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Pile and Pile Group Capacity: Some Findings from Centrifuge Tests

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Abstract

The London Geotechnical Centrifuge Centre at City University London is a major experimental research facility for the Geotechnical Engineering Research Group. Some findings from two recent doctoral research projects are presented. The projects were aimed at improving our understanding of piled foundations. Pile group behaviour was studied with particular emphasis in determining the efficiency and load capacity of non standard group arrangements. The project was related directly to a development in London UK in which high capacity foundations were constructed using a Perimeter group arrangement of minipiles since that was all that could be constructed given onerous site constraints. The centrifuge research gave new insights into how pile groups carry large loads and demonstrated that Perimeter group arrangements make much more efficient use of piles than Grid groups. The second project was again industry driven and demonstrated that modifying the profile of a pile shaft can give significant increase in capacity with relatively little additional pile material.

Keywords **:** Pile groups, Pile capacity, Efficiency, Centrifuge modelling

1. INTRODUCTION

Urban renewal and regeneration projects are widespread in many cities around the world and developers are often promoting larger structures built within in more confined spaces. This often leads to complex foundation design affected by difficult site constraints and sometimes with the need to maintain some over ground services while generating new foundations in confined basements in preparation for later superstructure construction. A couple of questions emerging from these demanding conditions are can pile groups constructed with small scale equipment (i.e. minipiles) be used efficiently to carry large loads and can the capacity of individual bored piles be increased without necessarily increasing either the diameter or length of the foundation. These issues, for which there is direct industry interest, have been investigated in two recent research projects at City University London.

Cannon Place was a £360M redevelopment in the City of London and used a piled foundation system that was believed to be the first of its kind (Hayward, 2009; Martin et al., 2009). Pile installation methods have been developed that allow piles with high slenderness ratios to be installed at a close centre-to-centre spacing with high accuracy. These techniques enable ‘perimeter groups’ to be formed, which enclose a body of soil in the centre of a group, with closely spaced piles installed around the perimeter. The foundations of the Cannon Place development include 11 such perimeter groups. This led to a research project exploring aspects of this novel foundation method, which involves the installation of closely spaced piles in a perimeter arrangement with a body of soil enclosed in the centre (Rose, 2012).

About a decade ago, Expanded Piling and Arup Geotechnics cooperated on a study to develop ribbed piles as a means to increase the shaft friction of bored piles. The jointly funded project (Anon, 2003) consisted of a limited number of full scale field trials, undertaken by Expanded Piling and supported by numerical analyses

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conducted by Arup Geotechnics. The field trials required preliminary development work on a special tool used for profiling the shaft of a bored pile. The analyses and tests yielded promising results and suggested that pile capacity could be increased by 30% – 40%. Subsequently, a research project was initiated at City University London that used centrifuge modelling techniques to investigate the relative behaviour of bored piles with profiled shafts compared to plain bored piles (Gorasia, 2013).

2. CENTRIFUGE MODELLING

2.1 Sample Preparation

Both research projects involved centrifuge modelling using Speswhite kaolin clay. This material is often used in centrifuge model studies due to its convenient supply in dry powder form and relatively high permeability making sample preparation reasonably rapid. The clay has the following properties: specific gravity: 2.62; liquid limit: 65; plastic limit: 30; critical state angle of friction: 22°. Each project required the development of specialist apparatus to facilitate the testing programme and used different model containers but many aspects of sample preparation were similar.

The clay was mixed into a slurry with water content of approximately 110 – 120% and then poured into a strongbox. A hydraulic press was used to consolidate the clay to a maximum vertical effective stress of 500 kPa. The consolidation pressure was applied in increments and the final pressure applied for a minimum three day period at which stage all measurable settlement had ceased. The pressure was then reduced to 250 kPa and the sample swelled for 24 hours. Pore pressure transducers were installed in the clay at this stage. These were used simply to indicate the progress towards effective stress equilibrium during the later centrifuge test. The consolidated soil sample was removed from the press for the model preparation phase.

2.2 Minipile Group Tests

2.2.1 Model Preparation

The aim of this research is to explore the behaviour of perimeter groups in firm to stiff clay under monotonic axial loading conditions. Complex centrifuge apparatus was developed to allow testing of multiple minipile groups within a single clay sample and to allow installation of piles with high positional accuracy. The results indicate that it is possible to achieve a group efficiency of greater than one, where group efficiency is defined as the ratio of the average load per pile in the group to the ultimate bearing capacity of a comparable single pile.

The rectangular strongbox used to contain the model was 200 mm wide, 550 mm long and 375 mm in height. The apparatus was designed to allow three or four pile groups to be tested in a single clay sample. The installation process is described by Rose and Taylor (2010).

The consolidated clay sample was trimmed in the strongbox to a height that would allow a gap of 10 mm between the base of the pile cap and the top of the clay and would also leave a distance of more than 100 mm between the toe of the piles and the base of the strongbox. The pile installation process was undertaken prior to the model being placed in the centrifuge. Installation at 1 g is considered acceptable since the analysis of results will focus on the relative load capacity values, rather than the absolute values. In addition, Craig (1984) found that when piles are installed at 1g the effects on subsequent behaviour are less pronounced in clay than in sand. The model pile is a 5 mm diameter aluminium rod and the toe of each pile was 250 mm below the surface of the clay model. The geometry of the scale model is 1:60, so an acceleration field of 60 g was applied to simulate the prototype. At prototype scale, the pile has a diameter of 300 mm, is 15 m long and the l/d ratio is equal to 50.

