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Donggyu Park
Yonsei University, South Korea

Doohyun Kyung
Yonsei University, South Korea

Kyujin Choi
Yonsei University, South Korea

Junhwan Lee
Yonsei University, South Korea

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Donggyu Park
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Seoul, Korea 120-749

Doohyun Kyung
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Kyujin Choi
Yonsei University
Seoul, Korea 120-749

Junhwan Lee
Yonsei University
Seoul, Korea 120-749

ABSTRACT

In the conventional design for piled rafts, the load capacity of the raft is not in general taken into account and the load capacity of piles is only considered for the estimation of the total load carrying capacity of the piled rafts. As a consequence, piled rafts are often designed with excessively conservative safety margin, raising a need of further investigation of the load capacity mechanism of piled rafts. In this study, a series of centrifuge load tests using model group piles and piled rafts are conducted and used to compare the axial load carrying behaviors of group piles and piled rafts for different soil conditions. Instrumented model piles and rafts are manufactured and introduced into the centrifuge tests. Different density conditions of test sands were considered in the tests. From the test results, it is revealed that the load carrying capacity increase for piled rafts differ for different soil conditions. The load capacity of piled rafts is greater than those of the group piles by 13% for dense sand cases and by 22% for loose sand cases.

INTRODUCTION

In current practice for the design of piled rafts, the load capacity of raft is not in general taken into account and the load capacity of piles are only considered into the total load carrying capacity of piled rafts. For more advanced and optimized design of piled rafts, the resistances from both components need to be properly considered and evaluated with consideration of interaction and load sharing effect between piles and raft. In much of researches on the estimation of foundation resistances for piled rafts, emphasis has been placed on the ultimate limit state that corresponds to large settlement conditions (Liu et. al. 1982; Phung 1993; Sanctis and Mandolini 2006).

For estimating the load-settlement and load sharing behavior of piled rafts, various methodologies including approximate analytical methods and experimental approach have been proposed. Poulos and Davis (1980) presented the analytical approach based on the individual pile and raft units. Randolph (1983) has combined the responses of pile group and raft considering the load sharing phenomenon between piles and raft introducing a piled raft interaction factor. Elastic-based computer methods have been adopted using the simplified piled raft model as given by a strip or plate on soil springs with equivalent stiffness (Poulos 1991; Clancy and Randolph 1993; Poulos 1994). The finite element methods (Chow 1986; Katzenbach and Reul 1997; Reul and Randolph 2004) and boundary element methods (Hain and Lee 1978; Poulos and Davis 1980) have also been applied for the plane-strain or axisymmetric and three–dimensional conditions. Experimental investigations were also often introduced to analyze the behavior of piled rafts, which include laboratory tests, field tests, and centrifuge model tests (Akinmusuru 1980; Liu et. al. 1982; Cooke 1986; Phung 1993; Lee and Chung 2005; Horikoshi and Randolph 1996; Conte el al. 2003).

In this study, a series of centrifuge load tests using model foundation are performed and used to compare the axial load carrying behaviors of group piles and piled rafts under different soil conditions. For this purpose, instrumented model piles and piled rafts were manufactured and adopted into the tests. Centrifuge test specimens were prepared using sands at different density conditions. From the test results, different load capacity from group piles and piled rafts are analyzed.

THE BEHAVIOR OF PILED RAFTS

Main components of piled raft foundation include raft, piles, and subsoil (Reul and Randolph, 2004; Sanctis and Mandolini, 2006). Piled rafts represent complex load responses and load carrying behavior due to the combined nature of piles and raft as well as interactions with surrounding soils. Key question arising in the design of piled raft is the proportion of loads carried by raft and piles. Conceptually, the resistance of piled raft is composed of those from raft and piles as follows:

$$Q_{pr} = Q_r + Q_p = Q_r + \sum Q_{pi} \tag{1}$$

where Q_{pr} = load carrying capacity of piled raft; Q_r and Q_p = load carrying capacities of raft and piles; and Q_{pi} = load carrying capacity of individual pile.

