Experimental and Numerical Study on Behaviours of Pile Group and Piled Raft Foundations Having Batter Piles Subjected to Combination of Vertical and Cyclic Horizontal Loading

Dissertation abstract

Experimental and Numerical Study on Behaviours of Pile Group and Piled Raft Foundations Having Batter Piles Subjected to Combination of Vertical and Cyclic Horizontal Loading

鉛直および繰返し水平載荷を受ける斜杭を有する群杭およびパイルド・ラフト基礎の挙動に関する実験的・解析的研究

Graduate School of

Natural Science and Technology

Kanazawa University

Division of Environmental Design

Student ID No.: 1424052004

Name: Vu Anh Tuan

Chief advisor: Matsumoto Tatsunori

Abstract

This thesis presents an experimental and numerical study on the behaviours of pile group and piled raft foundations having batter piles subjected to vertical loading and combination of vertical and horizontal loading. A series of vertical load tests and combination load tests on 3-pile foundation models and 6-pile foundation models, with or without batter piles, were carried out in a dry sand ground at the 1-g field. Numerical simulations of the experiments were performed using finite element method through a three-dimensional finite element program, PLAXIS 3D. The hypoplastic model was used for the soil model, of which the soil parameters was estimated from the triaxial tests of the sand. A hybrid pile model, in which the model pile was represented by beam elements surrounded by solid elements, was employed for modelling the piles.

1. Background, motivation and objectives

Pile foundations including pile group and piled raft foundations are usually applied to support heavy structures such as high-rise buildings, bridges, wind-turbine towers and offshore structures, etc. In working conditions, these pile foundations carry not only vertical loads but also horizontal loads. The horizontal load acting on these structures is wind load and/or wave load and can be considered as a cyclic load. Hence, these pile foundations are subjected to a combination of vertical and cyclic horizontal load.

A number of studies on batter piles were reported, e.g. Sadek and Isam (2004), Ghasemzadeh and Alibeikloo (2011), Isam et al. (2012), and Goit and Saitoh (2013). However, the studies investigated the behaviours of pile groups with batter piles (Sadek and Isam, 2004, Ghasemzadeh and Alibeikloo, 2011) or single batter piles (Goit and Saitoh, 2013). Moreover, these studies investigated the foundation behaviours subjected to vertical loading alone or horizontal loading alone. Therefore, the resistance mechanisms of foundations having batter piles subjected to combination loads have not been fully understood.

Some researches have been conducted to investigate the behaviours of pile group and piled raft subjected to combination loading e.g. Unsever et al. (2014), and Sawada and Takemura (2014). Unsever et al. (2014) carried out the experimental study on pile group and piled raft models having only vertical piles subjected to combination of vertical and cyclic horizontal load at the 1-g field. Sawada and Takemura (2014) studied on pile group and piled raft models having only vertical piles subjected to a combination load using a centrifuge device.

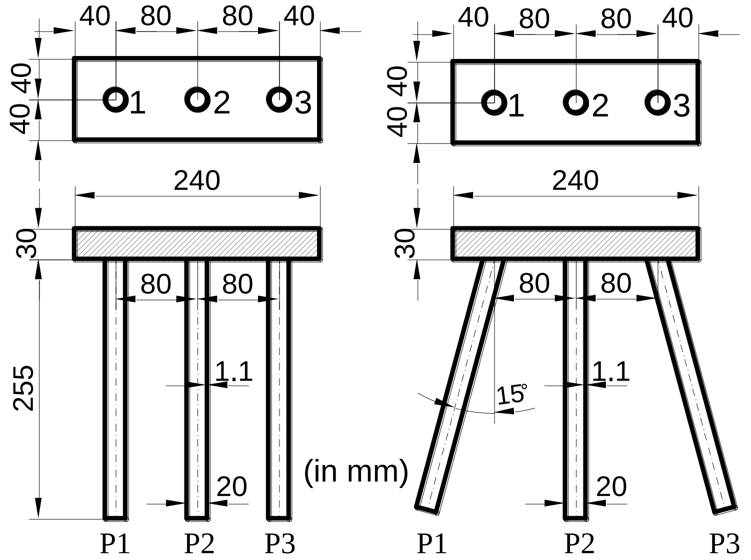
There is few experimental study on behaviours of piled rafts having batter piles. Hence, in this research, behaviours and resistance mechanisms of pile groups and piled rafts having batter piles subjected to a combination of vertical and cyclic horizontal load are investigated through a series of model load tests in a dry sand ground at the 1-g field and numerical analyses.