The pile installation process is shown schematically in Figure 1. The clay was extracted using a thin walled tube with an external diameter of 5 mm, which was pushed through the guide plate then through the pile cap located approximately 75 mm below. This process was adopted to maintain a good verticality. The cutting was repeated and the clay excavated in three sections for each pile (see Figure 3). The model pile is a 5 mm diameter and 270 mm long aluminium rod, which is placed into the hole and held down with a grub screw, which was tightened into the top of the pile cap. The toe of each pile was 250 mm below the surface of the clay model. The pile cap was an aluminium block with platforms at either end where probes from displacement transducers (LVDT type) could rest. Clay recovery during coring for the pile bore ranged between 65% and 85%, which was considered acceptable.

Once this process was complete, the pile guide and the pile cap holder were removed to leave just the pile cap

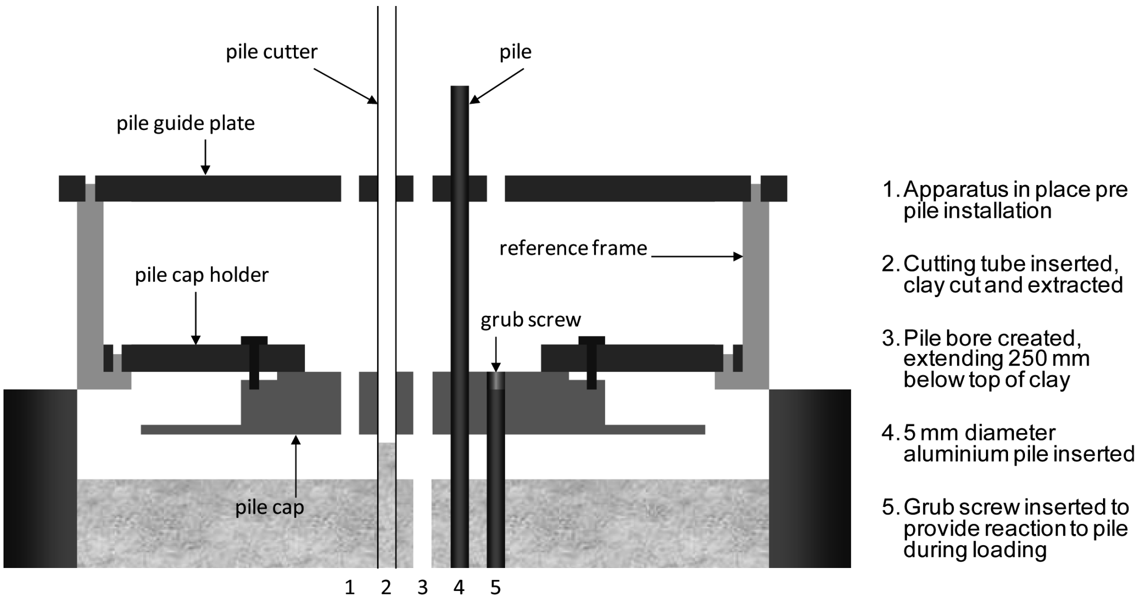


Fig. 1. Schematic showing pile installation process

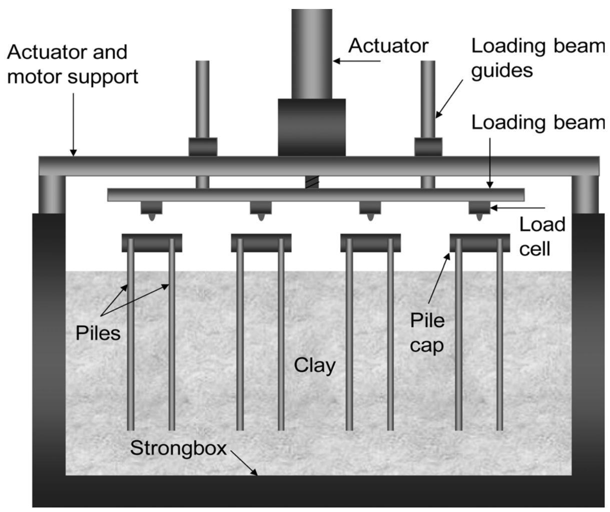


Fig. 2. Longitudinal section of strongbox (not to scale)

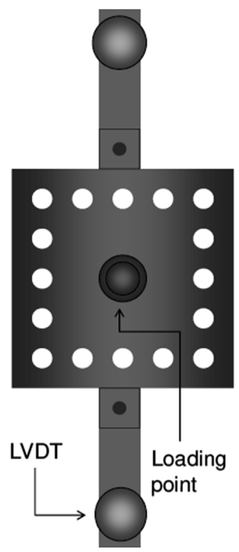


Fig. 3. Plan view of square perimeter pile cap (not to scale)

and the piles in place. Silicone fluid was used on the clay surface to prevent the clay from drying out and an up-stand ring around the outside of a pile group prevented any excess silicone fluid seeping between the clay bore and the pile shaft. The load guide was then located in the centre of the pile cap.

A 10 kN motor driven screw jack load actuator is bolted to the strongbox, which can apply a vertical force to each pile group via a guided stiff load beam. Load cells are connected to the load beam, allowing individual measurement of the force applied to each pile group. Each pile cap has a displacement transducer monitoring settlement at either end. The pile cap was an aluminium block with platforms at either end where the displacement transducer probes could rest. A diagram of the apparatus and all these components is shown in Figures 2 and 3.