Several piled raft design procedures and analyzing methods have been developed as summarized in Poulos et al. (1997) and Poulos (2001). For estimating the load-settlement behavior of piled rafts, Randolph (1994) suggested the stiffness method considering simplified piled raft unit as shown in Fig. 1. This method allows the overall stiffness and load distribution within piled rafts to be calculated by estimating the interaction effects between raft and pile components. From the Randolph's original approach, the stiffness of piled rafts is given as follows:

$$K_{pr} = \frac{K_p + K_r(1-\alpha_{rp})}{1-(K_r/K_p)\alpha_{rp}^2} \tag{2}$$

where K_{pr} = overall stiffness of piled rafts; K_p = stiffness of pile group; K_r = stiffness of raft; α_{rp} = interaction factor of pile group on raft. The raft stiffness, K_r, can be estimated from the elastic theory, for example, using the solutions presented by Fraser and Wardle (1976) or Mayne and Poulos (1999). The pile group stiffness can also be estimated from the elastic theory, using the approaches described by Poulos and Davis (1980), Poulos (1989), and Fleming et al. (1992).

Randolph(1983) has shown that the superposition of the displacement fields induced by single pile and circular raft in Fig. 1 can be estimated as follows:

$$\alpha_{pr} = 1 - \frac{\ln(r_c/r_0)}{\ln(r_m/r_0)} \tag{3}$$

$$r_m = 0.25 + \frac{E_{sl}}{E_{sb}}\left(2.5\frac{E_{sav}}{E_{sl}}(1-\upsilon) - 0.25\right) \tag{4}$$

where α_{pr} = interaction factor of raft on pile group; r_c = average radius of pile cap (corresponding to an area equal to the raft area divided by number of piles); r_0 = radius of pile; r_m = radius of pile influence; E_{sl} = elastic modulus at level of pile base; E_{sb} = elastic modulus of bearing stratum below pile base; E_{sav} = average elastic modulus along pile shaft; ν= Poisson's ratio of foundation soil.

From equations (1), a simplified piled raft load-settlement behavior can be expressed as shown in Fig. 2. The stiffness of piled rafts is computed from equation (1) considering the number of group piles, and will remain operative until the pile capacity is fully mobilized at point A in Fig. 2. Beyond the point A, the stiffness of the piled raft corresponds to that of the raft alone (K_r), and this holds until the ultimate load capacity of the piled raft foundation system is reached at point B in Fig. 2. Beyond this loading stage, the resistance of piled raft is not increasing, and the load settlement behavior becomes flat.

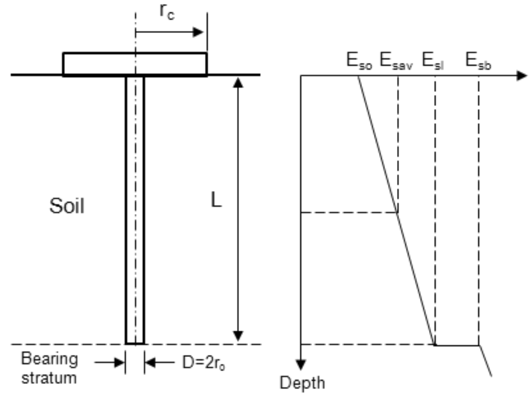


Fig. 1. Simplified representation of piledraft unit.

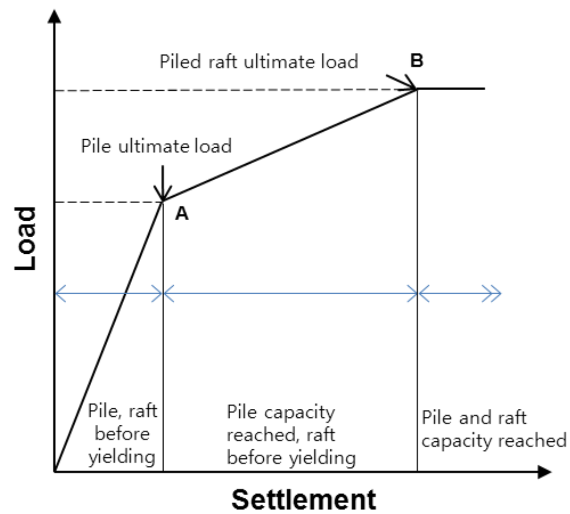


Fig. 2. Simplified contact piled raft load–settlement curve.

