Centrifuge model testing for pile foundation re-use

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Abstract

With continuous development in the urban environment the ground is becoming more and more congested with redundant foundations. The underground development of services and infrastructure already restricts the location of new building foundations and the redundant foundations only add to this problem. This paper describes how existing single pile foundations in overconsolidated clay are likely to behave when their loading conditions are changed by un-loading caused by demolition and subsequent re-loading from a new development. The influence of any new foundations on the existing foundations is also described. Experimental data were obtained from a series of centrifuge model tests undertaken at 60g in which a number of different geometries of novel pile groups were modelled. Model tests included comparison of the behaviour of bored piles when supplemented with mini-pile groups.

1. Introduction

The redevelopment of inner-city sites is at a premium in many world cities with requirements for taller buildings (thus dealing with greater loads) and the number of sites where construction requires a third set of deep foundations increasing. The preference in recent years has been to ignore the existing foundations or remove them where necessary to make way for new foundations (Butcher et al., 2006). However in urban environments, underground services and infrastructure already, to some extent, dictate the location of building foundations and by continuing to avoid the existing piles the problems are exacerbated (Chapman et al. 2001). If the foundations are not avoided, then the engineer is only left with a choice of removing or re-using the existing foundations. Removal of piles is time consuming, costly (up to four times of the cost of constructing new piles) and environmentally damaging. It seems logical therefore that there may come a time when re-use of foundations will be the only practical solution.

Initiatives to encourage foundation re use have included the RuFUS (Reuse of pile Foundations for Urban Sites) project, funded by the European Union. This was undertaken in 2003 with the aim of providing ways to overcome technical and non-technical barriers to re-use of foundations for sustainable development. The project resulted in a "best practice handbook" (Butcher et al., 2006) on the re-use of foundations. Amongst the issues that detract from reusing pile foundations are concerns about the future performance of a foundation that has been subjected to loading conditions, the effects of which are unknown.

The research presented in this paper makes use of geotechnical centrifuge modelling to examine the behaviour of piled foundations in overconsolidated clays. The research undertaken is an investigation into behaviour of bored piles in overconsolidated clay when subjected to load cycles with a view to their re-use for future redevelopments. If the existing piles are to be re-used, then by understanding the behaviour of pile foundations when subjected to load cycles, a decision can be made on the magnitude of the load to which the existing piles can be re-loaded. If the capacity of the existing piles is not sufficient for the new development, their capacity will need to be enhanced. Consequently, the research sought to explore the possibility of improving the capacity of the existing piles by placing a ring of new mini-pile foundations around an existing central pile. This new mini-pile group was constructed around an existing pile that had previously been subjected to its working or even failure load. The geometry of the group, i.e. the number of the mini-piles, centre to centre distance between the existing and new pile foundation and length of the new foundations were all varied.

The aims of the research were to improve understanding of the pile soil interaction during load/unload/reload cycles, to investigate the influence of time on pile load carrying capacity and study the influence of new pile foundations on existing pile foundations during the life of the structure.

1.1 The geotechnical centrifuge at City University London

The Geotechnical Engineering Research Centre at City University London uses the Acutronic 661 centrifuge described by Schofield and Taylor (1988) and is shown schematically in Figure 1. It combines a swing radius of 1.8 m with maximum acceleration of 200 g. A package weight of 400 kg at 100 g can be accommodated and this capacity reduces linearly with acceleration to give a maximum 200 kg at 200 g; thus the centrifuge is a 40 g / tonne machine. The package is balanced by a 1450 kg counterweight that moves radially on a screw mechanism. The swing platform at one end of the rotor has overall dimensions of 500 mm x 700 mm with a usable height of 960 mm in the central area between the arms.

Four strain gauged sensors are used to detect out-of-balance operations in the base of the centrifuge. The signals from these sensors are monitored and if the out-of-balance exceeds the pre-set maximum of 15 kN than the machine is shut down automatically. Such a safety feature enables unmanned overnight running of the machine.

The machine is situated in an aerodynamic shell which is surrounded by a block wall. This wall is in turn surrounded by a reinforced concrete containment shell.

Electrical and hydraulic connections are available at the swing platform and are supplied through a stack of slip rings. Electrical slip rings are used to transmit transducer signals (which are converted from analogue to digital by the on-board computer and may be amplified prior to transmission in bits), to communicate closed circuit television signals, supply power for lights or operating solenoid valves or motors as necessary. The fluid slip rings may be used for water, oil or compressed air.

2. The model and apparatus

The tests were carried out at 60 g thus for 10 mm diameter model piles 600 mm diameter prototype piles were modelled. The soil used for the tests was speswhite kaolin clay and samples were prepared by consolidating clay slurry with 120 % water content. The sample was prepared in a consolidation press before the model was assembled and placed on the centrifuge. The sample was subjected to incremental loading up to a vertical stress of 500 kPa and than swelled back to 250 kPa before being removed from the consolidation press. A preconsolidation pressure of 500 kPa followed by swelling to 250 kPa was used principally to ensure that measurable movements were achieved and model behaviour during testing represented the essential characteristics of overconsolidated clay. The distribution of pore pressure throughout the model was measured and consequent theoretical vertical and horizontal total and effective stresses were therefore also known from simple calculations.

The container used for testing was a cylindrical stainless steel tub with 420 mm internal diameter and 400 mm internal height. The container had a number of access ports at different levels above the base through which pore pressure transducers could be installed. A cross section of the general model apparatus is shown in Figure 2. The loading apparatus was designed such that it was possible for most of the apparatus to be assembled prior to removing the sample from the consolidation press. Piles were loaded directly using water filled plastic reservoirs. The plastic reservoirs rested on springs and were guided by an aluminium tubes moveing vertically, thus axially loading and unloading the pile foundations. Pile foundations were loaded using a loading pin that was connected to the base of the loading reservoir. The spring had a sufficient stiffness to support the weight of the reservoir at 60 g and allow further vertical movement when the reservoir was filled up with water during loading of the pile. After testing the piles were unloaded by emptying the reservoir through a solenoid valve. The applied load was measured using a load cell that was connected to the loading pin. The reservoirs and solenoid valves were supported by a 12 mm thick aluminium plate that was mounted, when the apparatus was put together, and connected to the top flange of the tub.

The position, depth and layout of the model piles was based on the foundation geometry used for some previous field tests carried out by Cementation Skanska under the Reuse of Foundations for Urban Sites (RuFUS) project. The model piles were made of solid aluminium rod of 10 mm diameter and 220 mm length (Figure 3) and embedded 200 mm into the clay. The model pile dimensions corresponded to 600 mm diameter x 12 m long piles at prototype scale and were installed in holes pre bored into the clay at 1 g prior to placing the assembled model onto the centrifuge swing. The holes were excavated using 10 mm outside diameter thin wall stainless steel tubes which were guided using jigs shown in Figure 4. Prior to placing the foundations in the hole a small amount of clay slurry was placed in the base of the hole using a syringe to ensure that the pile was in good contact with the clay. In order to release trapped air a 0.5 mm deep by 1 mm wide channel was machined on one side of each pile.

As the influence of the mini-pile group was also investigated there was a need to design the 10 mm diameter central piles in such a way that the length of the pile could be varied. This was to allow for either the mini-pile group alone or the existing pile together with the mini-pile group to be loaded. This resulted in the 10 mm diameter piles being formed in sections, which could be added or removed (see Figure 3), to suit each individual test requirements.

For the mini-piles, 5 mm diameter by 100 mm, 120 mm, 200 mm and 220 mm long solid aluminium rods were used (see Figure 3). The length of the mini-piles was varied depending on whether their function was sacrificial, and in providing a general stiffness effect, or if they were to be loaded.