2.2.2 Testing

Once the model had been placed in the centrifuge it was accelerated to 60 g; Figure 4 shows the centrifuge and the inset shows the strongbox on the centrifuge arm. The soil sample was allowed to come into effective stress equilibrium with the water table controlled by a standpipe connected to the base drain of the strongbox. This process took approximately 40 hours. The actuator was then advanced at a constant rate of 0.25 mm/minute. Axial loading was continued until no additional load could be sustained by

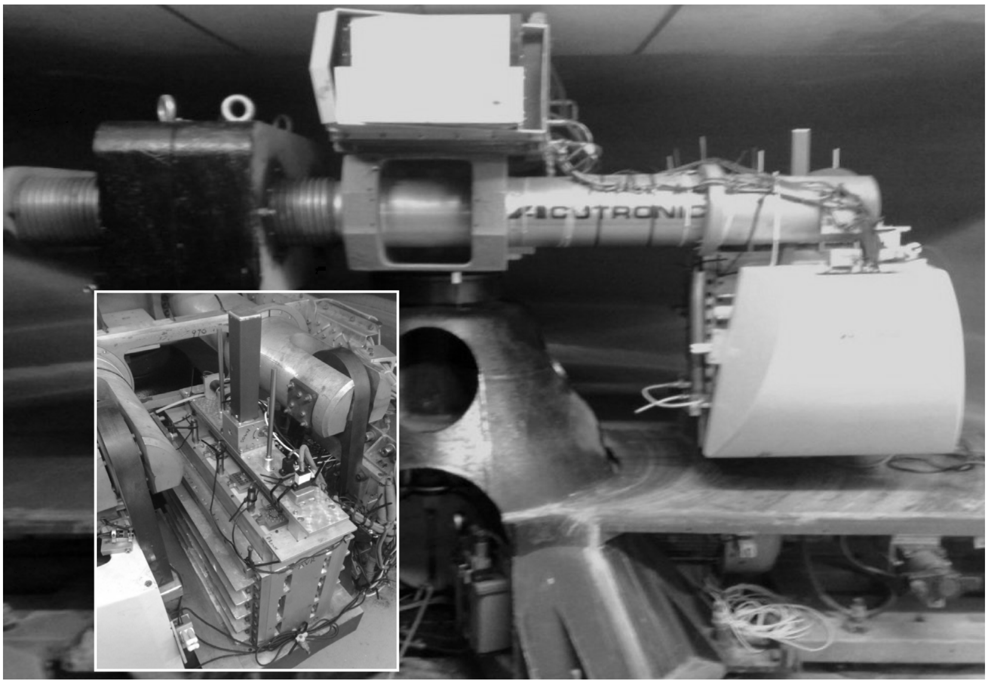


Fig. 4. The geotechnical centrifuge and model strongbox

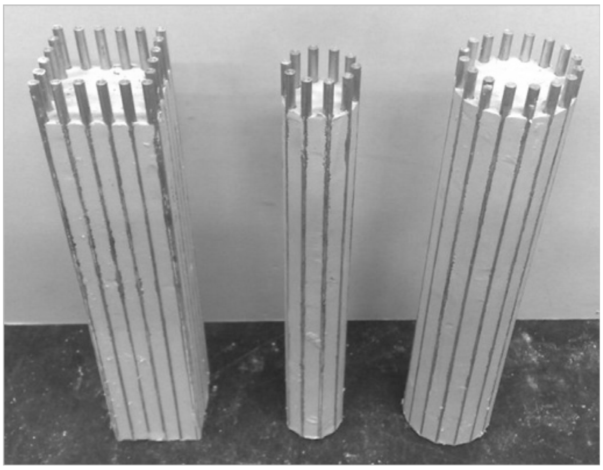


Fig. 5. Model perimeter pile groups after excavation from the clay sample

the pile groups.

Immediately after stopping the centrifuge, undrained shear strengths of the clay were measured at a range of depths using a hand vane. The model was carefully deconstructed and the pile groups excavated with minimal disturbance. Upon excavation, it was revealed that the verticality of the piles was exceptionally good (Figure 5).

2.3 Ribbed Pile Group Tsts

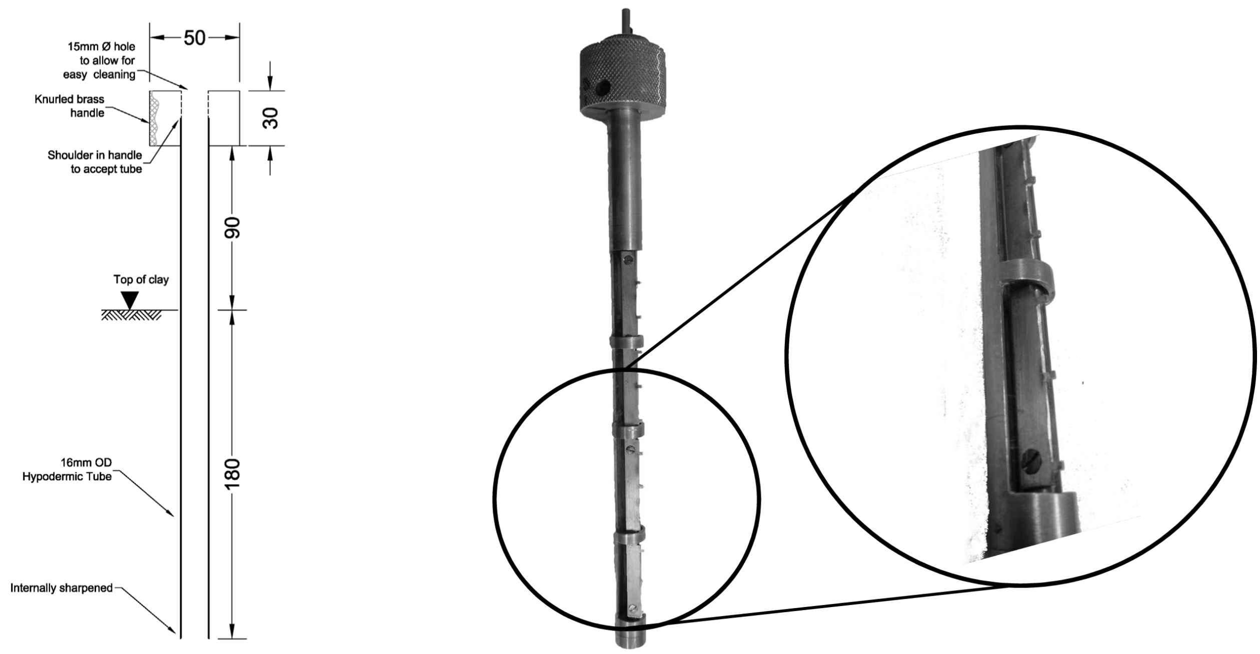
2.3.1 Model Preparation

The strongbox for these experiments was a 420 mm circular stainless steel container. Each experiment had three testing sites within the soil model; two of the sites were used for piles and the third for a T-bar penetrometer, used to measure the undrained strength of the clay. Since the soil container was cylindrical, it was decided to locate each test site on a pitch circle diameter of 240 mm. This ensured that each site was remote from the boundaries of the container and also from adjacent test sites, so minimising any influence they may have on each other.

