of 285 mm, an outer diameter of 20 mm and a thickness of 1.1 mm. The upper 30 mm of the pile was rigidly embedded in the raft, resulting in an effective length of 255 mm. Centre-to-centre pile spacing, s, was 80 mm, 4 times the pile diameter. In battered pile foundations (3BPR, 3BPG, 6BPR and 6BPG), the inclination angle of the batter piles was set at 15 degrees. Each model pile was mounted with strain gauges along the pile shaft to obtain axial forces, shear forces and bending moments in the model pile during load tests (Figure 2). The piles were covered with the silica sand particles in order to increase the shaft resistance. Young’s modulus of the piles, E_p, was estimated from bending tests of the piles. The geometrical and mechanical properties of the model pile are summarized in Table 1. Young’s modulus of the raft, E_r = 68670 N/mm^2, was given by the producer of the duralumin.

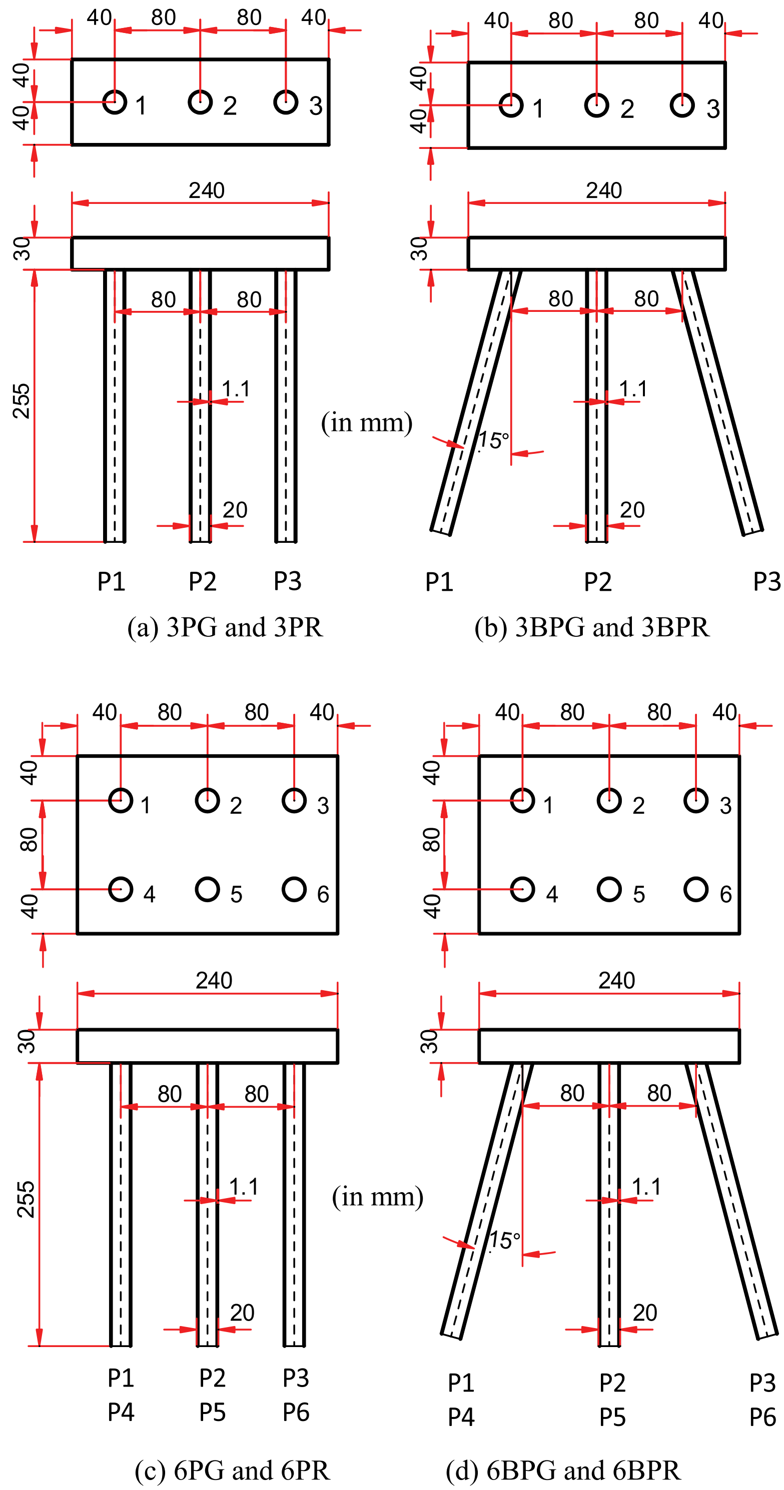

Figure 1. Dimensions of the foundation models.

Model ground

The soil used for model ground in the experimental study was dry silica sand with the physical properties shown in Table 2. The model ground with a relative density, D_r, of about 82% (ρ_d = 15.33 kN/m^3) was prepared in a soil box with dimensions of 800 mm in length, 500 mm in width and 530 mm in depth. In order to control the density of the model ground, the model ground was prepared by 11 layers (10 layers of 50 mm and 1 layer of 30 mm). In each layer, the sand was poured into the soil box and compacted by tapping until the target relative density of 82% was reached.

Loading method and measurement instruments

Figure 3 shows the experiment setup with measuring instruments. Vertical load was applied by placing lead plates of about

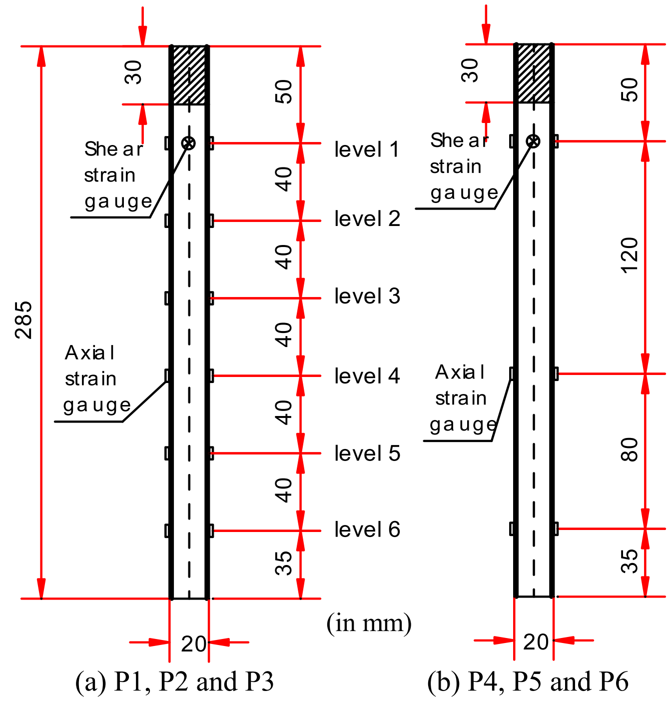

Figure 2. Model piles with strain gauge instrumentation.

Table 1. Geometrical and mechanical properties of the model pile.

Property	Value
Outer diameter, D (mm)	20.00
Wall thickness, t (mm)	1.1
Length from raft base, L (mm)	255
Cross section area, A (mm^2)	65.31
Moment of Inertia, I (mm^4)	2926.2
Young's modulus of the pile, E_p (N/mm^2)	70267
Poisson's ratio, v	0.31

Table 2. Physical properties of the silica sand.