Liu et al. (1985) performed systematic field test on bored pile groups and piled rafts in sandy soil. The results showed different effects of pile-cap-soil interactions on both the shaft and base resistances of the pile groups with "weakening effect" and "strengthening effect". Based on the observed pile-cap-soil interactions in sand, Liu et al. (1985) suggested the following the ultimate bearing capacity relationship for piled rafts considering both pile-soil-pile interaction and cap-soil-pile interactions:

$$P_{pr} = n(\beta_s\delta_s P_{ss} + \beta_b\delta_b P_{sb}) + P_c \tag{5}$$

where P_{pr} = ultimate bearing capacity of piled raft; n = the number of piles in the group; P_{ss} and P_{sb} = shaft and base capacities of reference single pile under equal soil conditions as the pile group; P_c = ultimate capacity of cap alone; β_s and β_b = coefficients considering effects of pile-soil-pile interaction on shaft and base resistance of the pile group; δ_s and δ_b = coefficients considering effects of cap-soil-pile interaction on shaft and base resistance of the pile group. In order to reflect the pile-cap-soil interactions on raft in piled rafts, Phung (1993) proposed a modified ultimate bearing capacity equation as follows:

$$P_{pr} = n(\eta_{1s}\eta_{4s}P_{ss} + \eta_{1b}\eta_{4b}P_{sb}) + \eta_6 P_c \quad (6)$$

where P_{pr} = ultimate bearing capacity of piled rafts; n = the number of piles in the group; P_{ss} and P_{sb} = shaft and base capacities of single; P_c = ultimate capacity of cap alone; η_{1s} and η_{1b} = the influence of the pile-soil-pile interaction on the pile shaft and base capacities; η_{4s} and η_{4b} = the influence of the pile-cap interaction on the pile shaft and base capacities; η_6 = the influence of the pile-cap-soil on the cap capacity (1.0 and 0.9 for loose and medium dense to dense sands).

CENTRIFUGE TESTS

In the centrifuge model tests, the behavior of structures associated with self-weight stresses and gravity-dependent system is correctly reproduced and test results translated into prototype scales using the similarity scaling factors given in Table 1. The presented centrifuge loading tests were performed using the geotechnical centrifuge testing system (Model C72-2 manufactured by ACTIDYN SYSTEMES SA, Elancourt France), as shown in Fig. 3. The general specification of the centrifuge system includes 5-m radius with 240 g-ton beam centrifuge as listed in Table 2. For the model load tests in this study, the geometrical scaling factor N = 60 was adopted, and all the model pile and raft were fabricated at a model scale of 1/60 down. All test results are presented at the prototype scale by use of the scaling factors presented in Table 1 to convert measured model scale to proto type.

Table 1. Scaling Factors for Basic Quantities in Centrifuge Modeling

Item	Scaling Factor	Item	Scaling Factor
Stress, modulus	1	Force, load	N^{-2}
Density	1	Mass	N^{-3}
Length, displacement	N^{-1}	Diffusion time	N^{-2}
Gravity	N	Stress wave velocity	1
Strain	1	Dynamic acceleration (earthquake)	N

TEST SANDS, MODEL PILE AND RAFT

Centrifuge load tests using model group piles and piled raft were conducted to investigate the efficiency and resistance behavior of piled rafts in comparison to those of group piles. The performances of piled raft (PR) and group piles (GP) are directly compared for the same soil conditions that were prepared within the circular chamber as shown in Fig. 4. Table 3 summarized the main characteristics of the tests program presented in this paper.

Fig. 3. Centrifuge testing system

Table 2. Specifications of KOCED Geotechnical Centrifuge

Item	Specification
Platform radius	5.0 m
Max. capacity	240 g-tons
Max. acceleration	130 g with 1,300 kg payload
Max. model payload	2,400 kg up to 100 g
Platform dimensions	1.2 m (L) × 1.2 m (W) × 1.2 m (H)
Power consumption	220kW for full capacity operation

The size of the circular chamber was 900 mm in diameter and 700 mm in height. The centrifuge test specimens were prepared by the raining method using a sand diffuser consisting of the sand hopper and moving equipment.
The relative density (D_R) of the centrifuge test specimens was controlled by falling height of sand particles, hole size and moving speed of hoper, as shown in Fig. 5, which were predetermined at a desired D_R through several preliminary tests. Using the sand diffuser, the soil layer with thickness of

Fig. 4. Soil sample forming with sand diffuser

1.0 to 1.5 cm was formed uniformly by controlling the fall height of sand diffuser, and then continued up to the desired depth of 400 mm.

