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Behaviour of three types of model pile foundation under vertical and horizontal loading

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ABSTRACT: In recent years, efficient installation methods of piles have been developed. A target in this research is to show a possibility to use steel sheet piles for permanent pile foundations, because time and cost of construction for sheet piles could be lower than those for pipe piles. In this study, a series of experiments were conducted to investigate the load transfer behaviours of model foundations supported by three different types of piles in dry sand ground subjected to vertical and horizontal loading. According to experiment results, PPF (Plate Pile Foundation) can carry almost the same loads with OPF (Open-ended pipe pile foundation) and larger loads than those of BPF (Box pile foundation) under both vertical and horizontal conditions. Hence, sheet pile foundation would be a promising alternative to conventional round pipe pile foundation, especially in high-seismic areas where foundations will experience both vertical and horizontal loading.

1 INTRODUCTION

In recent years, efficient installation methods of piles have been developed (e.g. IPA, 2016; Proc. of the 1st Int. Conf. on Press-in Eng., 2018). Nowadays, a challenge in piling engineering is to reduce costs including transportation and construction costs, and at the same time keep safety of foundation structures. Hence, a target in this research is to show a possibility to use steel sheet piles for pile foundations of permanent structures, because time and cost of construction of sheet piles could be lower than those of steel pipe piles.

In this study, a series of experiments were conducted to investigate the load transfer behaviours of model foundations supported by open-ended pipe piles, plate piles, or square box pile in dry sand ground subjected to vertical and horizontal loading. Load-displacement relationships and load sharing between the raft and the piles of three types of foundations during vertical loading and horizontal loading are presented and discussed.

2 EXPERIMENT DESCRIPTION

2.1 *Model ground*

The sand used as model ground was Silica sand #6. Table 1 shows the physical properties of the sand. The model ground was prepared in a rectangular box with dimensions of 500 mm in width × 800 mm in length × 530 mm in height. The model ground was prepared with 10 layers of 50 mm thick and one top layer of 30 mm thick. The sand of each layer was poured into the soil box and compacted by hand tamping to get a target relative density, D_r = 82% (ρ_d = 1.533 ton/m^3).

2.2 *Model foundations*

The model piles used in all experiments were made of aluminium round pipes, plates representing sheet piles or square box pipe. Three different types of model pile foundations were used in the experiments, as shown in Figure 1. The first one is

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Table 1. Physical properties of Silica sand #6 (after Vu et al, 2018).

Property	Value
Soil particle density, ρ_s (ton/m^3)	2.679
Minimum dry density, ρ_{dmin} (ton/m^3)	1.268
Maximum dry density, ρ_{dmax} (ton/m^3)	1.604
Maximum void ratio, e_{max}	1.089
Minimum void ratio, e_{min}	0.652
Model ground relative density, D_r (%)	82.5
Model ground density ρ_d (ton/m^3)	1.533

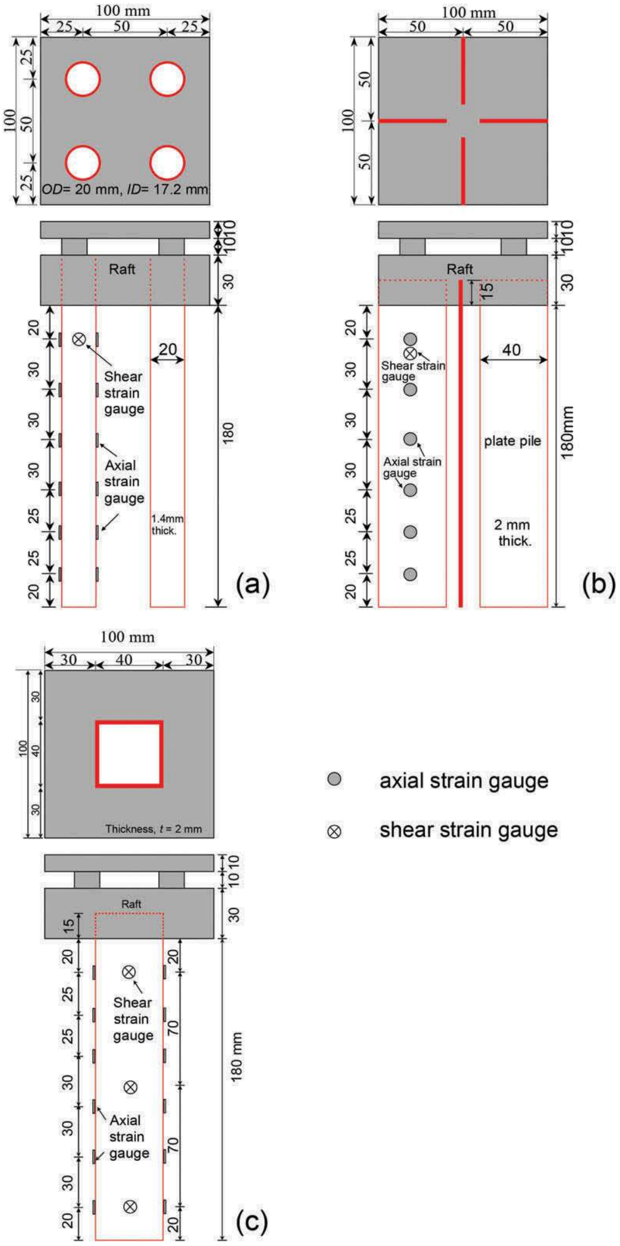


Figure 1. Model pile foundations: (a) Pipe pile foundation; (b) Plate pile foundation; (c) Box pile foundation.

