Effect of pile spacing on the behaviours of pile, pile group and piled raft models supported by jack-in piles under vertical loads in dry sand

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ABSTRACT

In this study, the behaviours of jacked piles, pile groups and piled rafts supported by jack-in piles were investigated by experiments. Focus was given on the effects of sequence of pile installation and pile spacing on performance of the piles and the pile foundations. Model ground was dry silica sand of a dense state. Model foundations consisted of a square raft and 4 piles with centre-to-centre pile spacing, *s*, equal to 3.5*D* or 6.5*D* (*D*: pile diameter). In the experiments, 4 piles were jacked into ground one by one, thereafter the raft was placed on the top of the 4 piles and vertical loading was conducted. The raft of the foundation was not in contact with the ground surface until it settled by around 6 mm. After the raft touched the ground surface, the foundation turned from pile group condition to piled raft condition. The experimental results show that the pile jacked later had higher resistance during jacking process and higher performance in static load tests; the piles in piled rafts had higher resistance than those in pile groups. The piles in 3.5*D* group (narrower pile spacing) have higher resistances than the corresponding piles in 6.5*D* case. Higher bearing capacity, smaller settlement and larger pile axial forces were found in piled rafts, in comparison to the corresponding pile groups, because the load transfer from the raft base to the ground, which increases stresses and stiffness of soil surrounding the piles.

Keywords: pile group; piled raft; experiment; sand ground; jack-in piles; vertical loading

1 INTRODUCTION

Pile foundations (PFs) including pile group foundations (PGs) and piled raft foundations (PRs) have been worldwide applied to support heavy structures, although the use of PGs is still more popular. Behaviours of PGs and PRs in sand have been investigated in many researches. Physical modelling of piled rafts in dry sand subjected to vertical loads were carried out (e.g., Unsever et al. 2014; Patil et al. 2014; Vu et al. 2017). In these experiments, model piles were first prepared in soil boxes and then sand was poured around the model piles. Therefore, basically, there was no influence between piles when they were prepared in the soil boxes, and each pile would have had similar performance when it is vertically loaded in an isolated manner, regardless of pile spacing and order of pile installation.

However, if displacement piles, such as jack-in or driven piles, are used for a PF, performance of each pile may differ from each other according to pile-spacing and order of pile installation.

Hence, one of objectives in this paper is to study effects of sequence of pile installation and pile spacing on behaviours of pile alone, and PGs and PRs supported by jack-in piles in dry sand ground.

2 OUTLINE OF THE EXPERIMENTS

2.1 Model ground

In the experiments, dry Silica sand #6 was used for model grounds and its properties are showed in Table 1. Soil box was a cylindrical chamber with 580 mm in height and 566 mm in diameter

To prepare the model ground, the sand was poured inside the soil chamber and compacted by 12 thin layers until it reached a target relative density, D_r, of 81% (ρ_d = 1.53 Mg/m^3). Cone penetration tests (CPTs) were carried out in each model ground to check the uniformity of the model ground. An example of the CPT results is shown in Fig. 1. It is seen from Fig. 1 that cone tip resistance, q_t, increase almost linearly with depth, and similar results were obtained at 4 different locations of the ground. CPT results in all the model grounds were similar to those in Fig. 1.

Table 1. Properties of the sand used for model ground.

Density of soil particle, ρ_s (Mg/m^3)	2.668
Maximum dry density, ρ_{dmax} (Mg /m^3)	1.604
Minimum dry density, ρ_{dmin} (Mg /m^3)	1.269
Internal friction angle at peak, ϕ_p' (degree)	42.8
Maximum void ratio, e_{max}	1.103
Minimum void ratio, e_{min}	0.663

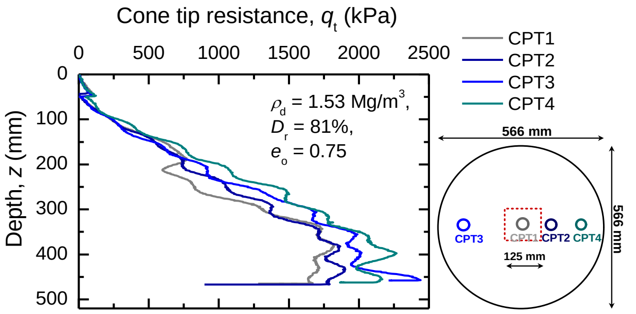


Fig. 1. Results of CPTs in a model sand ground.