Property	Value
Density of soil particle, ρ_s (kg/m^3)	2668
Maximum dry density, ρ_{dmax} (kg/m^3)	1604
Minimum dry density, ρ_{dmin} (kg/m^3)	1269
Maximum void ratio, e_{max}	1.103
Minimum void ratio, e_{min}	0.663
Relative density, D_r (%)	82.0
Dry density, ρ_d (kg/m^3)	1533

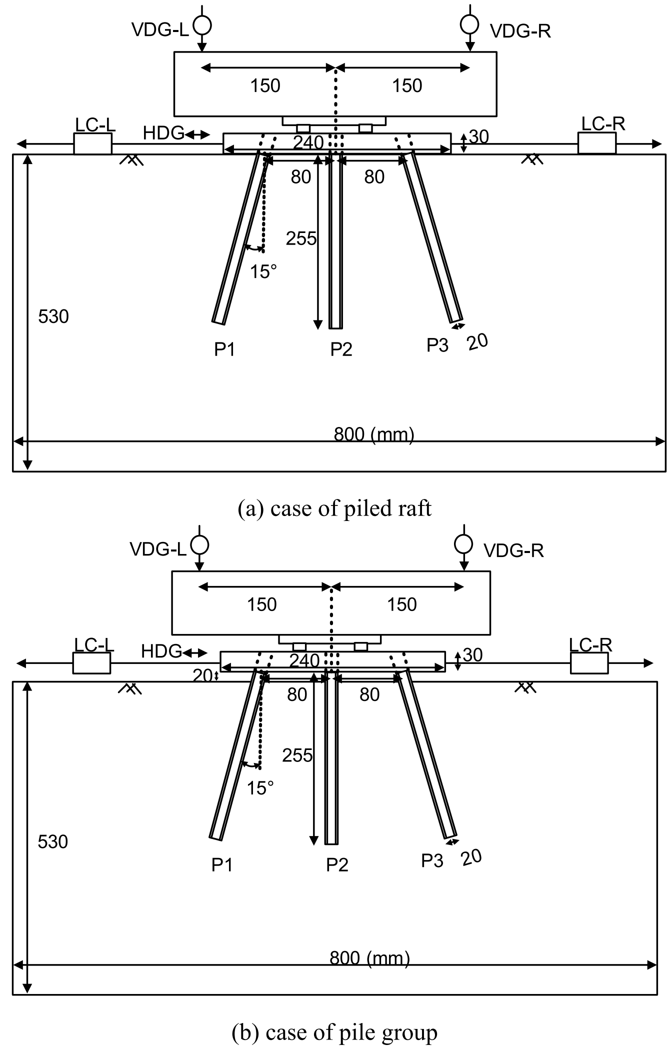

Figure 3. Schematic illustration of load test.

Table 3. Characteristics of the measuring devices.

Item	Capacity	Calibration factor	Precision
Horizontal load cell, LC-R	2000 N	0.4866 N/µST	0.0243 N
Horizontal load cell, LC-L	5000 N	0.8196 N/µST	0.0410 N
Horizontal dial gauge, HDG	50 mm	0.01 mm/µST	0.0005 mm
Vertical dial gauge, VDG-R	50 mm	0.01 mm/µST	0.0005 mm
Vertical dial gauge, VDG-L	50 mm	0.01 mm/µST	0.0005 mm

600 N and 1200 N on the raft in the cases of 3-pile pile foundations and 6-pile pile foundations, respectively, to simulate the dead weight of the superstructure. After that, cyclic static horizontal load was applied at the raft in longitudinal direction of the raft utilizing winches and pulling wires. The horizontal load was measured by two load cells (LC-R and LC-L) arranged in the right (positive) direction and the left (negative) direction. Both the horizontal and vertical displacements of the foundations were measured by horizontal and vertical dial gauges (HDG and VDG). The characteristics of the measuring devices are summarized in Table 3.

It should be noticed that the experiments here did not aim to simulate the behaviour of a prototype but to investigate the influence of inclusion of batter piles on the behaviour of pile foundations (piled raft and pile group) subjected to a combination of vertical and cyclic horizontal loading. Hence, the small-sized experiments were carried out at 1 g field. Note that the results shown in this paper are presented in model scale.

Ovesen (1979) carried out a series of centrifuge modelling of vertical loading of rafts on a model sand ground. The diameter of the model raft was varied from 14.2 mm to 79.8 mm, while the same sand having grain sizes from 0.3 to 0.6 mm was consistently used. Centrifugal acceleration was varied from 70.7 g to 12.5 g to simulate a prototype raft having a diameter of 1 m in all the modelling. The ratio of the raft diameter to the grain size of 0.6 mm varied from 24 to 133. The measured load–settlement relations obtained from all the centrifuge modelling almost coincided in the prototype scale, regardless of the ratio of the raft diameter to the grain size.

In the experiments in this research, the ratio of pile diameter to the grain size is 40 (pile diameter is 20 mm, the maximum soil particle is 0.5 mm). According to the results of the experiments by Ovesen (1979), it can be judged that the influence of the grain size is negligible.

FEM modelling

Soil simulation

In this study, the hypoplastic model, an incrementally non-linear constitutive model, was employed to model the sand. The early version of the hypoplastic model was introduced by Kolymbas (1985), which describes the stress-strain behaviour of granular materials in a rate form. After that, modifications and implementations of the model were proposed by Gudehus (1996), Wolffersdorff (1996), Masin (2005). The basic hypoplastic model for granular materials includes eight parameters such as critical friction angle φ_c, granular hardness h_s, exponential factors *n, α* and *β*, and minimum, maximum and critical void ratios at zero pressure e_{d0}, e_{i0}, e_{c0}. A shortcoming of the basic hypoplastic model is over prediction of accumulation deformation due to cyclic loading. Niemunis and Herle (1997) introduced an extended hypoplastic model to improve the performance of the basic hypoplastic model in cyclic loading. Five additional parameters were implemented in the extended hypoplastic model such as stiffness multiplier for initial and reverse loading m_R, stiffness multiplier for neutral loading m_T, small strain stiffness limit R_{max}, parameters adjusting stiffness reduction β_r and χ. To evaluate the soil parameters, soil index tests, triaxial tests and numerical simulations of the triaxial tests were carried out (Herle 1999; Anaraki 2008; Pham 2009). The calibration of the hypoplastic model has been presented in Vu et al. (2018).

Table 4 shows the soil parameters of the hypoplastic model used in this study.

FEM modelling of loading tests

Complementary roles of physical modelling and computational modelling were emphasized by Randolph and House (2001) to have a clear understanding of a particular mechanism. To confirm the experimental results and to clarify the resistance mechanism of the batter pile foundations, the numerical simulations of the model experiments are conducted.

Numerical analyses were carried out using a three-dimensional FEM program, PLAXIS 3D. Dimensions of the model ground, the piles and the raft were presented above. Only half of the foundation and the ground was modelled owing to symmetric conditions. Figure 4 shows the finite element mesh of the modelling.

Boundary conditions are applied as follows:

- Vertical model boundaries with their normal in *x*-direction (i.e. parallel to *yz*-plane) are fixed in *x*-direction ($u_x = 0$) and free in *y*- and *z*-directions.

- Vertical model boundaries with their normal in *y*-direction (i.e. parallel to *xz*-plane) are fixed in *y*-direction ($u_y = 0$) and free in *x*- and *z*-directions.

- The model bottom boundary is fixed in all directions ($u_x = u_y = u_z = 0$).

- Displacements at the ground surface are free in all directions.

The raft and the piles were considered as linear elastic materials. The piles were rigidly fixed to the raft (fully restrained connection). A hybrid model proposed by Kimura and Zhang (2000) was used to model the piles. In the hybrid model, the pile is replaced by a pile beam element surrounded by solid elements as shown in Figure 5. A big advantage of the hybrid pile is that it is easy to obtain axial forces, bending moments and shear forces in a pile from those in the beam elements by multiplying stiffness ratios of the hybrid pile to the beam. Also, the influence of the pile volume is considered in using the hybrid pile, which is impossible if using only embedded pile element to simulate the pile. In the hybrid model of this study, the beam element carried large proportion (90%) of the bending stiffness, EI, and axial stiffness, EA, of the pile. In the hybrid pile, stiffness of the surrounding elements is reduced to 10% of the actual value. However, the reduced stiffness of the surrounding elements of the hybrid pile is still much higher than that of the soil. Under such conditions,

Table 4. Parameters of the hypoplastic model.

Property	Value
Critical friction angle, φ_c (deg.)	31
Granular hardness, h_s (N/mm^2)	2000
Exponential factor, *n*	0.28
Lower limit of void ratio, e_{d0}	0.663
Critical voil ratio, e_{c0}	1.1
Upper limit of void ratio, e_{i0}	1.2
Exponential factor, *α*	0.12
Exponential factor, *β*	1.2
Stiffness multiplier for initial and reverse loading, m_R	5
Stiffness multiplier for neutral loading, m_T	2
Small strain stiffness limit, R_{max}	5×10^{-5}
Stiffness reduction parameter, β_r	0.5
Stiffness reduction parameter, *χ*	1
Shift of mean stress due to cohesion	3×10^{-3}
Initial void ratio, *e*	0.739

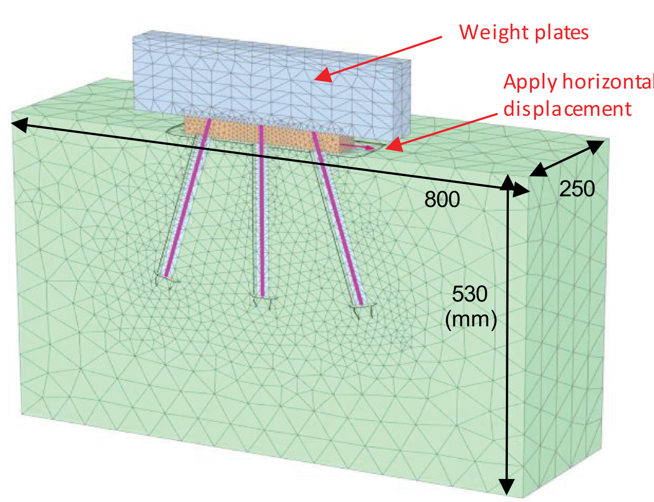

Figure 4. Finite element mesh.