a foundation supported by open-ended pipe piles with an outer diameter of 20 mm, an inner diameter of 17.2 mm, a wall thickness of 1.4 mm and a length of 210 mm (called OPF, Figure 1a). The 2nd is a foundation supported by plate piles with a width of 40 mm, a length of 195 mm and a thickness of 2 mm (called PPF, Figure 1b). The 3rd is the one supported by square box pile with a width of 40 mm, a length of 195 mm and a thickness of 2 mm (called BPF, Figure 1c). The geometrical and mechanical properties of the model piles are listed in Table 2.

It was intended to use the same volume of pile material for the three model foundations with the same length. Note that one BP was used, while 4 OPs or 4PPs were used. Hence, the total volume of piles of each foundation was almost same, as shown in Table 2.

Fourteen strain gauges were attached on opposite sides of each pile of PP and OP. And eighteen strain gauges were attached on sides of BP.

The model square raft had a side length of 100 mm and a thickness of 30 mm, as shown in Figure 1. Pile heads were rigidly connected to the raft in all the foundations.

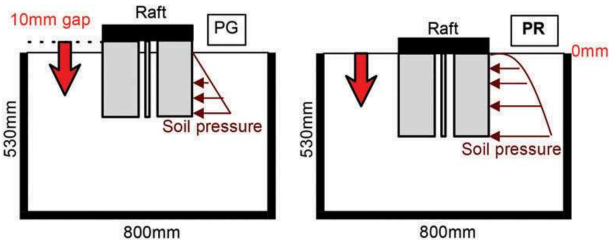
2.3 *Experimental procedure*

For each model foundation, two cases were carried out. The first case was aimed to obtain the penetration resistance during PPT (Pile Penetration Test) and the bearing capacity of the foundation in VLT (Vertical Load Test). The second case was mainly aimed to obtain the performance of the foundation subjected to horizontal loading. In the 2nd case, HLT (Horizontal Load Test) was carried out after PPT.

In PPT, the foundation was penetrated in the model ground using a screw jack (Figure 4a) until the pile embedment length reached 170 mm. After that, in the 1st case, vertical load test (VLT) was conducted with the raft base being untouched to the ground surface (called PG stage or PG condition, PG: Pile group) as shown in Figure 2. After the raft base touched the ground surface (called PR stage or PR condition, PR: Pile raft), VLT was again conducted. In the 2nd case, after the raft base touched the ground surface, the vertical load by screw jack was unloaded. HLT was carried out immediately after PPT. A death

Table 2. Properties of model piles.

	OP	PP	BP
Length from raft base, L (mm)	180	180	180
Cross sectional area, A (mm)	81.8	80	304
Wall thickness, t (mm)	1.4	2	2
Young's modulus, E (GPa)	71.3	69.5	75.6
Poisson's ratio, v	0.343	0.297	0.356
Bending rigidity, EI (MNmm^2)	253.7	1.85	5546.1
Bending rigidity, EI (MNmm^2) (strong axis)	—	742	—



(a) Pile Group (PG) (b) Pile Raft (PR)

Figure 2. Illustrations of load tests of PG and PR.

weight of 1000 N was placed on the foundation prior to the start of HLT, as shown in Figure 4 (b).

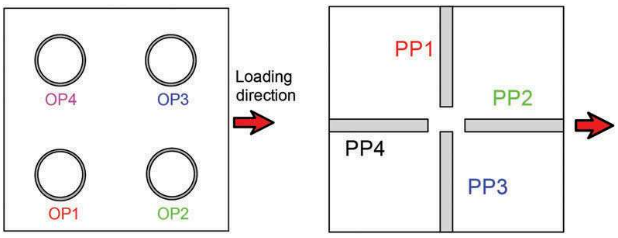
Locations of open-ended pipe piles and plate piles are shown in Figure 3. In OPF, OP2 and OP3 are "front pile" while OP1 and OP4 are "back pile". In PPF, PP2 is called "front pile", PP1 and PP3 are called "middle pile", and PP4 is called "back pile".

A total of 6 experiments were carried out. After the completion of each experiment, cone penetration tests (CPTs) were conducted in the model ground. The cone used in CPTs had a diameter of 20.5 mm and an apex angle of 60 degrees. The diameter of the cone was similar with that of the model pipe pile.