2. Experimental study on behaviours of pile group and piled raft foundations having batter piles subjected to vertical loading

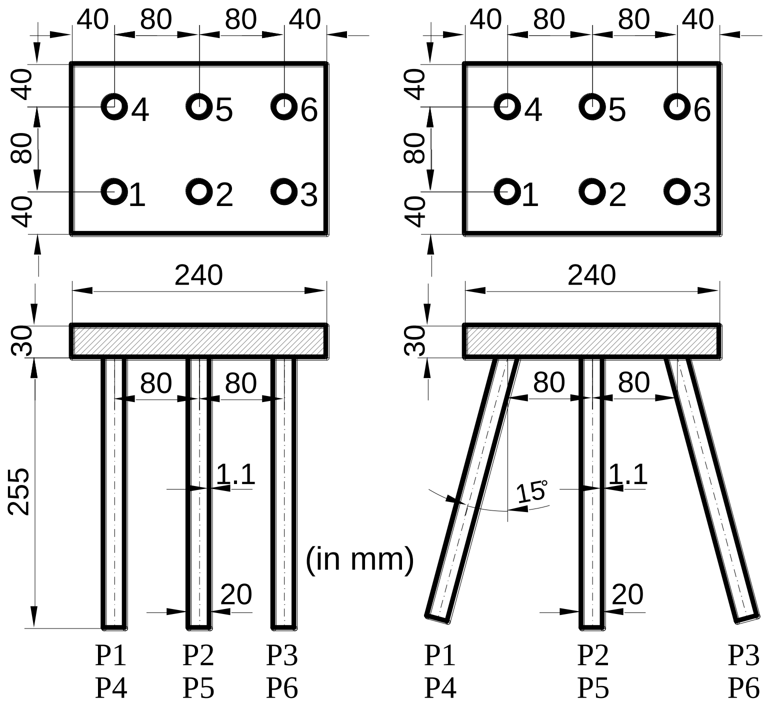
2.1. Description of the experiments

A dry sand 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. The foundation models consist of 3 piles or 6 piles (with or without batter piles). Figure 3.7 shows the dimensions of the foundation models used in the experiments.

In vertical load tests, the load was applied by the help of a screw jack with a constant displacement rate of about 2 mm/min. The vertical load was measured by a load cell placed at the centre of the raft. The vertical displacements of the foundation were recorded by 4 dial gauges arranged at the corners of the raft.



a) 3PG and 3PR (b) 3BPG and 3BPR



c) 6PG and 6PR (b) 6BPG and 6BPR

Figure 3.1. Dimensions of the foundation models

2.2. Vertical load tests on 3-pile pile foundations (3PG, 3BPG, 3PR and 3BPR)

Figure 3.11 shows load-settlement curves in cases of the 3-pile foundations (3PG, 3PR, 3BPG and 3PR). The results indicate that 3BPR has the highest resistance and stiffness followed by those of 3PR, 3BPG and 3PG, subsequently. It is seen from the results that the resistances of the foundations with batter piles at any settlement are larger than those of the corresponding foundations with only vertical piles. For instance, the resistance of 3BPR is 2511 N at a settlement w = 2 mm (10% pile diameter), which is 8% higher than that of 3PR of 2326 N. The resistance of 3BPG is 1355 N at a settlement of 2 mm (10% pile diameter), which is 22% higher than that of 3PG of 1113 N.

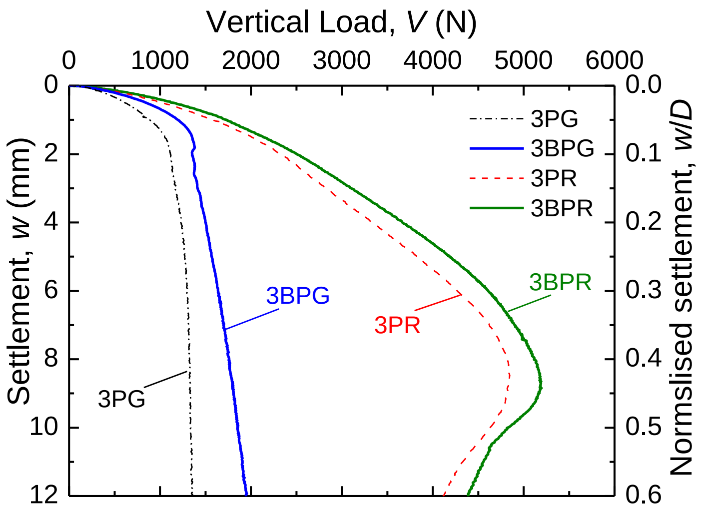


Figure 3.2. Load-settlement curves of the 3-pile foundations

The settlement of 3PR is 1.5 mm at a vertical load V = 2000 N while the corresponding settlement of 3BPR is 1.3 mm, resulting in 13% decrease of the settlement. A similar effect of inclusion of batter piles is also seen for a larger vertical load. For instance, the settlement of 3PR is 3.3 mm at a vertical load V = 3000 N while the corresponding settlement of 3BPR is 2.8 mm, resulting in 15% decrease of the settlement. In cases of the pile groups (3PG and 3BPG), the effect of batter piles in settlement reduction is more significant. The settlement of 3PG is 1.3 mm at a vertical load V = 1000 N while the settlement of 3BPG is only 0.7 mm, resulting in 46% decrease of the settlement.

The advantages the piled rafts over the pile groups can be found also in Figure 3.11. The resistances of the piled rafts are much higher than those of the corresponding pile groups, and settlements of the piled rafts are smaller than those of the corresponding pile groups at any vertical load.