Early tests concentrated on measurement of the load that was applied to the foundations and their displacement. Although the tub had a large number of ports for instrumentation, it proved very difficult to place the pore pressure transducers sufficiently close to the piles for any pore pressure changes to be measured during the pile loading. It was therefore decided that pore pressure transducers should be installed in the base of the pile as shown in Figure 3, to enable a better understanding on the proportion of load supported by the shaft and by the base of the pile.

For all the tests undertaken the pile cap was not in contact with the clay surface, thus this gave no contribution to the pile performance. The cap was used as a reference point for measuring the displacement of pile foundations due to loading. The displacement was measured using two linearly variable differential transformers (see Figure 2) and the mean value from these two readings was used in the results presented.

3. Centrifuge modelling procedure

A total of twenty one centrifuge tests were carried out with two foundations located in each model.

After the model was removed from the press and prepared it was put onto the swing and the loading reservoirs were connected to the water supply. Connection of the transducers, standpipe, load cells and solenoid valves then followed. A camera and a light, to allow the reservoir movements to be observed, were positioned at the front side of the loading plate. All the above operations took around 30 minutes to complete.

When the model was spinning at 60 g it was left for about 20 hours for the pore pressures to come into hydrostatic equilibrium. The rate of increase of the pore pressure was used as a guide to assess the best time to perform the test. The foundations were loaded by filling the reservoirs with water through slip rings. The water supply valves were adjusted to ensure a constant loading rate. The foundations were loaded to failure (defined as vertical displacement equal to 10 % of the base diameter) or working load given by a value equal to half the ultimate (failure load). Piles remained loaded for a period of 10 minutes whereupon the load was removed by dumping the water from the reservoirs and the centrifuge was stopped.

When piles were to be enhanced with mini piles the following procedure was undertaken:-

- the loading apparatus plate and the LVDT support plate were removed
- the mini piles were installed using the same installation procedure as for the 10 mm diameter piles
- the model was put back together and was left spinning for 4 hours for the pore pressures to come into equilibrium
- the foundations were then loaded as explained in the previous paragraph

4. Observations and analysis

Table 1 presents number of tests carried out during the research at City University London.

4.1 Behaviour of single pile foundation when subjected to load/unload/reload cycle – Tests LQ6(A), LQ19(B), LQ7(A) and LQ13(B)

Tests LQ6(A), LQ19(B), LQ7(A) and LQ13(B) investigated the effects of load/unload/reload cycles on single pile foundations. Two different scenarios were investigated:-

- the behaviour of piles that had initially been loaded to failure (LQ6 and LQ19)
- the behaviour of piles that had initially been loaded to working load (LQ7 and LQ13)

A number of centrifuge tests on single piles were undertaken and in all these tests the failure load was around 100 N. To calculate the working load a factor of safety (FOS) of two was used, thus giving a working load of 50 N. During the second loading, in all the above tests, piles were loaded to failure.

Figure 5 shows a plot of first and second loading on a single pile foundation for tests LQ6, LQ19, LQ7 and LQ13.

Tests LQ6 and LQ19 were performed using the same testing method and, as expected, the piles performed in a similar manner. During the second loading an increase of around 20 % in pile capacity was observed in both tests.

In tests LQ7 and LQ13 the piles were loaded for the first time up to the working load, and displacements reached during loading were measured. When subjected to first loading, piles in tests LQ7 and LQ13 did not perform in the same manner; the pile in test LQ13 settled more than expected. Even though the performance of the piles during the first loading was different, during the second loading cycle they both reached an ultimate load capacity of around 85 N (see Figure 5).

The tests indicated an increase in capacity when subjected to second loading. It was also noticed that the behaviour of piles during the second loading was dependent on the loading history to which the piles were subjected. Soil behaviour is a direct function of past stress history, together with the recent and anticipated stress path. Various relationships have been proposed by Skempton (1957), Bjerrum (1973) and Lerouil et al. (1985) to link S_u, the undrained shear strength, and σ'_v, effective vertical stress, in one dimensional normal compression via peak values obtained from field vane shear tests. By using the Bjerrum's factor, μ, the following relationship was suggested by Muir Wood (1990):-

$$\mu S_u / \sigma'_v = 0.22 \qquad 1$$

Where: μ – Bjerrum's factor

S_u – Undrained shear strength

σ'_v – Effective vertical stress

When allowance is made for overconsolidation ratio, it was found by Nunez (1989), Phillips (1987) and Springman (1989) that for the current effective vertical stress:-

$$S_u / \sigma'_v = aOCR^b \qquad 2$$

Where: a and b – Correlation factor as per Nunez (1989), Philips (1987) and Springman (1989)

OCR – overconsolidation ratio

Springman (1989) proposed the following relationship which represents the mean value obtained from a series of vane shear tests conducted in-flight in the centrifuge:-

$$S_u = 0.22\, \sigma'_v\, (OCR)^{0.706} \qquad 3$$

Using Equation 3 the distribution of undrained shear strength, after equilibrium was reached in the centrifuge model, is shown in Figure 6. For comparison also shown in Figure 6 is the distribution of undrained shear strength as suggested by Garnier (2002), however for the purposes of this research Su was estimated based on findings by Springman (1989).

After the undrained shear strength distribution was determined, it was then possible to calculate the bearing capacity of the model piles using conventional methods (Patel, 1992).

When determining the ultimate shaft capacity of model piles the initial assumptions on the value of the adhesion factor, α, were too high, thus giving a higher calculated ultimate load for the piles, compared to that obtained from the centrifuge model tests. Using the values obtained from the centrifuge tests the adhesion factor of α=0.12 was back calculated. The value of the empirical adhesion factor, α, depends on a number of factors (Patel, 1992), such as:-

- strength, stiffness and plasticity of clay
- the size and type of pile
- method of pile installation

Side friction is a measure of shear strength of the bond between the material of the pile and the soil mass. The actual skin friction is greater than the shear strength of the soil and before full skin friction is mobilized, pile settlement is a result of shear deformation of the surrounding soil.

However, in the centrifuge testing the shear strength of the soil was greater than the skin friction between the pile and the clay, which explains the low values obtained for the adhesion factor α.

Owing to changes in pore pressure, throughout preparation of the model and during testing, the vertical and horizontal effective stresses (σ'_v and σ'_h) were continually changing. The horizontal effective stress σ'_h is stress history dependent and is calculated from the coefficient of earth pressure at rest (K_o) and vertical effective stress σ'_v:-

$$\sigma'_h = K_o \, \sigma'_v \qquad (4)$$

For normally consolidated deposits the coefficient of earth pressure at rest (K_{onc}) is given by (Mayne and Kulhawy, 1982) as:-

$$K_{onc} = 1 - \sin\phi' \qquad (5)$$

Where: ϕ' - angle of friction

When the normally consolidated deposits are unloaded the ratio of horizontal and vertical effective stresses (σ'_h/σ'_v) changes. The way that the earth pressure coefficient changes as a result of variation in vertical effective stresses is relatively complex. The influence of the stress history was described by Burland et al. (1979) and Mayne and Kulhawy (1982) by way of similar diagrammatic representations. Mayne and Kulhaway (1982) compiled data from over 170 different soils and concluded that for overconsolidated clays:-

$$K_o = (1 - \sin\phi')\,(OCR)^{\sin\phi'} \qquad (6)$$

Al-Tabbaa (1987) investigated the behaviour of Speswhite Kaolin using an instrumented oedometer and found that:-

$$K_o = 0.69\,(OCR)^{0.46} \qquad (7)$$

Using Equations 4 and 7 the distribution of the horizontal stresses in the centrifuge sample can be calculated and the influence of the initial loading conditions on foundation performance during reloading and the behaviour of pile foundations on the overconsolidated clay can be assumed to be dependent on the stress history to which the soil has been subjected.