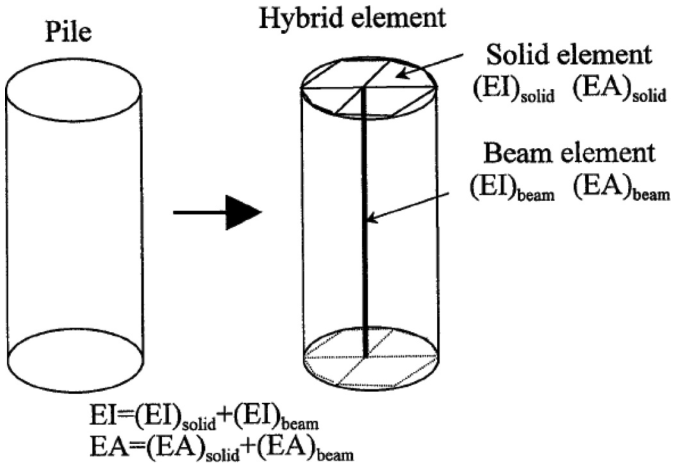

Figure 5. Mechanism of the hybrid model (Kimura and Zhang 2000).

Table 5. Properties of elastic elements.

	Beam	Solid pile	Raft	Weight plate
Unit weight, γ (kN/m^3)	23.81	0.55	26.50	124.0
Young's modulus, E (kN/m^2)	63.24×10^6	14.61×10^5	68.67×10^6	16.10×10^6
Poisson's ratio, ν	0.31	0.31	0.33	0.4

Kimura and Zhang (2000) discussed the validity of the hybrid pile in comparison with experimental results.

The raft was modelled by using solid elements. The properties of the raft, the beam, the solid pile and the weight plates are summarized in Table 5.

To simulate the slippage and detachment between the foundations and the soil, interface elements of Mohr-Coulomb type were assigned at the raft base (in the cases of the piled rafts) and along the pile shafts. Interface cohesion was set at 0, and the interface friction angle was set at 40.2° following Unsever, Matsumoto, and Ozkan (2015).

The analysis procedure is as follows:

Step 1: Self-weight analysis of the model ground alone, where K_0 = 1-sinφ (φ is internal friction angle of the soil) was assumed.

Step 2: Setting the foundation in the ground, and self-weight analysis including the foundation.

Step 3: Applying vertical load by activating weight plates (see Figure 5).

Step 4: Analysis of cyclic horizontal loading process using displacement control manner.

Results and discussions

Note here that the model foundations including 3-pile pile foundations and 6-pile pile foundations were horizontally loaded until various normalized horizontal displacements, u/D, including loading, unloading and reloading processes in the experiments. Then, analyses of horizontal loading including loading to $u/D = 0.27$, unloading to $u/D = -0.27$ and reloading to $u/D = 0.27$ were conducted. This is because the objectives of the numerical analyses are not merely to simulate the experiments, but also to get more insight into the mechanisms of resistance behaviours of the foundations, based on both the results of experiments and numerical analyses.

Figures 6 and 7 show the relationships of horizontal load, H, and normalized horizontal displacement, u/D, in the cases of the 3-pile pile foundations in the experiments and FEM, respectively. Both the experimental and FEM results indicate clearly that the piled rafts have much higher horizontal resistances than the corresponding pile groups. It is also found that the resistances of the foundations are effectively improved by the inclusion of batter piles in both cases of piled raft (BPR) and pile group (BPG).

Similar results are also obtained in the cases of the 6-pile pile foundations, in which the piled rafts have much higher horizontal resistances than the corresponding pile groups and the resistances of the foundations are enhanced by inclusion of batter piles, as shown in Figures 8 and 9. It is found from the above results that the FEM calculations simulate the experimental results very well.

Figures 10 and 11 show comparisons of the inclination of the raft during cyclic horizontal loading between 6PG and

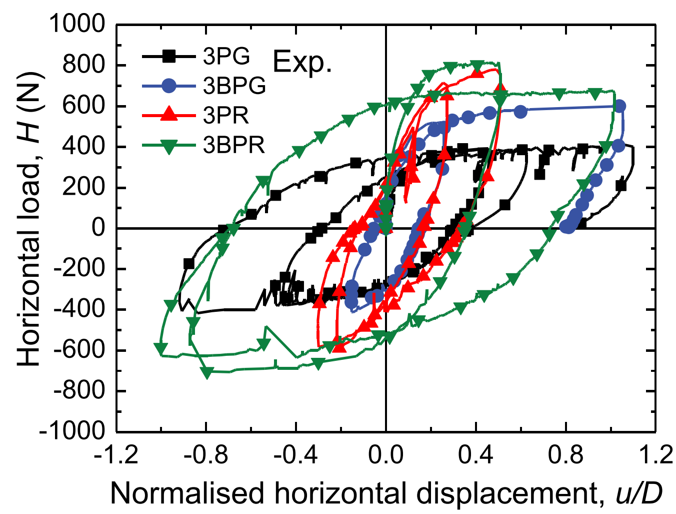

Figure 6. Horizontal load vs. normalized horizontal displacement for 3-pile pile foundations by experiments.

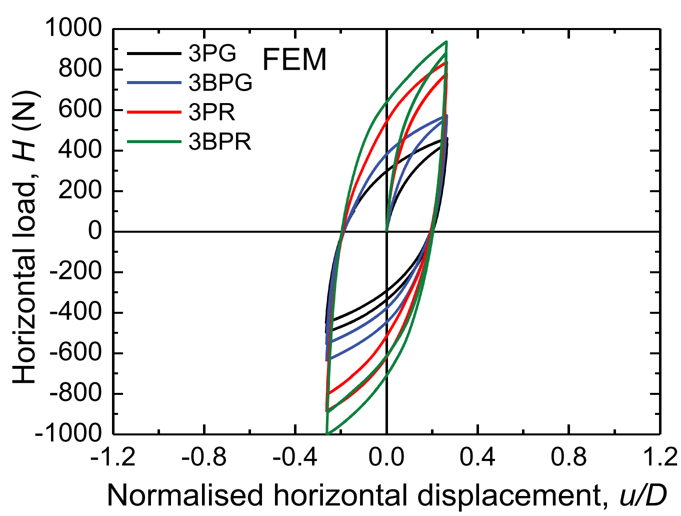

Figure 7. Horizontal load vs. normalized horizontal displacement for 3-pile pile foundations by FEM.

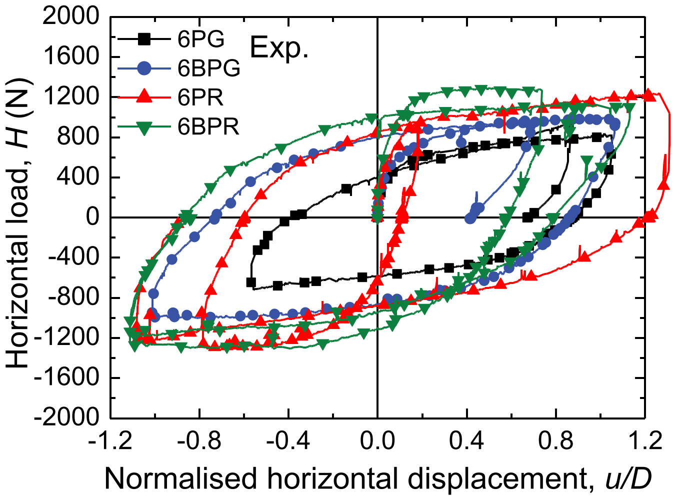

Figure 8. Horizontal load-normalized horizontal displacement for 6-pile pile foundations by experiments.