2.3. Vertical load tests on 6-pile pile foundations (6PG, 6BPG, 6PR and 6BPR)

Figure 3.19 shows the load-settlement curves in cases of the 6-pile foundations. Similar to the above-mentioned results of the 3-pile foundations, 6BPR has the highest resistance and stiffness followed by those of 6PR, 6BPG and 6PG, subsequently. It is obvious that the resistances of the piled rafts are much higher than those of the corresponding pile groups, and the resistances of the foundations are considerably improved by the inclusion of batter piles, in both types of piled raft and pile group.

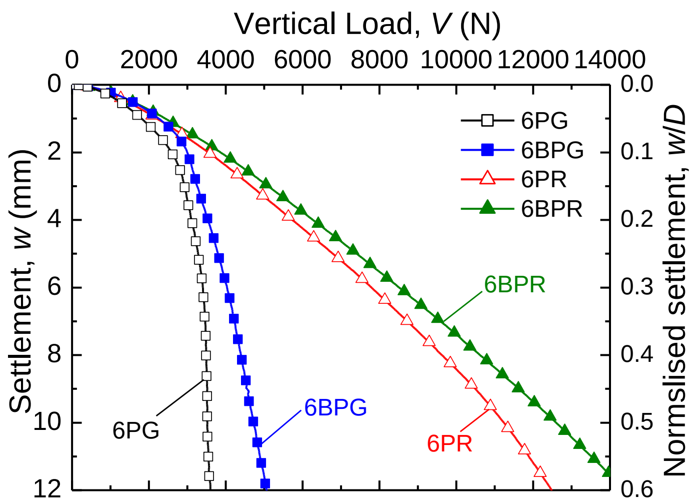


Figure 3.3. Load-settlement curves of the 6-pile foundations

3. Experimental study on behaviours of pile group and piled raft foundations having batter piles subjected to combination of vertical and cyclic horizontal load

3.1. Description of the experiments

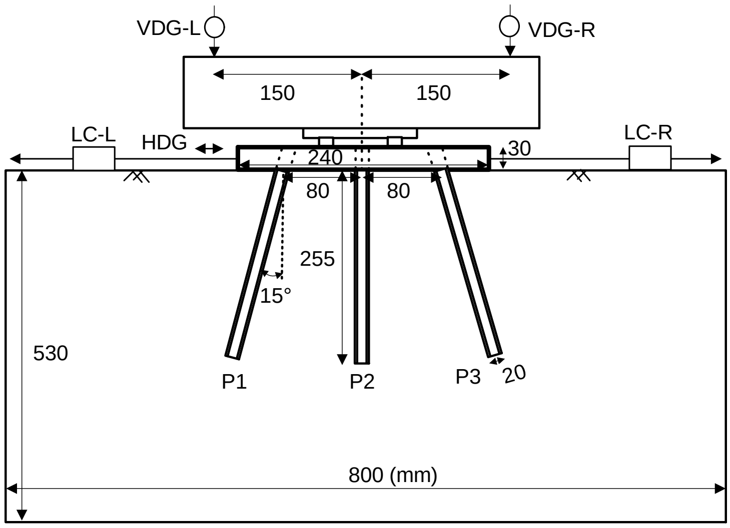


Figure 4.1. Schematic illustration of a horizontal load test

Figure 4.1 shows the schematic illustration of the experiment setup in a horizontal load test. A vertical load was applied by placing lead plates in order to simulate the dead weight of the superstructure. After that, the cyclic static horizontal load was applied at the raft in the longitudinal direction of the raft by means of winches and pulling wires (see Figure 4.2). Hence, the foundations would be subjected to a combination of vertical load and horizontal load during the horizontal loading stage.

3.2. Combination load tests on 3-pile pile foundations (3PG, 3BPG, 3PR and 3BPR)

Figure 4.3 shows the relationships between horizontal load, *H*, and normalised horizontal displacement, *u*/*D*, in the cases of 3PG, 3BPG, 3PR and 3BPR.

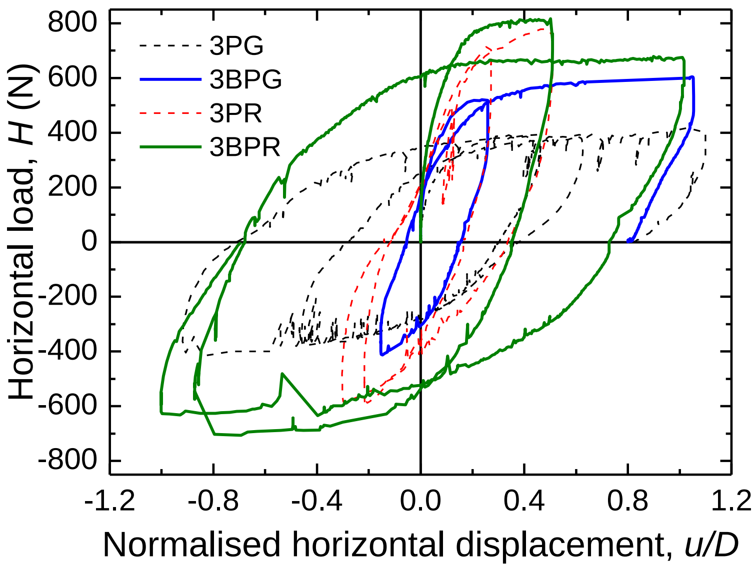


Figure 4.3. Horizontal load vs. normalised horizontal disp. for 3PG, 3BPG, 3PR and 3BPR

The results from Figure 4.3 indicate clearly that the piled rafts have much higher horizontal resistance and stiffness than the corresponding pile groups. It is also seen 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).

