3D finite-element analysis on behaviours of pile group and piled raft foundation models subjected to cyclic horizontal loading

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ABSTRACT: In this research, the authors carry out a numerical study through three-dimensional finite element method to investigate the behaviours of pile foundations subjected to 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 analysed results indicate that the piled rafts have higher horizontal resistance than the corresponding pile groups and the horizontal resistance of the foundations are improved by inclusion of batter piles. The results also show that the resistance of six-pile pile foundations is not equal two times the resistance of the corresponding three-pile pile foundations due to the influence of interaction.
Keywords: Piled raft, pile group, numerical analysis, cyclic loading

1. INTRODUCTION

Pile foundations including pile group and piled raft foundations are usually applied to structures subjected to large horizontal load, such as bridges, wind-turbine towers or offshore structures. Horizontal loads acting on these structures are wind load and/or water wave load and can be considered as cyclic load.

Piled raft has been increasingly used as an effective foundation type to reduce average and/or differential settlement, e.g. Poulos et al. (2011), and Yamashita et al. (2011). Experimental studies as well as numerical analyses on piled raft foundations having vertical piles alone have been conducted, e.g. Randolph (1994), Horikoshi et al. (2003), Matsumoto et al. (2004), Reul (2004), Unsever et al. (2014), Hamada et al. (2015), Vu et al. (2017), and Vu et al. (2018).

It seems that the behaviours of pile foundations under cyclic horizontal loading have not been fully understood. Hence, the authors carry out a numerical study through three-dimensional finite element method to investigate the behaviours of pile foundations subjected to cyclic horizontal loading.

2. DESCRIPTION OF EXPERIMENTS

The experimental study has been presented in Vu et al. (2017). However, it is appropriate to describe the outline of the experiments here again for comparisons with the numerical analyses.

2.1 Pile foundation models

Figure 1 shows the foundation models used in the experiments. The foundation models consist of 3 piles or 6 piles (with or without batter piles). They are pile groups (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.

Close-ended aluminium pipes having a total length of 285 mm, an outer diameter of 20 mm and a wall thickness of 1.1 mm were used for the model piles. The upper 30 mm of the pile is embedded in the raft, resulting in the effective length of 255 mm. Centre-to-centre pile spacing, *s*, is 80 mm, 4 times the pile diameter. The inclination angle of the batter piles is 15 degrees. 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 summarised in Table 1. In order to obtain axial forces, bending moments and shear forces in the model piles during load tests, strain gauges were arranged on the pile shafts (Figure 2). The piles were covered with the silica sand particles in order to increase the shaft resistance.

