MODELLING THE AXIAL CAPACITY OF MICROPILES AT CLOSE SPACING

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ABSTRACT

Pile installation systems have been developed that allow micropiles with slenderness ratios in excess of 100 to be constructed to a high positional accuracy and this in turn allows micropiles to be installed at a close centre-to-centre spacing. These techniques enable 'perimeter groups' of micropiles to be formed, which enclose a body of soil in the centre of a group, with closely spaced micropiles installed around the perimeter only. The behaviour of individual micropiles is well understood, but little is known about their performance when formed in a perimeter group arrangement. It is hypothesised that a group may behave as a single foundation, similar to a caisson, or that the central soil may contribute to the group capacity. If this is the case, a more efficient and economical piled foundation solution may be discovered.

The first stage of the research investigated closely spaced linear groups with piles installed at a range of centre-to-centre spacing. The second stage investigated perimeter groups, where a range of group geometries were tested and the number of piles per group was also varied (and hence the group diameter). Pile group capacities are compared to the capacity of a single pile. The initial results show that there is a positive group effect and suggest that the capacity of a perimeter group, in some cases, is significantly greater than the sum of the individual piles.

1 INTRODUCTION

1.1 Outline of the research project

The aim of the project is to explore the behaviour of micropile perimeter groups in firm to stiff clay. Complex apparatus has been specifically developed to allow geotechnical centrifuge testing of multiple micropile groups within a single clay sample and to allow installation of piles with high positional accuracy. Aluminium model piles are installed in overconsolidated kaolin clay; the piles are loaded vertically and tested to failure. The initial tests comprise five piles in a linear arrangement at a variety of centre-to-centre spacing ranging from 1.25 to 3.0 pile diameters, d. The main purpose of the linear group tests was to determine an optimum pile spacing, which could then be carried through to the perimeter groups (as shown in Figure 1).

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1.2 Cannon Place

Cannon Place is a £360M redevelopment under construction in the City of London. The foundations of the development include 11 of these micropile perimeter groups. This unique design and layout is believed to be the first of its kind and the foundations of this redevelopment were the main driver behind the research project. Each group is in a square or rectangular arrangement, comprising between 16 and 24 piles, with each group capable of supporting the 16 MN load imposed. A typical pile group is shown in Figure 2. The piles are 305 mm diameter and approximately 30 m long. The pile spacing is 1.64 pile diameters, which was dictated by site constraints as well as the structural capacity requirements and geotechnical limitations. Precise levelling is taking place to monitor the response of the pile groups whilst the building is constructed and the loads are applied. It is anticipated that these data will be interpreted in the light of findings from the centrifuge model tests in due course.

Figure 1. Circular and square perimeter groups after excavation from the clay sample

Figure 2. A pile group during construction at Cannon Place

2 MODEL DESCRIPTION

2.1 Soil sample

The soil used was Speswhite kaolin clay, which has the following properties: specific gravity = 2.62, liquid limit = 65%, plastic limit = 35%, friction angle = 23^{o}. The clay was mixed to a moisture content of 120% before being poured into the strongbox and undergoing consolidation in a hydraulic press to a pressure of 500 kPa. The consolidation pressure was applied in increments over a 10 day period and consolidation was known to be complete when measureable settlements had ceased. The pressure was then reduced to 250 kPa and the sample swelled for 24 hours. The sample was trimmed to a height that allowed a gap of 10 mm between the base of the pile cap and the top of the clay and also left a distance of more than 100 mm between the toe of the piles and the base of the strongbox.

2.2 Apparatus geometry

The geometry of the scale model is 1:60, so an acceleration field of 60 g was applied to simulate prototype stress conditions. The rectangular strongbox used to contain the model has the following internal dimensions: width = 200 mm, length = 550 mm, height = 375 mm. The apparatus was designed to allow three or four pile groups to be tested in a single clay sample.

Figure 3 is a cross section of the strongbox showing the reference frame that holds the guide plates and the pile cap holders in position above the pile caps and explains the pile installation procedure in five stages. Figure 4 shows a long section of the strongbox and the loading apparatus. Figure 5 shows the model construction process.

After pile installation, the guide plates and pile cap holders are removed and two displacement transducer brackets are located on the reference frame. The brackets are placed along the length of the strongbox and each support up to four displacement transducers. The transducers are linear variable differential transformers (LVDTs). Each pile cap has a displacement transducer monitoring settlement at either end.