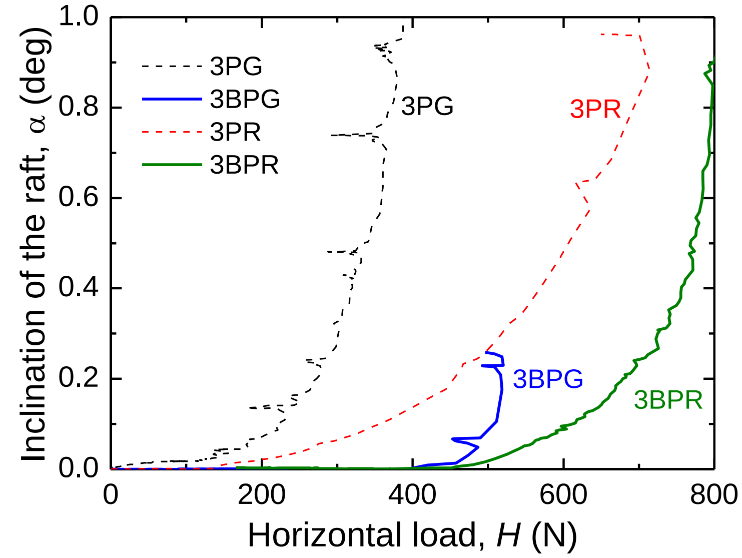


Figure 4.8. Inclination of the raft vs. horizontal load in the cases of 3PG, 3BPG, 3PR and 3BPR

Figure 4.8 shows the relationships of inclination of the raft, α, and horizontal load, *H*, in the cases of 3PG, 3BPG, 3PR and 3BPR. The results also show that the battered pile foundations (3BPG and 3BPR) are more favourable than the pile foundations with only vertical piles (3PG and 3PR) in reducing the raft inclination. Also, it is seen that 3BPR the most effective type to prevent the raft inclination at any horizontal load.

3.3. Combination load tests on 6-pile pile foundations (6PG, 6BPG, 6PR and 6BPR)

Figure 4.19 shows the relationships between horizontal load, *H*, and normalised horizontal displacement, *u*/*D*, in the cases of 6PG, 6BPG, 6PR and 6BPR.

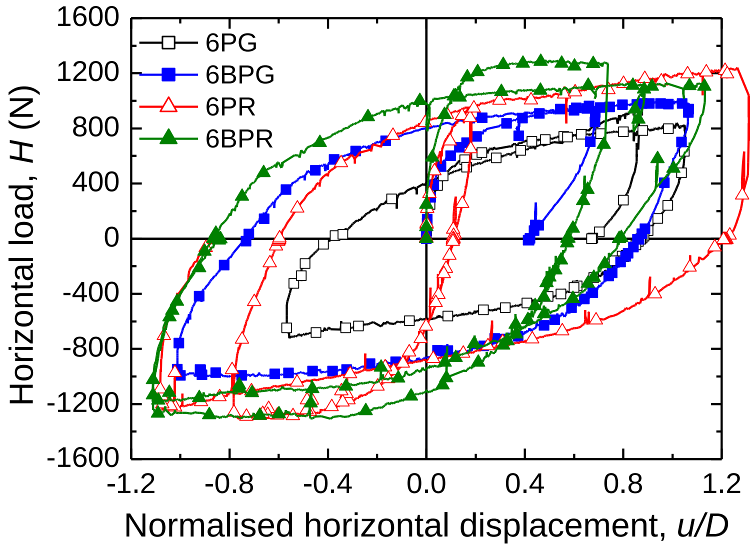


Figure 4.19. Horizontal load vs. normalised horizontal disp. for 6PG, 6BPG, 6PR and 6BPR

Similar to the results of the 3-pile foundation models, it is clearly seen that the 6-pile piled rafts have much higher horizontal resistances than the corresponding pile groups. Also, the resistances of the 6-pile foundations are effectively improved by the inclusion of batter piles in both cases of piled raft (BPR) and pile group (BPG).

Figure 4.21 shows the inclination of the raft against horizontal load during the initial loading stage for 6PG, 6BPG, 6PR and 6BPR.

The results indicate that the inclinations of the piled rafts are smaller than those of the corresponding pile groups at any given horizontal load. Also, the inclinations of the foundations with batter piles are smaller than those of the corresponding pile foundations without batter piles at any given horizontal load. It is worth to notice that the piled raft with batter piles is the most favourable foundation type to reduce the inclination.