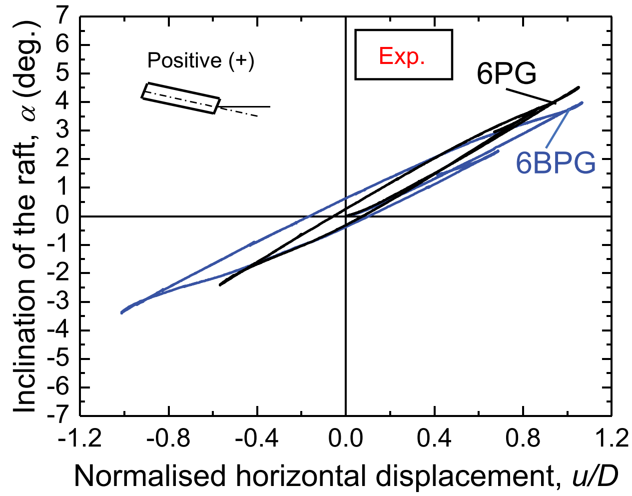

Figure 10. Inclination of the raft of 6PG and 6BPG during cyclic horizontal load by the experiments.

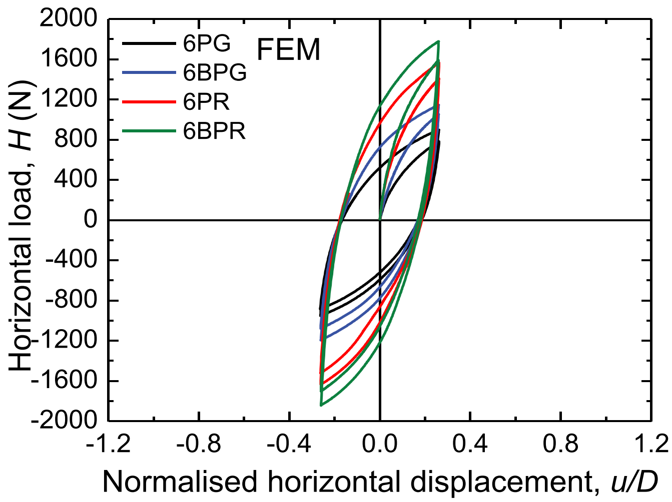

Figure 9. Horizontal load-normalized horizontal displacement for 6-pile pile foundations by FEM.

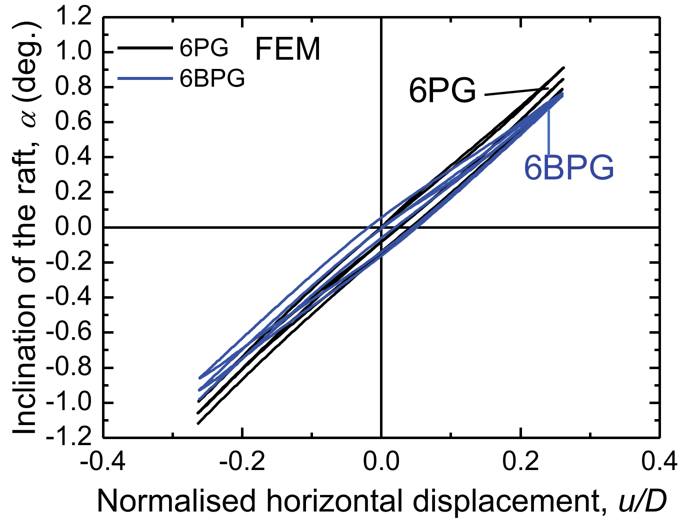

Figure 11. Inclination of the raft of 6PG and 6BPG during cyclic horizontal load by FEM.

6BPG by the experiments (Figure 10) and FEM (Figure 11). Figures 12 and 13 show the corresponding results of 6PR and 6BPR. It is indicated from both experimental and FEM results that the inclination of raft increases almost linearly with the increase of normalized horizontal displacement in all the cases, and the inclination is suppressed by the inclusion of the batter piles.

Figures 14 AND 15 show the relationship between the horizontal load and the normalized horizontal displacement during the initial loading stage for the 6-pile pile foundations according to the experiments (Figure 14) and FEM analyses (Figure 15). The numerical results are in a very good agreement with the experimental results, indicating that the piled rafts have larger resistance than the corresponding pile groups, and the foundations having batter piles have larger resistance than the corresponding foundation with only vertical piles.

Figures 16 and 17 show the relationship between the inclination of the raft and horizontal load during the initial loading stage for 6PG, 6BPG, 6PR and 6BPR by the experiments (Figure 16) and FEM analyses (Figure 17). The numerical results are in a very good agreement with the experimental results, indicating that the inclinations of the piled rafts are smaller than those of the corresponding pile groups at any given horizontal load, and the inclination of the foundations is effectively reduced by the inclusion of batter piles. It is worth to notice that the piled raft with batter piles is the most favourable foundation type to minimize the inclination induced by horizontal loading.

Table 6 shows comparisons between the foundations through the experimental results and the FEM results for the cases of 6-pile pile foundations. Firstly, please focus on the resistance of the foundations at the normalized horizontal displacement, $u/D = 0.1$. Through the experimental results, it is obvious to see that the piled raft with batter piles (6BPR) has the largest resistance, which is followed by the piled raft without batter piles (6PR), the pile group with batter piles (6BPG), and the pile group without batter piles (6PG), subsequently. If the relative resistance of 6PG is assumed as 100, the corresponding relative resistance of 6BPG, 6PR and 6BPR is 127,

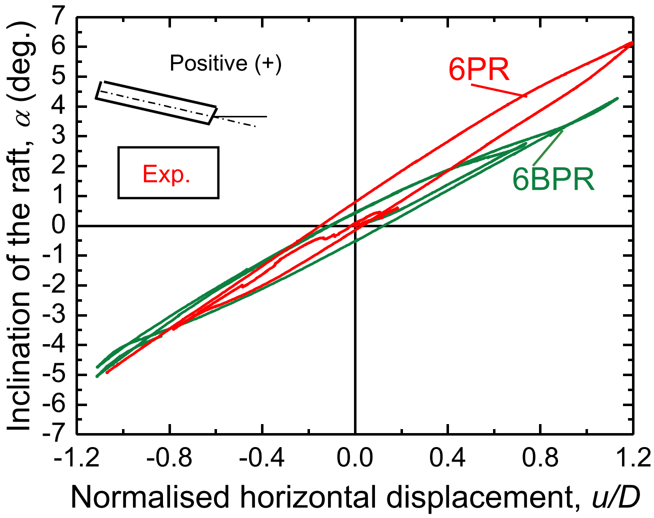

Figure 12. Inclination of the raft of 6PR and 6BPR during cyclic horizontal load by the experiments.

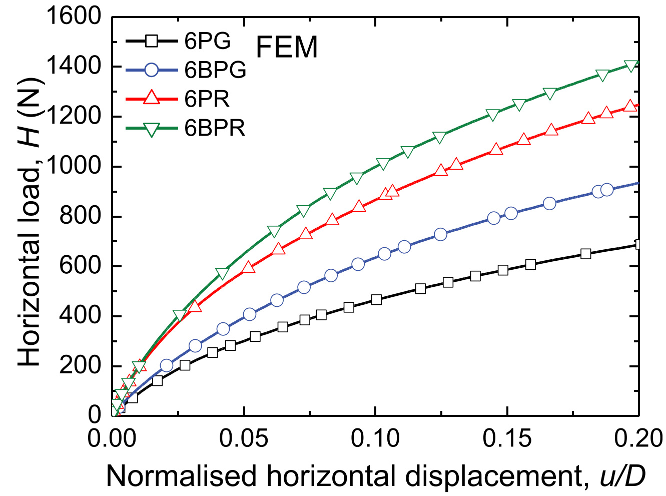

Figure 15. Horizontal load-normalized horizontal displacement during the initial loading stage for 6-pile pile foundations by FEM.