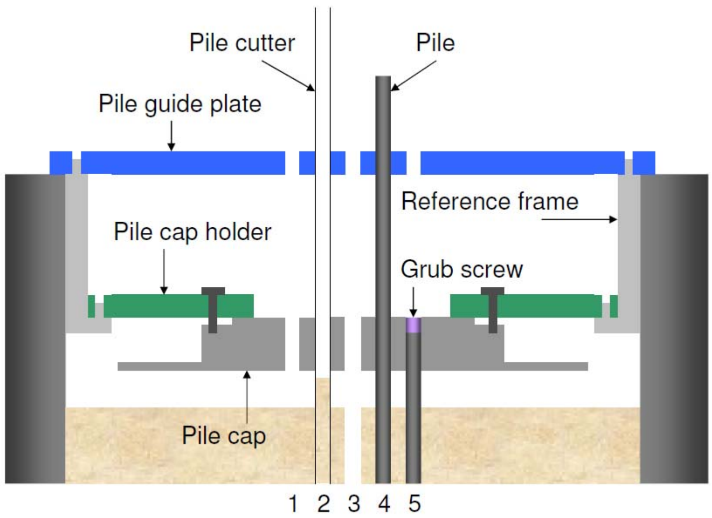
A 10 kN motor driven screw jack load actuator is bolted to the strongbox, which can apply a vertical force to each pile group via a guided stiff load beam. Load cells are connected to the load beam, allowing individual measurement of the force applied to each pile group.

2.3 Pile installation

The pile installation process was undertaken prior to the model being placed in the centrifuge. Installation at 1g 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 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 the LVDT probes could rest. Clay recovery during coring for the pile bore ranged between 65% and 85%, which was considered acceptable.



1. Apparatus in place pre pile installation
2. Cutting tube inserted, clay sheared and extracted
3. Pile bore created, extending 250 mm below top of clay
4. 5mm diameter aluminium pile inserted
5. Grub screw placed into the top of the pile cap

Figure 3. Cross section of strongbox showing pile installation

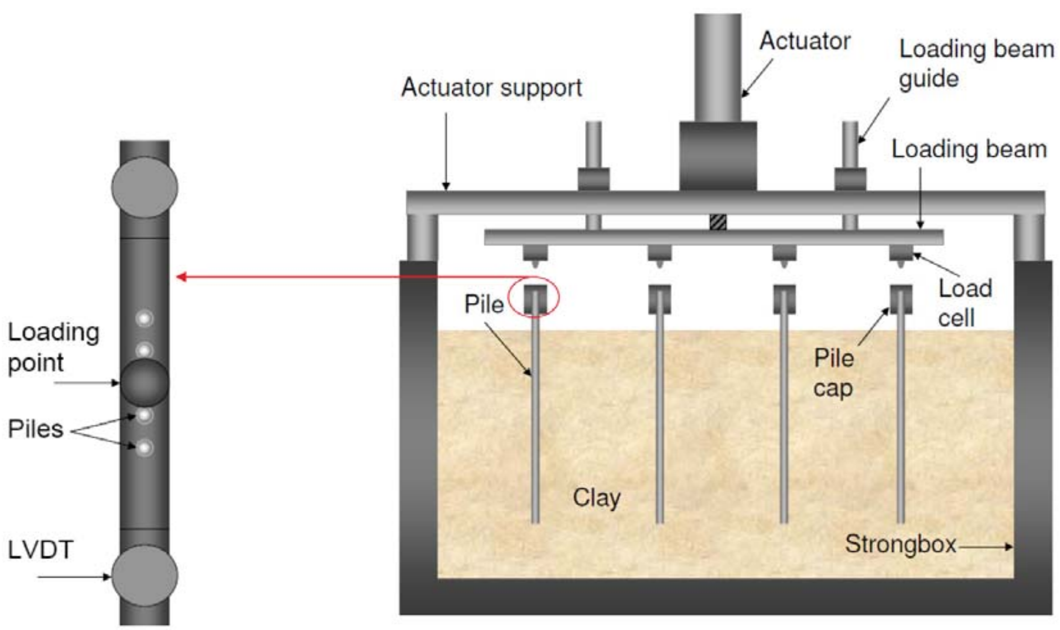


Figure 4. Long section of strongbox and plan view of pile cap

Once this process was complete, the pile guide and the pile cap holder were removed to leave just the pile cap and the piles in place. Silicone oil was poured on the clay surface to prevent the clay from drying out. A number of techniques have been used to try and prevent the oil seeping down between the clay bore and the pile shaft. So far the most successful has been to use a thin brass ring bund around the outside of the group, 20 mm high and pressed 5 mm into the clay. These bunds contribute additional capacity, which is accounted for in the final calculations of those tests in which they have been used. The load guide was then located in the centre of the pile cap.