The tests showed that the single pile foundation which was initially loaded up to ultimate load showed an increase in capacity of 20 % when reloaded. In contrast the single pile foundations that were initially loaded to working capacity reached a 15 % lower ultimate load when reloaded to failure.

4.2 Effect of the mini-pile group on the existing pile

When the capacity of an existing pile is not sufficient for a new development, the capacity may be improved if a ring of sacrificial mini-piles is installed around it. The influence of these new foundations on the performance of the existing pile was investigated by changing the geometry of the group. The number of the mini-piles, the length and the spacing between the existing pile and the mini-piles were all varied. It was observed that the capacity of a single pile belonging to a group is different from that of an isolated single pile due to the confinement offered by the surrounding piles.

4.2.1 Effects of spacing of mini-piles on the existing pile – Tests LQ9(A), LQ11(A), LQ10(B) and LQ12(A)

When investigating the influence of the centre to centre spacing of the mini-pile group from the centre pile, the following scenarios were investigated:-

- a centre to centre distance of 1.5D between the existing pile and the new mini-pile foundations
- a centre to centre distance of 2D between the existing pile and new mini-pile foundations.

Where D is the diameter of the existing pile and D=10 mm.

As the diameter of the existing pile and the new mini-pile foundations was different, it was decided to model the geometry in terms of centre to centre distance between the old and new foundations (not between the mini-piles in the group).

In all tests described, single piles were loaded to working load during first loading and to failure load during the second loading when enhanced by the mini-pile group. All models were prepared and tested in the same manner. The single piles were subjected to first loading, the centrifuge was then stopped and the mini-piles were installed. After the model had reached equilibrium stresses, only the existing piles were re-loaded to failure.

Test LQ7 was used as a datum. Test LQ7 investigated the behaviour of single pile foundation subjected to load/unload/reload cycles when the piles were initially loaded to working load.

Tests LQ9 and LQ11 investigated the effect on the existing centre pile of eight 100mm long mini piles at the spacing shown in Figure 7. Figure 8 shows the load settlement behaviour for tests LQ9 and LQ11 during first and second loading. For the mini-pile group with 2D spacing the load/displacement behaviour suggested an increased capacity of around 10 % compared to the mini-pile group with 1.5D spacing. The same behaviour was observed for 200 mm long mini-piles. The load/displacement behaviour for the mini-pile group with 2D spacing (LQ12) suggested a higher capacity compared to the group with 1.5D spacing (LQ10), see Figure 8. In this case an increase in capacity of around 15 % was observed.

When comparing with test LQ7 (see Figure 8), it can be seen that the mini-pile group has a positive effect, in terms of improving the performance of the existing pile foundation. The length of the mini-pile also influences the performance of the existing pile, but this will be discussed in more detail later.

The effective geometry of the enhanced centre pile observed from the centrifuge model tests is shown in Figures 9 (a) and (b) for 100 mm long mini-piles. No contribution from the mini-pile group was considered when back calculating below the toe level of the mini-piles as the foundations tested were on clay soils (i.e. main contribution to pile capacity is from the shaft friction).

The effect on the performance of the centre pile of the 200 mm long mini-piles up to 100 mm depth (i.e. the length of previously described model mini-piles) was considered to be the same as for the 100 mm long mini-piles. The effective diameter for the lower section of the existing pile (i.e. below 100 mm) was then calculated based on the assumptions made above. The behaviour of the enhanced centre pile during centrifuge model testing is shown in Figures 9 (c) and (d) for 200 mm long mini-piles.

Although the existing pile was retested after pore pressure equilibrium was reached in the soil model, there is no information available to determine the effective stresses around the existing pile, as no pore pressure transducer could be installed next to the pile shaft. If the existing piles were retested after a longer period of time of the model spinning in the centrifuge, than it would be expected that the closer spaced mini-pile group would improve the capacity of the existing pile foundation to a greater extent as the excess pore pressures would have dissipated to the equilibrium state and the effective stresses would have increased.

The centrifuge tests showed that by increasing the centre to centre spacing between the centre pile and the mini-pile group, the effective diameter of the centre pile increased by approximately the same percentage as the pile spacing.

4.2.2 Effects of number of mini-piles on the existing pile – Tests LQ11(A), LQ10(A), LQ12(A) and LQ12(B)

For tests LQ11 and LQ10 100 mm long mini-piles were used with 2D (20 mm) spacing. Due to the geometry of the model, the maximum number of the mini-piles in the group that it was possible to investigate was sixteen.

For test LQ11 eight mini-piles were constructed around the existing pile after the first loading. For test LQ10 sixteen mini-piles were constructed around the existing pile after the existing pile was subjected to first loading. Comparing tests LQ10 and LQ11 with the behaviour of the single pile subjected to load/un-load/re-load cycles when loaded for the first time to working load (test LQ7), it can be seen clearly that both mini-pile groups have a positive effect on the performance of the existing pile (see Figure 10). When comparing test LQ11 with test LQ10, at the same pile displacement, the existing pile surrounded by a mini-pile group of eight reached a higher load capacity compared to the existing piles enhanced using a group of sixteen mini-piles by around 10 %.

For test LQ12 the mini-piles were 200 mm long. Test LQ12(A) had eight mini-piles constructed around the existing pile and test LQ12(B) had sixteen mini-piles constructed around the existing pile. During the second loading, as the piles showed no more increase in load with continued displacement, the existing piles were not loaded to failure (the existing piles were displaced by only 4% of the pile diameter), The behaviour observed was similar to the 100 mm long mini-piles (see Figure 11).

The effective diameter of the enhanced pile foundations with eight and sixteen mini-piles is shown in Figure 9 (e). Mini-pile installation will change the stress conditions around the existing pile. By increasing the number of the mini-piles in the group the change in the stress conditions around the existing pile will be more significant. Also as the spacing between the existing centre pile and mini-piles in the group remains the same, the spacing between the mini-piles within the group will reduce as the number of the mini-piles increases (see Figure 7).

The existing centre pile was re-loaded after the pore pressure transducers in the soil mass and at the base of the model piles reached equilibrium stresses. In all tests there was no reaction observed on the pore pressure transducers installed in the soil mass during foundation loading. Thus, the equilibrium readings of the pore pressure transducers in the soil mass do not represent the stresses in the soil surrounding the centre pile. If the existing model pile was tested after the excess pore pressures have fully dissipated, it would be expected that the existing pile would reach a higher load capacity when the number of the mini-piles in the group is higher.

4.2.3 Effects of length of mini-piles on the existing pile – Tests LQ11(A), LQ12(A), LQ10(A) and LQ12(B)

The effects of the length of the mini-piles in the group on the performance of the existing piles was also investigated. Groups with 100 mm and 200 mm long mini-piles were considered. In tests LQ10(A), LQ11(A), LQ12(A) and LQ12(B) the existing piles during the first loading were loaded up to working load.

In tests LQ11(A) and LQ12(A), see Figure 12, the groups investigated were of eight mini-piles with 2D spacing. In tests LQ10(A) and LQ12(B), see Figure 13, the groups investigated were of sixteen mini-piles with 2D spacing.

During the first loading in tests LQ11 and LQ10 the model piles displayed greater displacements compared to the performance observed in tests LQ12 (A) and (B). When subjected to a second loading cycle the existing piles in test LQ11 and LQ10 were loaded until the piles reached displacements of 10 % of the pile diameter. In tests LQ12 (A and B) the existing piles were displaced by only 4 % as the piles showed no more increase in load with continued displacement. Therefore it was decided that the performance of pile foundations in tests LQ10, LQ11 and LQ12 to be compared at vertical displacements of 4 %. The 200 mm long mini-piles increased the capacity of the existing pile by around 20 % compared to the 100 mm long mini-piles. Similar performance was observed for mini-pile groups of eight and sixteen mini-piles and it therefore seems that there would be a limit to the number of piles needed to enable enhanced capacity.