2.2 Model foundations

Model piles used in this study were ABS (Acrylonitrile Butadience Stayrene) solid bars. The geometrical and mechanical properties of the model piles are summarised in Table 2. In order to measure axial forces, strain gauges were installed on the pile shafts at different locations as shown in Fig. 2. Model raft was a square aluminium plate with a thickness of 12 mm and a width of 125 mm.

The foundation models used in the experiments included raft alone, and pile foundation models with centre-to-centre pile spacing, *s*, of 3.5*D* (called PF-3.5*D*) and 6.5*D* (called PF-6.5*D*). The dimensions of the foundation models are indicated in Fig. 3.

Table 2. Geometrical and mechanical properties of the model piles.

Diameter, *D* (mm)	10.09
Length from raft base, *L* (mm)	200
Young's modulus, E_p (N/mm^2)	2920
Poisson's ratio, ν	0.406

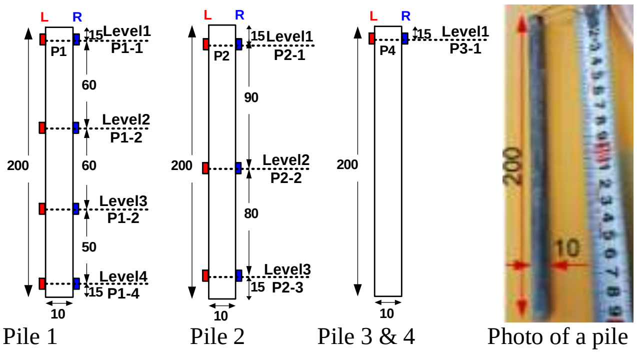
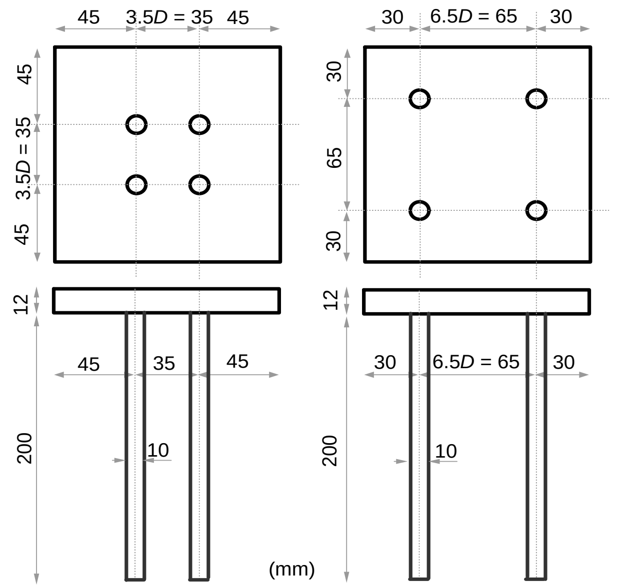


Fig. 2. Model piles and locations of strain gauges.

2.3 Test procedure and cases

Fig. 4 shows the setup of experiments. The experiments were conducted by the help of a loading system including: a screw jack to apply vertical load with a constant displacement rate; a load cell to measure applied load and dial gauges to measure settlement of the foundation. Load tests on single piles, raft alone, the two pile foundations were carried out.

As for the load tests of the pile foundations, 4 piles were first jacked-in the model ground one by one with two different pile spacing, *s* = 3.5*D* or 6.5*D*. Static load test was then carried out independently on each pile to obtain load-settlement relation of each pile. After that, the raft was placed on the 4 pile heads with a distance from the raft base to the ground surface of around 6 mm, and vertical static load tests of PFs were conducted. The foundations were in pile group condition at earlier stage of loading. After the rafts touched the ground surface, the foundations changed to piled raft foundations.



(a) PF with *s* = 3.5*D* (b) PF with *s* = 6.5*D*

Fig. 3. Dimensions of the pile foundation models.

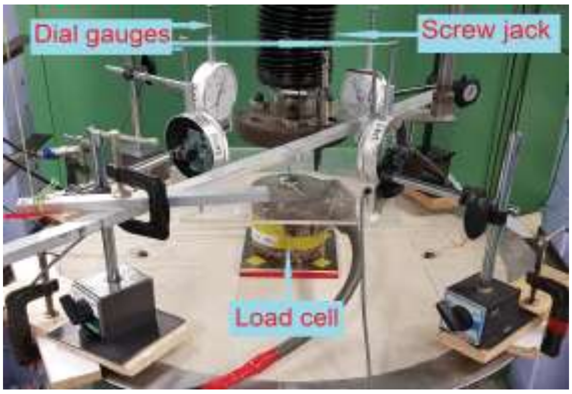


Fig. 4. The setup of experiments.