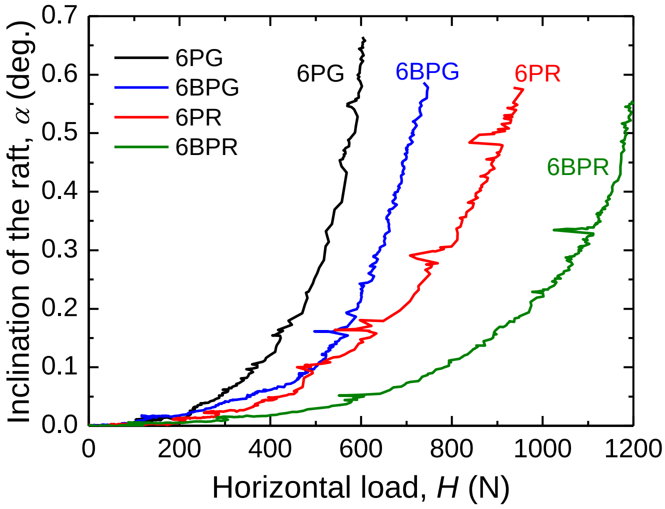


Figure 4.21. Inclination of the raft vs. horizontal load during the initial loading stage for 6-pile foundations (Experiment)

4. Numerical study on behaviours of pile group and piled raft foundation having batter piles subjected to vertical loading and combination of vertical and cyclic horizontal loading

4.1. FEM results of vertical load tests

Figure 5.4 shows measured and calculated load-settlement relationships in the cases of the 3-pile foundations (3PG, 3PR, 3BPG and 3PR). It is seen that the trends of measured load-settlement curves are simulated reasonably in FEM calculation, in which the piled rafts (3PR or 3BPR) have much higher resistance and stiffness than those of the corresponding pile groups (3PG or 3BPG) and the foundations with batter piles (3BPG or 3BPR) have higher resistance and stiffness than those of the corresponding foundations without batter piles (3PG or 3PR).

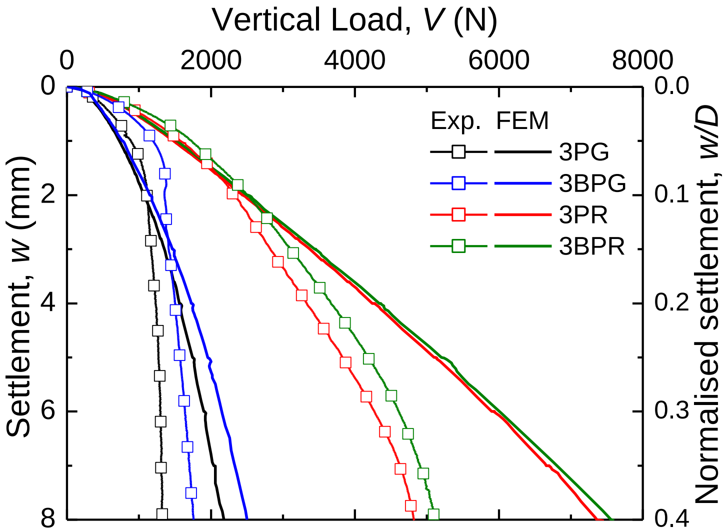


Figure 5.4. Load-settlement curves of the 3-pile foundations (FEM and Exp.)

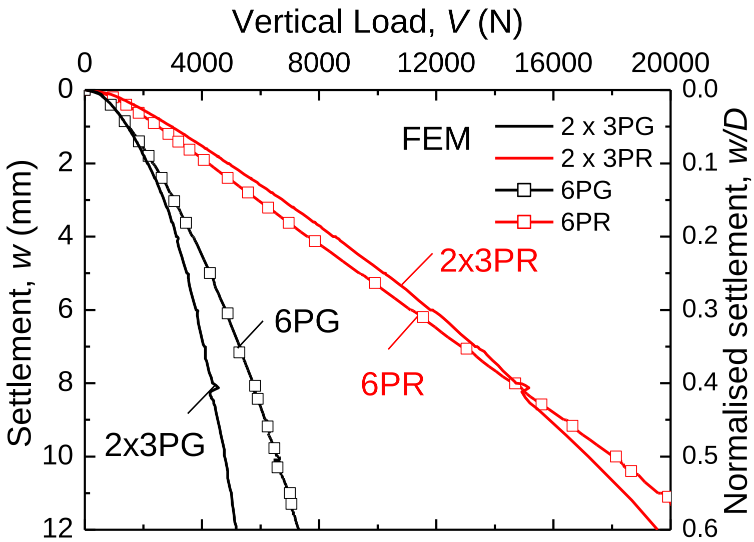
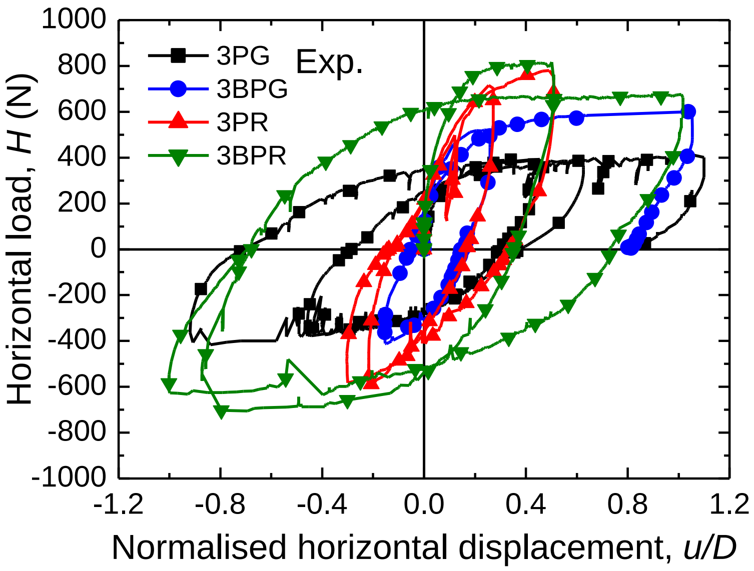


