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Centrifuge tests on piled raft foundations in sand subjected to vertical load

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ABSTRACT: Static centrifuge tests of piled rafts subjected to vertical load were performed in order to examine the interaction of piles-ground-raft. Piles were instrumented with continuous Rayleigh-based optical fiber sensors to measure deformation occurring in the piles. Optical fiber was also set up in the soil to measure deformation of the ground around the foundation. Two types of piled rafts foundation were tested: a rigid raft (1.5cm thick) and a flexible raft (0.2cm thick). A pile group (without raft touching the ground) was also tested in centrifuge to compare the performance. The optical fiber in the soil showed the extent of the deformation resulting from the loading in the container.

1 INTRODUCTION

As high-rise buildings are becoming more common and the concept of environmental cost is now central to the construction sector, piled raft foundations combining deep and shallow foundations will be used more and more frequently.

Piled raft foundations consist of a surface foundation that is in contact with the ground and a group of piles connected to the shallow foundation. There are two possible design strategies for mixed foundations:

- reducing settlements by adding piles when the bearing capacity is provided by the shallow foundation but settlements are excessive for the proposed structure (Burland et al. 1977),
- increasing the bearing capacity of the deep foundations by taking into account the additional bearing capacity provided by the surface foundation, with a view to limiting costs and the use of raw materials.

In both cases, the combination of these two types of foundations implies that the behavior of the piled raft foundation is different from the foundations taken separately. Indeed, the addition of a footing in contact with the ground on a pile group implies additional interactions.

Centrifuge model can represent the reality with a small scale model better than a 1g model. In this study, a series of vertical loading tests was conducted for three type of foundation model. These three types of foundations have respectively 9 piles embedded in rigid raft, flexible raft and free headed.

2 MODEL FOUNDATION AND TEST PROCEDURES

2.1 Loading devices and instrumentation

The centrifugal acceleration employed in the present study was 50g. Figure 1 shows a schematic illustration of the model setup for this study. A model container used for the test is a rigid box with inner dimensions of 120cm in length, 80cm in width and 72cm in depth. Vertical loading test is carried out by displacement control with constant loading rates of 0.01mm/s. The hydraulic jack is used to apply the vertical load. A force sensor with a range of 2200daN was used and four displacement potentiometers have been placed at the four corners of the raft. All foundations models were placed as shown in figure 2 in the same container.

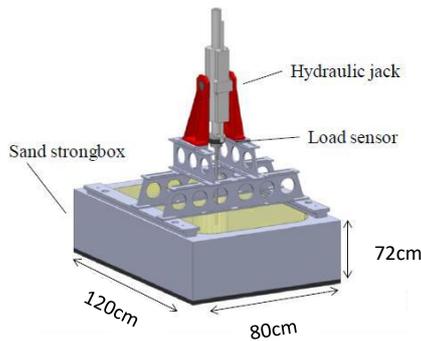


Figure 1. Model setup

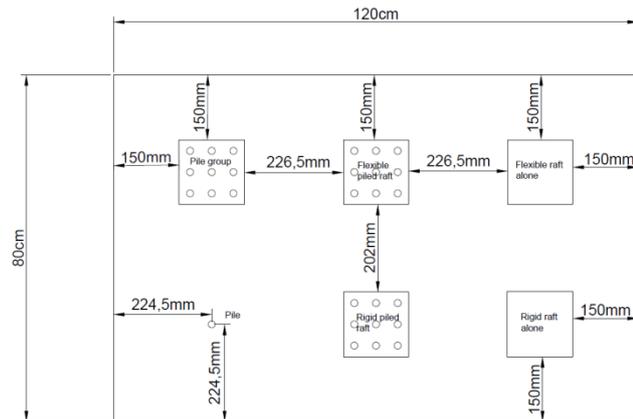


Figure 2. Model foundation position in container

2.2 Model foundations

In the present study static vertical loading tests were conducted on the pile group and two piled rafts. Figure 3 shows the raft and the pile models used in the centrifuge tests.