The piles used were nominally 16 mm in diameter by 180 mm in length. The centrifuge tests were conducted at 50 g giving an equivalent prototype scale of 800 mm diameter by 9 m long pile. For the ribbed piles the shaft diameter remained constant at 16 mm, and the ribs protruded outwards.

2.3.2 Pile Installation

The piles were made by first boring cavity and then filling this with resin to create a cast-in-place pile. The straight shafted pile bore was cut using a thin-walled stainless steel tube with an external diameter of 16 mm and wall thickness of 0.5 mm (Figure 1). The pile cutting tube was guided using collars to maintain a high positional tolerance and verticality. Several steps were taken to reduce the friction on the cutter and minimise soil disturbance within the pile bore. These included; the use of a spray silicone lubricant inside the pile bore to allow the cut soil



(a) (b)

Fig. 6. Apparatus for cutting model pile bores (a) straight shafted pile cutting tool; (b) rib cutting tool

to move more freely inside the tube, a sharpened edge on the tube and incremental boring in three equal stages.

The ribbed piles were formed by initially boring a hole in the clay using the straight shafted pile cutter and the shaft was profiled using custom made tooling. These apparatus are shown in Figure 6. The tool consisted of a brass tube with a section of the wall removed; a rotating rod is mounted with an interchangeable toothed plate positioned to one side of the tube. The cutting tool could then be inserted into the bore with the rib cutting teeth retracted. The inner rod was then be rotated exposing the teeth and therefore beginning the cutting of the rib, at that point the entire tool was rotated within the pile bore. Once the rib had been formed the inner rod could be rotated back into the tool, thereby forcing any spoil into the tube. The tool had been designed to make use of the same guide system used by the straight shafted pile cutter. This increased the accuracy of the pile boring system and also reduced the duration of the model preparation.

2.3.3 Pile Casting

McNamara (2001) experimented with several resins in attempt to source a resin that was capable of being poured at room temperature and could cure rapidly without excessive exotherm whilst providing good resistance to shrinkage. A suitable material was found to be Sika Biresein G27, a polyurethane two part "fast cast" resin, used commercially for complex and rotational moulding. The two parts were first mixed with an aluminium trihydrate (ATH) filler, and then mixed together. The casts were observed to shrink less than 1% during curing and the measured exotherm was found to be acceptable. The resin and filler mixture produced an easily pourable fluid, capable of filling the pile holes and leaving few if any voids. The fluid was found to have a pot life of 2 minutes and a curing time of 20 minutes. By experimentation, it was found that a mixture of 2 parts resin to 3 parts filler produced a reasonably pourable fluid resulting in good quality cast piles with a density of approximately 1800 kg/m^3; whilst this was not the same as concrete it was deemed sufficiently close.

The piles bores were cut and profiled in the clay sample immediately after its removal from the consolidation press. The resin was weighed out in its constitutive parts on the lab bench before being mixed together and loaded into a syringe. The syringe was fitted with an 8 mm diameter tube to ensure the resin was delivered efficiently to the bottom of the pile bore.

Owing to the manner in which the piles were loaded it was imperative that they were installed in the correct horizontal alignment and with good verticality. The pile cutting tools, therefore needed to be guided to achieve this, the design used a plate mounted on top of the soil container with two collars as shown in Figure 7. The