The test soil used in the centrifuge test was a clean dry silica sand characterized by minimum dry density, $\gamma_{d,min}$ = 12.19 kN/m^3; maximum dry density, $\gamma_{d,max}$ = 16.12 kN/m^3; D_{50} (mean particle size) = 0.21 mm; C_u (uniformity coefficient) = 1.96; and ϕ_{cv} (angle of shearing resistance at the critical state) = 33.5°. Two D_R values of 42 and 74%, corresponding to medium and dense conditions, were adopted in the tests to consider density conditions of typical foundation soils. From triaxial tests, peak friction angles of the sand at D_R = 40 and 70% were 36.3° and 41 °, respectively. Fig. 5 shows the grain-size distribution of the test sands.

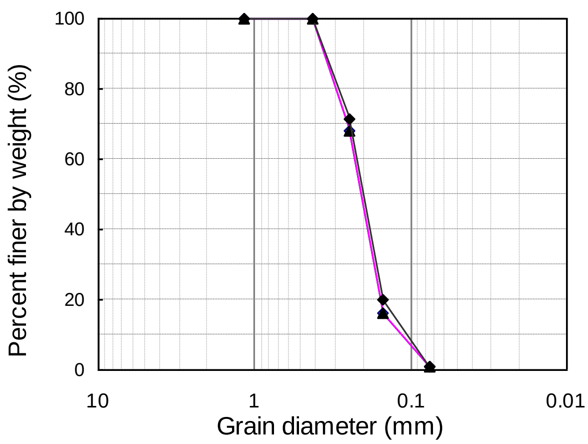


Fig. 5. Grain-size distribution of the test sands.

Table 3. Model test schemes for GP and PR.

Test no	Test name	soil condition
1	Group pile (GP) (4×4, D=600mm, s=4D, L=15m)	Dense sand
2	Group pile (GP) (4×4, D=600mm, s=4D, L=15m)	Loose sand
3	Piled raft (PR) (4×4, D=600mm, s=4D, L=15m)	Dense sand
4	Piled raft (PR) (4×4, D=600mm, s=4D, L=15m)	Loose sand

MODEL PILE PLACEMENT AND LOADING TEST PROCEDURE

The soil specimens were constituted at the rigid steel cylindrical container with an internal diameter of 900 mm and a height of 700 mm, and the soil specimens were located at a level 400 mm (i.e., 24 m in a prototype scale) above the container bottom container. Fig. 6 shows the main geometrical characteristics of the model piled raft and group piles, the set-up of loading test, and the boundary conditions. After soil deposition, the model foundation s (GP and PR) were installed at 1g as shown in Fig. 7, and test set-up including the four LVDT, placed at the corner of raft, group pile and piled raft, and load cell were arranged at the centrifuge platform.

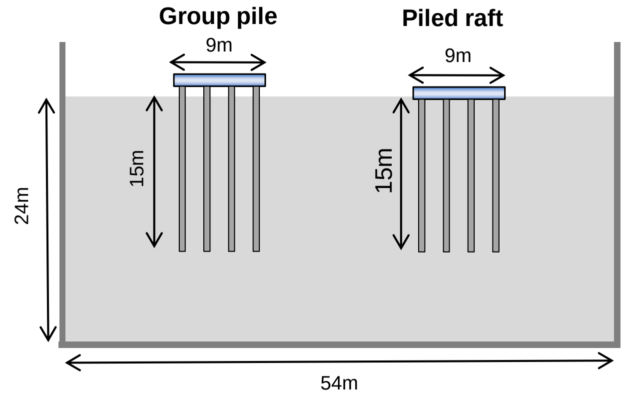


Fig. 6. Model test schemes: group pile (GP), piled raft (PR)