Guide plate, pile cap holder and pile cap

Pile cap, LVDT brackets and LVDTs

Pile group (with clay bund) post testing

Figure 5. Model construction process

2.4 Instrumentation

Four pore pressure transducers (PPTs) were installed in the clay sample at the end of the swelling process. The installation method has been used with success in previous studies and is detailed in a number of centrifuge modelling projects (Begaj-Qerimi, 2009). The strongbox had access ports at depths of 110, 170, 230 and 250 mm from the top, through which the transducers were placed. Two LVDTs and one load cell were required for each pile group.

3 TEST PROCEDURE

3.1 In the centrifuge

Once the model had been placed in the centrifuge and all the instrumentation connected, the centrifuge was accelerated to 60 g. Before the load could be applied, the pore pressures within the clay sample were required to stabilise and reach equilibrium, which took approximately 40 hours. The screw jack was then advanced at a constant rate of 0.25 mm/minute. Axial loading was continued until no additional load could be sustained by the pile groups.

3.2 Post centrifuge test

Immediately after stopping the centrifuge, undrained shear strengths of the clay were measured at a range of depths using a Pilcon hand vane, which was operated in accordance with BS 1377-9. The results are shown in Figure 6. Generally, the profiles show a consistent trend, although the shear strengths vary between tests. The only anomaly was test 3b, where problems were encountered during consolidation and the sample began drying out in the centrifuge. Moisture contents were also measured at various depths and the average moisture content for all twelve tests completed to date was between 45 and 49%. A full list of completed tests is presented in Table 1.

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. Even the most closely spaced linear pile group with a gap of just 1.25 mm between the piles showed equal and consistent spacing down the length of each of the piles.

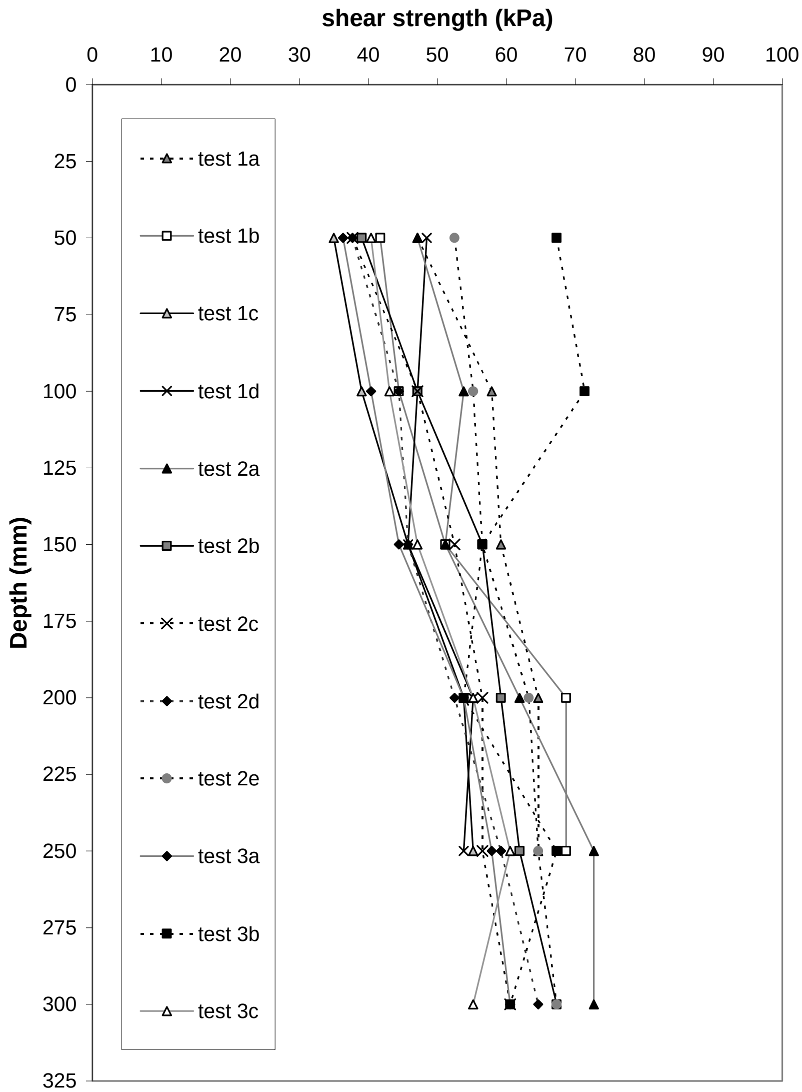


Figure 6. Shear strength profiles

Test reference	Group 1	Group 2	Group 3	Group 4
1a	Preliminary single and linear group tests to test equipment and procedure Data not presented			
1b				
1c				
1d				
2a	S12	T12	C12	n/a
2b	C16	C18	S08	
2c	C10	S20	T09	
2d	S16	C08	S18	
2e	C14	T18	S10	
3a	L5 (1.25d)	L5 (2.0d)	L5 (2.75d)	single pile
3b	S20	C10	C16	n/a
3c	L5 (2.5d)	single pile	single pile	L5 (2.25d)