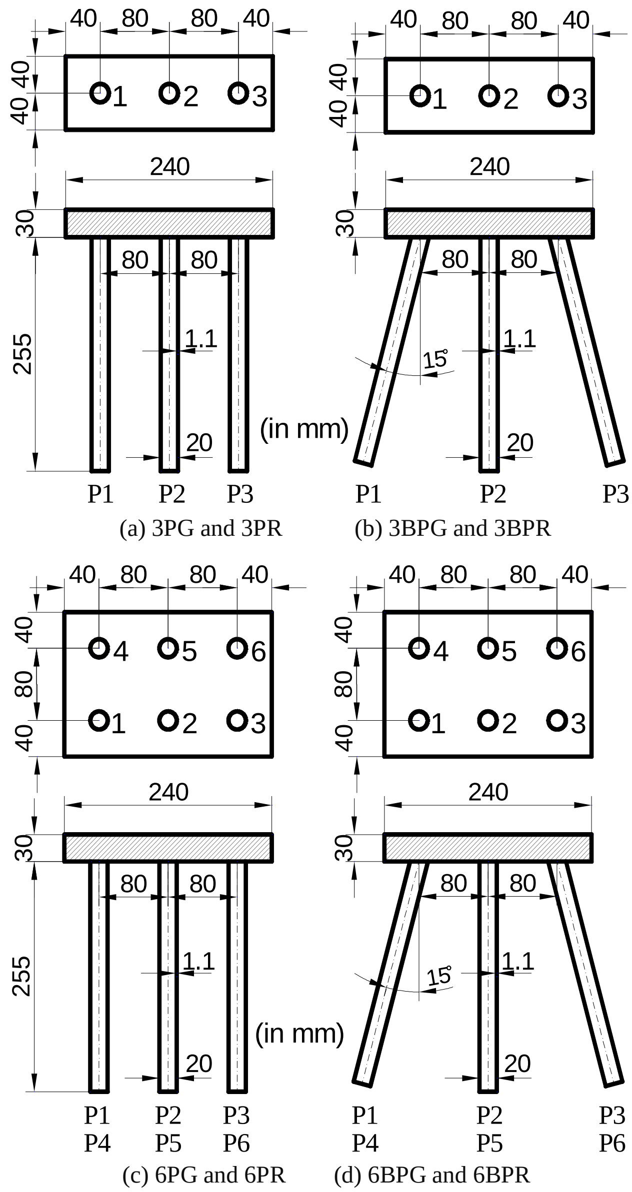
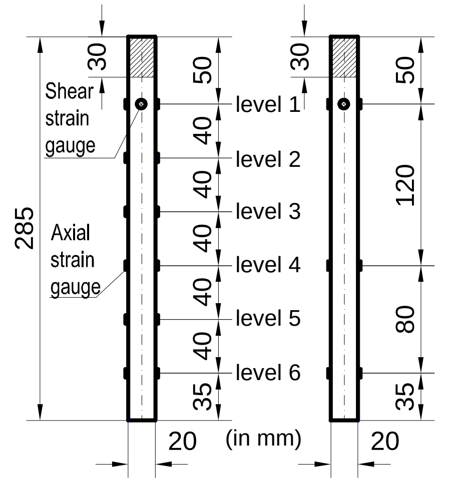


Figure 1 Dimensions of the foundation models



(a) P1, P2 and P3 (b) P4, P5 and P6

Figure 2 Model piles with strain gauge instrumentation

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

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

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
Young's modulus of the raft, E_r (N/mm^2)	68670
Poison's ratio, v	0.31

2.2 Model ground

The soil used for model ground in this study is a dry silica sand having the properties shown in Table 2. The model ground with a relative density, D_r, of about 82% (ρ_d = 1.533 t/m^3) was prepared in a soil box having 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 and compacted by tapping so that the target relative density of 82% was achieved.

Table 2 Physical properties of silica sand #6

Property	Value
Density of soil particle, ρ_s (t/m^3)	2.668
Maximum dry density, ρ_{dmax} (t/m^3)	1.604
Minimum dry density, ρ_{dmin} (t/m^3)	1.269
Maximum void ratio, e_{max}	1.103
Minimum void ratio, e_{min}	0.663
Relative density, D_r (%)	82.0
Dry density, ρ_d (t/m^3)	1.533

2.3 Loading method

Figure 3 shows a photo of the experiment setup with measuring instruments. Vertical load was applied by placing lead plates of about 600 N and 1200 N on the raft in the cases of 3-pile foundations and 6-pile foundations, respectively, in order to simulate the dead weight of the super structure. After that, cyclic static horizontal load was applied at the raft in longitudinal direction of the raft by means of winches and pulling wires. The horizontal load was measured by 2 load cells (LC-R and LC-L) arranged in the right (positive) direction and in the left (negative) direction. Both the horizontal and vertical displacements of the foundations were measured by horizontal and vertical dial gauges.