Not surprisingly the length of the mini-piles has been shown to play an important part in the performance of the enhanced pile foundation. In all of the geometries tested 200 mm long mini-piles performed better compared to the 100 mm long mini-piles by approximately 20 %.

The sacrificial mini-piles can be assumed to increase the stiffness of the soil, thus improving the capacity of the existing pile when re-loading. As the existing pile is loaded, this load is distributed along the length of the pile until the soil strength is fully mobilised. Thus by increasing the length of the mini-piles the performance of the existing centre pile is enhanced as shown in Figure 9 (f).

The increase in capacity in the top sections of the model piles (i.e. the top 100 mm of the embedded length) is the same for piles enhanced with either 100 mm or 200 mm long mini-piles if the number and spacing of mini-piles in the group is the same. The 200 mm long mini-piles influence the performance of the centre pile along the whole length of the pile, thus improving the performance of the existing centre pile by 20 % more compared to 100 mm long mini-piles.

5. Conclusions

There are obvious advantages for redevelopment if as much as possible of the existing building foundations can be reused to reduce the environmental impact, time and cost of the construction. The research investigated the behaviour of bored piles in overconsolidated clay when subjected to load cycles and foundation improvement using new mini-pile groups with a view to re-using of the existing piles for future redevelopments.

The work presented investigates aspects of performance of single pile foundations subjected to load/unload/reload cycles. An increase in capacity was observed when pile foundations were subjected to load cycles. The pile foundation performance observed in the centrifuge model tests has been consistent thus allowing the following conclusions to be drawn:-

- when the single pile foundation, which was initially loaded to failure (foundation displacement of 10 % of the pile base diameter), was reloaded the foundation showed an increase in capacity of about 20 %
- single pile foundations which were initially loaded to working load, when reloaded to failure, reached a lower ultimate load by about 15 % compared to the piles loaded to failure for the first time. Hence the initial loading conditions influence foundation performance during reloading

Where circumstances exist such that the existing piles have insufficient capacity for the new development, the research also sought to explore if the capacity of an existing pile could be improved by placing around it a ring of new mini-pile foundations. The new mini-pile group was constructed around the existing pile that had previously been subjected to a working or failure load. The geometry of the group was varied, i.e. the number of the mini-piles, centre to centre distance between the existing and new pile foundation and length of the mini-pile foundations.

All tests, in which the existing pile foundations were enhanced with the sacrificial mini-pile group, were compared to the performance of a single pile foundation when subjected to the same loading conditions. In all cases presented the introduction of mini-pile groups around the existing pile had a positive effect on the performance of the existing pile during reloading. This improvement during reloading was dependent on the number of the mini-piles in the group, the length of the mini-piles and also the centre to centre spacing between the existing pile and mini-pile foundations.

When considering the influence of spacing between the centre pile and the mini-pile group on the performance of the existing pile foundation, both 100 mm and 200 mm long mini-piles were investigated. The increase in capacity observed, when using a group of eight mini-piles, for the 1.5 D spacing was lower compared to the 2 D spacing by 10 % and 15 % for the 100 mm and 200 mm long mini-piles respectively.

The number of the sacrificial mini-piles in the group also influenced the performance of the existing piles when reloading. Mini-pile groups of eight and sixteen, with 2 D centre to centre spacing between the existing pile and mini-pile group, were investigated. It was observed that for both 100 mm and 200 mm long mini-piles the mini-pile group of eight increased the capacity of the existing piles by 10 % more compared to a group of sixteen mini-piles. When comparing with the single pile foundation subjected to load-unload cycles the performance of the existing pile was improved by the sacrificial piles in a range from 17 % to 60 %.

The length of the mini-piles appears to be an important component in the performance of the enhanced pile foundation. In all geometries tested 200 mm long mini-piles performed better compared to 100 mm long mini-piles by approximately 20 %.

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Figures:

Figure 1 Schematic diagram of the Acutronic 661 geotechnical testing facility at City University, London – capacity 40g tonnes, radius 1.8m to swing base in flight (after McNamara 2001).

Figure 2 New loading apparatus developed for centrifuge model testing.

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Figure 6 Distribution of undrained shear strength after equilibrium of the centrifuge model was reached at 60g based on the findings by Garnier (2002) and Springman (1989).

Figure 7 Details of the geometry of the novel pile groups used to investigate the influence of 1.5D and 2D centre to centre spacing between the centre pile and the mini-pile group (D – diameter of centre pile).

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Figure 9 (a) Effective geometry of the enhanced centre pile with 100 mm long mini-piles installed at 1.5D centre to centre spacing with the existing centre pile.

(b) Effective geometry of the enhanced centre pile with 100 mm long mini-piles installed at 2D centre to centre spacing with the existing centre pile.

(c) Effective geometry of the enhanced centre pile with 200 mm long mini-piles installed at 1.5D centre to centre spacing with the existing centre pile.

(d) Effective geometry of the enhanced centre pile with 200 mm long mini-piles installed at 2D centre to centre spacing with the existing centre pile.

(e) Effective geometry of the enhanced centre pile with 100 mm long mini-piles installed at 2D centre to centre spacing with the existing centre pile:

(e-1) Mini-pile group of 8 (Test LQ11(A))

(e-2) Mini-pile group of 16 (Test LQ10(A)).

(f) Tests LQ9(A) and LQ10(B). Enhanced pile foundations with eight mini-piles at 1.5D centre to centre spacing.

(f-1) 100 mm long mini-piles (Test LQ9(A))

(f-2) 200 mm long mini-piles (Test LQ10(B)).

Figure 10 Tests LQ7(A), LQ10(A) and LQ11(A). 1^{st} loading cycle – single pile foundations loaded up to working load. 2^{nd} loading cycle – enhanced piled foundations loaded to failure: test LQ7(A) – single pile, test LQ10(A) enhanced pile foundation with sixteen 100 mm long mini-piles at 2D spacing and test LQ11 enhanced pile foundation with eight 100 mm long mini-piles at 2D spacing.

Figure 11 Tests LQ12(A) and LQ12(B). 1^{st} loading cycle – single pile foundation loaded up to working load. 2^{nd} loading cycle – enhanced pile foundation: Test LQ12(A) eight 200 mm long mini-piles with 2D spacing; Test LQ12(B) sixteen 200 mm long mini-piles with 2D spacing.

Figure 12 Tests LQ11(A) and LQ12(A). 1^{st} loading cycle – single pile foundation loaded up to working load. 2^{nd} loading cycle – enhanced pile foundation: Test LQ11(A) eight 100 mm long mini-piles with 2D spacing; Test LQ12(A) eight 200 mm long mini-piles with 2D spacing.

Figure 13 Tests LQ10(A) and LQ12(B). 2^{nd} loading cycle – enhanced pile foundation: Test LQ10(A) sixteen 100 mm long mini-piles with 2D spacing; Test LQ12(B) sixteen 200 mm long mini-piles with 2D spacing.

