Experimental study on time-dependent behaviour of a vertically-loaded piled raft foundation model in soft clay

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ABSTRACT

In this study, long-term behaviours of a piled raft foundation were investigated through experiments. The model ground was prepared by consolidating a slurry mixture of Kasaoka clay and Silica sand. The model foundation consisted of a square raft and 4 piles. Load tests of the raft alone and the single pile were also carried out. In the experiment, vertical load on the piled raft was increased by 3 steps and each load step was maintained for a reasonable time to obtain the long-term behaviours of the foundation. The experimental results showed that, the piles effectively suppressed the settlement of the foundation for relatively smaller loads during times of increasing the applied load. In primary consolidation process, the pile resistance increased while the raft resistance decreased with elapsed time. This is due to the dissipation of pore water pressure at the raft base and the corresponding increment of effective stresses of the soil surrounding the piles. When creep settlement occurred after the primary consolidation stage, the resistance of both raft and piles were stable with time. In general, large part of settlement occurred in primary consolidation time.

Keywords: piled raft; experiment; clay ground; time effect; vertical loading; pore water pressure

1 INTRODUCTION

In recent years, the application of piled raft foundation (PR) to support heavy structures has become more widespread because of its economic efficiency and safety, as both raft and piles share the load together.

Behaviours of PRs in clay have been investigated in many researches by different methods, in which, numerical methods are the most popular. A few physical modelling of PRs in clay subjected to vertical loads were carried out (e.g., Horikoshi et al. 1996; Thoidingjam et al. 2016; Rodriguez et al. 2018). These experiments aimed to investigate load distributions and settlements of PRs at the end of construction, disregarding long-term behaviours after full construction load was applied. However, if PR is located on clayey ground, the foundation will continue to settle for a very long time after the construction, due to primary consolidation process and creep behaviour of the ground.

Hence, one of objectives in this research is to study time-dependent behaviours of piled raft foundations in soft saturated clay through small-scale physical modelling. In this paper, focus is placed on the change of load share by raft and piles, and on the settlement of foundation with time due to the dissipation of pore water pressures and creep behaviour of clayey soil.

2 OUTLINE OF THE EXPERIMENTS

2.1 Model ground

In the experiments, clay ground was prepared in a cylindrical chamber with an inside height of 420 mm and an inner diameter of 420 mm. The soil used for the model ground was a mixture of commercial Kasaoka clay powder and Silica sand #6.

The model ground was prepared as follows: Firstly, Silica sand #3 was poured into the chamber, saturated and compacted until it reached a high relative density, D_r, of about 81% and a thickness of 50 mm for a drainage layer. This bottom drainage layer was considered as a stiff layer. Secondly, in a rectangular box, dry Kasaoka clay powder and Silica sand #6 were mixed at a mass ratio of 1:1 (K50S50). Water was then added to the mixed soil to have soil slurry having a water content of 1.3 times the liquid limit, *LL*. This soil slurry was poured into the soil chamber to have an initial thickness of 370 mm. The soil then started consolidating under its self-weight during two days. After that, a surface layer of Silica sand #6 with a thickness of 10 mm was placed on the clay to provide the top drainage layer, and a rigid circular loading plate was placed on the top drainage layer. Next, vertical load on the loading plate was increased to consolidate the soil one-dimensionally in several steps, up to a vertical stress of 100 kPa. Each load step was maintained until degree of consolidation reached 90% following the Terzaghi's one-dimensional consolidation theory. The final load step was kept for one more week to have higher degrees of consolidation. Finally, the consolidation pressure was removed and the ground was allowed for swelling process in 10 days.

Cone penetration tests (CPTs), T-bar tests and unconfined compression tests (UCTs) were carried out immediately after completing the load test of a model foundation to obtain properties of the model ground. Undrained shear strength, c_u, was deduced from the cone tip resistance, $q_{cone\ tip}$, and average stress acting on cylinder of T-bar, $q_{u\ T\text{-}bar}$, using empirical equations proposed by Low et al. (2010).