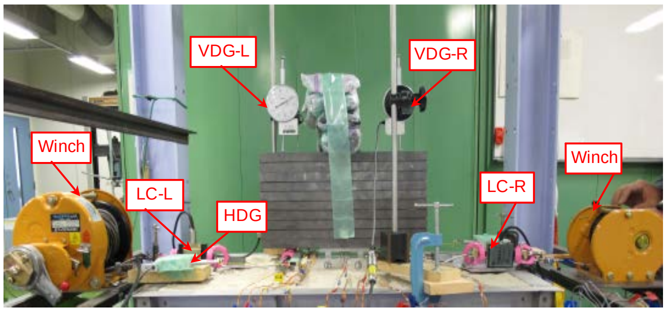
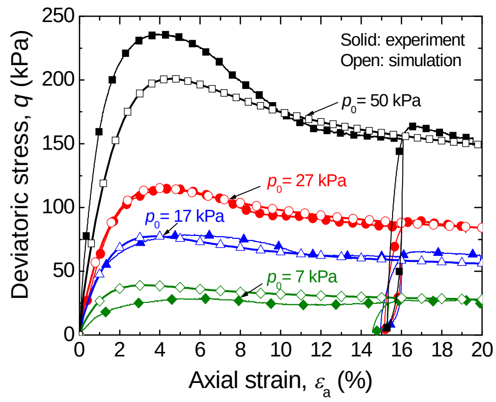


Figure 3 Experiment setup with measuring instruments

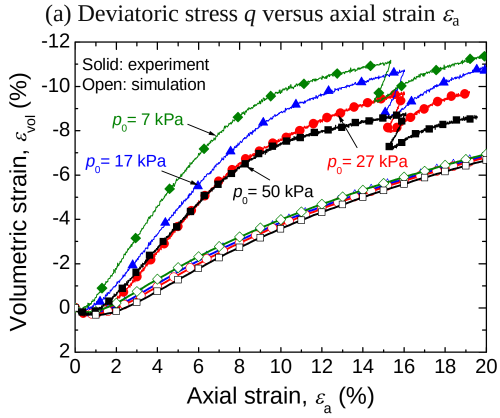
3. FEM MODELLING

3.1 FEM simulations of the triaxial tests

A series of triaxial CD tests of the sand having a relative density D_r = 82% were conducted under different confining pressures, p_0 = 7, 17, 27 and 50 kPa, in order to obtain the mechanical properties and to investigate the behaviour of the sand. To select an appropriate soil model and to evaluate the soil parameters, simulations of the triaxial tests were carried out, prior to the analyses of the load tests. The experimental and simulation results of the triaxial tests are shown in Figure 4 (Vu et al., 2018).



(a) Deviatoric stress q versus axial strain ε_a



(b) Volumetric strain ε_{vol} versus axial strain ε_a

Figure 4 Experimental and simulation results of triaxial CD tests of the sand

In this research, the hypoplastic model (Wolffersdorff, 1996) having the parameters shown in Table 3 was employed to model the sand.

Table 3 Parameters of the hypoplastic model

Property	Value
φ_c (deg.)	31
h_s (kN/m^2)	2x10^6
n	0.28
e_{d0}	0.663
e_{c0}	1.100
e_{i0}	1.200
α	0.12
β	1.2
m_R	5
m_T	2
R_{max}	0.5×10^{-4}
β_r	0.5
χ	0.5
p_t (kN/m^2)	3
e	0.739

3.2 FEM modelling of loading tests

Numerical analyses were carried out using a three-dimensional FEM program, PLAXIS 3D. Only a half of the foundation and the ground was modelled owing to symmetric conditions. Figure 5 shows an example of the finite element mesh of the modelling.

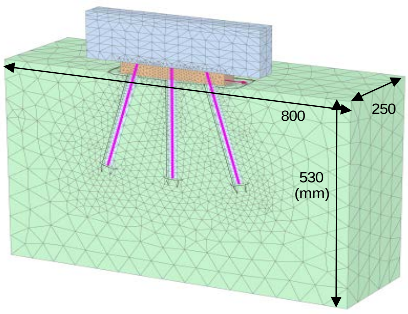


Figure 5 Finite element mesh

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 (uy = 0) and free in x- and z- directions.
- The model bottom boundary is fixed in all directions (ux = uy = uz= 0).
- The ground surface is free in all directions.