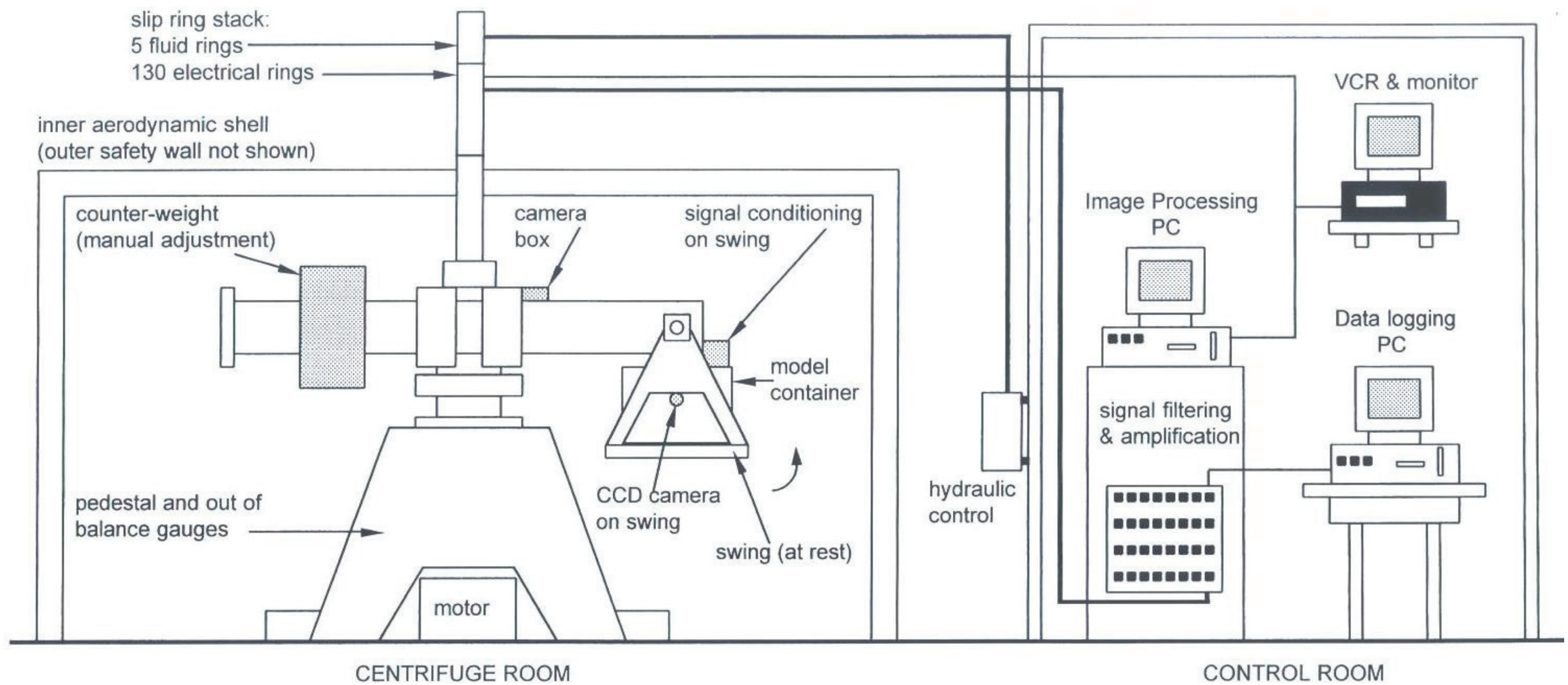
Table 1

Test	**Pile**	**First Loading**	**Second Loading**
LQ6	**A**	Single Pile	Single Pile
LQ19	**B**	Single Pile	Single Pile
LQ7	**A**	Single Pile	Single Pile
LQ9	**A**	Single Pile	8MP 1.5D 100mm
LQ10	**A**	Single Pile	16MP 2D 100mm
	B	Single Pile	8MP 1.5D 200mm
*** LQ11**	**A**	Single Pile	8MP 2D 100mm
*** LQ12**	**A**	Single Pile	8MP 2D 200mm
	B	Single Pile	16MP 2D 200mm
*** LQ13**	**B**	Single Pile	Single Pile

Note: * Piles installed after the sample was accelerated to 60g for 12h

Table 1 Details of tests reported.

Figure 1



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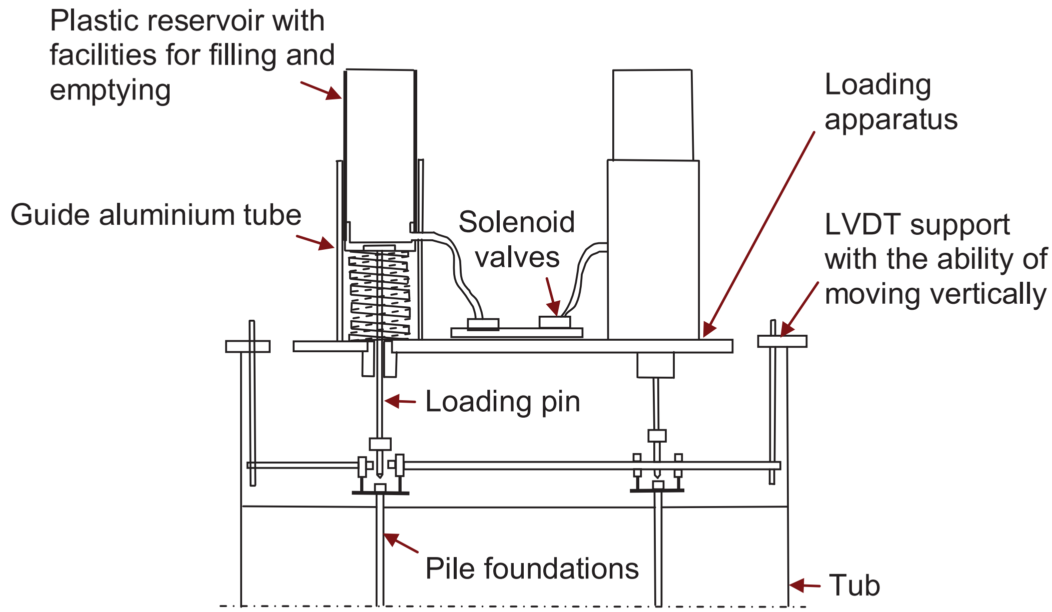
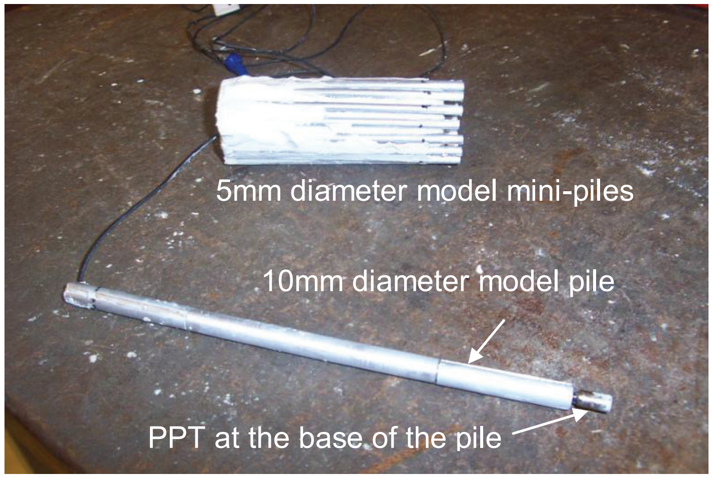
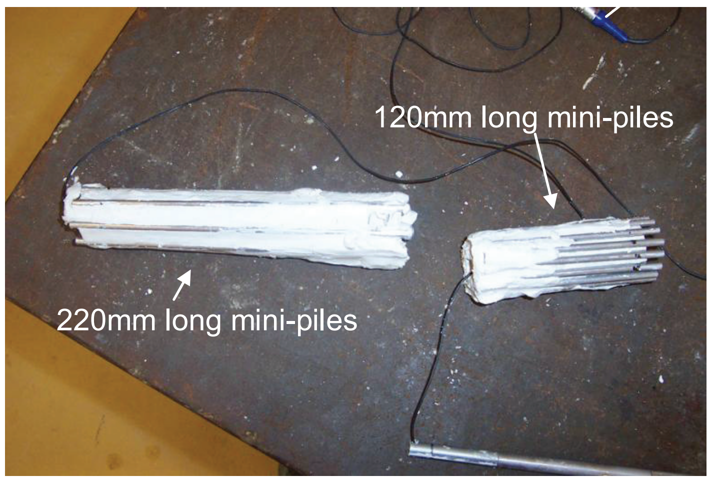


Figure 2 New loading apparatus developed for centrifuge model testing.