2.4 *Measurement*

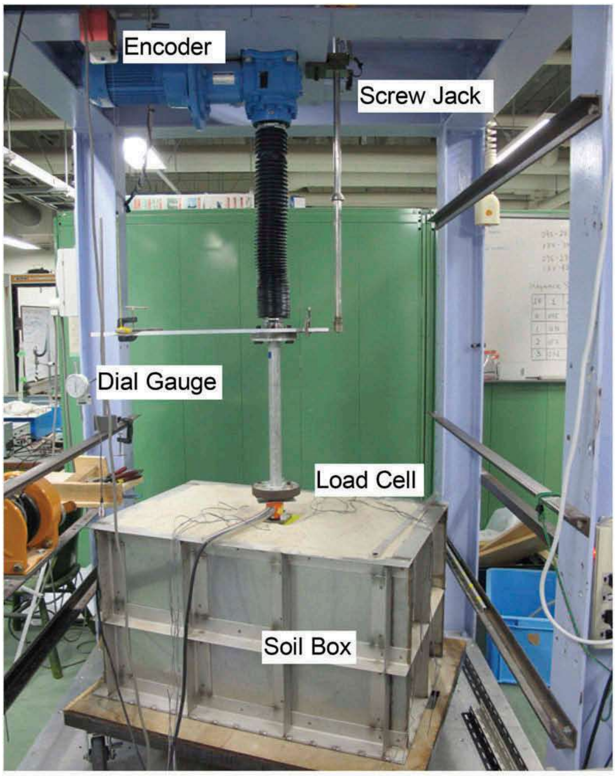
During the load test, the horizontal load applied to the foundation was measured by means of a load cell attached between the raft and the winch. Horizontal displacement and vertical displacements of the raft were measured by means of dial gauges (Figure 4b). And the inclination of the raft was obtained from an inclinometer. Axial forces and bending moments of the model piles were estimated from the measured axial strains, and the horizontal load of each pile was estimated from the shear strain gauges (cross-gauges) near the pile top.

In HLT, distribution of horizontal displacements along the pile shaft was calculated from the measured distribution of bending moments, the horizontal displacement at the loading point and the raft inclination. It is noticed that the inclination of the pile top was equal to the raft inclination as the piles were rigidly connected to the rigid raft. Unfortunately, some data of BPF was not obtained due to a technical problem.

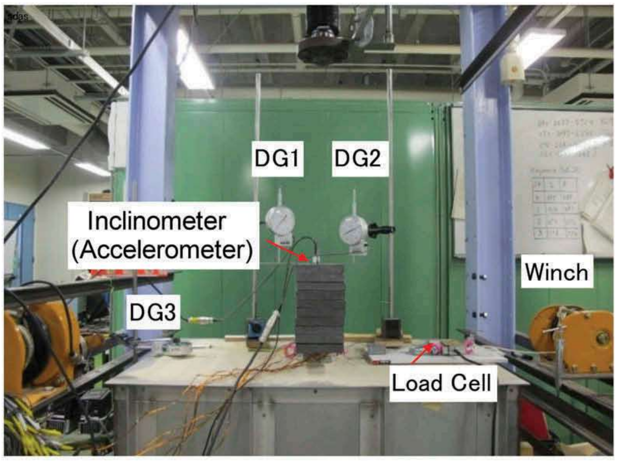


(a) OPF (b) PPF

Figure 3. Locations of piles in two foundations (top view).



(a) VLT



(b) HLT with a constant vertical load of 1000 N

Figure 4. Experimental set-up.

3 EXPERIMENT RESULTS

3.1 *Results of CPTs*

Figure 5 shows the locations of CPTs. As shown in Figure 6, CPT tip resistant q_c increased almost linearly with depth from the ground level. And, distributions of q_c with depth are almost uniform among the cases. That is, all the experiments were conducted under the same ground condition.

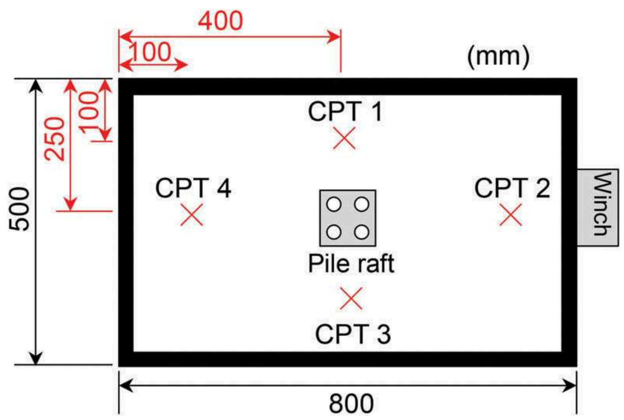


Figure 5. Location of CPTs.

3.2 *Results of PPT and VLT*

Figure 7 shows the relationships of the vertical load *P* and the settlement *w* of three model foundations during the PPT and VLT in the first cases. The results show that the load of open-ended pipe piles is around two times that of plate piles in the PPT and PG stages. However, in the PR stage, the loads of OP and PP are almost the same. This will be discussed in detail later.