3 EXPERIMENTAL RESULTS

3.1 Pile resistances during jacking process

Fig. 5 shows the jacking forces of individual piles of the foundations in cases of (a) PF-6.5*D* and (b) PF-3.5*D*. In both cases, Pile 1 was jacked first, followed by Pile 2, Pile 3 and Pile 4. Therefore, Pile 1 behaved as a single pile during jack-in process. The results clearly show that the single pile (Pile 1) has the smallest pile resistance, and the pile jacked later has higher pile resistance. The results also indicate that the piles in 3.5*D* group have slightly higher jacking forces, in comparison to 6.5*D* group. Therefore, the sequence of pile installation and pile spacing have effect on pile resistances.

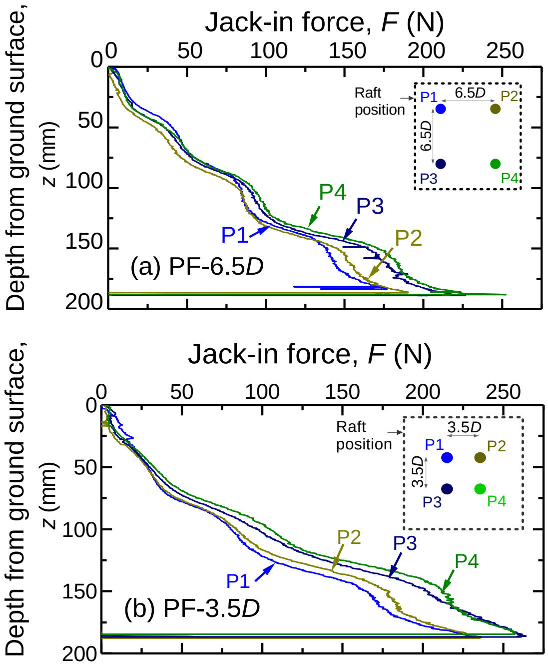


Fig. 5. Comparison of jacking forces of piles.

3.2 Pile resistance in static load tests of each pile

Fig. 6 shows the results of static load tests (SLTs) of individual piles in cases of (a) 6.5*D* case and (b) 3.5*D* case. In the case of *s* = 6.5*D*, the pile jacked later has higher resistance. In the case of *s* = 3.5*D*, similar trend is found. However, the piles in 3.5*D* group (narrower pile spacing) have higher resistances than the corresponding piles in 6.5*D* case. It should be noted that the static load tests were carried out after jacking-in process of all the 4 piles. Hence, it is reasonable that the resistance of P1 in case of *s* = 3.5*D* becomes greater than that in case of *s* = 6.5*D*.

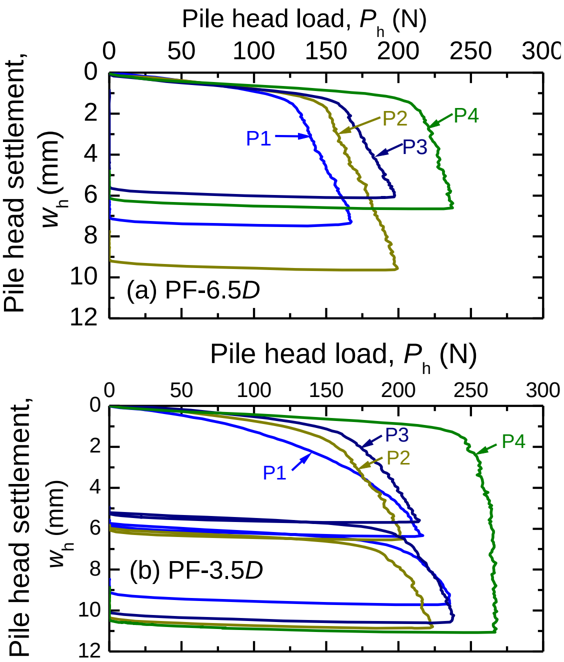


Fig. 6. Static load test results of individual piles.

3.3 Pile resistances in SLTs of pile foundations

Fig. 7 shows the changes of the resistance of each pile in the foundations ((a) PF-6.5*D* and (b) PF-3.5*D*). It is interesting to note that the pile resistance increased significantly in PR condition. In both cases, the resistances of the piles range from 150 N to 300 N at the end of PG condition, meanwhile the resistance of the piles in PR condition were almost three times at the peak strength. This advantage was caused by the load transfer from raft base to the ground, which increased stress and stiffness of soil surrounding piles.