Fig. 1 shows the results of undrained shear strength of the model ground obtained from three different methods. The undrained shear strength varied in depth and could be described approximately by the following equation:

$$c_u\ (\text{kPa}) = 9\ (\text{kPa}) + z\ (\text{mm}) \times 0.04\ (\text{kPa/mm}) \qquad (1)$$

To obtain more properties of the model ground soil, other laboratory soil tests such as oedometer, Atterberg limits, density and water content were conducted, and their results are summarised in Table 1.

Table 1. Properties of the model ground soil (called K50S50).

Parameter	Notation and unit	Value
Density of soil particle	ρ_s (Mg/m^3)	2.653
Saturated density	ρ_{sat} (Mg /m^3)	1.98
Plastic limit	*PL* (%)	13.6
Liquid limit	*LL* (%)	33.9
Plastic index	*PI* (%)	20.3
Compression index	C_c	0.291
Swelling index	C_s	0.055
Water content*	*w* (%)	26.2
Void ratio*	*e*	0.7

* after the consolidation with vertical pressure of 100 kPa

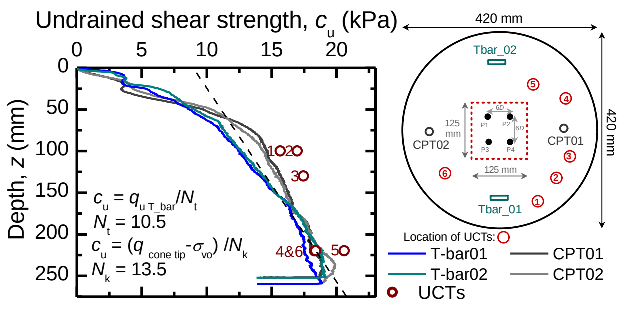
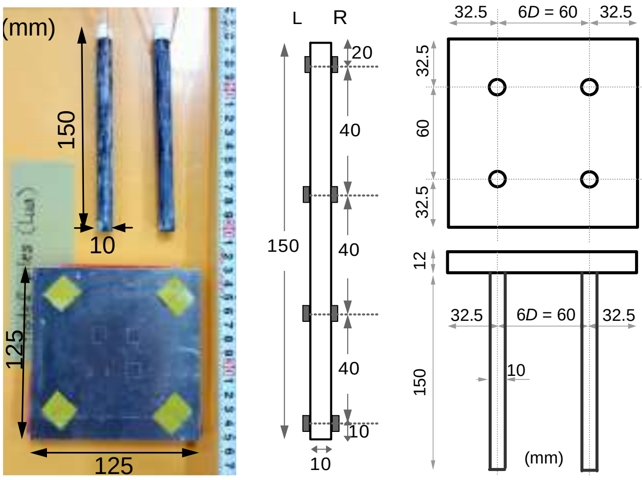


Fig. 1. Results of CPTs, T-bars and UCTs of the model ground.

2.2 Model foundations

Model piles used in this study were ABS (Acrylonitrile Butadience Stayrene) solid bars (Fig.2a) having a diameter, *D*, of 10.09 mm and a length, *L*, of 150 mm. Young's modulus, E_p, and Poisson's ratio, ν, of the model piles are 2920 N/mm^2 and 0.406, respectively. In order to measure axial forces along each pile, strain gauges were installed on the pile shafts at 4 different levels as shown in Fig. 2b Model raft was a square aluminium plate with a thickness of 12 mm and a width of 125 mm (Fig.2a). The raft could be regarded as rigid.

In the experiments, the foundation models included raft alone, pile alone and 4-pile pile foundation. Fig. 2c shows the dimensions of the foundation models.



a. Model piles and model raft
b. Locations of strain gauges
c. Model foundation

Fig. 2. Model piles, raft and foundation.

2.3 Test procedure

Fig. 3 shows the set-up of an experiments. The loading system in the experiment includes an air cylinder to apply constant vertical load, a load cell to measure the applied load and 4 dial gauges to measure settlement of the foundation.