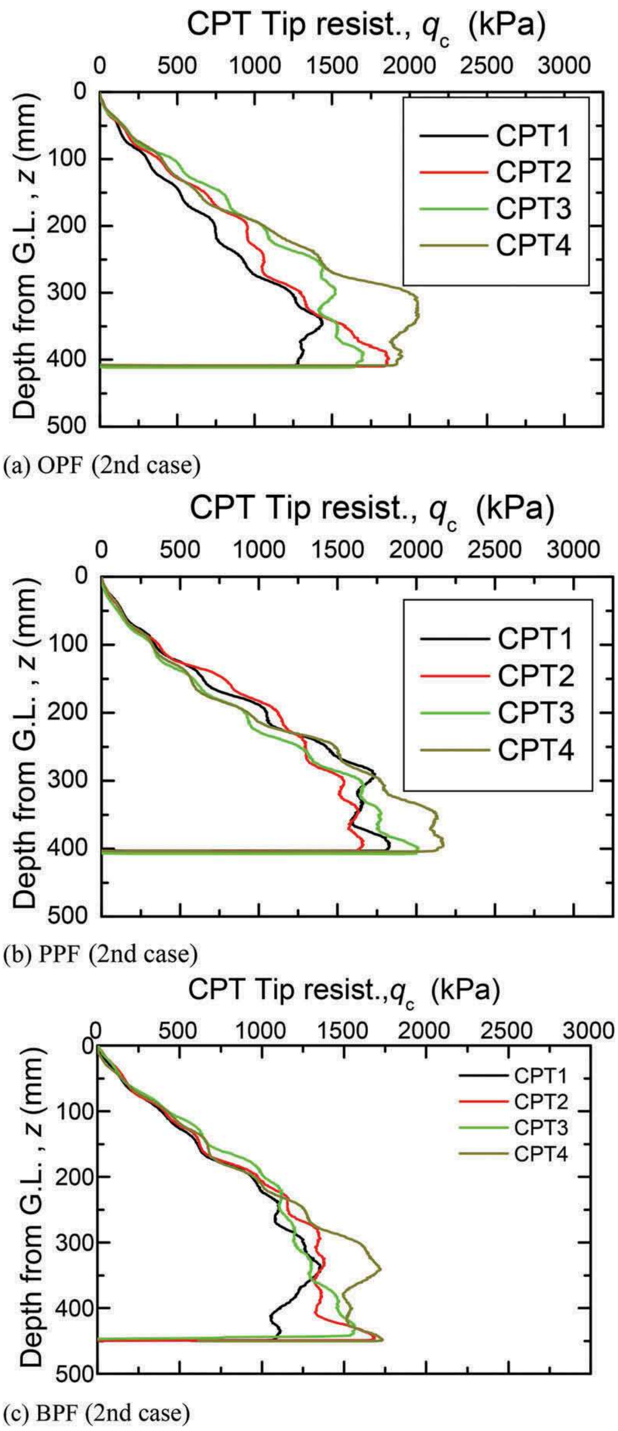
3.3 *Results of VLT on PG and PR*

Figure 8 shows comparisons of vertical load-settlement relationships of the foundations in stages of PG and PR. The loads of piles were calculated from axial strain gauges. The loads carried by 4 OPs, 4 PPs and BP are also shown by the dashed lines. The difference between the total load and the pile load is the load carried by the raft. Note that touch down level of each foundation is different. It was intended to leave a gap about 10 mm between the raft and the soil surface after the end of the PPT. However, due to the limited precision of the instrument, there was a difference about 3 mm of the gap between three types of foundation prior to the start of VLT. The vertical displacement, *w*, was zeroed at the start of VLT in Figure 8.

In the PG condition, of course, the load carried by piles was almost equal to the total load. The load of OPs was around two times that of PPs and 1.5 times that of BP.

In the PR condition, the total loads of the foundations increased rapidly when the experimental stage turned to PR condition after the raft base touched the ground surface. It is interesting to notice that the loads of 4 OPs, 4 PPs and BP continued to increase in PR condition. However, the load of 4 PPs increased significantly faster than that of 4 OPs or BP. The load of 4 PPs is only around 1000 N in the PG condition, while in the PR condition, this value became about 2.5 times when the settlement of the foundation reached about 27 mm.

A possible reason for this result is as follows. In the PR condition, because a part of vertical load is



(a) OPF (2nd case)

(b) PPF (2nd case)

(c) BPF (2nd case)

Figure 6. Results of CPTs in model ground.

transferred to the ground through the raft base, stress levels in the soil surrounding the piles increase. Hence, the unit shaft resistance of the piles in PR condition increases compared to that in PG condition. Moreover, since the shaft area of PPs is the largest among the three model foundations, the increase in the shaft resistance (= the unit shaft resistance × the shaft area) of PPs is greater than that of OPs and BP in PR stage. As a result, the load carried by 4 PPs increased significantly faster than that carried by 4 OPs and BP under PR condition.

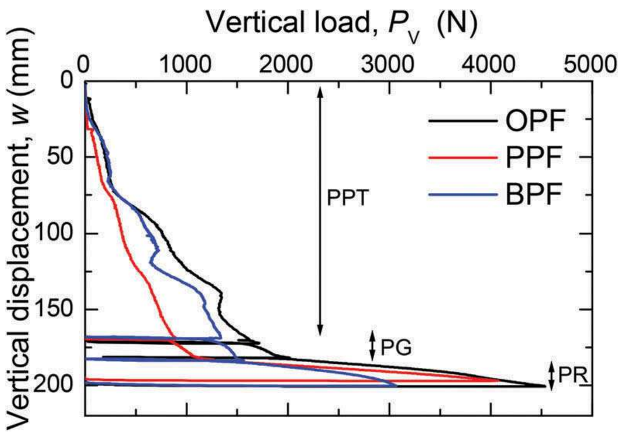


Figure 7. Load-settlement relations of foundations.