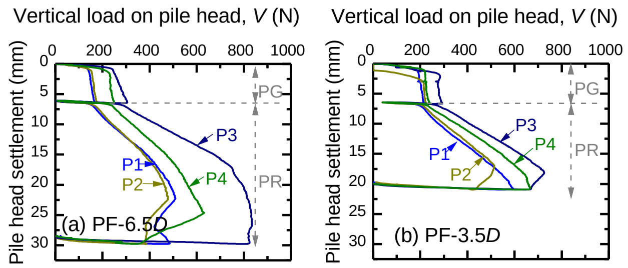


Fig. 7. Load-settlement curves of piles in pile foundations.

3.4 Load-settlement relationships of the foundations

Fig. 8(a) shows the load-settlement relationships of the foundations. Figs. 8(b) and 8(c) are zoom-in of initial parts of the load-settlement curves.

The settlements of the foundations were zeroed when the foundations turned to PR condition, in order to easily compare the PGs with the PRs. The difference between them is that the PGs had no raft resistance while the PRs had the raft resistance.

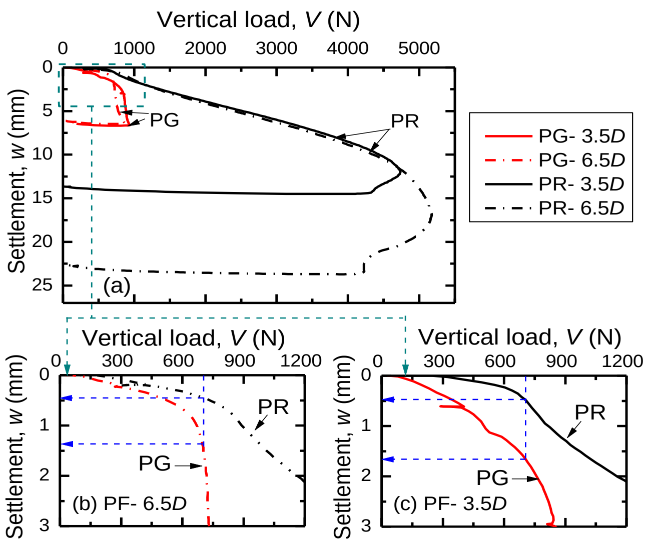


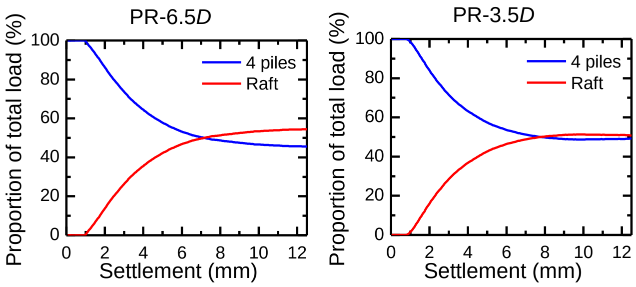
Fig. 8. Load-settlement relationships of the foundations.

In PG condition, PG-3.5*D* (narrower pile spacing) had larger capacity than PG-6.5*D* (Fig. 8(a)). In PR condition, both PRs with different pile spacings seemed to behave similarly with much larger resistances, compared to the corresponding PGs. Reasons for similar load-settlement behaviours of PRs will be presented at the end of section 3.6.

In terms of stiffness of PFs, focusing on Fig. 8(b) of PF-6.5*D*, at a vertical load of about 700N, the settlements of PG-6.5*D* and PR-6.5*D* are 1.4 mm and 0.5 mm, respectively. The settlement of the PR is reduced to about 1/3 of that of the PG. Similar result is seen in PF-3.5*D* (Fig. 8(c)).

3.5 Load sharing of piled raft foundations

Fig. 9 shows the proportions of loads carried by the rafts and the 4 piles in (a) PR-6.5*D* and (b) PR-3.5*D*. At very early stages of loading, the 4 piles carried a very large proportion of the applied load. Proportion of the load carried by the piles then decreases with increasing settlement. In contrast, the load carried by raft increases from a small proportion at the early stages to almost a half of the total applied load at larger settlements over 5 mm (= 0.5*D*). The raft in PR-6.5*D* supported larger proportion of the total load than the raft in PR-3.5*D* did.



(a) in PR-6.5*D* case (b) in PR-3.5*D* case

Fig. 9. Load sharing ratio in the piled raft.