The model pile was made from brass with 17mm outer diameter and 0.72mm of thickness. A plastic made cap was inserted on the pile tip to close the pile. An optical fiber was glued on the both side of the pile to measure the strain. The optical fiber forms a loop at the tip of the pile to measure the pile tip resistance. To attach the optical fiber at the side of the pile, a groove was made in the pile with a very small width and depth. After this, a two-component adhesive was used to implement the fiber inside the groove. The glue creates a relatively smooth and uniform pile surface. In the present paper, the results of the optical fiber located in pile will be not shown because of lack of place in this paper.

The piles were rigidly fixed to a steel raft with 150 x 150mm. There is two type of raft model. A flexible raft model with 2mm of thickness and a rigid raft model with 15mm of thickness. The raft was composed of 9 holes for embedding 9 piles with pile spacing of 3 diameters as shown in figure 3.

The raft model and the piles were used for the test of piled raft, pile group, raft alone and single pile. For the pile group, the rigid raft was used and a gap between the ground surface and the raft base was provided. The piles in the pile group were embedded into the ground at 24cm as the same in each test. Table 1 summarize the specifications of the pile and raft both in model scales.

The soil was instrumented by optical fiber to measure the strain of the ground under the raft base and between the piles. The optical fiber is set up just before the end of the sand pouring with different spaces between each line of the fiber. It is placed considering the position of each foundation and so as not to damage the optical fiber during the installation of the foundations as shown in figure 4.