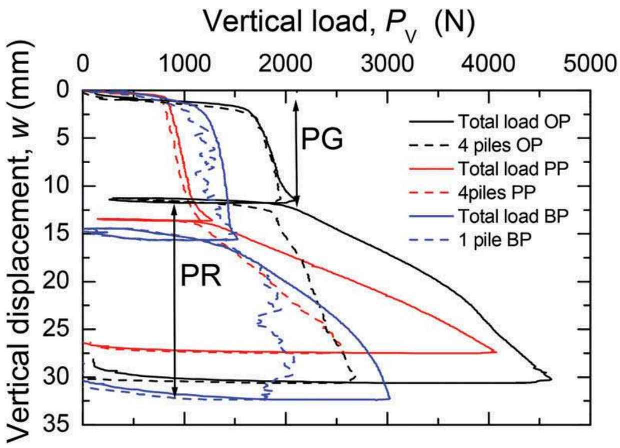


Figure 8. Load-settlement curves of foundations.

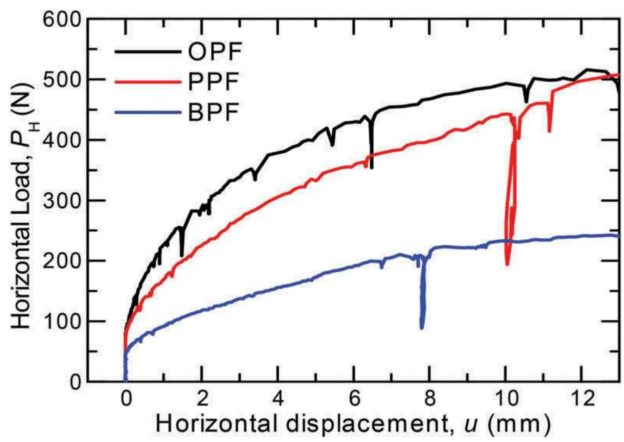


Figure 9. Horizontal displacement vs. displacement load.

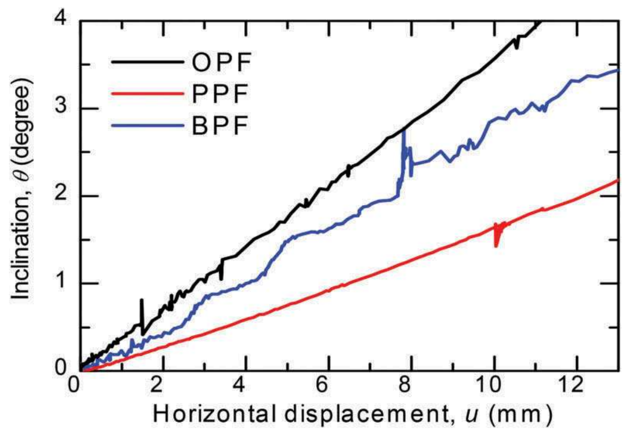


Figure 10. Horizontal displacement vs. inclination.

3.4 *Results of HLT*

3.4.1 *Horizontal load vs. horizontal displacement*

HLT with a constant vertical load of 1000 N was conducted after the raft base touched the ground surface. When 1000 N was applied on the raft prior to HLT, almost 100%, 93% and 94% of the vertical load was supported by piles in OPF, PPF and BPF, respectively.

Figure 9 shows horizontal load P_H vs. horizontal displacement u of OPF, PPF and BPF. It can be clearly seen from the figure that P_H of OPF is larger than that of PPF and BPF, and reached peak at u = 12 mm. On the other hand, PPF carried the almost same horizontal load with OPF after u reached 12 mm and kept increasing. Among three model foundations, the load of BPF was smallest.

3.4.2 *Inclination of raft*

Figure 10 shows horizontal displacement u vs. inclination θ of the raft in cases of OPF, PPF and BPF. It can be seen that the inclination of the raft in PPF is much smaller than that in OPF and BPF. It is thought that a high value of bending rigidity EI of PP2 and PP4 (strong axis, see Table 2 and Figure 3) contributes to supressing the inclination. Another reason is considered that even the bending rigidity EI of the whole (four) PPs including two PPs in weak axis and another two PPs in strong axis is smaller than that of BP, the greater distance between the front and the back edges of PPs can also contribute to preventing the foundation from rotating, as shown in Figure 3.