Figure 3



(a)



(b)

Figure 3 (a) Model pile made of aluminium sections with the pore pressure transducer at the base (Test LQ10).

(b) Examples of mini-pile groups removed from the model soil after testing (Test LQ16).

Figure 4

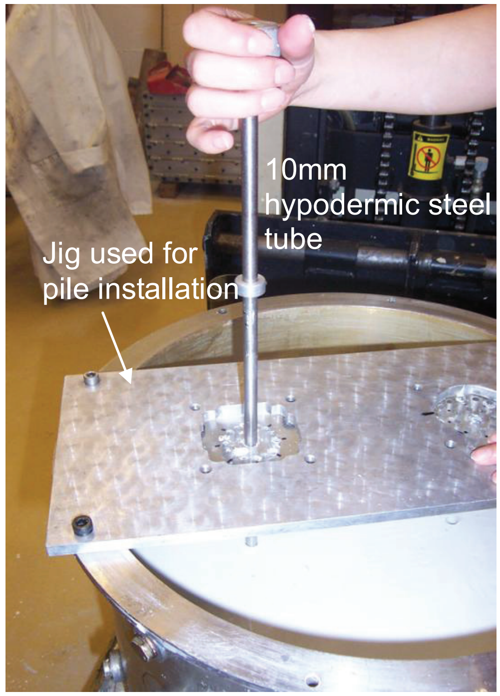


Figure 4 Model pile installation at 1g using a template to position and install piles.

Figure 5

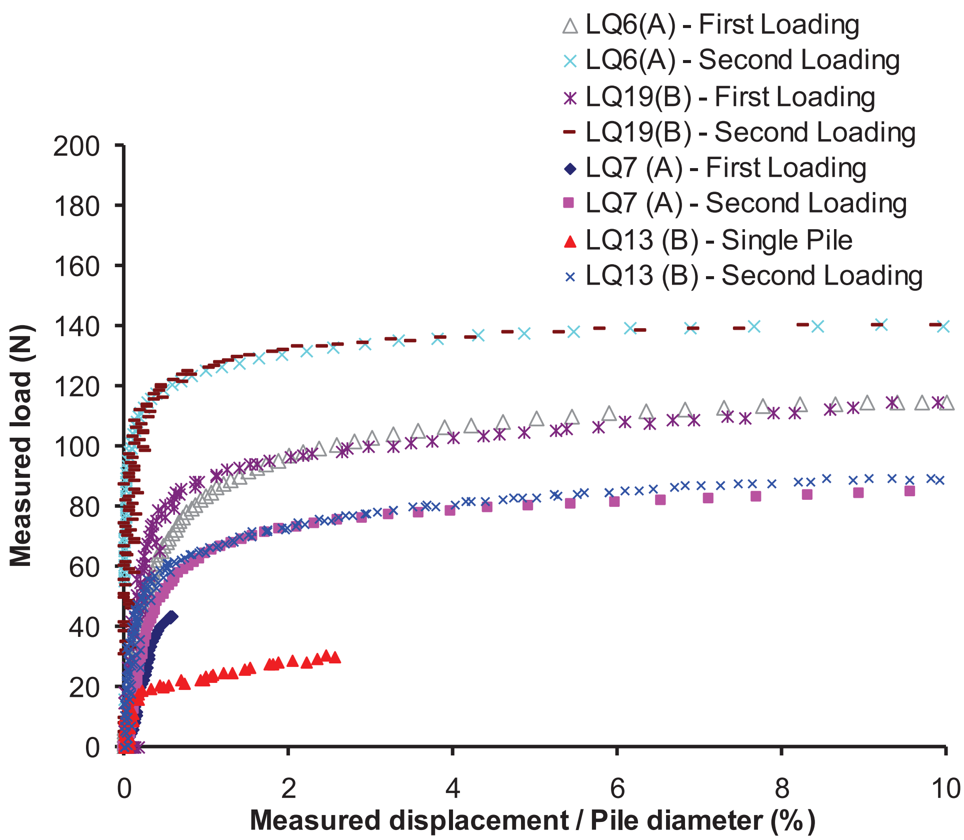


Figure 5 Test LQ6(A) and LQ19(B) single pile foundations subjected to 1st and 2nd loading to failure. An increase in pile capacity of 20 % was observed during 2nd loading.
Tests LQ7(A) and LQ13(B) single pile foundations subjected to 1st loading and 2nd loading. The piles were subjected to working load during the 1st cycle. The piles were loaded to failure during the 2nd cycle.