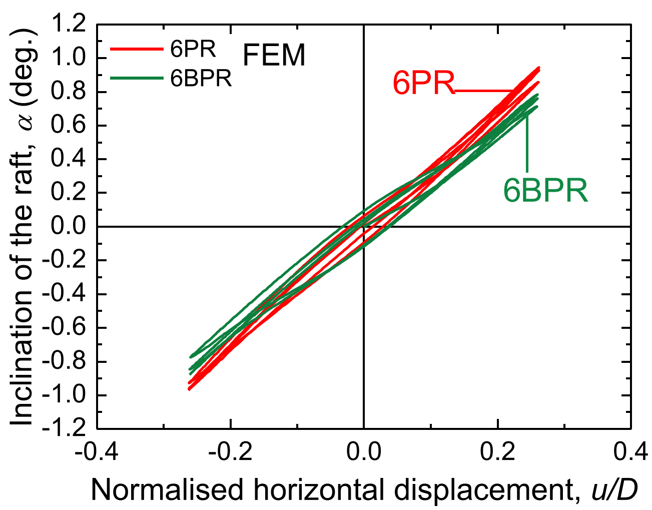

Figure 13. Inclination of the raft of 6PR and 6BPR during cyclic horizontal load by FEM.

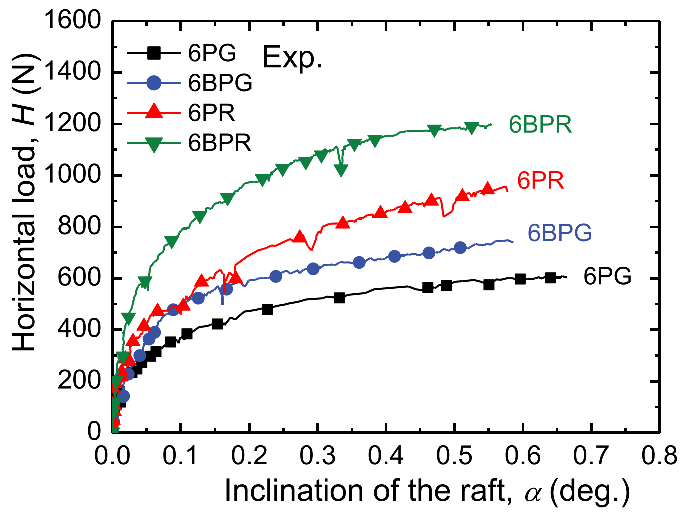

Figure 16. Inclination of the raft vs. horizontal load during the initial loading stage for 6-pile pile foundations by experiments.

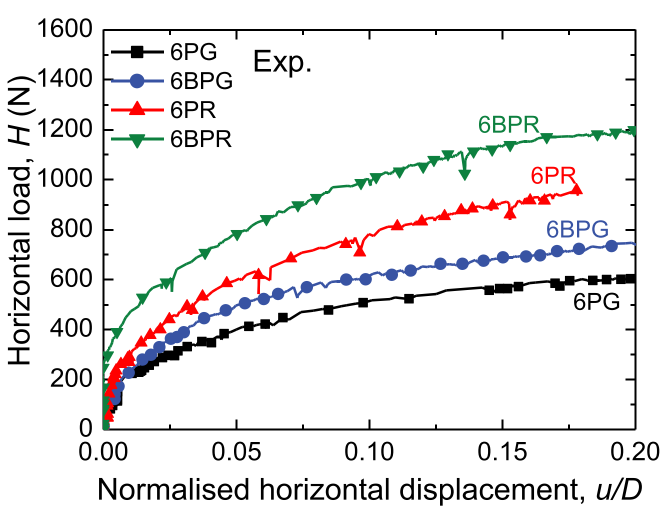

Figure 14. Horizontal load-normalized horizontal displacement during the initial loading stage for 6-pile pile foundations by experiments.

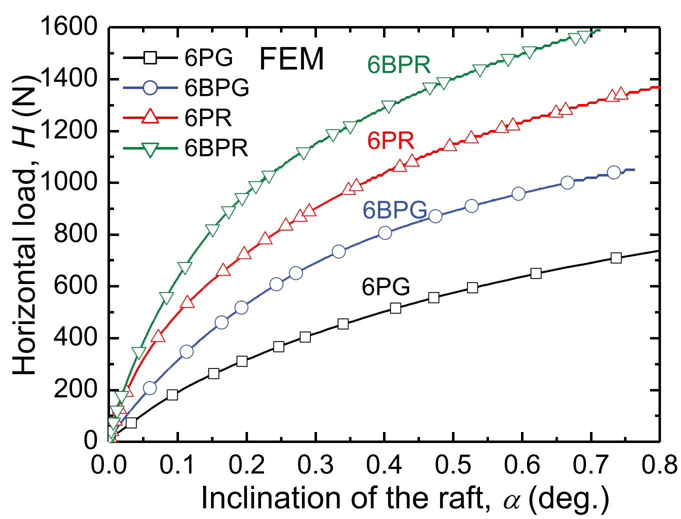

Figure 17. Inclination of the raft vs. horizontal load during the initial loading stage for 6-pile pile foundations by FEM.

Table 6. Comparions between the foundations.

Horizontal load	Experimental results				FEM results			
	6PG	6BPG	6PR	6BPR	6PG	6BPG	6PR	6BPR
Resistance at u/D = 0.1 (N)	486	619	785	1031	465	639	856	1010
Relative resistance at u/D = 0.1 (%)	100	127	162	212	100	137	184	217
Displacement at H = 400 N (mm)	0.998	0.626	0.434	0.120	1.596	1.030	0.560	0.501
Relative disp. at H = 400 N (%)	100	63	43	12	100	64	35	31
Inclination at H = 400 N (deg.)	0.121	0.061	0.047	0.018	0.282	0.137	0.071	0.052
Relative inclin. at H = 400 N (%)	100	50	39	15	100	49	25	18

162 and 212, respectively. The corresponding FEM results are well matched to the experimental results. Next, it is found from the displacement at the horizontal load, H = 400 N, that the displacement of 6BPR is smallest, which is followed by 6PR, 6BPG and 6PG, subsequently, indicating the advantages of the batter pile foundations over the foundations with only vertical piles, and the advantages of the piled rafts over the pile groups in reducing displacement. Furthermore, it is interesting to move on to the results of the inclination. If the relative inclination of 6PG is assumed as 100, the corresponding relative inclination of 6BPG, 6PR and 6BPR is only 50, 39 and 15, respectively, indicating high efficiency in reducing the inclination by using batter piles. Also, the FEM results are compatible with the experimental results.

Figure 18 shows a comparison of bearing mechanism of the vertical pile and the batter pile. The reaction force in the horizontal direction of batter piles, R_H, increases the horizontal resistance and reduces the horizontal displacement and inclination of the batter pile foundations compared with those of the foundations with only vertical piles.

Figures 19 and 20 present the numerical results of the mean stress contour in the ground after vertical loading for pile group and piled raft, respectively. Figures 21 and 22 show the corresponding results at a horizontal displacement u = 1 mm. The results indicate that the stress level in the ground under the raft and surrounding the piles in the case of the piled raft is higher than that of the pile group. The triaxial test results of the same sand showed that the stiffness of the sand increased with the increase of stress confining pressure (Vu et al. 2018). Hence, the increase of the soil stiffness due to the increase of stress level by pressure transferred from the raft base enhanced the resistance of the piled raft foundations compared with the pile group foundations.

Figure 23 shows comparisons of horizontal load vs. normalized horizontal displacement between 6PG and 2 × 3PG (two times the resistance of 3PG), and between 6PR and 2 × 3PR at the initial loading stage according to the experimental results. Similarly, the FEM results are shown in Figure 24. It is seen from both the experimental and FEM results that the horizontal resistances of the 6-pile pile foundations (6PG and 6PR) are smaller than two times the resistances of the 3-pile pile foundations (2 × 3PG and 2 × 3PR), in which the difference of resistance between 6PR and 2 × 3PR is more prominent than that between 6PG and 2 × 3PG. Obviously, the influence of interaction between the raft and the piles on the ground is indicated from the results. It is seen that the FEM analyses simulate the experimental results very well both qualitatively and quantitatively.

Figures 25 and26 show the numerical results for 3PR and 3BPR, respectively, in which changes of bending moments with normalized horizontal displacement, u/D, at different levels (see Figure 2) of each pile during horizontal loading are given. Note that P3 is the front pile and P1 is the rear pile for positive loading (in the right direction), and vice versa for negative loading (in the left direction). These numerical results are in good agreement with the experimental results presented in Figures 27and 28 by Vu et al. (2017) as follows:

As for the piled rafts without batter piles (3PR), the largest magnitudes of bending moments in the front piles and the centre piles are similar and higher than those in the rear piles. The magnitudes of bending moments in the centre piles are similar between positive loading and negative loading. In all piles, the maximum bending moments occur at the top of the piles (level 1).