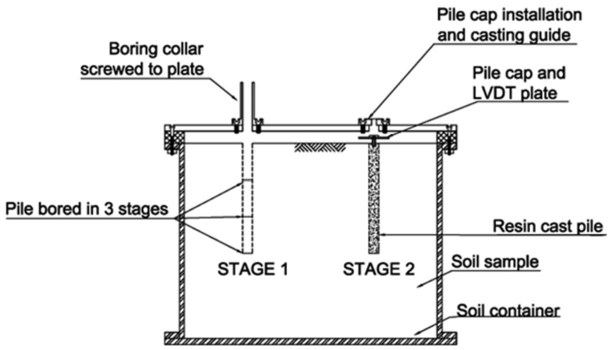


Fig. 7. Pile cutting plates and guide collars

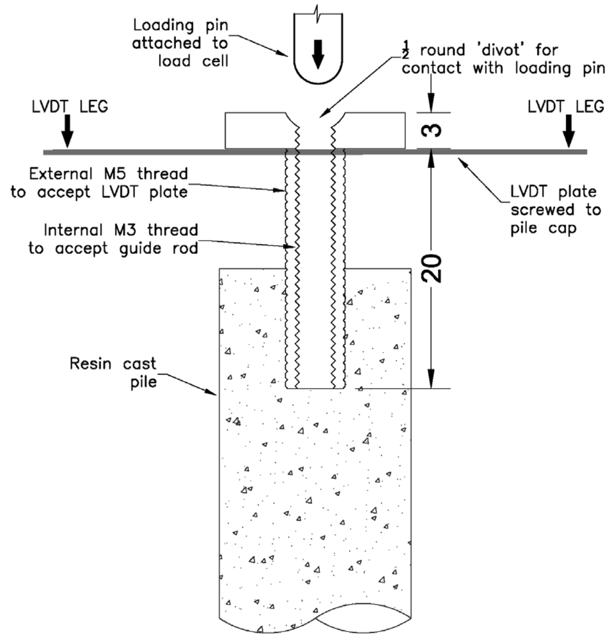


Fig. 8. Detail of model pile cap

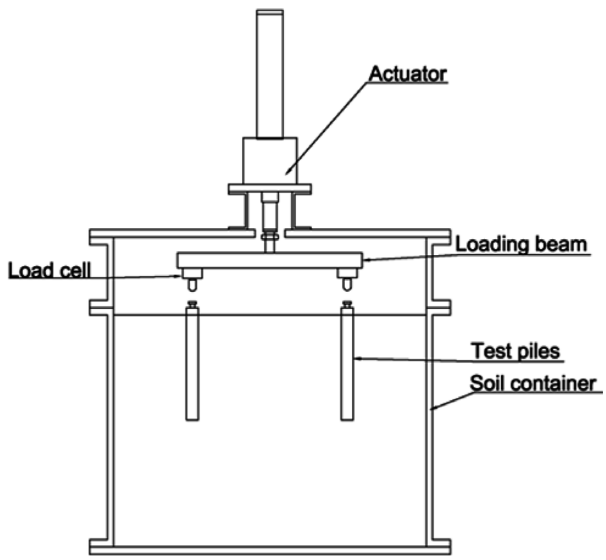


Fig. 9. Cross section showing ribbed pile loading apparatus

collars have a good fit with the outer diameter of the cutting tools and are sufficiently long to restrict horizontal movement.

2.3.4 Pile Loading

A pile cap provides the connection in between the superstructure and substructure. These centrifuge tests were focussed on the axial capacity of the foundation and the pile cap was designed to transfer only vertical loads and horizontal loads or moments. A load cell attached to the loading beam was fitted with a bull nose loading pin and this in turn sat in a matching recess in the pile cap as shown in Figure 8. The lack of mechanical connection and the bull nose profile at the point of contact ensured only an axial force is transmitted to the pile. The pile cap connected to a thin metal plate, on which two displacement transducers (LVDT) rested. This allowed measurement of pile settlement and also provided a check as to the verticality of the pile loading. The pile cap was cast into the model pile using a two part resin as discussed in section 3.4. To guarantee sufficient room for the test pile to settle, the underside of the pile cap was 10 mm above the top of the pile.

The piles were driven simultaneously with independent measurements for load and settlement. The most robust way of achieving this was by using an actuated lead screw, connected to a loading beam. The loading beam was designed to be sufficiently stiff, and therefore would not bend from being subjected to differential loads at its extremities. The loading beam had a threaded load cell attached, at the location of the piles. In order to ensure the loading beam descended vertically and in the correct position two 8 mm linear bearings and matching shafts were provided.

The screw jack, manufactured by Zimm was capable of providing 5 kN of axial force, and had a maximum stroke of 250 mm with a stroke per revolution of 1mm. The screw jack was driven by a Maxon motor and planetary gear head that used a gearbox ratio of 1:156 and was capable of providing 15 Nm of torque. Figure 9 shows a section through the piles and loading apparatus.

2.3.5 Pile Geometries

This paper presents a number of centrifuge tests with concentrically ribbed piles. In each test a 16 mm (800 mm at prototype) plain pile was also used in order to provide a control. The rib outstands and heights were constant for all tests (1.5 mm or 75 mm at prototype) and therefore the only variation between the tests was the distance between the ribs. Figure 10 show the range of tested pile geometries.

2.3.6 Centrifuge Model Testing

Model preparation typically took two hours from removal of the soil sample from the consolidation press to starting the centrifuge. It is normal practice to seal the surface of a clay model with silicone oil or similar to prevent drying during flight. However a preliminary trial showed that oil could easily be drawn into the void created around the ribs. In view of this it was decided that the top of the clay should be sealed with a spray on plastic. The product used for this is commercially known as PlastiDip. The spray on membrane sticks to the top of the clay and once dried (3-4 minutes) can be cut with a sharp scalpel, the cured membrane has been measured to be 400 microns thick. The PlastiDip was removed at both the pile test and T-bar sites, so as not to influence the test.

Testing consisted of accelerating the model on the centrifuge swing to 50 g and then waiting approximately 50 hours for pore pressure equalisation. Once fully hydrostatic pore pressures were established, testing of the piles could commence. The piles were loaded simultaneously at a rate of 0.25 mm/min for at least 12 minutes or 3 mm of settlement, whilst the T-bar was driven at a rate of 60 mm/min to a depth of approximately 200 mm.

3. RESULTS

3.1 Minipile Tests

The centrifuge test programme included a number of experiments in which the capacity of a single pile was measured and correlated with calculated load capacity based on the measured undrained strength profile. In this way, it was possible to determine the individual pile capacity for all the centrifuge samples tested and for the tests reported here the average individual pile capacity was 148 N. A diagram of the group arrangements is shown in Figure 11, and a selection of results from the tests are