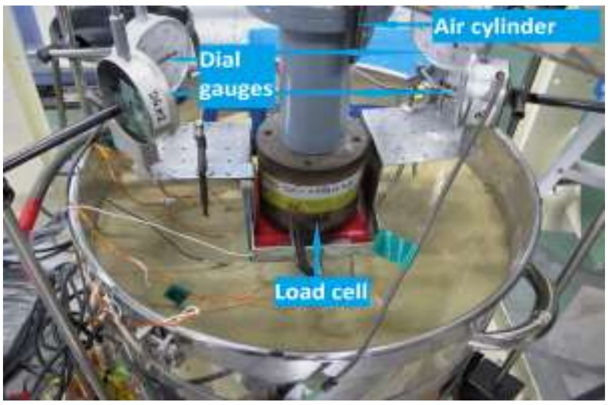


Fig. 3. The set-up of experiments.

One pore water pressure transducer and one earth pressure cell were installed at the centre of the raft base.

Vertical static load tests on single pile and raft alone in undrained condition were carried out to obtain bearing capacity of each element and to determine the magnitude of the vertical load applied on the piled raft.

As for the load tests of the pile foundations, 4 piles were firstly jacked into the ground one by one with a centre-to-centre pile spacing, *s*, equal to 6*D*. Thereafter the raft was placed on the 4 pile heads with a gap from the raft base to the ground surface of around 5 mm, and vertical static loading of the pile group was conducted in a displacement-controlled manner. The pile group changed to piled raft after the raft base touched the ground surface. In the piled raft condition, vertical load was increased by 3 steps in a load-controlled manner. Each load step was maintained for a reasonable time to obtain the long-term behaviours of the foundation.

3 EXPERIMENTAL RESULTS

3.1 Load vs. settlement of single pile and raft alone

Fig. 4 shows the results of vertical load tests of the pile alone and the raft alone. The bearing capacity of the raft alone and the pile alone were about 2100 N and 100 N respectively. The summing-up bearing capacity of the raft and 4 times of a single pile was 2500 N. Based on these results, the three load steps applied on the 4-pile piled raft foundation were determined to be 750 N, 1250 N and 2000 N respectively, corresponding to 30% (Factor of safety F_S = 3.3), 50% (F_S = 2) and 80% (F_S = 1.25) of the total bearing capacity.

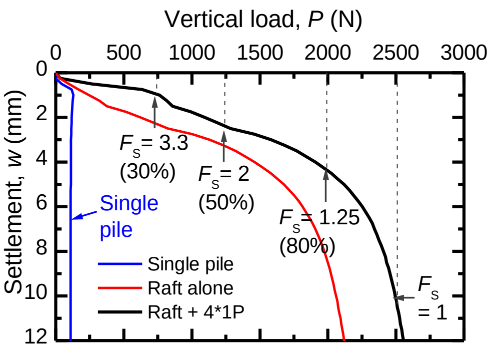


Fig. 4. Load-settlement curves of single pile and raft alone.

3.2 Long-term behaviours of piled raft foundation

Fig. 5(a) shows the relationship between the applied load, P, and the settlement, w, of the foundation. Figs. 5(b), 5(c) and 5(d) are zoom-in of the time of increasing load of the three steps. Fig. 6(a) shows the change of excess pore water pressure (PWP) and settlement with the whole experimental duration. Figs. 6(b), 6(c) and 6(d) are zoom-in of the time of increasing load of the three steps.

a. *During the time of increasing the load*

Focusing first on Fig. 5(b), at early stages of increasing load, the increment of the settlement was almost zero. The reason for this phenomenon is that, when the initial small loads were applied, the resistance of piles increased rapidly. The piles effectively suppressed the settlement of the foundation in this stage. After pile resistances reached their peak strength (indicated by the red dot lines in the figure), the foundation started settling under undrain condition, and pile resistances reduced a little. The raft load is obtained as the difference of the applied load and the pile resistance.