Figure 6

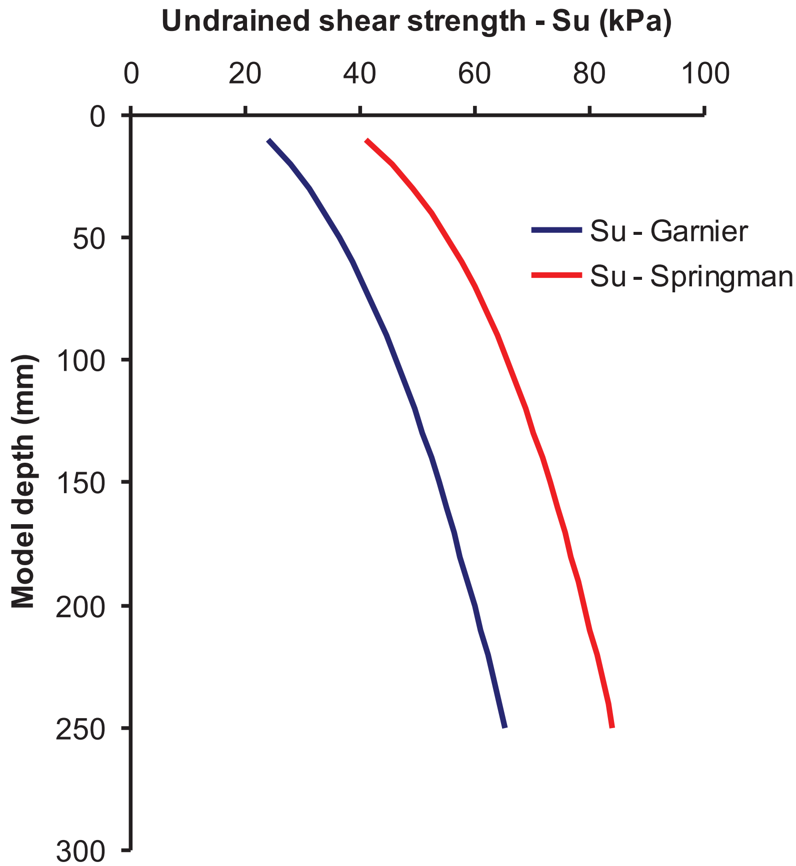


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Figure 7

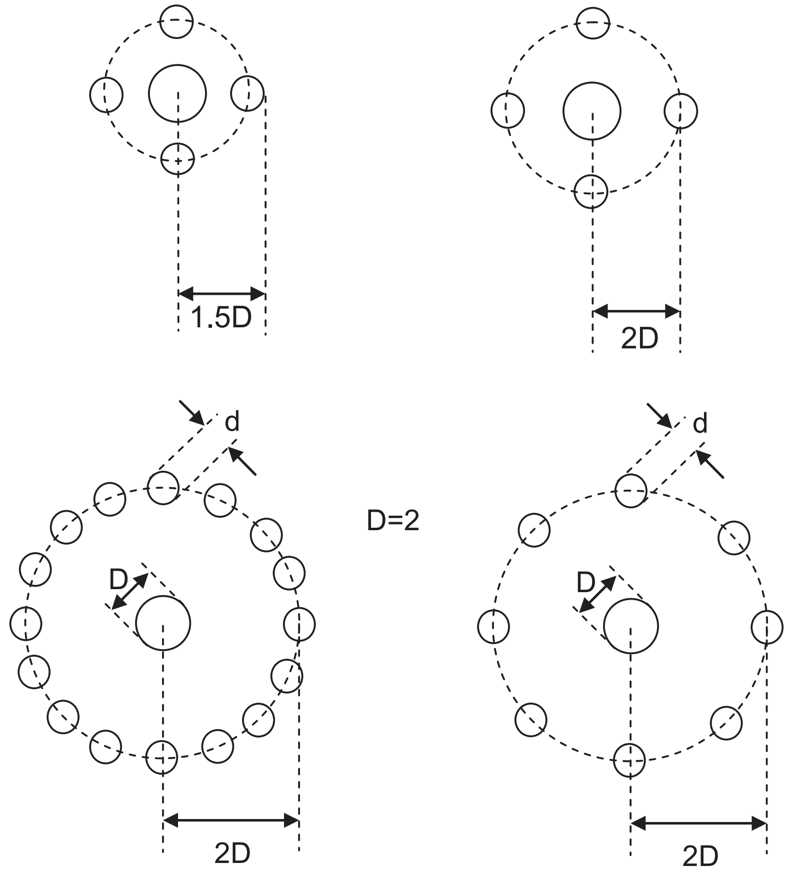


Figure 7 Details of the geometry of the novel pile groups used to investigate the influence of 1.5D and 2D centre to centre spacing between the centre pile and the mini-pile group (D – diameter of centre pile).
Details of the geometry of the model of novel pile groups of 8 and 16 mini-piles.

Figure 8

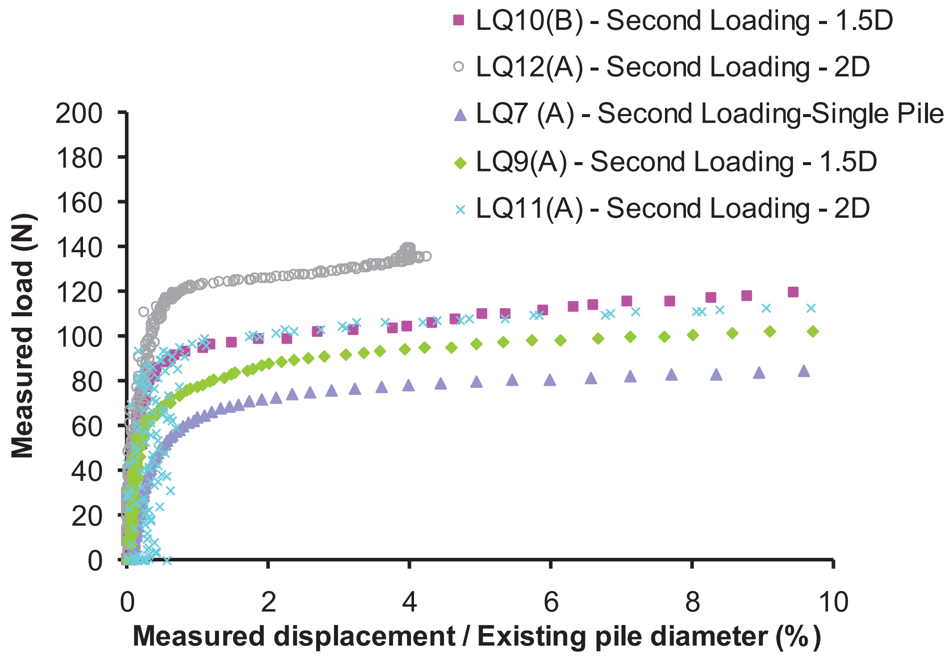
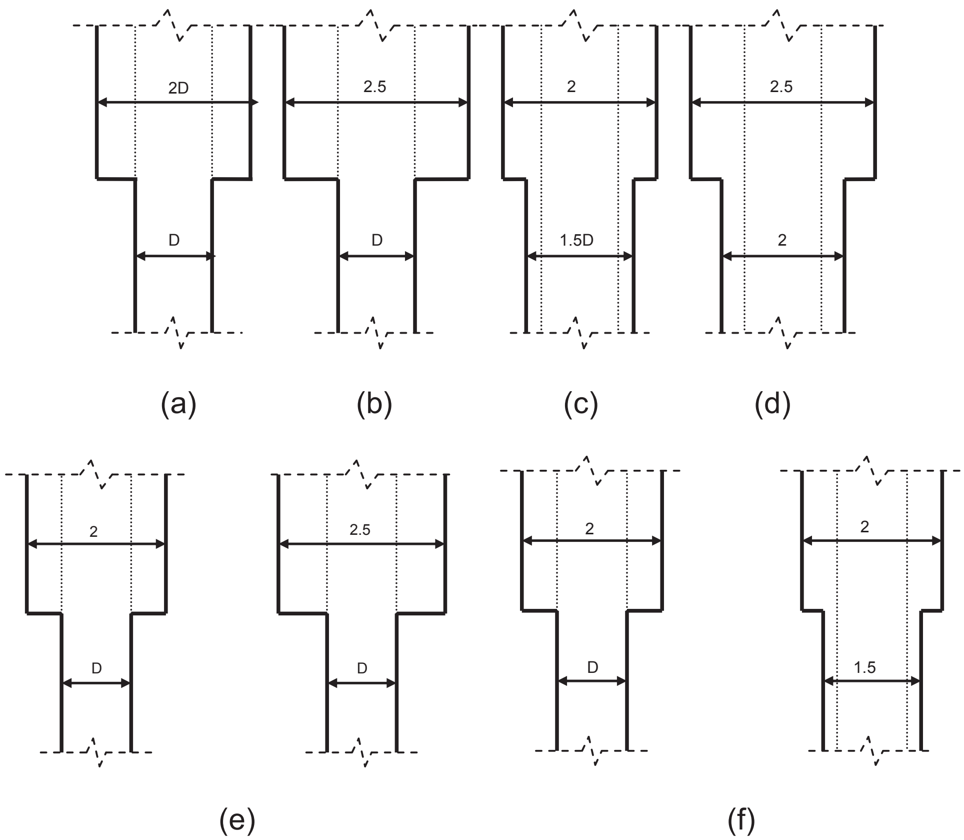


Figure 8 The performance of tests LQ7(A), LQ9(A), LQ10(B), LQ11(A) and LQ12(A) during second loading cycle. During testing only the existing centre pile was loaded.

Figure 9



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(e) Effective geometry of the enhanced centre pile with 100 mm long mini-piles installed at 2D centre to centre spacing with the existing centre pile:
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(f) Tests LQ9(A) and LQ10(B). Enhanced pile foundations with eight mini-piles at 1.5D centre to centre spacing.
  (f-1) 100 mm long mini-piles (Test LQ9(A))
  (f-2) 200 mm long mini-piles (Test LQ10(B)).