NB: C=circle, S=square, T=triangle, L=linear, followed by the number of piles. For example, S12 = square group containing 12 piles. Linear groups have variable pile-to-pile spacing (as shown in brackets). All perimeter groups have a pile-to-pile spacing of 2.0d.

Table 1. Summary of tests completed

4 RESULTS

Tests have only been completed recently and analysis is yet to be conducted in full. At this stage only initial observations will be made.

The results from the single pile tests are shown in Figure 7 and indicate an average individual pile capacity of 128 N. Results from the linear group tests are shown in Figure 8 and indicate an average pile capacity of approximately 144 N. The total capacity of the group has been divided by the number of piles (five) to obtain the average pile capacity.

The linear pile groups appear to pick up load at different points in the initial stages of the test (eg, the biggest difference is between test 3a (1.25d) and test 3c (2.25d)). However, this is believed to be an effect of the differing locations within the sample and small variations between the heights of the pile caps and loading guides. It is not thought that these effects will alter the ultimate capacity of the pile groups. There appears to be no clear relationship between capacity and pile spacing and therefore results suggest that the capacity of the group is constant for a pile-to-pile spacing between 1.25 and 3.0 d.

The results from the perimeter group tests are presented in Figures 9 and 10 as the average capacity per pile (some test results have been omitted for clarity). The pile spacing is 2.0d in each of the perimeter group tests. This spacing was chosen so that the piles are sufficiently close to be considered ‘closely spaced’ without being difficult to install. In addition, it represents the mid-point between piles that are touching (1.0d) and piles that are generally considered far enough apart not to influence each other (3.0d).

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. These results indicate both linear and perimeter groups have an efficiency of greater than one. A sample of the results is presented in Table 2.

These findings are contrary to some published results for comparable model tests. For example, Whitaker (1957) showed that closely spaced piles driven in soft clay have an efficiency of less than one. Other Authors present similar results and suggest pile groups should be designed with appropriate reduction factors. However, test conditions and procedures are not analogous and therefore are not necessarily applicable to all pile groups in clay. This comparison with existing literature requires further investigation.

Group	Ultimate capacity (N)	Capacity per pile (N)	Efficiency
average single pile	128	128	n/a
average linear group	720	144	1.13
S08	1080	135	1.05
C10	1315	131	1.02
C14	2190	156	1.22
S20	3485	174	1.36