3.4.3 *Axial force on each pile*

Figure 11 shows the changes of the axial force ΔF_a on each pile during HLT. In both cases of OPF and

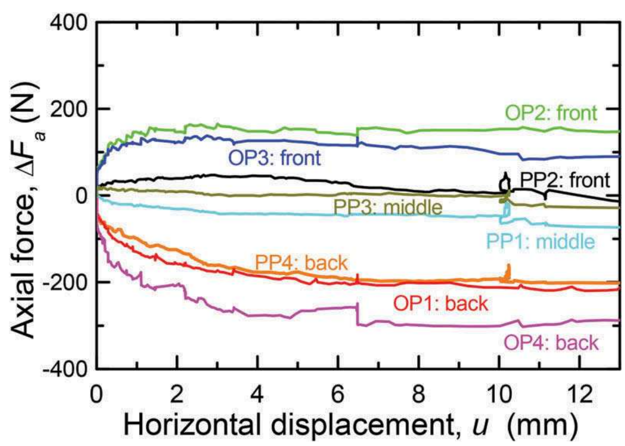


Figure 11. Axial force on each pile during HLT.

PPF, compression forces were generated on the front piles (OP2, OP3, PP2), while tension forces were generated on the back piles (OP1, OP4, PP4). The compression force of PP2 was smaller than that of OP2 and OP3, while the tension force of PP4 was almost equal to that of OP1. It is noticed that ΔF_a of the middle piles in PPF (PP1 and PP3) remained almost unchanged.

3.4.4 *Horizontal load sharing*

Figure 12 shows the relationship between horizontal displacement u and horizontal resistances between different piles in OPF, PPF and BPF. As for PP2 and PP4, the shear force near the pile head was estimated from the cross-gauges near the pile head (see Figure 1). However, since the cross-gauges of PP4 were damaged during HLT, the data of shear force in PP4 is not available.

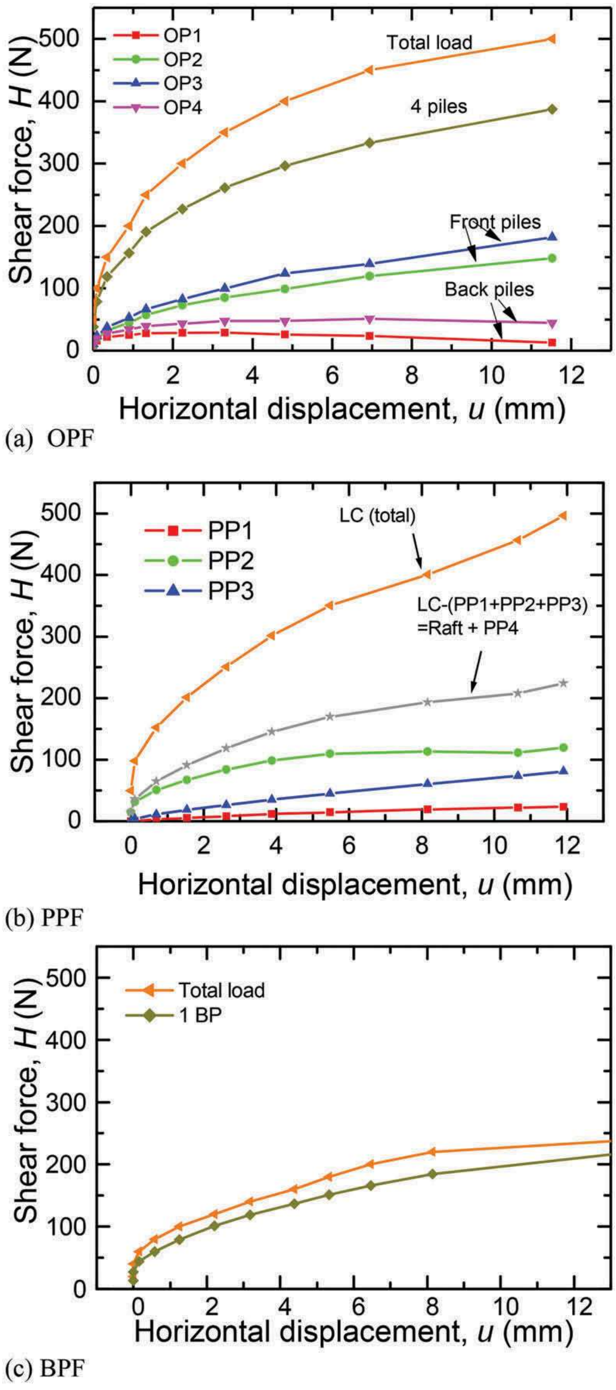


Figure 12. Horizontal resistance vs. horizontal displacement.

In OPF (Figure 12a), four OPs carried around 80% of the total horizontal load. It is clearly seen that the front piles (OP2 and OP3) carried larger horizontal resistance than the back piles (OP1 and OP4). It is interesting that the horizontal resistance of the front piles (OP2 and OP3) continued to increase with increasing u, while the horizontal resistance of the back piles (OP1 and OP4) showed a softening behaviour.

One mechanism for the smaller horizontal resistance of the back piles would be the existence of the front piles. This may be related to larger inclination of OPF (see Figure 10). The soil in front of the foundation was compressed during the HLT, and the horizontal earth pressure on the front OPs increased. On the other hand, because of the inclination of OPF, the earth pressure on the back OPs decreased, and the shear forces of the back OPs increased slightly and then decreased gradually. As a result, there is a larger difference of the horizontal resistance between the front OPs and the back OPs, as pointed out by e.g. Horikoshi et al. (2003) and Vu et al (2018).