The raft and the piles were considered as linear elastic materials. In order to model the pile, a hybrid model in which beam element surrounded by solid elements was used, according to Kimura and Zhang (2000). The raft was modelled by using solid elements.

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 as 0, and the interface friction angle was set as 40.2˚ following Unsever et al. (2015). The analysis procedure is as follows:

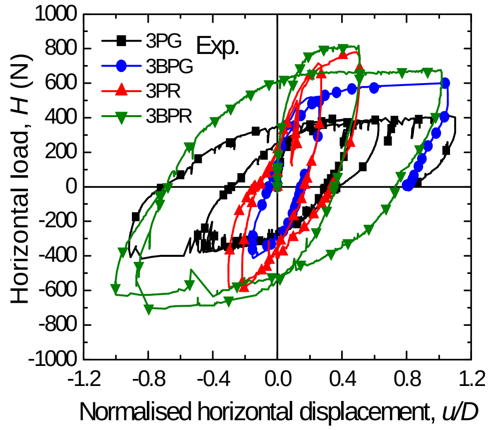
Step 1: Self-weight analysis of the model ground alone, where K_0= 1-sinφ (φ is internal friction angle of the soil) was assumed.

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

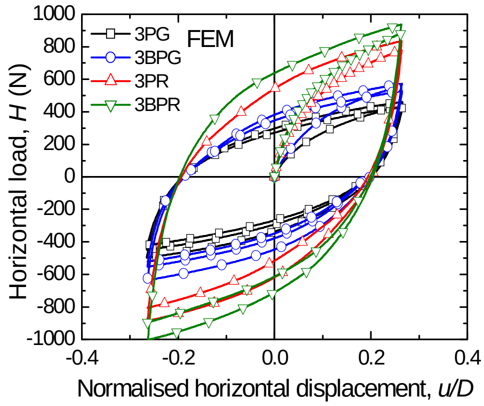
Step 3: Analysis of loading process using displacement control manner.

4. RESULTS AND DISCUSSIONS

Figure 6 shows the relationships of horizontal load, *H*, and normalised horizontal displacement, *u*/*D*, in the cases of the 3-pile foundations. 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 seen that the resistances of the foundations are effectively improved by inclusion of batter piles in both cases of piled raft (BPR) and pile group (BPG).



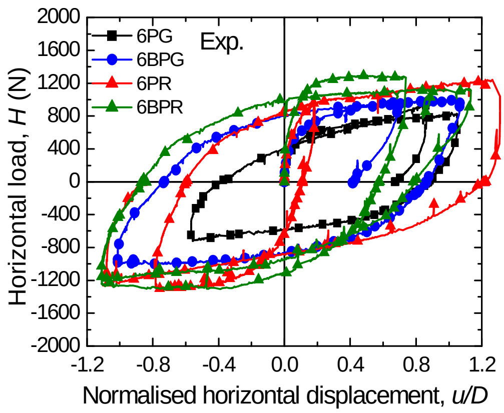
(6a) Experimental results



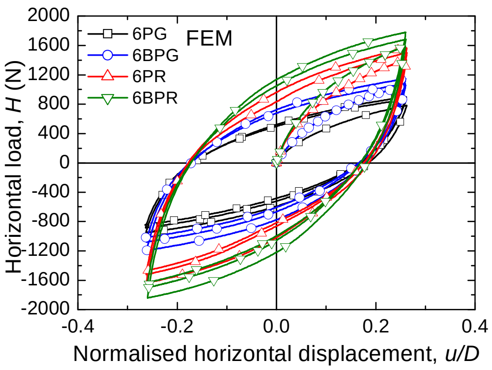
(6b) FEM results

Figure 6 Horizontal load vs. normalised horizontal displacement for 3-pile pile foundations

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 Figure 7. It is seen from the above results that the FEM calculations simulate the experimental results very well.