Figure 5.15. Vertical load vs. settlement in cases of 6PG, 6PR, 2×3PG and 2×3PR (FEM)

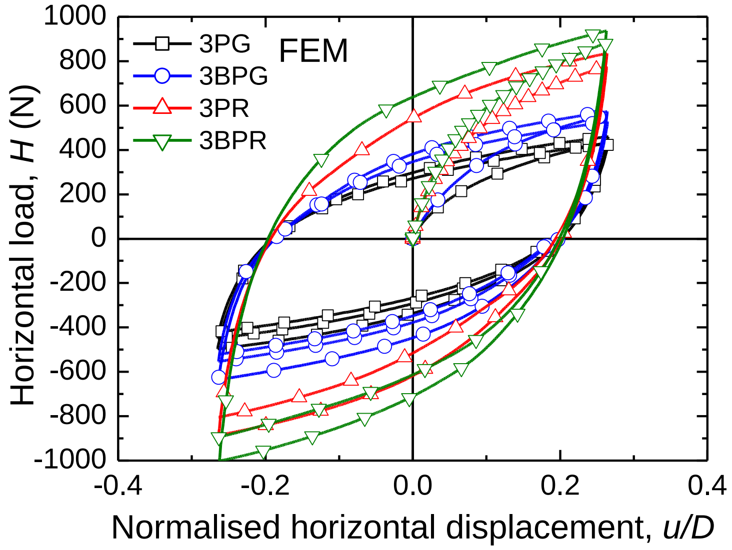
Figure 5.15 shows comparisons of vertical load-settlement curves between 6PG and 2×3PG, and between 6PR and 2×3PR. It is seen from the curves of the pile groups that the resistance of 6PG is the same with two times of the resistance of 3PG when normalised settlement, w/D, is smaller than 0.08. After that, the resistance of 6PG is considerably larger than that of 2×3PG. As for the piled rafts, the resistance of 6PR is smaller than that of 2×3PR until w/D reaches 0.40. After that, the resistance of 6PR is notably larger than that of 2×3PR. These FEM results are compatible with the experimental results although the softening behaviour of 2×3PR was not obtained in FEM analysis.

4.2. FEM results of combination load tests

Figure 5.19 shows the relationships of horizontal load, H, and normalised horizontal displacement, u/D, in the cases of the 3-pile foundations. Similarly to the experimental results, 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 the inclusion of batter piles in both cases of piled raft (BPR) and pile group (BPG).

