Physical Modelling in Geotechnics

Physical & numerical modelling of piled rafts under lateral loading

Z. Katsanevaki, G. Viggiani & G.S.P. Madabhushi
Department of Engineering, University of Cambridge, UK

ABSTRACT: Piled rafts represent an interesting soil-structure interaction problem, which has been extensively studied both by numerical and reduced scale physical modelling. Most of the research effort has been devoted to piled rafts under vertical loads, for which rational design procedures have been developed that take into account the collaboration of the raft and the piles in determining the overall stiffness and capacity of the foundation and permit to control differential settlements and reduce bending stress in the raft. Physical modelling of piled rafts under complex loading including significant lateral components is rather challenging. One of the reasons for this is that conventional aluminium alloy hollow sections, typically used for model piles, do not represent correctly the behaviour of prototype reinforced concrete piles failing in combined compression and bending. This paper presents the results of a centrifuge test carried out at 100g in which a reduced scale model of a raft on a 4x4 group of 20 m-long and 1 m-diameter piles was brought to failure under horizontal loading. The model consisted of an aluminium rigid raft and reinforced micro-concrete piles embedded into a thick layer of soft clay. The results show that the structural strength of the piles governs the failure mechanism with the formation of two plastic hinges on each pile. The experimental results and their interpretation by numerical analysis indicate that the second plastic hinges in a row of piles in the direction of the lateral load follows a parabolic trend with the plastic hinges on the external piles formed at a lower depth.

Keywords: soil-structure interaction, reinforced concrete piles, piled rafts, centrifuge modelling, numerical modelling.

1 INTRODUCTION

Piled rafts are a common type of foundation for tall structures such as, *e.g.*, high-rise buildings, bridge piers, and wind turbines on weak soils where shallow foundations may not be able to meet bearing capacity (ULS) and settlement and rotation demands (SLS) with sufficient safety factors. The behaviour of piled rafts under vertical loading conditions has been studied extensively in the last three decades both experimentally and numerically. However, critical loading conditions for these structures typically include significant horizontal loads and therefore moment loads on the foundation. Full scale models of piles and pile groups under axial, lateral or bending loading have been performed at 1-g (Kim *et al*., 1979; Brown *et al*., 1988; Rollins *et al*., 1998). Since full-scale modelling can be very expensive and challenging when dealing with structures of such big size in soil, the behaviour of piled foundations has also been explored using small-scale physical modelling at 1-g (Cooke, 1986; Fukumura *et al*., 2003; Matsumoto *et al*., 2004). However, if the size of the model foundation becomes too small, the stress state in the soil and hence its mechanical behaviour may not be representative of the prototype.

Centrifuge modelling takes advantage of the increased gravity field and allows modelling the prototype structure and soil in a smaller scale predicting at the same time the actual stress state. Geotechnical centrifuge tests on piled rafts have been successfully implemented (Horikoshi & Randolph, 1996; Conte *et al*., 2003; Nguyen *et al*., 2013; Sawada & Takemura, 2014; Park & Lee, 2015), mostly focused on the bearing capacity of the system and the control of the settlements due to vertical loading. In all the studies quoted above, the piles were modelled using aluminium alloy hollow sections. This is an optimal way of modelling piles under vertical loads. However, for loading conditions that include significant horizontal actions, aluminium sections are inadequate to replicate the behaviour of an actual reinforced concrete section (Katsanevaki & Viggiani, 2022). Only very recently have experimental attempts been made to investigate the possibility of creating pile sections for centrifuge tests that simulate the actual behaviour of the RC section (Knappett *et al*., 2011; Louw *et al*., 2020).

2 MODEL PREPARATION

Based on the construction process of small RC piles for geotechnical centrifuge testing developed by the authors (Katsanevaki & Viggiani, 2022), this paper presents the model preparation and the results of a centrifuge test of a piled raft that fails under horizontal loading.

The prototype piled raft comprises 16 reinforced concrete piles with a diameter of 1 m and a length of 20 m arranged in a 4×4 group. The pile spacing, *i.e.*, the

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distance between the pile axes, is 4 m. The pile heads are fully restrained at the connection with the rigid raft. The raft is square with a dimension of 14 m and it is in contact with the soil surface. The structure is founded on soft clay with an undrained shear strength increasing with depth. The model was tested at a nominal centrifugal acceleration of 100*g*.