(7a) Experimental results



(7b) FEM results

Figure 7 Horizontal load-normalised horizontal displacement for 6-pile pile foundations

Figure 8 shows comparisons of horizontal load vs. normalised horizontal displacement between 6PG and 2×3PG, and between 6PR and 2×3PR at the initial loading stage according to the experimental results. Similarly, the FEM results are shown in Figure 9. It is seen from both experimental and FEM results that the horizontal resistances of the 6-pile foundations (6PG and 6PR) are smaller than two times the resistances of the 3-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 through the ground is indicated from the results.

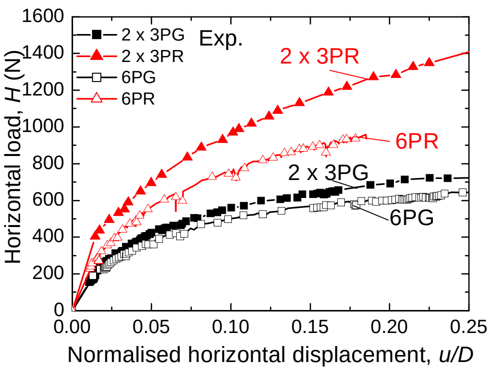


Figure 8 Horizontal load vs. normalised horizontal disp. curves for 6PG, 6PR, 2×3PG and 2×3PR (Experimental results)

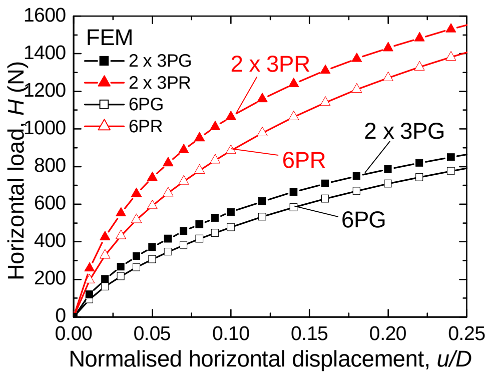
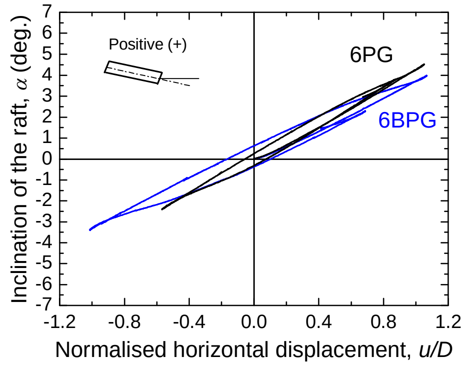
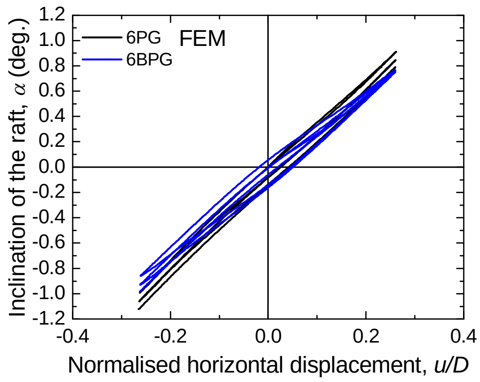


Figure 9 Horizontal load vs. normalised horizontal disp. curves for 6PG, 6PR, 2×3PG and 2×3PR (FEM results)

Figure 10 shows comparisons of inclination of the raft during cyclic horizontal loading between 6PG and 6BPG by the experiments (Figure 10a) and FEM (Figure 10b). Figure 11 shows 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 normalised horizontal displacement in all cases, and the inclination is suppressed by inclusion of the batter piles.