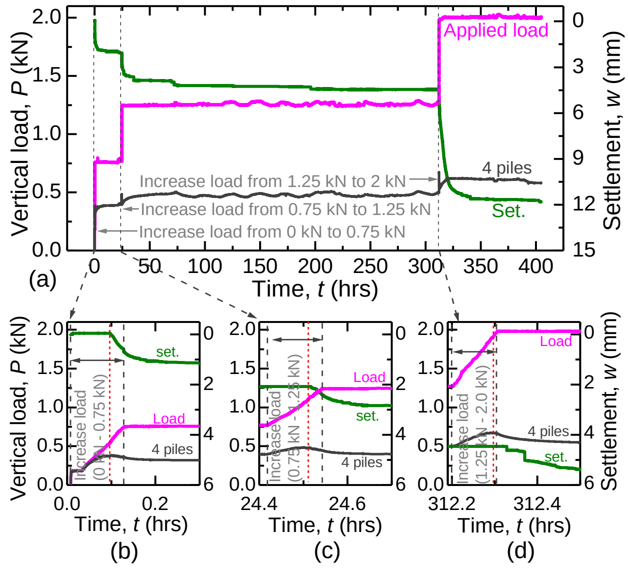


Fig. 5. Load and settlement curves: (a) full-time of loading test; (b), (c) and (d) zoom-in the time of increasing the applied load.

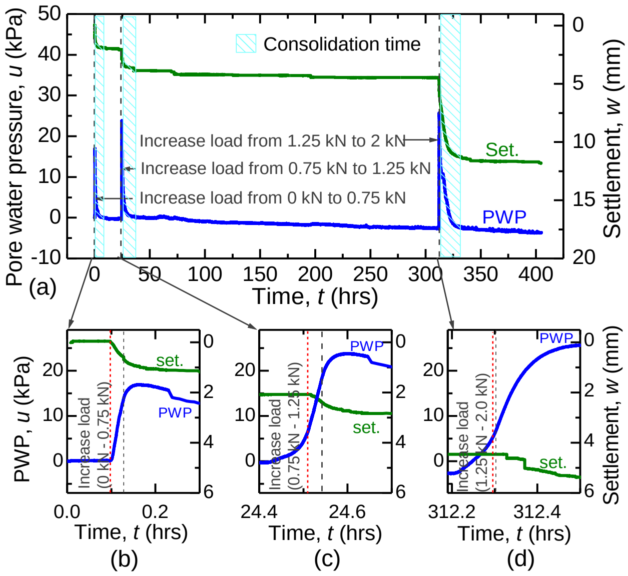


Fig. 6. Pore water pressure and settlement curves: (a) full-time of loading test; (b), (c) and (d) zoom-in the load-increased times.

Let us look at Fig. 6(b). It is clearly seen that PWP started to increase sharply when the pile resistance reached the peak. It is interesting to note that the force by the peak PWP was about 60% of the raft load, if it is assumed that the measured PWP was uniform over the raft base. When the applied load was maintained, the settlement of the foundation continued to increase due to the primary consolidation of the ground as well as the creep phenomena even after the PWP dissipated.

Similar trends were measured for the 2nd and the 3rd loading stages (Figs. 5(c), (d) and Figs. 6(c), (d)). It is seen that the peak pile resistances of the three load steps of P = 0.75 kN, 1.25 kN and 2kN, were 0.375 kN, 0.483 kN and 0.686 kN, respectively. The increase of pile resistances with increasing the applied load is caused by increase of effective stresses in the ground.

The increase of the effective stresses in the ground increased also the ground stiffness. Hence, the undrain settlement was smaller in the second load step than that in the first load step, and the undrain settlement was the smallest in the third load step.

b. *During primary consolidation stage*

The PWP dissipated after increasing the applied load and returned to the steady state. These time durations could be regarded as primary consolidation stages (highlighted areas on Figs. 6(a) and 7(a)). It is clearly seen from Fig. 6(a) the creep settlement occurred after the primary consolidation stages. It is seen from Fig. 6(a) that the settlement rates in the primary consolidation stages were proportional to the dissipation rates of the PWP, and the large parts of settlements occurred in the primary consolidation stages.