In addition, the bending moment distributions of different piles in the same pile group is also different (see Figure 13). Although the pile head displacement of front OPs is the same as that of the back OPs (see Figure 14), the change of bending moment of the front OPs is more obious and the peak bending moment is higher. As a result, they are more likely to suffer damage.

In PPF (Figure 12b), the front pile (PP2) carried larger horizontal resistance than the middle piles (PP1 and PP3). Since the width (thickness) of PP2 in the loading direction is only 2 mm, the horizontal resistance of PP2 is mainly the friction resistance acting on two side walls. The behavior of the PP4 might be similar to the PP2, although the horizontal resistance was not obtained due to the damage of the cross-strain gauges.

In BPF (Figure 12c), BP carried around 85% of the total horizontal load.

3.4.5 *Bending moments in piles*

Figure 13 shows the distributions of bending moment in piles for three types of foundations. It was difficult to obtain bending moments in PP2 and PP4 in PPF, because of very large bending stiffness of these piles in strong axis. Unfortunately, strain data of BPF deeper than 80 mm was not obtained due to a technical problem.

When the horizontal load reached 500 N, the maximum bending moment of PP3 is about 1/3 of that of OP3, as shown in Figure 13(b) and (f). However, the bending stress in PP3 is much larger than that of OP2, because EI of PP (weak axis) is only 1/135 of that of OP (Table 2).

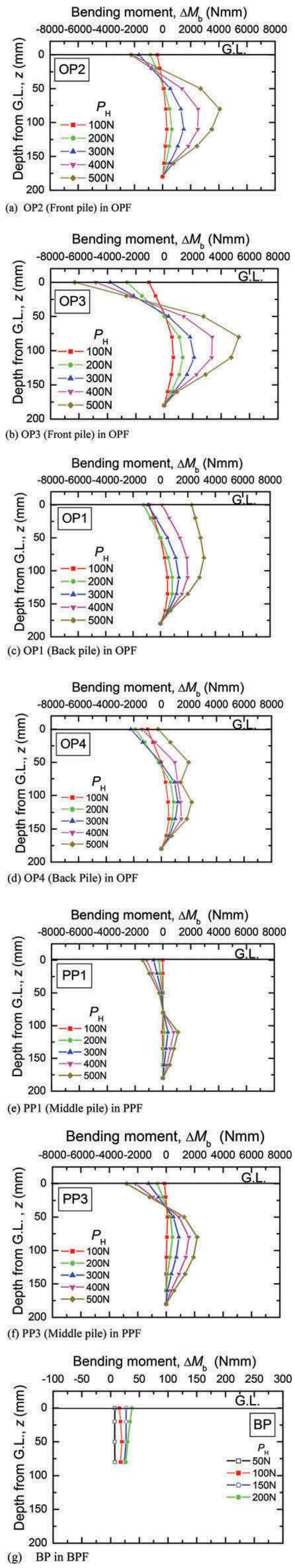


Figure 13. Distribution of bending moment of piles.

Under the horizontal loading condition, the performance of PP is better than that of OP.

As shown in Figure 13(g), the bending moment of BP is much smaller than that of OPs and PPs at the same horizontal load level. To explain this phenomena, further study is necessary.

3.4.6 *Horizontal displacements of piles*

Figure 14 shows the distributions of horizontal displacements of the piles with depth for different P_H. Local horizontal displacements were estimated from the measured bending moments, pile head displacement, and inclination of the pile head.

In general, the horizontal displacement of the PP head is greater than that of OP head especially for P_H less than 500 N. It is seen that OPs exhibited a behaviour of so-called "short pile".

And, the bending deformation of PP was also larger than that of OP, which is reasonable because OP had very large *EI* compared with PP. The local horizontal displacement of BP decreases significantly with increase in z, compared with that of PPs and OPs at the same horizontal load level (P_H = 150 N, 200 N).

3.4.7 *Shear forces in piles*

Figure 15 shows the distributions of shear forces in piles. The shear forces of OPs and PPs were estimated from the measured bending moments. The shear force of BP was obtained directly from the shear strain gauges.

From Figures 15(a) to (d), the shear forces in OPs changed the direction at a depth z of about 90 mm from ground level. The largest shear forces along OP2 and OP3 occurred at z = 35 mm and 145 mm. On the other hand, the shear forces along OP1 and OP4 showed a little difference at different levels.

The horizontal resistance of each pile is almost equal to the shear force near the pile head. It is clearly seen that the front piles (OP2 and OP3) carried significantly larger horizontal resistance than the back piles (OP1 and OP4) in OPF. Moreover, as shown in Figure 12, front pile (PP2) carried larger horizontal resistance than the middle piles (PP1 and PP3) in PPF, but when u exceeded 6 mm, the horizontal resistance of PP2 levelled off at 100 N. In contrast, the horizontal resistance of middle piles (PP1 and PP3) continued to increase even after u exceeded 6 mm. Although the middle piles in PPF had a larger width in the horizontal loading direction, it carried less horizontal resistance than the front piles in OPF.