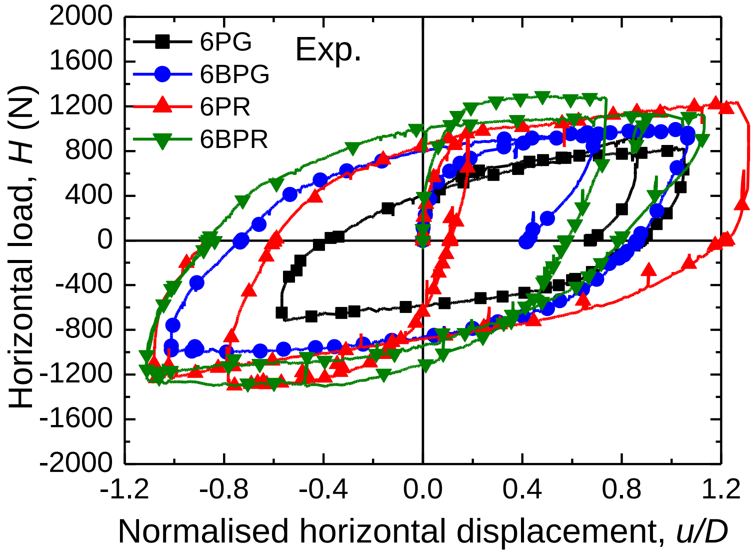


(a) Experimental results

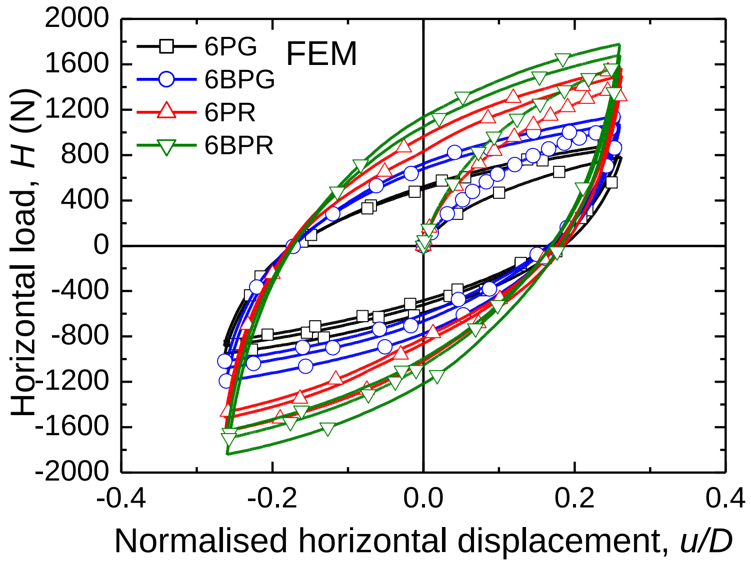


(b) FEM results

Figure 5.19. Horizontal load-nor. horizontal disp. for 3-pile foundations (Exp. and FEM)



(a) Experimental results



(b) FEM results

Figure 5.20. Horizontal load-nor. horizontal disp. for 6-pile foundations (Exp. and FEM)

Similar results are also obtained in cases of the 6-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 the inclusion of batter piles, as shown in Figure 5.20.

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

Figure 5.22 shows the inclination of the raft vs. horizontal load during the initial loading stage for 6-pile foundations. Also, the numerical results are completely compatible with the experimental results, indicating that the piled rafts have smaller inclination of raft than the corresponding pile groups, and the inclination is effectively reduced by inclusion of batter piles.

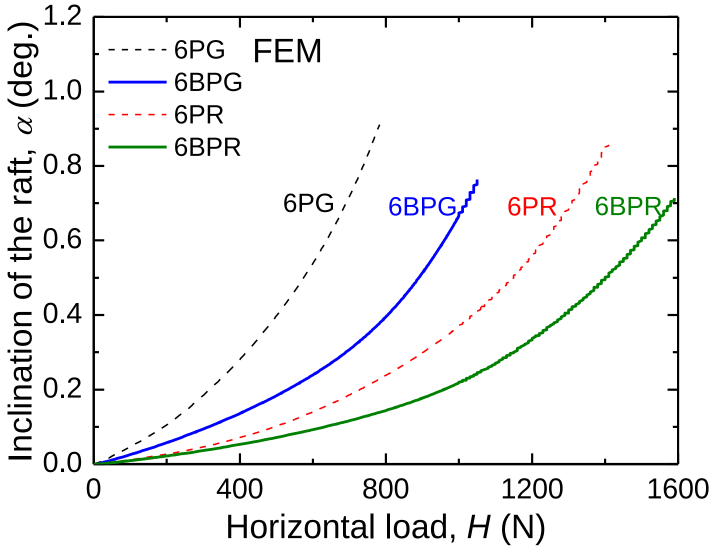
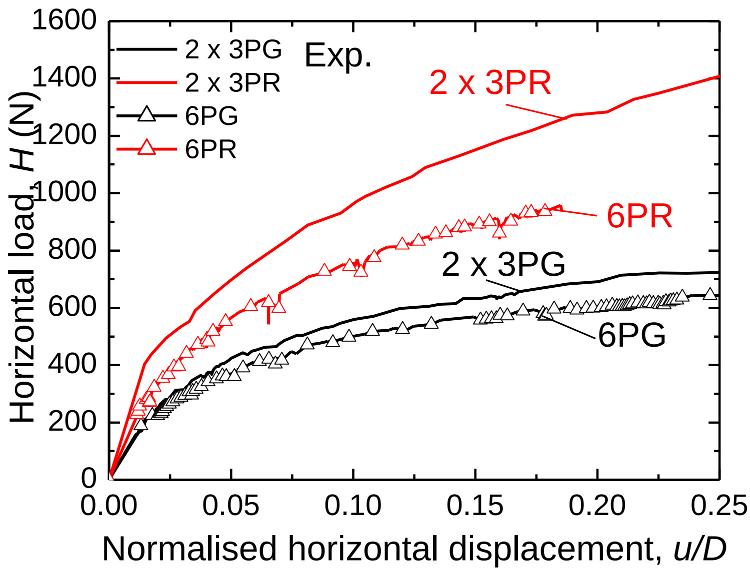
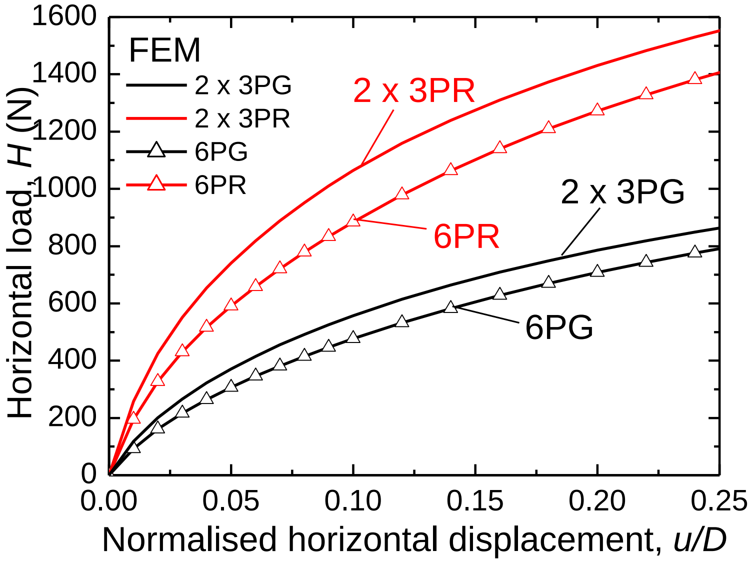