It is obvious to see from the result of 3BPR that significantly larger bending moments are generated in the vertical centre piles (P2) compared with the other piles (P1 and P3), as shown in Figure 26. The bending moments in P2 of 3BPR are also considerably larger than those in P2 of 3PR.

Conclusions

In the research, three-dimensional numerical analyses were carried out to investigate the behaviours of pile foundation models subjected to a combination of vertical and cyclic horizontal loading. The numerical results are compared with the corresponding results measured from the experiments carried out by the authors.

The mechanisms of the resistance and the reduction of displacement and inclination of the piled raft with batter piles were clarified in this study.

The inclination of the piled rafts due to cyclic horizontal load is significantly smaller than that of the corresponding pile groups. In addition, the inclination of the foundations is significantly reduced by the inclusion of batter piles.

It is worth to notice that the piled raft with batter piles is the most favourable foundation type to minimize the inclination and the displacement induced by horizontal loading.

It is firmly confirmed from the analysed results as well as the experimental results that the piled rafts have higher horizontal resistance than the corresponding pile groups and the

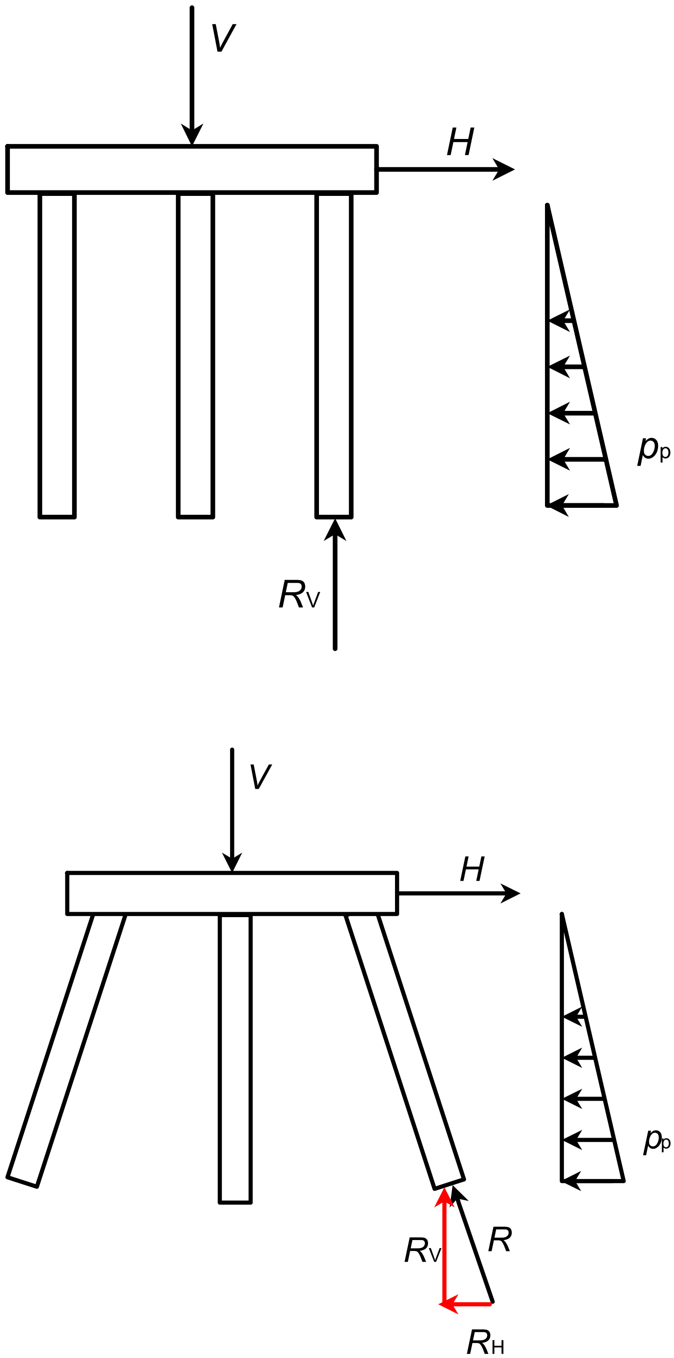

Figure 18. Comparison on bearing mechanism of vertical and batter piles.

horizontal resistance of the foundations is considerably improved by the inclusion of batter piles.

The numerical analysis indicated that the confinement in the sand due to the raft in the cases of piled rafts improves the stiffness of the sand, resulting in the increase of the resistance of the piled raft foundations compared to that of the corresponding pile group foundations.

The results also show that the resistance of six-pile pile foundations is not equal to two times the resistance of the corresponding three-pile pile foundations due to the influence of interaction.

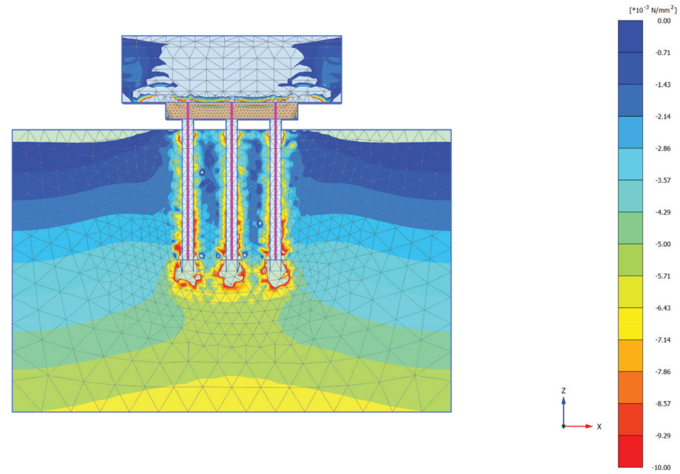

Figure 19. Mean stress contour for PG after vertical loading (u = 0).

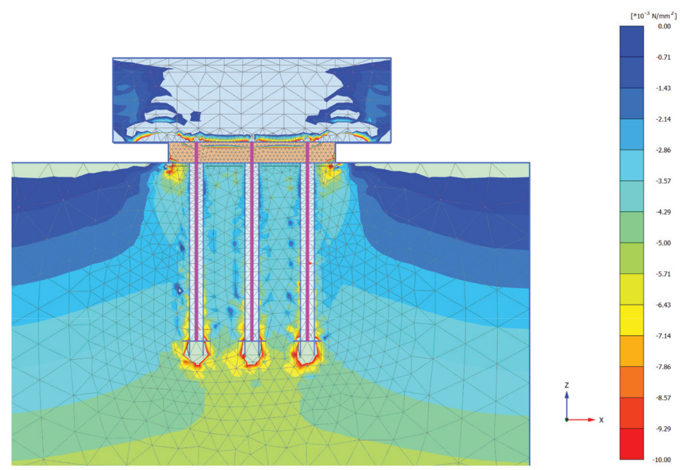

Figure 20. Mean stress contour for PR after vertical loading (u = 0).

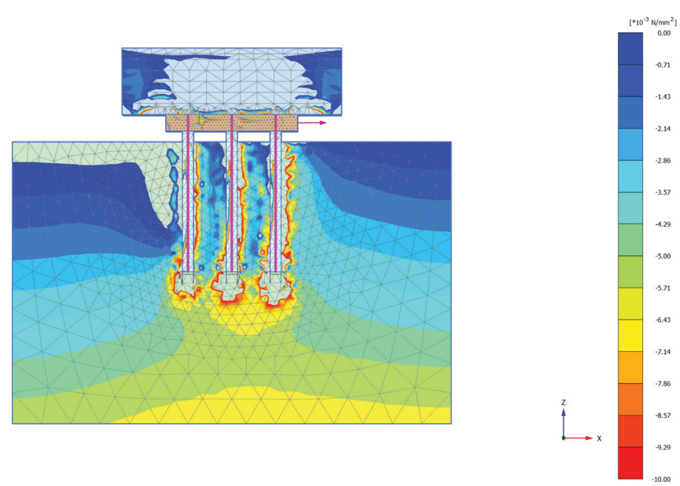

Figure 21. Mean stress contour for PG at horizontal displacement u = 1 mm.

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the author(s).