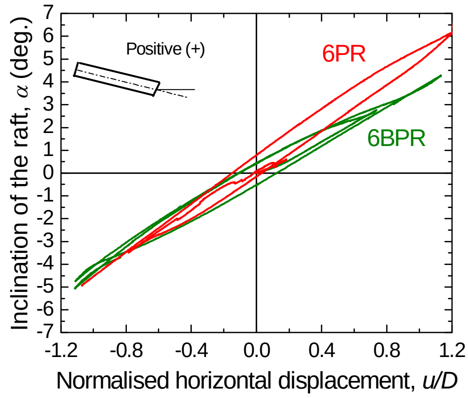


(10a) by experiments

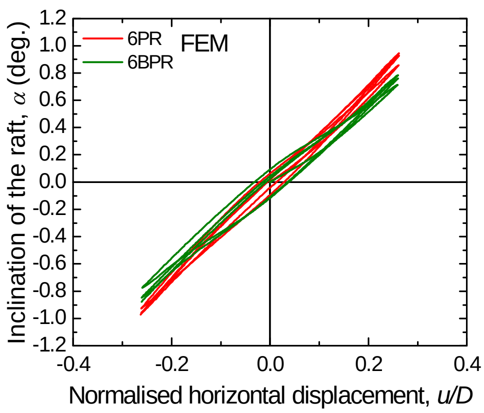


(10b) by FEM

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



(11a) by experiments



(11b) by FEM

Figure 11 Inclination of the raft of 6PR and 6BPR during cyclic horizontal load by the experiments and FEM

Figure 12 and Figure 13 show the relationship between the inclination of the raft and horizontal load during the initial loading stage for 6PG, 6BPG, 6PR and 6BPR according the experiments (Figure 12) and FEM results (Figure 13). The numerical results are in a 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.

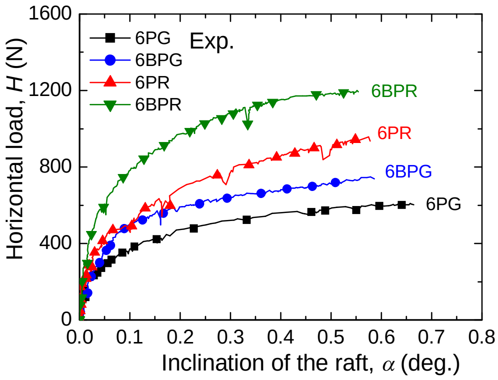


Figure 12 Inclination of the raft vs. horizontal load during the initial loading stage for 6-pile foundations (Experimental results)

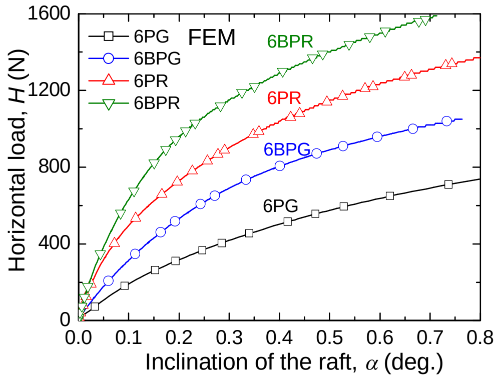
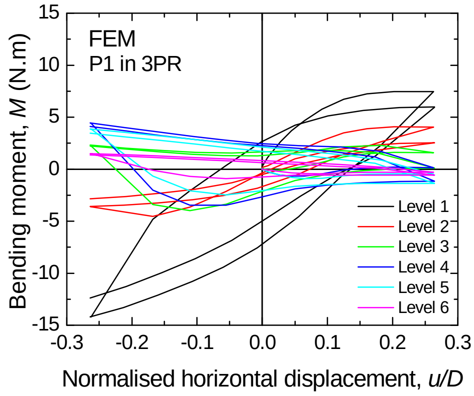


Figure 13 Inclination of the raft vs. horizontal load during the initial loading stage for 6-pile foundations (FEM results)

Figures 14 and 15 show the numerical results for 3PR and 3BPR, respectively, in which changes of bending moments with normalised 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, and vice versa for negative loading. These numerical results are in good agreement with the experimental results presented in Figures 16 and 17 (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 in 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. 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). The bending moments in P2 of 3BPR are also considerably larger than those in P2 of 3PR.