The load tests were performed sequentially from group piles to piled raft at the same ground container to reduce effect of the boundary condition and ground disturbance occurred at the precedent loading test. After finishing the group pile load test, the centrifuge system was stopped and the group pile was replaced carefully and then the piled raft was installed in the soil specimen. The centrifuge testing system was then re-started to next loading test, and the next loading test was performed. The group pile was partially jacked into the soil until 20mm (1.2m at the prototype) of piles remained between the soil surface and raft; the embedded depth of group pile is same with the depth of piled raft 250mm(15m at the prototype).

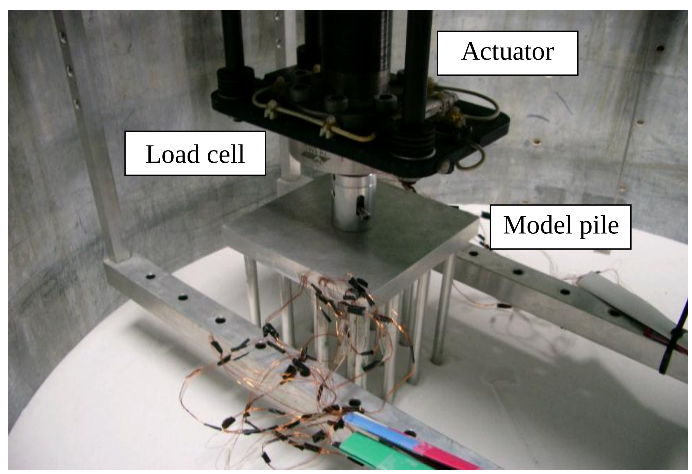


Fig. 7. Model pile installation

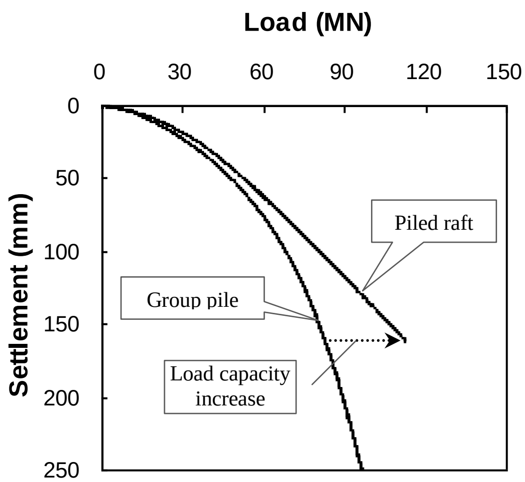
TEST RESULTS

Fig. 8 shows the load-settlement curves of group pile (GP), piled raft (PR). As described previously, the piled raft is composed of group pile and raft (pile cap), which represent different resistance mechanisms. The resistance of group pile, the shaft friction and base resistance, is fully mobilized at relatively small settlement level (eg, 0.1B where B = pile diameter) comparing to that of the raft. At the initial loading stage, stiffer load response of the group pile is observed and then gradually degraded with increasing settlement level until their capacity is fully mobilized. The behavior of piled raft is similar to that of group pile within the range from initial to group pile yielding. Thus the stiffness of piled raft is mainly obtained by the group pile stiffness, as indicated in Fig. 8.

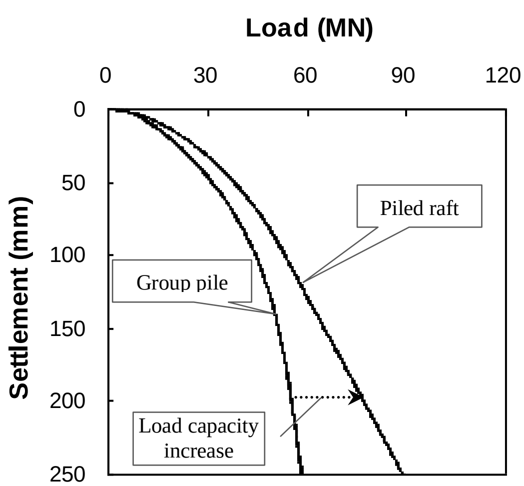
It is seen that the load carrying capacity of piled raft increases gradually with settlement after the group pile reaches yielding (point of A: shown in Fig. 2). The load-settlement curve of the piled raft, after the initial nonlinear region, shows constant tangent stiffness due to the mobilization of raft load capacity. Therefore, the stiffness of piled raft, after group pile yielding, is mainly affected by the load-settlement behavior of raft.