The trend of shear force distribution of BP in BPF (Figure 15g) is similar to that of the front OPs in OPF (Figure 15a and b). During HLT, BP in BPF carried about 85% of the horizontal load (Figure 15g). This result can be found also in Figure 12.

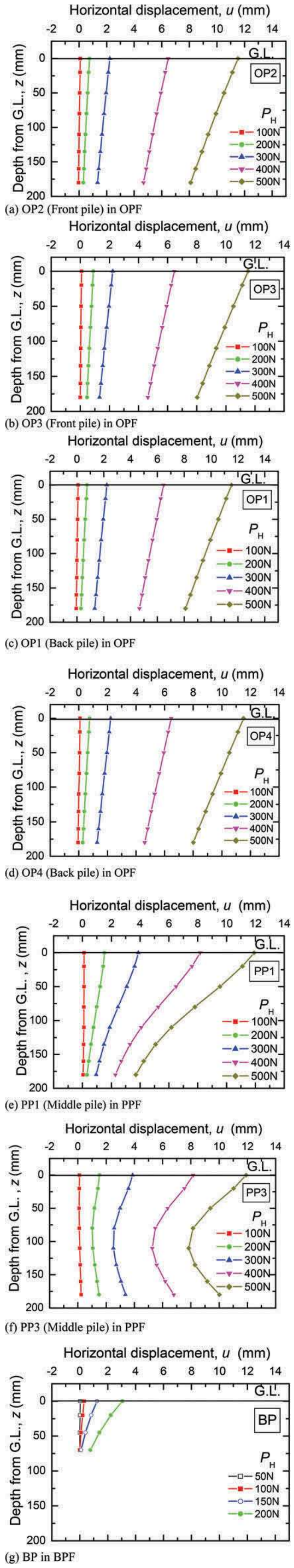


Figure 14. Horizontal displacement of each piles during HLT.

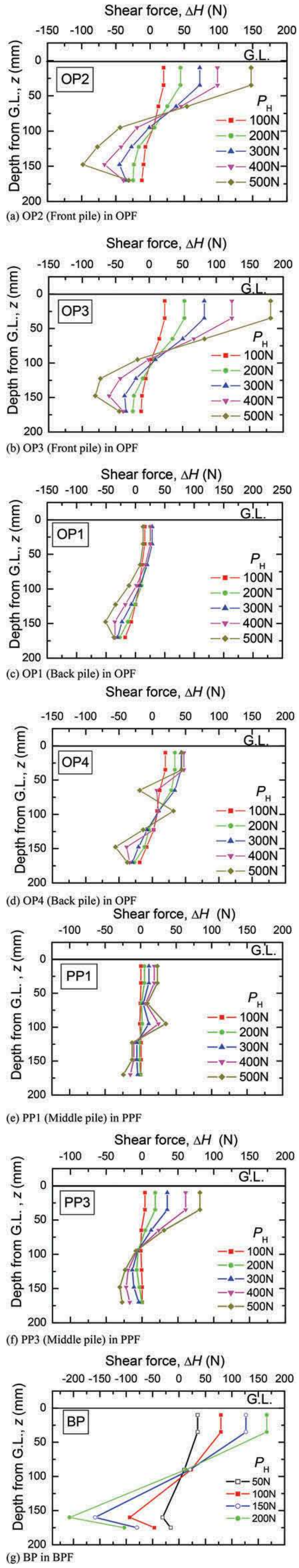


Figure 15. Distribution of shear forces in piles.

4 CONCLUDING REMARKS

In this research, a series of model experiments were conducted to explore the load transfer behaviours of pile foundations supported by OPs, PPs or BP in dry sand ground subjected to vertical and horizontal loading.

Interesting findings from this experimental study are as follows:

(1) In case of vertical loading, the vertical resistance of OPs was around two times that of PPs and 1.5 times that of BP in PG condition.

(2) In vertical loading under PR condition, the vertical load of PPF increased faster than other two model foundations. The reason is considered that the shaft resistance of the piles under PR condition increases with the increase in soil pressure transferred from the raft base. And increase of the shaft resistance of PP is larger than that of OP and BP in PR condition, due to larger shaft area of PP.

(3) In case of horizontal loading, the horizontal resistance of BPF is the smallest among three model foundations. P_H of PPF tended to increase continuously, and PPF carried the almost same horizontal load as OPF after u reached 12 mm. Moreover, the inclination of raft in PPF is smaller than that in OPF and BPF.

(4) Under horizontal loading, the front OPs carries larger horizontal resistance than the back OPs. And the front PP (PP2) carried larger horizontal resistance than the middle PPs (PP1 and PP3).

In summary, PPF can carry almost the same load as OPF under both vertical and horizontal loading conditions. It should be noted that the time and cost of construction for sheet piles are lower than those for pipe piles. Sheet pile foundation would be a promising alternative to conventional round pipe pile foundation, especially in high-seismic areas where foundations will experience both vertical and horizontal loading.

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