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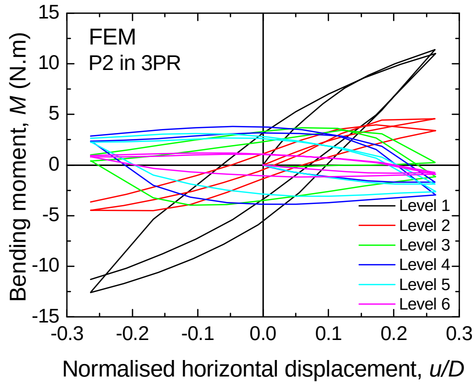
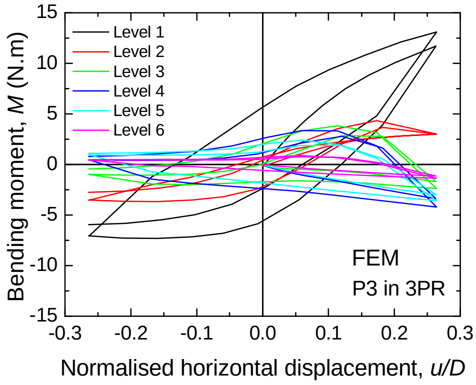
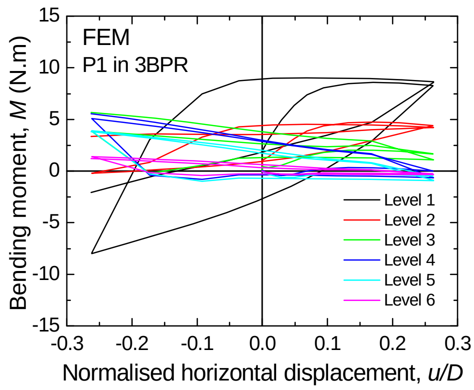


(b)

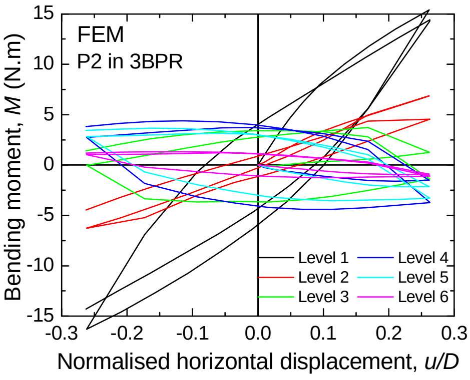


(c)

Figure 14 Bending moments of piles for 3PR (FEM)



(a)



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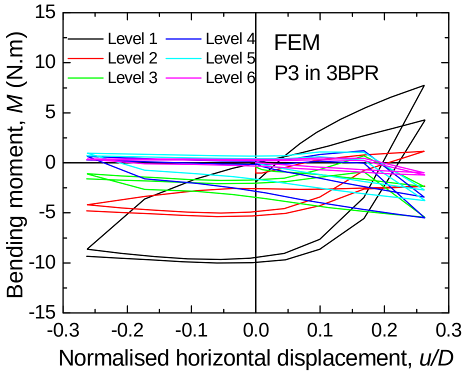
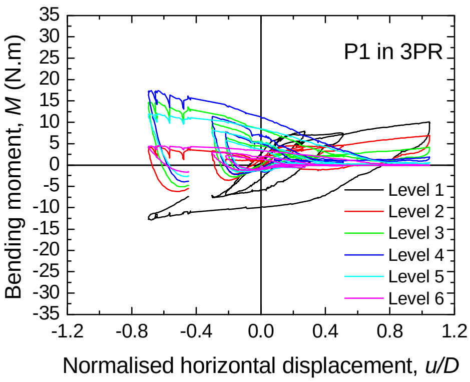