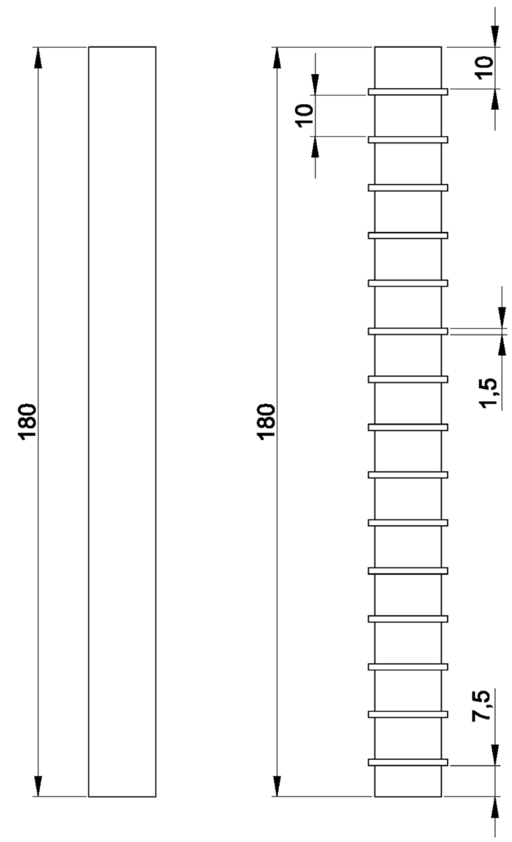


Fig. 10. Pile geometries and rib detail

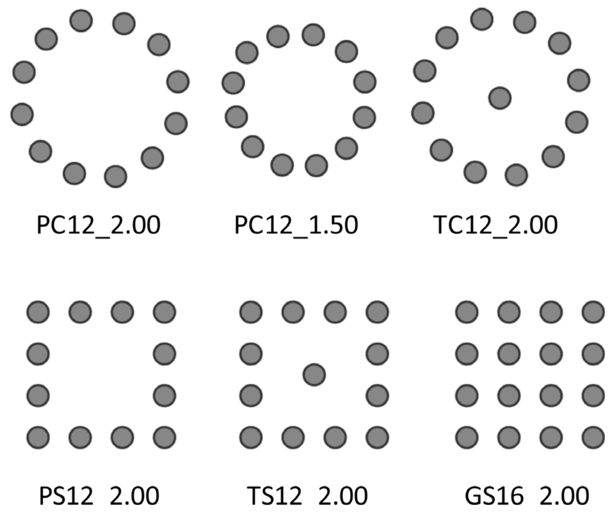


Fig. 11. Examples of pile group arrangements

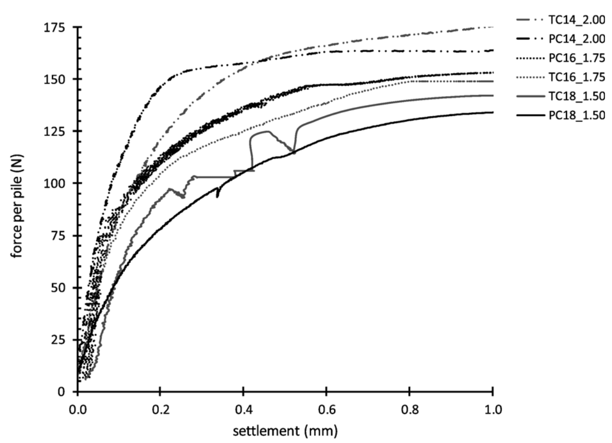


Fig. 12. Results from circular pile groups

presented in Figures 12 and 13. The nomenclature system used identifies each group by the pile arrangement (G: Grid, P: Perimeter and T: Target), group geometry (C: Circular and S: Square) and pile centre-centre spacing as a ratio of the 5 mm diameter d of an individual model pile. Target groups (T) are the same as Perimeter groups (P) but with the addition of a central pile, whilst Grid groups (G) contain all central piles.

Data from circular pile groups are shown in Figure 12. The load acting on a pile group has been divided by the total number of piles in the group to give force per pile and this is plotted against the average settlement determined from the transducers at either end of the pile cap. The erratic behaviour in the response from TC18_1.50 was due to a mechanical problem in the load actuator which was resolved for later experiments. In general terms, the responses are fairly consistent. All the groups shown had approximately the same circumference i.e. PC18_1.50 has more piles at closer spacing but the same overall diameter as group PC14_2.00. Taking into account the number of piles in each group, they are all supported approximately the same total force. This is an interesting observation for a series of pile groups with the same overall diameter but different number of individual piles. Interaction effects between adjacent piles resulted in smaller load carried per pile in groups with larger number of piles at closer spacing.

Figure 13 presents load vs. settlement data for a number of square pile groups. All the pile groups in this figure had the same pile spacing of 2 pile diameters. The group GS25_2.00 had 25 piles in total and had the same outer dimensions as groups PS16_2.00 and TS16_2.00. Group TS16_2.00 was the same as PS16_2.00 but with the addition of a central pile i.e. 17 piles in total. There are a number of points to note from this figure. There are two results from identical groups (TS16_2.00) that were tested in different centrifuge models. The test data are reasonably consistent indicating good repeatability. At the end of the test with a model pile settlement of 1 mm (i.e. 20% pile diameter) all the groups, which have the same overall footprint, were supporting approximately the same total force. As expected, this demonstrates that the central piles do little work. The force applied to a pile group is carried mainly by the external boundary piles leading to the grid group GS25_2.00 having the lowest average force per pile.

Group efficiency is defined as the ratio of the average load per pile in the group when failure occurs to the ultimate bearing capacity of a comparable single pile. Failure was defined to be at a pile or group settlement of 1 mm i.e. 20% of an individual pile diameter. The results from the pile groups above indicate that the efficiency of the groups varied between 0.81 and 1.18 (see Table 1). The Target group TS16_2.00 was tested twice, one of which showed considerable shear failure around the perimeter of the group, revealing that ‘block failure’ had occurred (Figure 14). The repeat test, while having a very similar capacity showed no obvious signs of developing vertical shear failure surfaces synonymous with block failure. Two tests of the same pile group exhibited a block failure mode and an individual pile failure mode which suggests this group and pile spacing are on the cusp of block failure. The equivalent Perimeter group (PS16) did not show obvious signs of a shear surface, although it did have a very similar overall capacity. A summary of failure modes is included in Table 1.