Fig. 9 shows increases in load capacity of piled raft in comparison to that of group piles. In the conventional piled raft design approach, pile cap is regarded as a structural member that connects the superstructure and piles, and the load capacity of raft is not in general taken into account for foundation design. For the optimized design of piled rafts, it is important to properly evaluate and consider the load sharing behavior between raft and piles at the allowable settlement levels. As shown in Fig. 9, the resistance increase effect and load sharing of raft occur from initial loading stages, and the increase effect becomes larger steadily with settlement. From the test result, increases of the load capacity of piled raft were measured as 4.3 and 4.7 MN for dense and loose sands, respectively, at allowable settlement equal to 25 mm.

Fig. 10 shows the load capacity increase ratio (LCIR) of piled raft for dense and loose sands. The load capacity increase ratio was calculated with the load capacity increase of piled raft divided by that of group piles at the same settlement level. Considering that the group pile is composed of 16 single piles (4×4), the optimized piled raft design can be achieved by reducing the number of piles corresponding to 13% and 22% increase of load capacity from the raft at dense and loose sands, respectively, at allowable settlement equal to 25 mm.



(a) Dense sand



(b) Loose sand

Fig. 8. Load-settlement curves of group pile and piled raft

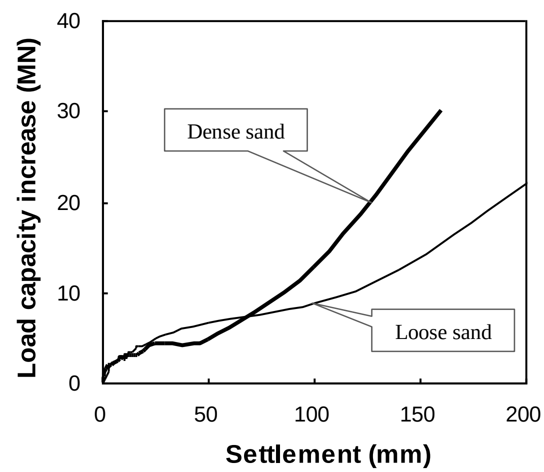


Fig. 9. Load capacity increase in piled raft

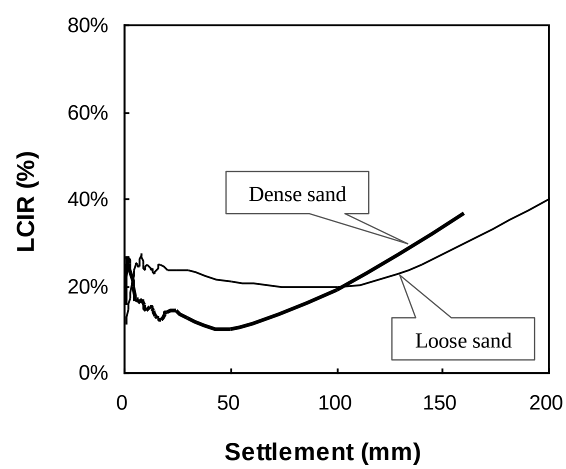


Fig. 10. Load capacity increase ratio in piled raft

CONCLUSIONS

A series of centrifuge tests were conducted to analyze and compare the axial load carrying behaviors of group piles and piled rafts. The behaviors of piled raft are influenced by both of group piles and raft load-settlement behavior. At the initial non-linear range of piled raft is decided by the group pile behavior, while the load capacity of piled raft increases linearly after the yielding of group pile as affected by the linear behavior of raft.

From the test results, it was observed that the load capacity increase effect of piled raft in comparison to that of group piles occurs from initial loading stages. The load capacity increases of piled raft was measured as 4.3MN at dense sand and 4.7MN at loose sand, respectively, at the allowable settlement level equal to 25mm.

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