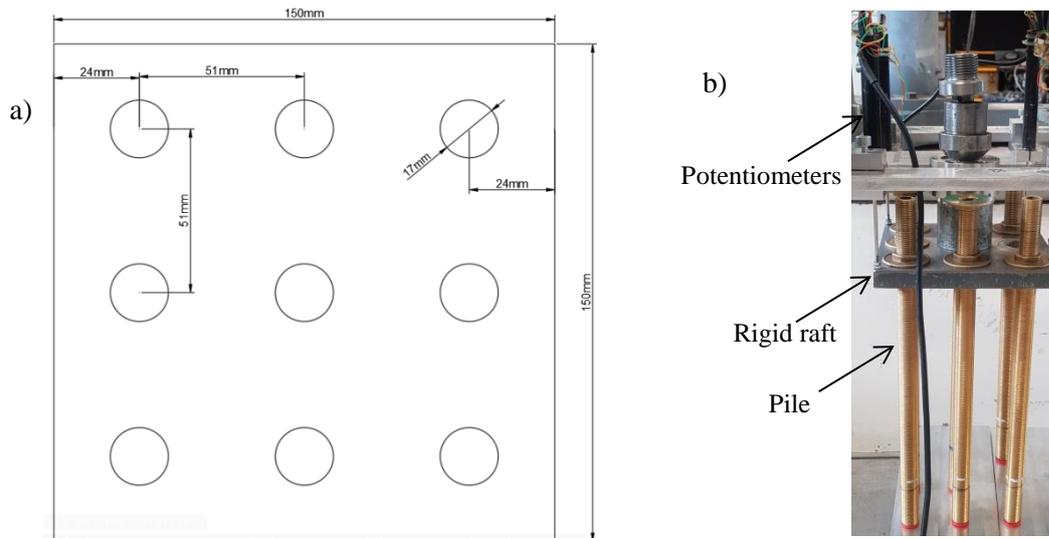


Figure 3. a) Raft model ; b) Piled raft model

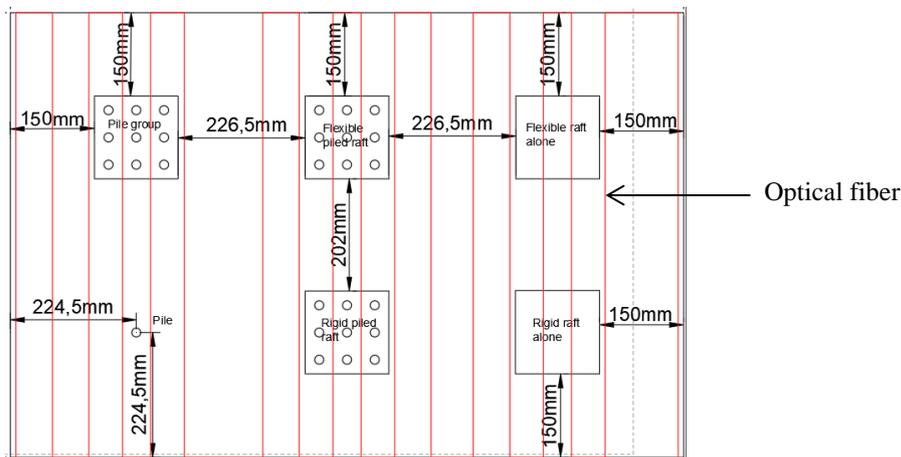


Figure 4. Optical fiber implementation plan

Table 1. Specification of models foundations

Properties	Flexible raft	Rigid raft	Pile
Thickness (cm)	0.2	1.5	
Length (cm)	15	15	
Width (cm)	15	15	
Diameter (cm)			0.17
Embedment depth (cm)			24
Materials	steel	steel	brass
Young modulus (GPa)	210	210	105

2.3 Soil and model preparation

The soil used for the tests was Hostun sand referred as HN31. The characteristics of the sand and the grain size are presented in Table 2. A soil at a required density in the laboratory is fundamental for the solution of geotechnical problems. Sandy soils are reconstituted in the laboratory using various methods: sand pouring or vibration. Sand pouring particles is the preferred method. It produces homogeneous samples and reproduces the natural deposition process of sands (Le Kouby, 2003).

Table 2. Physical properties of Hostun (HN31) sand

Properties	
Mean particle diameter, D_{50} (μm)	341
Maximum void ratio, e_{max}	0.961
Minimum void ratio, e_{min}	0.624
Solid particle density, ρ_s (g/cm^3)	2.65
Maximum particle density, ρ_{min} (g/cm^3)	1.59
Minimum particle density, ρ_{max} (g/cm^3)	1.32

Densification by sand pouring is effective for drop heights between 0 and 50cm (Vaid and Negussey, 1984, Levacher et al., 1994). For the sand used during these tests, a logbook of the different heights and rates allowed the determination of the parameters required to obtain a relative density of 80%.

After the sand pouring of the model ground, the piled raft foundation was driven in the soil at 1g with a rate of 0.1mm/s. The piles attached to the raft were penetrating into the ground vertically using the rotule. During the process of driving pile, the force and the displacement were capture to determine the contact of the raft bas on the ground surface for each piled raft model. After the penetration of the foundation the instrumentation of the potentiometer has been made and then the centrifuge acceleration was increased up to 50g.

3 RESULTS AND DISCUSSIONS

3.1 Load-displacement

The foundations were driven in soil at 1g as explained in section 2.3. Figure 5 shows the load-displacement curve of different foundations during the installation. The load-displacement curve of the pile group is continuous and stopped when the pile reach a depth under the ground of 24cm. The load-displacement curve show a displacement of 21cm because of the pile group weight when it was placed on the ground and the piles sunk a few centimeters. The rigid piled raft and the flexible piled raft present a slope discontinuity at the end of the loading. As the base of the raft reaches the surface of the ground, the load increases substantially, but the movement increases slightly. This variation of the load is caused by the raft base pressure. When the contact between the raft and the soil is made, the rotation of the centrifuge starts to reach 50g.