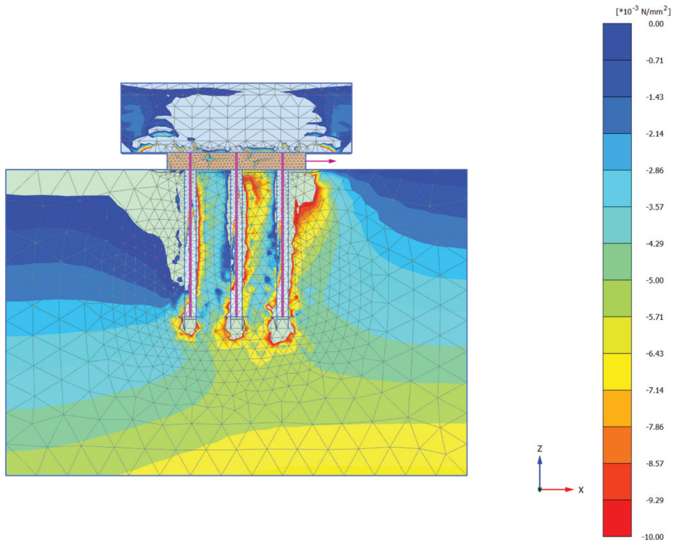

Figure 22. Mean stress contour for PR at horizontal displacement $u = 1$ mm.

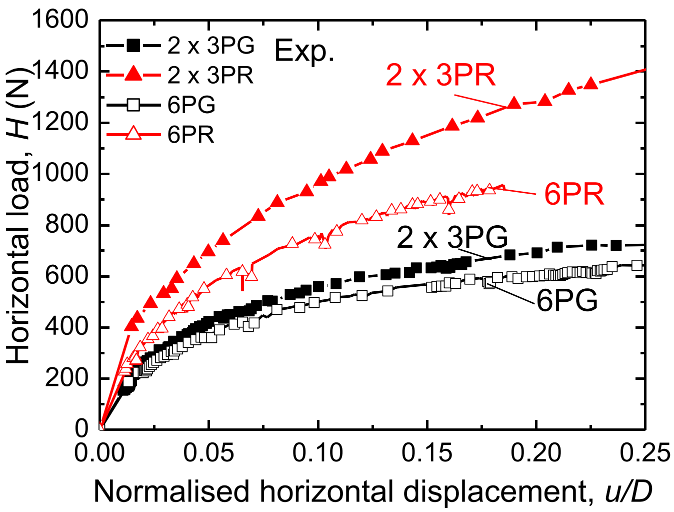

Figure 23. Horizontal load vs. normalized horizontal displacement curves for 6PG, 6PR, 2 × 3PG and 2 × 3PR (Experimental results).

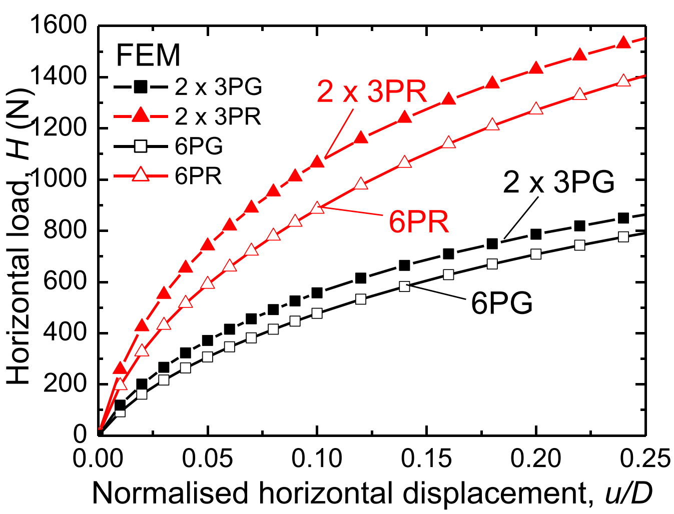

Figure 24. Horizontal load vs. normalized horizontal displacement curves for 6PG, 6PR, 2 × 3PG and 2 × 3PR (FEM results).

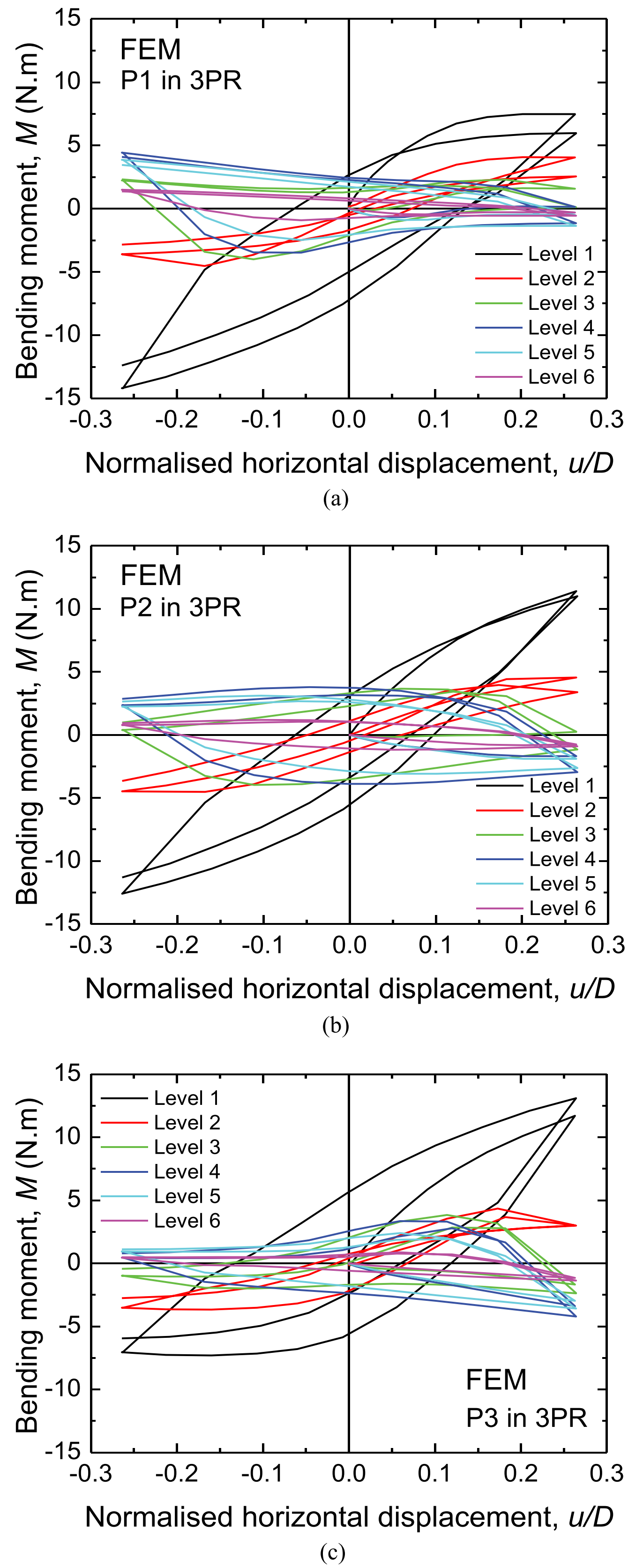

Figure 25. Bending moments of piles for 3PR (FEM).