2.1 Model raft

The model raft consists of a solid aluminium rigid plate with a thickness of 12 mm and holes with the same diameter of the pile drilled with in a 4×4 symmetric pattern. To record the vertical load at the pile heads while ensuring a rigid connection between the RC pile and the aluminium raft, a double raft had to be adopted, as shown in Figure 1. A second aluminium plate with the same geometry was added on top of the main plate. The top plate is bolted on three 5-mm thick aluminium plates. These 'knives' are used as spacers between the raft and the top plate. Any load cells or studs bolted on the pile heads pass through the top plate and are fixed on it with nuts above and below the plate. The pile-raft connection is hence rigid and any load applied to the top plate is transmitted to the raft and the piles through the knives and the studs or load cells respectively.

2.2 Model soil

The model clay soil is prepared from a mixture of Speswhite Kaolin clay and de-aired water in a 1:1.20 ratio poured in a 850 mm diameter centrifuge container with 400 mm height. A 40 mm thick sand layer of Fraction B Leighton Buzzard sand, which allows water flow downwards into an external pipe, underlays the clay slurry. Water is also free to flow upwards to the free-soil surface. The slurry undergoes two-way drainage consolidation at 1*g* using a computer-controlled hydraulic pump developed at the Schofield Centre, University of Cambridge (Madabhushi, 2015). External load is applied on the soil surface through a piston. The maximum consolidation pressure is 70kPa and corresponds to a point load of 40kN at the piston, which is applied in increments. To obtain an undrained shear strength profile increasing with depth, suction is applied to the bottom drainage using an external vacuum pump. Suction is again applied incrementally until a maximum of 70kPa. At the end of consolidation, the clay surface is scraped down to the desired clay thickness of 300mm. Further consolidation will take place in-flight in the centrifuge at 100 *g*-level.

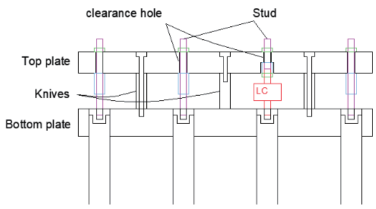

Fig. 1. Pile-raft connection.

2.3 Installation of raft and instrumentation

After 1g consolidation, the RC piles are driven vertically in the soil at the desired positions. To avoid high stresses in the soil and damage of the RC piles during installation, holes are preliminary created into the model soil using an auger. To ensure contact between the piles and the soil, the diameter of the auger is a little smaller than the pile diameter. The raft, *i.e.*, the ensemble of bottom and top plate and knives, is then assembled to include the miniature load cells at the pile heads.

The piled raft examined in this paper was tested under lateral load and the small vertical load corresponding to the self-weight of the raft. Considering the small thickness of the raft relatively to the size of the actuator and other layout restrictions, since more piled rafts with different configurations were also tested in the same flight, the actuator was placed vertically. Lateral displacement is applied to the raft with a system consisting of a pulley and a cable connecting the tip of the actuator with the side of the raft, as shown in Figure 2. A horizontally placed load cell records the total load applied to the piled raft and an LVDT the horizontal displacement of the raft. Because an additional settlement of the soil and hence of the piled raft is expected during the in-flight consolidation, there has to be a starting cable inclination for the cable to be horizontal at the end of the in-flight consolidation.

3 EXPERIMENTAL RESULTS

3.1 Soil

The undrained shear strength of the soil was measured using a T-bar penetrometer with a projection surface 4×40 mm^2. The T-bar records the soil resistance with depth, which is then converted to undrained shear strength. Because of limitation in the stroke of the actuator, the measurements are taken down to a depth of around 165 mm. Figure 3 illustrates the measured undrained shear strength profile at prototype scale, with an average value of about 12 kPa to a depth of about 14 m, and then gradually increasing with depth, by about 1 kPa/m.

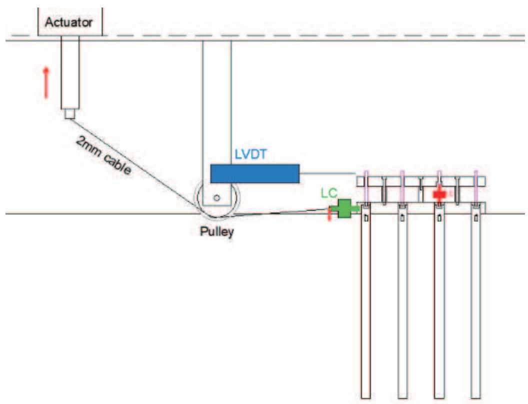

Fig. 2. Loading assembly for the laterally loaded piled raft.