(c)

Figure 15 Bending moments of piles for 3BPR (FEM)



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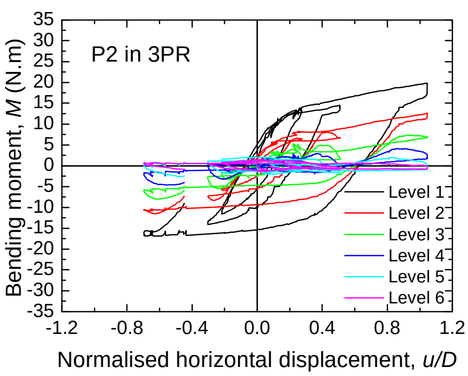

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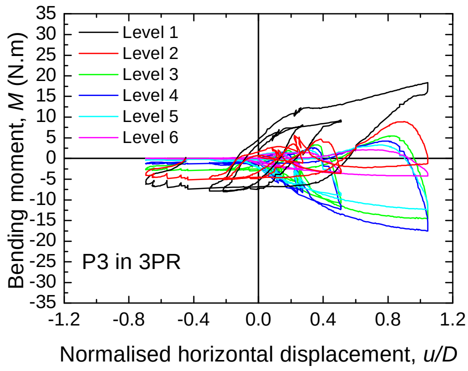
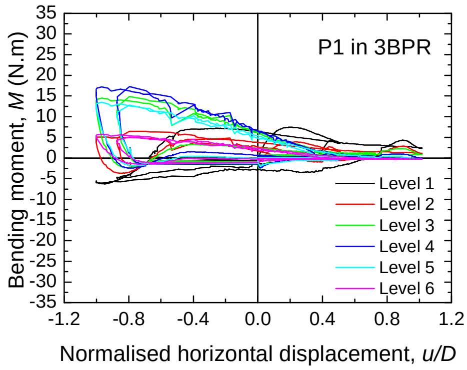


(c)

Figure 16 Bending moments of piles for 3PR (Experiment)



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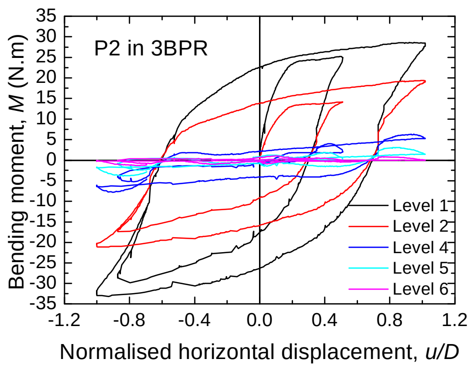

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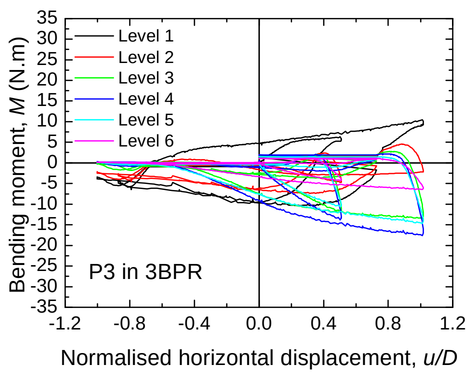

(c)

Figure 17 Bending moments of piles for 3BPR (Experiment)

5. CONCLUSION

A numerical study through three-dimensional finite element method was carried out to investigate the behaviours of pile foundations subjected to cyclic horizontal loading and the results were compared with the corresponding experimental study.

The analysed results indicate that the piled rafts have higher horizontal resistance than the corresponding pile groups and the horizontal resistance of the foundations are improved by 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.

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

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