The observations of failure given in Table 1 suggest

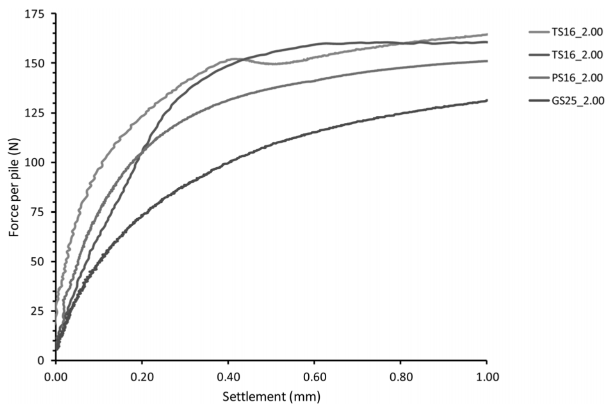


Fig. 13. Results from square pile groups (pile spacing 2d)

Table 1. Centrifuge testing summary

Pile group	Pile spacing	Pile group efficiency	Failure mode
GS25	2	0.81	block effect
PC14	2	1.07	individual
PC16	1.75	1.09	block
PC18	1.5	0.95	block
PS16	2	1.04	individual
TC14	2	1.18	individual
TC16	1.75	0.94	block
TC18	1.5	0.99	block
TS16	2	1.06	block effect

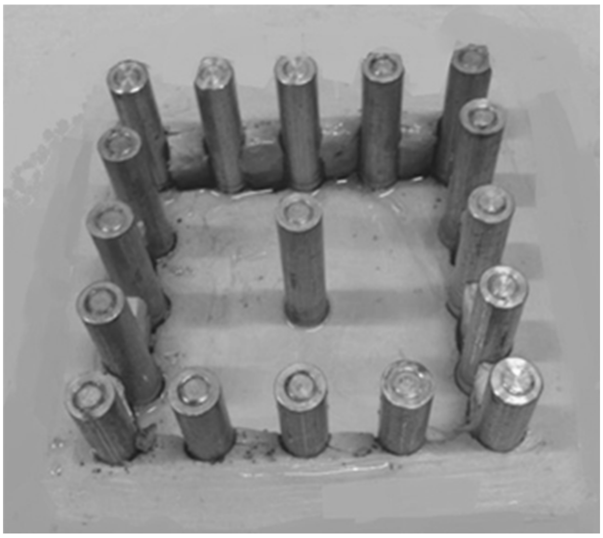


Fig. 14. Block failure of pile group TS16

that lower pile group efficiencies are observed when block failure occurs. If the piles fail individually, then the group tends to have a high efficiency and this mode of failure is more likely if the piles have a spacing of at least 2 pile diameters. Pile Group GS25_2.00 was repeated with a clear block failure occurring in one test and a hint of a block failure starting to develop in the repeat test which for unknown reasons had a greater soil strength. In later centrifuge tests, the soil surface was profiled before and after the test. With careful measurement, it was possible to detect if the central soil within the group perimeter had been pushed down relative to the outer surrounding soil during the pile group loading phase. This has been termed a block effect failure mode. Comparable geometry Perimeter groups and Target groups had similar efficiencies and failure modes. This suggests that the addition of a single central pile to form the Target group has little effect on the failure mechanism and force supported by each pile. However, since the groups have an extra pile relative to the equivalent Perimeter group then the overall pile group capacity will be increased.

3.2 Ribbed Pile Test Results

3.2.1 Verification Tests

Initial tests were conducted using two plain shafted piles. The purpose of these tests was to verify the consistency of the apparatus and testing regime. Two separate tests were conducted; Figure 15 shows the average load vs. settlement curves of the tests for both piles. The data show good consistency between the two piles and the

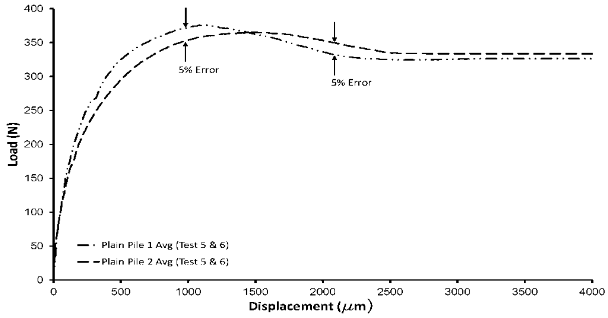


Fig. 15. Load settlement curves for verification tests

maximum error observed was less than 5%. This was then reasonably assumed to be the maximum error in any future tests.

3.2.2 Main Test Series

Figure 16 shows normalised load vs. settlement curves for the main series of tests. The figure shows data from piles with concentric ribs and also from tests where a special cutter was developed to create helical (spiral) ribs. In each test the pile rib height and outstand were kept constant, whilst the rib spacing was varied. The load data for each ribbed pile has been normalised against the straight pile in that test, thus eliminating any inconsistencies within the soil sample.

The data shows that piles with ribs spaced at 10 mm have the greatest increase in capacity when compared to a plain pile. This increase in capacity tends to reduce as the rib spacing is increased to 15 mm. With a rib spacing of 20 mm the load at the lower displacement range was less than that of a plain pile, but this quickly recovered and at larger displacements had a capacity in excess of the plain pile.

The helical rib tool was developed as there was some consideration that this might be an easier profile to cut in practice. As can be seen, the helical rib profiled piles tended to have a greater load capacity than the concentric ribs. This may be due to the total length of rib being greater or due to the inclination of the ribs. Further analysis is needed to investigate this.

The test series also included a 19 mm plain pile. The data are not shown in the figure, but this pile was found to have a capacity comparable to a profiled pile with ribs at 15 mm spacing. It was somewhat surprising that the profiled piles performed better than a pile with a diameter equivalent to the rib diameter.