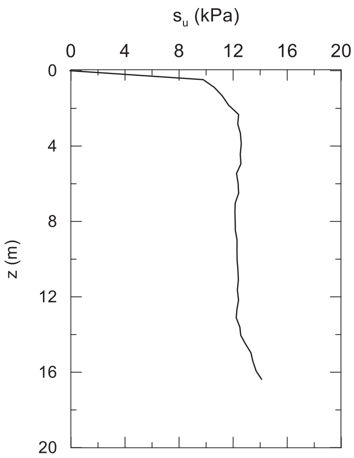

Fig. 3. Undrained shear strength profile from T-bar measurements.

3.2 Lateral Capacity

Figure 4 shows the lateral load – displacement curve for the prototype 4×4 piled raft. The initial response of the foundation is very stiff, possibly due to a small initial embedment of the bottom plate of the raft. In fact, the self-weight of the piled raft results in settlement of the group during in-flight consolidation, which is larger than that of the soil surface in the far field. The lateral stiffness then reduces until the piled raft reaches its peak horizontal capacity of about 8500 kN for around 0.5 m displacement. Softening occurs after the peak strength, with a sustained value of horizontal capacity at large horizontal displacement (2.5 m) of about 6200 kN.

3.3 Plastic hinges

The failure mechanism as uncovered after the test is shown in Figure 5 for an external and an internal row of piles. In both cases, the piles failed with the formation of one plastic hinge at the pile head and one at depth. The depth of the second plastic hinge varies from one pile to another as indicated by the parabolic trends in Figure 6. To exclude the possibility that the observed trends may be due to inconsistencies in the strength of the manually produced piles, the expected failure mechanism was examined also numerically.

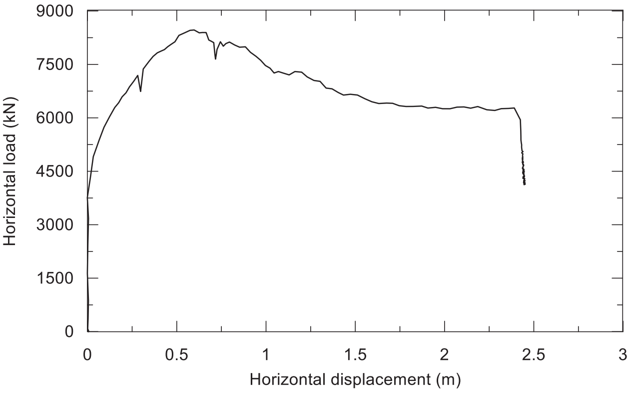

Fig. 4. Horizontal load – displacement curve for the 4x4 piled raft.

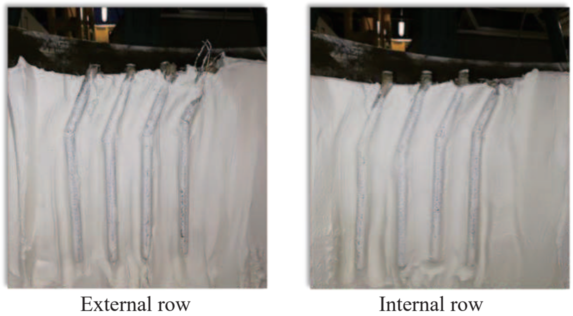

Fig. 5. Failure mechanism uncovered post-test.

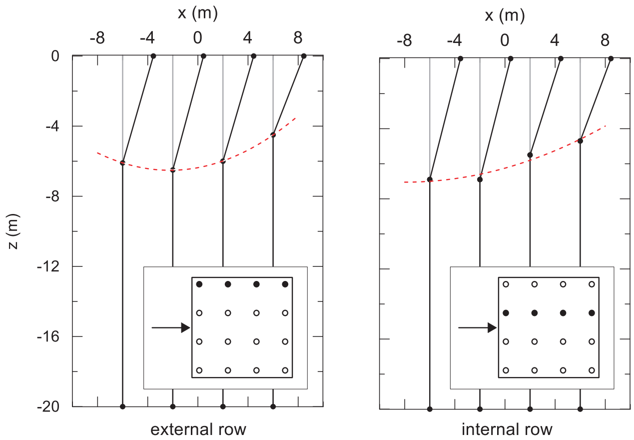

Fig. 6. Trend of the position of the second plastic hinge, post-test.