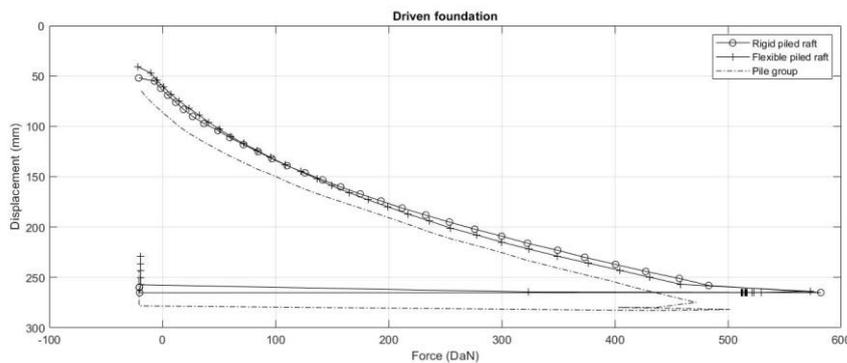


Figure 5. load displacement curve of driven pile group, rigid piled raft and flexible piled raft

At 50g the load-displacement is shown in figure 6. The test experiment could reach small displacement because of the force sensor is limited at 2200daN. The load of the pile group, rigid piled raft and flexible piled raft is shown in the same figure. It is shown that the load carrying by the flexible piled raft is more resistant than rigid piled raft. The pile group is less resistant than other. The flexible piled raft had settled by 1mm for 2200daN, 1.5mm for rigid piled raft and 1.95mm for pile group. However, the figure 7 shows the displacement of the piled raft and group with the displacement sensor of the hydraulic jack. The flexible piled raft had settled more than the other foundation, with a settlement of 9mm. The difference with the figure 6 and 7 is that the flexible raft is loaded at the center of the raft. This occurs a bending of the founda-

tion. The potentiometers placed at the corner of the raft are not moving during the test. The piles have undergone a bending moment and were not working. The entire load was concentrated on the center of the raft.

The figure 9 shows the load-displacement between the rigid piled raft and the pile group. The variation of the resistance between the two of them is due to the contact of the raft on the ground. More the load is increasing, more the gap between pile group and piled raft is increasing. It shows that the raft is an immediate asset and transfers a small part of the load to the ground. The difference of these curves is the load carrying by the raft. The development of the difference of the settlement between the pile group and the piled raft during the reloading is shown in figure 8. This difference is the expression of the resistance provided by the raft in the piled raft foundation. This variation is linear for the most part of the reloading until 1500daN and reached a level of 2.25mm for the rest of the loading process. This level of settlement means that the raft is providing the same resistance between 1500daN and 2200daN. To better understand the behavior of the raft, further tests are required.

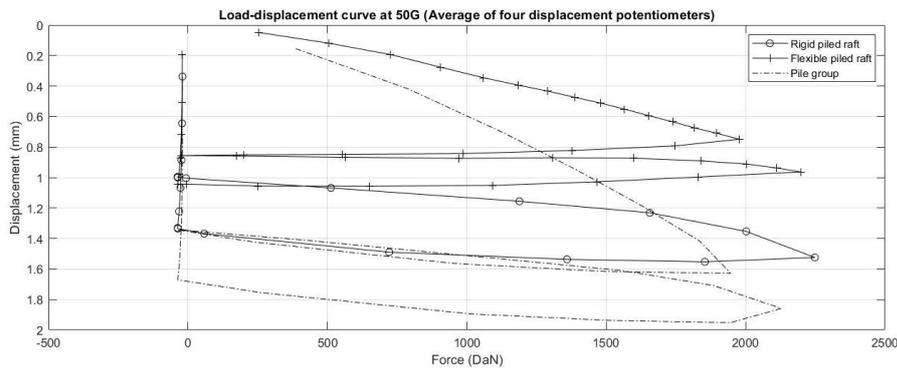


Figure 6. Load displacement curve at 50G (average of four displacement sensor)