Figure 5.22. Inclination of the raft vs. horizontal load during the initial loading stage for 6-pile foundations (FEM)

Figure 5.32 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. 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). Obviously, the influence of interaction is indicated from the results.



(a) Experimental results



(b) FEM results

Figure 5.32. Horizontal load vs. normalised horizontal displacement for 6PG, 6PR, 2×3PG and 2×3PR (Exp. and FEM)

6. Conclusions of the thesis

The following conclusions and findings are derived:

1) The piled rafts have higher resistance and stiffness than the corresponding pile groups in both vertical and horizontal directions.

2) The pile foundations including pile groups and piled rafts with batter piles have higher resistance and stiffness than the foundations with only vertical piles in both vertical and horizontal directions.

3) Load pressure transferred from the raft base to the ground increase the stress level of the ground under the raft, resulting in increase of the stiffness and the strength of the soil, which enhances the pile resistance in the piled raft.

4) The inclination of the piled rafts due to horizontal loading is smaller than that of the corresponding pile groups.

5) The inclination of the foundations due to horizontal loading is considerably reduced by inclusion of batter piles in both cases of pile group and piled raft.

6) Larger axial forces generated in batter piles in cases of BPG or BPR compared with those in corresponding vertical piles in case of PG or PR enhance the horizontal resistance of BPG or BPR compared with PG or PR.

7) In the cases of the batter pile foundations subjected to horizontal load, larger bending moments are generated in the vertical centre piles compared with those in the batter piles.

8) The vertical and horizontal resistances of 6-pile foundations are not equal two times the vertical and horizontal resistances of corresponding 3-pile foundations, indicating influence of interaction. Hence, the influence of interaction of the raft, the piles and the soil is required to be considered in pile foundation design.

9) FEM using the hypoplastic model, of which parameters were estimated from triaxial tests of the sand, produced reasonable simulations.

平成~~27~~ 29年　2月　6日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Experimental and Numerical Study on Behaviours of Pile Group and Piled Raft Foundations Having Batter Piles Subjected to Combination of Vertical and Cyclic Horizontal Loading　（鉛直および繰返し水平載荷を受ける斜杭を有する群杭およびパイルド・ラフト基礎の挙動に関する実験的・解析的研究）

2．論文提出者　(1) 所　　属　環境デザイン学　　専攻

(2) 氏　　名（ふりがな）　Vu Anh Tuan（ぶぃ あん とうあん）

3．審査結果の要旨（600～650字）

本学位申請論文に対して，審査委員全員で口頭試問を行うとともに，平成２８年２月６日開催の口頭発表及び同日開催の審査委員会にて協議の結果，以下の通り判定した。

本研究は，波力，風力などの繰返し水平載荷を受ける群杭基礎およびパイルド・ラフト基礎の挙動のメカニズムの解明とその解析（設計）手法に関する研究である。研究内容は，模型載荷実験とそれらのＦＥＭ解析から構成されている。群杭基礎およびパイルド・ラフト基礎模型に対し，鉛直載荷試験，一定の鉛直載荷を与えた条件での一連の繰返し水平載荷実験を実施した。実験では，杭の本数，斜杭の有無などが基礎構造物の挙動に及ぼす影響を詳細に調べた。特に，斜杭の導入が，基礎構造物の鉛直，水平，回転抵抗性能改善に効率的であることを示した。この効果は，パイルド・ラフト基礎において，より顕著であることを示した。使用した砂試料の三軸試験から得られた砂の力学パラメータを用い，実験の３次元ＦＥＭ解析を実施し，実験結果を高い精度で再現した。実験と解析結果から種々のタイプの杭基礎の抵抗メカニズムを，これまでの研究に比べて，より詳細に説明した。研究は，静的荷重を受ける場合に限られたが，今後，本研究の成果は，地震力のような動的載荷を受けた場合の杭基礎構造物の解明につながるものである。

博士論文の内容は，４編の英文学術雑誌論文として発表されている。口頭発表における質疑からも，Vu Anh Tuan 氏の理解力，研究能力は非常に高いものと判断できた。

4．審査結果　(1) 判　　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（工学）