Following completion of the tests the piles were removed

Table 2. Summary of pile test analysis

Pile shaft diam. (mm)	Rib type	Rib spacing	Improvement in capacity over 16 mm plain pile
16	Concentric	10 mm spaced	+34%
16	Concentric	15 mm spaced	+33%
16	Concentric	20 mm spaced	+20%
16	Helical	10 mm spaced	+56%
16	Helical	20 mm spaced	+24%
19	None (plain pile)		+27%

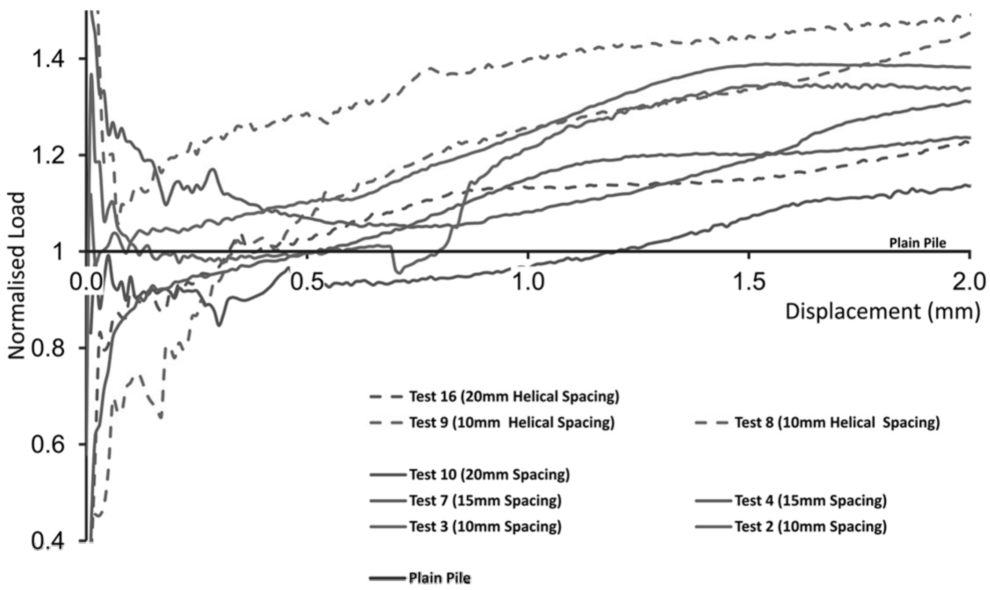


Fig. 16. Normalised load settlement curves for concentric ribs and helical ribs with similar spacing

from the model and it was observed in all tests that there was less adhesion between the straight shafted pile and the soil then with the ribbed pile.

3.2.3 Pile Data Analysis

The results of each test have been analysed using several pile test analysis techniques, including;

The Chin (1970, 1971) Failure Method, where failure is defined as the inverse slope of a load/settlement against settlement graph.

The BS8004:1986 Method, where the ultimate bearing capacity may be taken to be the load applied to the head of the pile, which causes the head of the pile to settle by 10% of the piles diameter.

The Fuller and Hoy (1970) Method, where pile failure is defined as the load corresponding to the point on a load movement curve where the gradient is equal to 0.14 mm/kN.

The Brinch Hansen (1963) Method, where by failure is defined as the load giving twice the movement at the pile head as is recorded for 90% of that load.

Of these various techniques for analysing failure, none proved to be more favourable or particularly consistent than any other. For this reason, all were used to define the failure load and the results of these analyses are present in Table 2. It is clear that at failure the 10mm ribbed pile was clearly the most optimised spacing, with a 34% improvement over the plain pile for concentric ribs and a 56% increase in capacity for the helical ribs.

Whilst the 10 mm spacing was shown to provide the most improvement, there is likely to be a point of diminishing return. This can be seen by comparing the 10 mm spaced ribs to the 19 mm plain pile which can effectively be thought of as a ribbed pile with zero spacing, since it has the same external diameter as that of the ribs. The 19 mm plain pile was clearly inferior to the pile with 10 mm spaced ribs. The improvement in ultimate capacity is likely due to the shear plane being moved from the pile/soil interface to one which is further away from the pile where the soil is less disturbed and hence more of the clays undrained shear strength can be mobilised.

4. CLOSING REMARKS

Two research projects involving centrifuge modelling of piled foundations have been presented. The two series of experiments each required successful development and commissioning of complex and novel apparatus to allow intricate experimentation. The research has demonstrated that geotechnical centrifuge modelling can be invaluable in giving insights into the failure mechanisms and behaviour of pile groups and single piles.

The tests on minipile groups demonstrated that piles need to be spaced at least 2 diameters apart if high efficiencies are to be achieved. As the spacing reduced below 2 diameters, the load carrying efficiency of a pile reduced and the failure mechanism changed to that of block failure. With this type of failure there appears to be less shear strain developed within the central soil column of the pile group leading to the low observed efficiency. Perimeter groups with the same overall footprint as a grid group was found to have the same overall load capacity suggesting both that the central piles within a Grid group carry only a small proportion of the applied load, probably due to interaction effects, and that in practice there can be good cost savings by only constructing the outer perimeter piles of a group. Target groups have a very similar behaviour to their corresponding Perimeter groups. It appears that het central pile is sufficiently remote so as not to suffer from adverse pile proximity interaction effects and it can add effectively to the overall pile group capacity.

The ribbed pile tests involved casting model piles into samples of overconsolidated clay. Good consistency in data was achieved by testing a ribbed pile and plain pile in the same clay sample. The results were remarkably consistent and demonstrated a significant increase in the piles ultimate bearing capacity; especially when closer rib spacing was used. Further research should allow an optimum rib spacing to be determined for both the concentric and helical rib arrangements which will then inform later design at prototype scale.

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