Figure 10

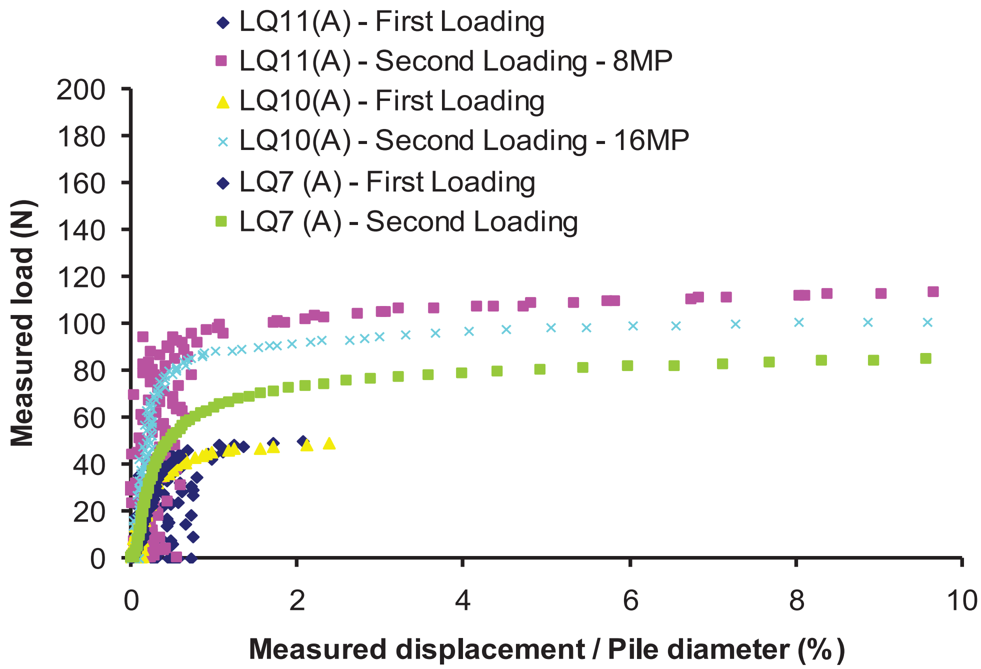

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Figure 11

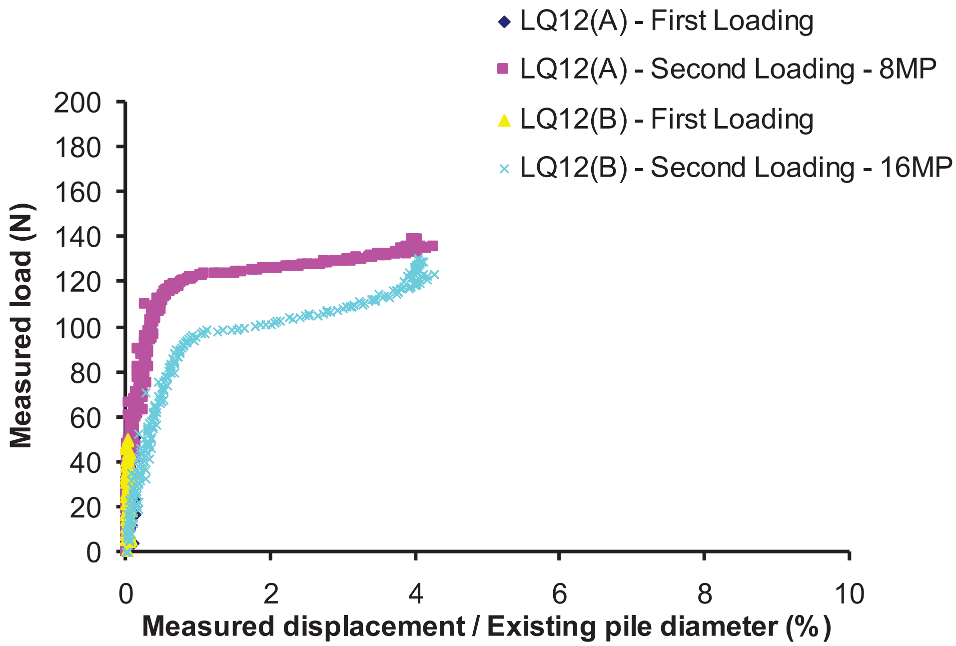

Figure 11 Tests LQ12(A) and LQ12(B). 1st loading cycle – single pile foundation loaded up to working load. 2nd loading cycle – enhanced pile foundation: Test LQ12(A) eight 200 mm long mini-piles with 2D spacing; Test LQ12(B) sixteen 200 mm long mini-piles with 2D spacing.

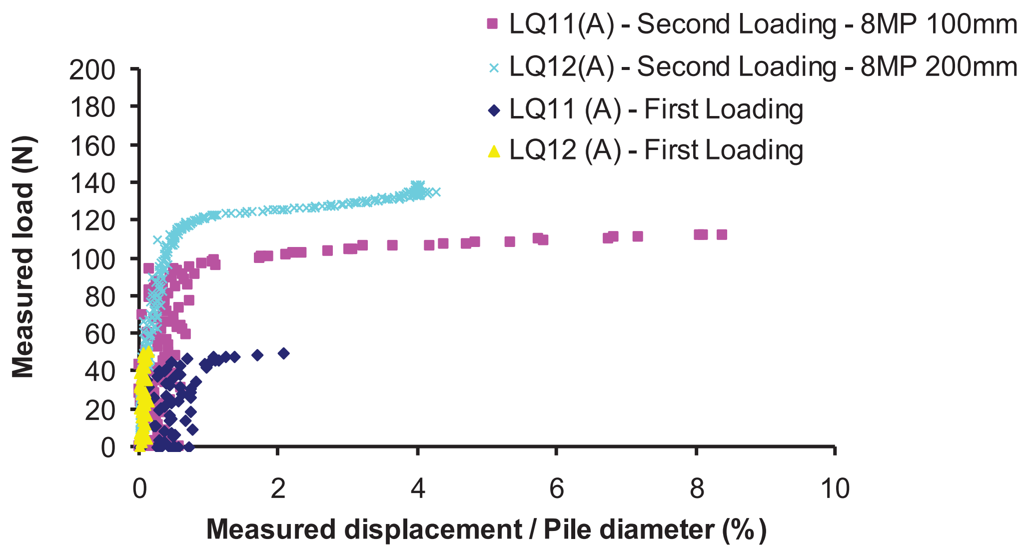

Figure 12 Tests LQ11(A) and LQ12(A). 1st loading cycle – single pile foundation loaded up to working load. 2nd loading cycle – enhanced pile foundation: Test LQ11(A) eight 100 mm long mini-piles with 2D spacing; Test LQ12(A) eight 200 mm long mini-piles with 2D spacing.

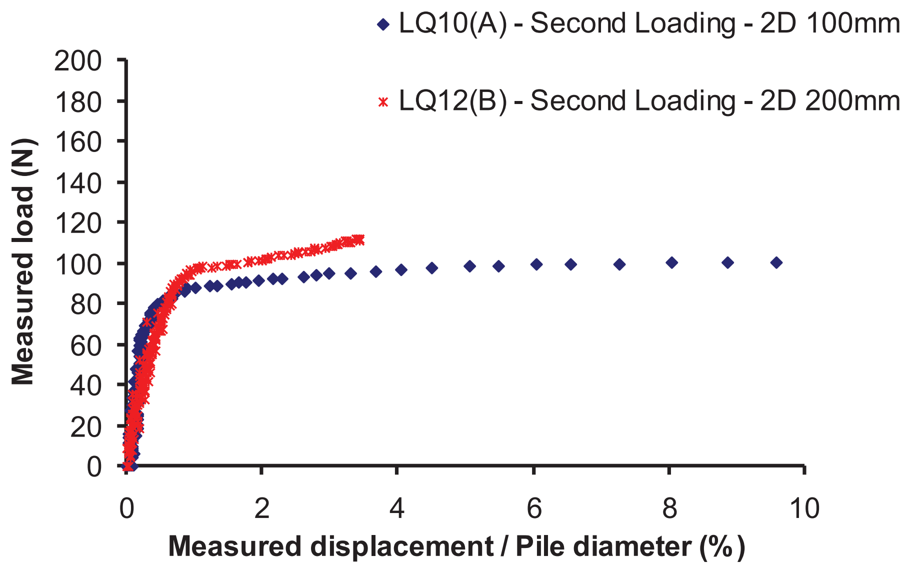

Figure 13 Tests LQ10(A) and LQ12(B). 2nd loading cycle – enhanced pile foundation: Test LQ10(A) sixteen 100 mm long mini-piles with 2D spacing; Test LQ12(B) sixteen 200 mm long mini-piles with 2D spacing.