4 NUMERICAL ANALYSES

4.1 Numerical model

Two different pile sections were implemented in the numerical model to represent the actual RC section consisting of (a) an equivalent homogeneous isotropic elastoplastic material and (b) concrete with an embedded steel tube. Both sections had the same estimated plastic moment of the model piles. An undrained analysis in total stress using an elastic-perfectly plastic constitutive model for the soil with a Tresca failure criterion was performed. The raft was modelled as rigid and cohesive interfaces were included between the soil and the structural elements. The profile of undrained shear strength was the same as that determined experimentally.

4.2 Numerical Results

The two models confirm the formation of two plastic hinges on each pile following the parabolic trend observed experimentally. Figures 7 and 8 illustrate this trend in an external and an internal row for the homogeneous and the RC section respectively. The second plastic hinge on the two external piles of each

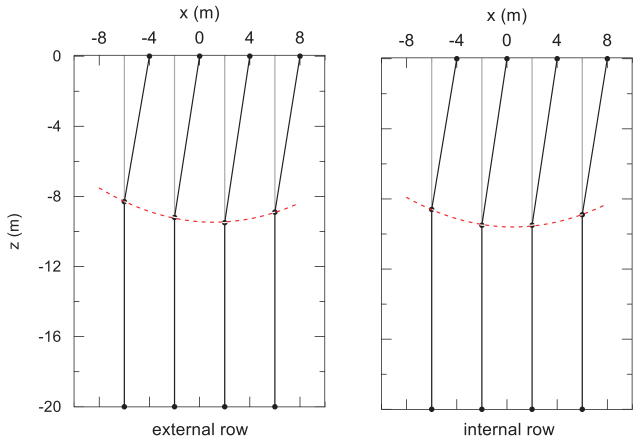

Fig. 7. Second plastic hinges, homogeneous section.

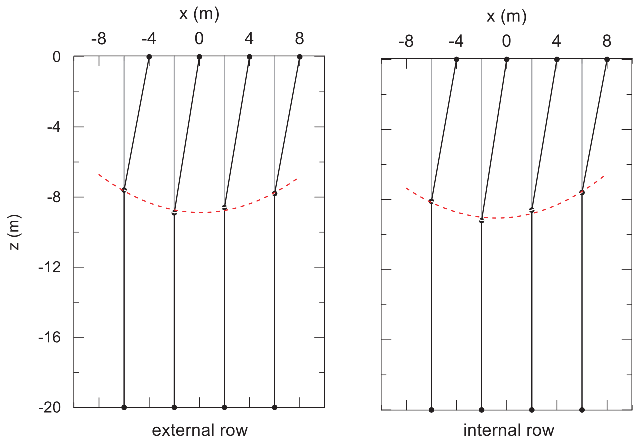

Fig. 8. Second plastic hinges, RC section.

row is formed at a shallower depth than on the internal piles. This is probably due to the initial non-uniform distribution of vertical load due to the self-weight of the raft, with the internal piles receiving more load than the external. It can be therefore concluded that the piles with higher normal load fail at a higher depth. As regards the two ways of modelling the pile section, the simple homogeneous section results in a very similar trend of the second plastic hinges, with maximum differences of about 5%. Loading conditions in which some of the piles may be undergoing tension would probably result in large differences between the two different modelling techniques for the piles.

5 CONCLUSIONS

Miniaturised RC model piles were successfully implemented in a centrifuge experiment on a piled raft taken to failure under lateral load. The model piles behaved as expected, with the formation of two plastic hinges at failure; the first at the pile head and the second at some depth. The trend of the second plastic hinges in a row of piles in the direction of loading resembles a parabola. This has been confirmed by a numerical study replicating the experimental conditions with two different ways of modelling the pile section; a homogeneous and a RC section. In any case, it is observed that the normal load on the pile affects the position of the second plastic hinge. The higher the normal load, the deeper the plastic hinge. For the case of the rigid raft, where the external piles receive higher vertical load, the second plastic hinge on those piles is at a lower depth than the internal piles.

ACKNOWLEDGEMENTS

The present study was supported by the Cambridge Trust and the EPSRC.

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