3.6 Pile axial forces during static load tests

Fig. 10 presents the axial forces of Pile 1 (P1): (a) isolated pile condition; (b) in PG; and (c) in PR, in case of *s* = 6.5*D*. Figs. 10 (d), (e) and (f) are the corresponding results in case of *s* = 3.5*D*.

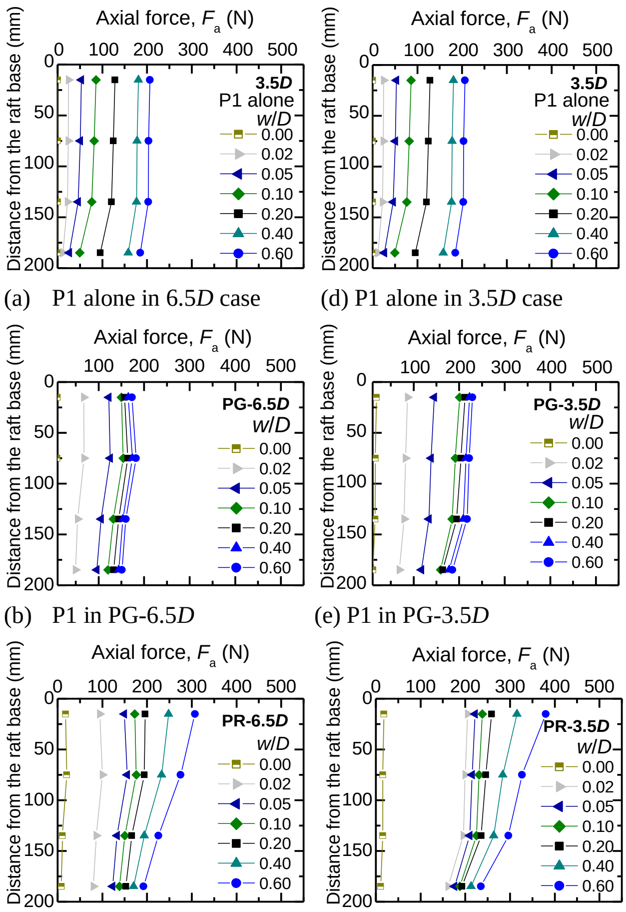
Focusing first on the case of *s* = 6.5*D*, the behaviours of P1 alone (Fig. 10(a)) and P1 in PG (Fig. 10(b)) are similar. In these cases, the shaft resistances are small. However, in PR condition (Fig. 10(c)), the shaft resistance as well as the pile tip resistance increase significantly. At *w*/*D* = 0.6, the resistance of P1 in PR-6.5*D* is almost a double of the resistances of P1 in PG-6.5*D* and the P1 alone. At the same settlement, the tip resistance in PR increases by about 30%, compared to that of the corresponding PG and the P1 alone. This is due to the load transfer from the raft base to the ground, which increases stresses and stiffness of the soil surrounding the piles, as pointed out by Vu et al (2017).

The results of the case of *s* = 3.5*D* (Fig. 10(d), (e) and (f)) have similar trend to the results of *s* = 6.5*D*. However, in 3.5*D* cases, pile 1 has larger tip resistance and larger shaft resistance along the bottom section (where is deeper than 130 mm), compared to those in 6.5*D* case. These results clearly show influence of pile spacing of the jacked-in piles on pile performance.

Summing up Sections 3.4, 3.5 and 3.6, if we compare the behaviours of PR-3.5*D* to the behaviours of PR-6.5*D* at the same settlement, the pile in PR-3.5*D* had larger axial force (Fig. 10(c) and (f)), meanwhile the raft in PR-6.5*D* supported larger load proportion (Fig. 9). This explains the reason why two piled rafts with different pile spacings have almost similar load-settlement relationships (Fig. 8(a)).

4 CONCLUDING REMARKS

In this study, influence of piling sequence and pile spacing on behaviours of isolated piles, pile groups and piled rafts were investigated through small-scale experiments in dry sand ground. It was suggested from the experiments that interaction between the piles and the raft through the sand should properly considered, taking into account of stress dependency of stiffness and strength of the soil surrounding the piles.



(a) P1 alone in 6.5*D* case (d) P1 alone in 3.5*D* case

(b) P1 in PG-6.5*D* (e) P1 in PG-3.5*D*

(c) P1 in PR-6.5*D* (f) P1 in PR-3.5*D*

Fig.10. Increment of axial force distributing along pile 1.

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