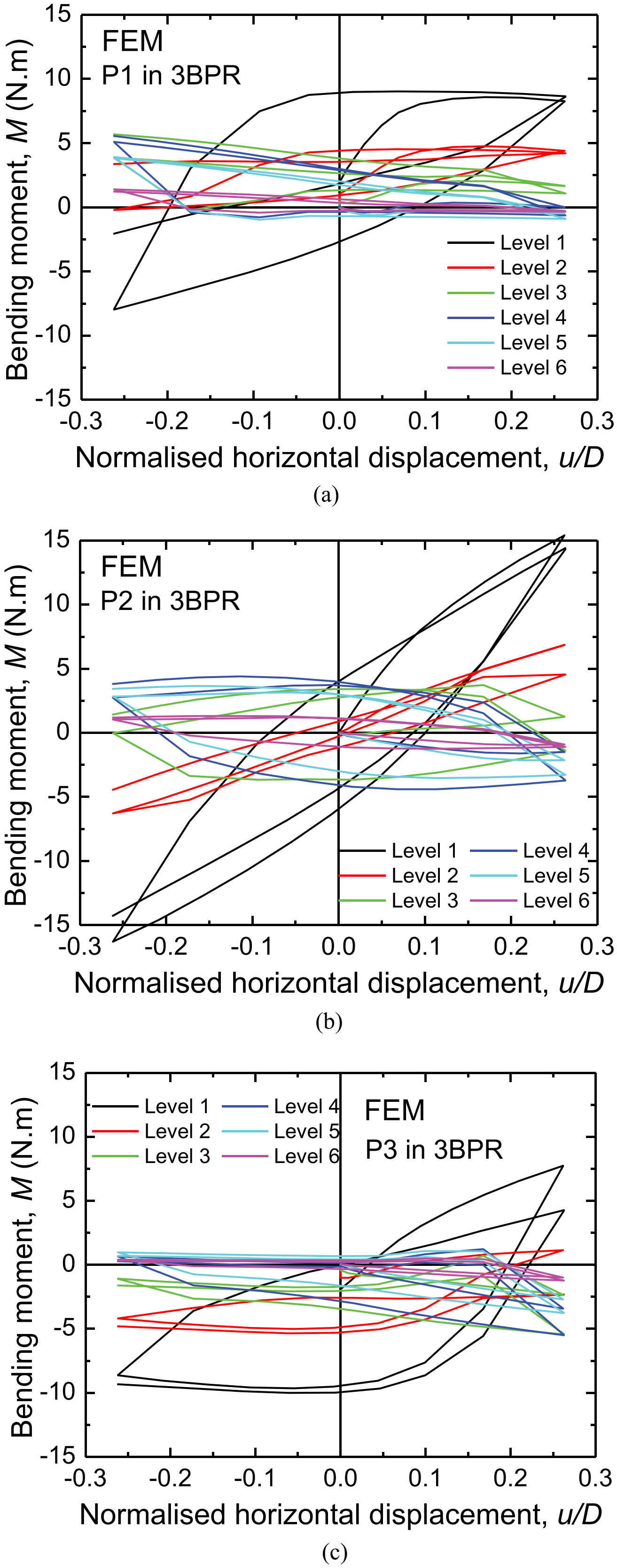

Figure 26. Bending moments of piles for 3BPR (FEM).

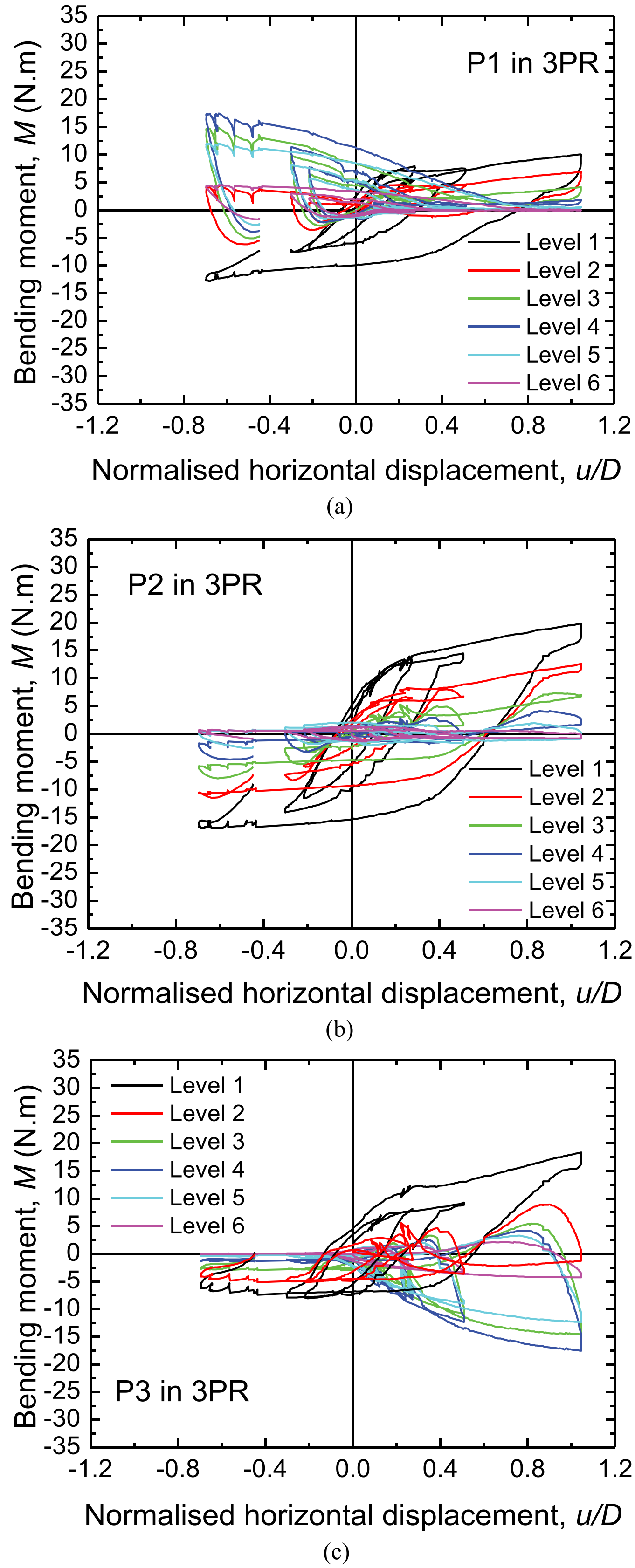

Figure 27. Bending moments of piles for 3PR (Experiment).

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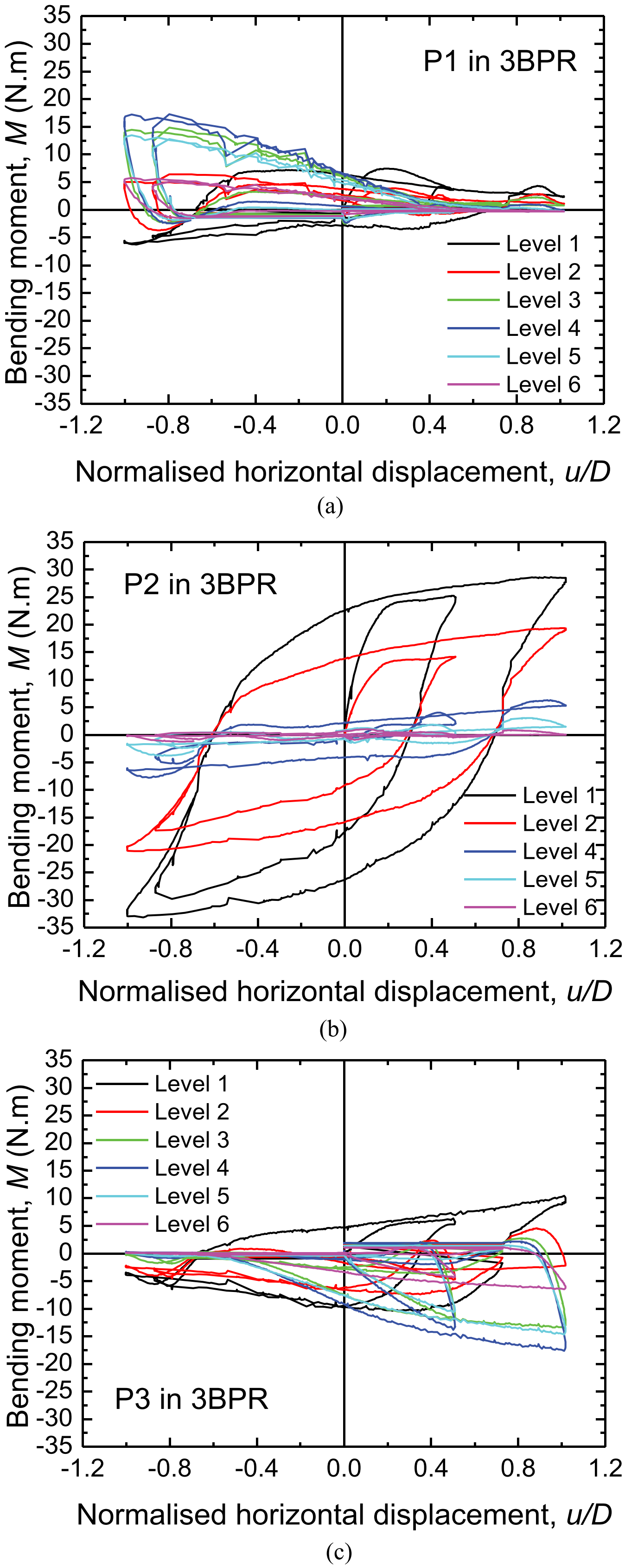

Figure 28. Bending moments of piles for 3BPR (Experiment).

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