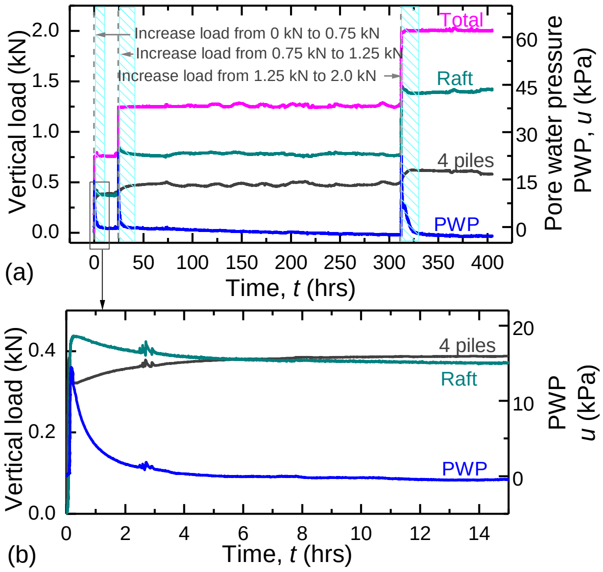


Fig. 7. Load transfer with time: (a) full-time of loading test; (b) zoom-in the primary consolidation time of the first load step.

The change of load sharing with time of the piled raft foundation is shown in Fig. 7(a). Fig. 7(b) is a zoom-in of the primary consolidation stage of the first load step. Fig. 7(b) clearly shows that, during the primary consolidation stage, the load supported by the raft decreased while the load supported by the 4 piles increased with the elapsed time. The pile load reached 0.38 kN at the time of increasing the first load step and then rapidly decreased to 0.32 kN, and again increased during the primary consolidation stage to 0.38 kN at the end of the primary consolidation stage. This phenomenon is caused by the consolidation process of the ground. The dissipation of the PWP resulted in the corresponding increase of the effective stress in ground, resulting in the increase of pile resistances. Similar trends were measured in the 2nd and 3rd load steps.

This is an advantage of piled raft because the stress from the raft base causes consolidation of the ground. Consequently, the effective stresses in the ground increase and the stiffness of the ground also increases¸ resulting in the increase of the pile resistance.

c. *During secondary consolidation stage*

After the primary consolidation stages, the foundation continued to settle due to the creep phenomenon of the ground. Here let us define the creep settlement index, C_{cs}, as follows where B is raft width:

$$C_{cs} = \mathrm{d}(w/B)/\mathrm{d}(\log t) \quad (2)$$

C_{cs} for the three load steps of P = 0.75 kN, 1.25 kN and 2 kN were 0.001, 0.0015 and 0.0018, respectively. C_{cs} was higher when the applied load was larger.

In terms of the load distribution during the secondary consolidation stages, Fig. 7(a) shows that, in all the three load steps, the resistances of the both raft and piles were stable. The loads carried by the 4 piles in the three stages were 0.38 kN, 0.476 kN and 0.626 kN. The load of 0.63 kN supported by the 4 piles at the final stage was larger than 4 times of the bearing capacity of single pile (4 x 0.1 kN = 0.4 kN).

4 CONCLUDING REMARKS

In this paper, long-term behaviours of a piled raft foundation model in a soft saturated clay was investigated through a small-scale physical modelling.

Main findings from this study are as follows:

(1) During the time of increasing the vertical load, the piles effectively suppressed the settlement of the foundation for relatively smaller loads.

(2) During the primary consolidation stages, stresses from the raft base cause consolidation of the ground. As a result, the effective stresses in the ground and the stiffness of the ground increase¸ resulting in the increase of the pile resistance.

(3) After the primary consolidation stages, the creep settlement continued. Creep index (Eq. (2)) was higher when the applied load was larger. The loads supported by both the raft and the piles were stable during the secondary compression stages.

Although the small-scale experiments were conducted in this study, the above findings could be applied to prototype foundations qualitatively.

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