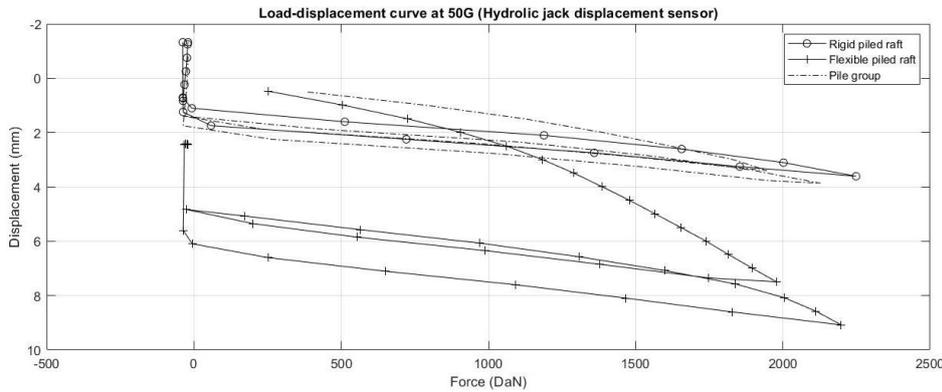


Figure 7. Load displacement curve at 50G (hydraulic jack displacement sensor)

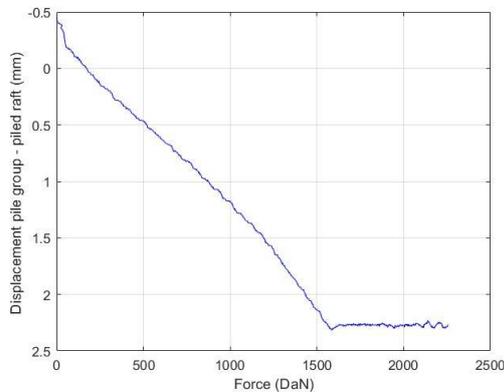


Figure 8. Difference of settlement between pile group and rigid piled raft

3.2 Strain in ground

In this section, the results of the strain measured in the ground with the optical fiber will be shown for the rigid piled raft at 2200daN. The variation of the strain in the ground between the piles for a load at 2200daN is shown in figure 10. The strain is increasing at the center of the raft and decreases as you get closer to the ends of the raft. For the optical fiber, positive strain means an extension deformation. Figure 11 shows the extent of the deformation in the container at 2200daN. The deformation decreases with a nonlinear curve and tends toward 0 closer to the edge of the container.

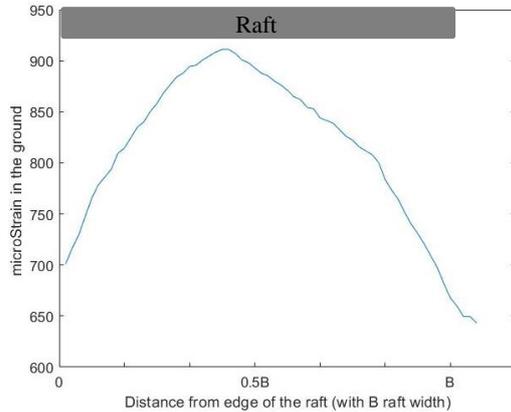


Figure 10. Deformation measured under the raft base

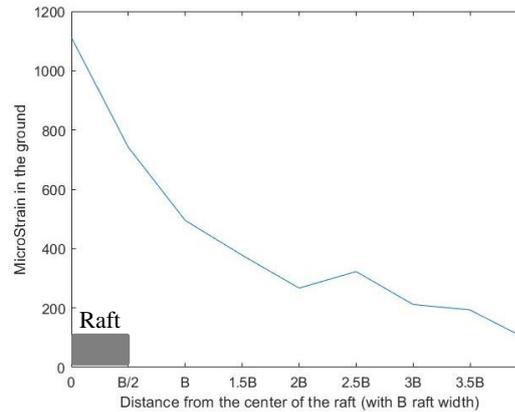


Figure 11. Development of the deformation between the center raft and the wall of container

4 CONCLUSION

To conclude, models of three type of foundation were tested in centrifuge. Rigid piled raft foundation, flexible piled raft foundation and pile group were loaded vertically at 50g. The results shows that the flexible raft has a very low stiffness and bended in the center of the raft. The rigid raft shows that compare to the pile group the resistance provided by the raft was increasing and reached a level without evolution. The results shows that the force sensor was low compare to the resistance of the foundations. It should be more tests with higher level of force load. The results of the optical fiber in the ground show the evolution of the strain under the base of the raft and around the raft until the edge of the container as expected.

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