Table 2. A sample of results and group efficiencies

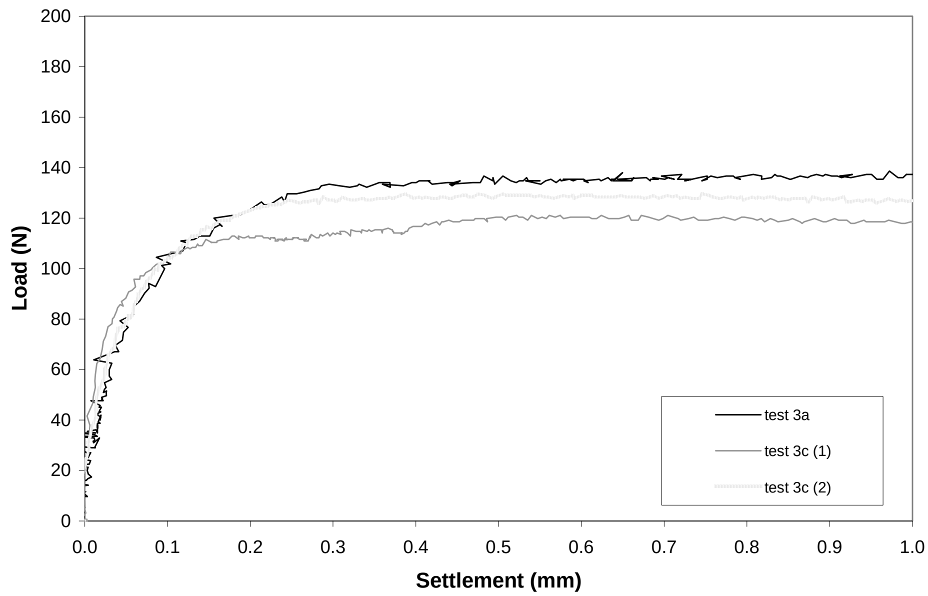


Figure 7. Results from single pile tests

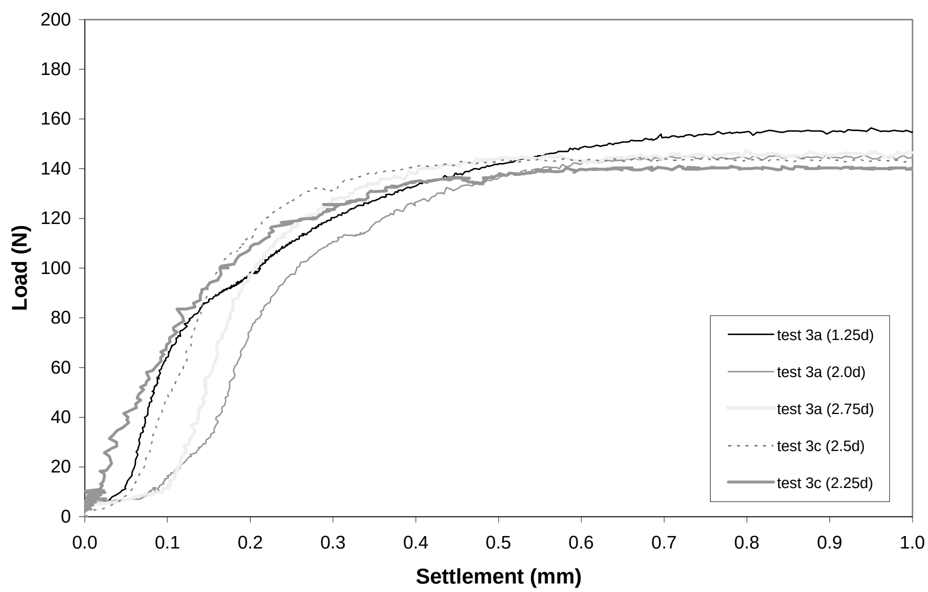


Figure 8. Results from linear group tests

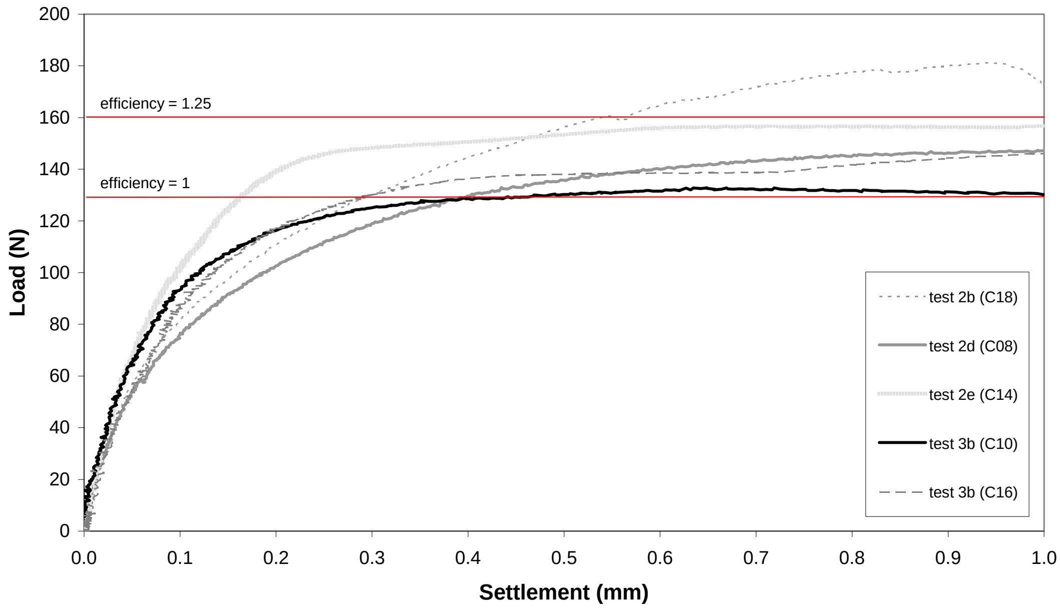


Figure 9. Results from perimeter group tests (circular groups)

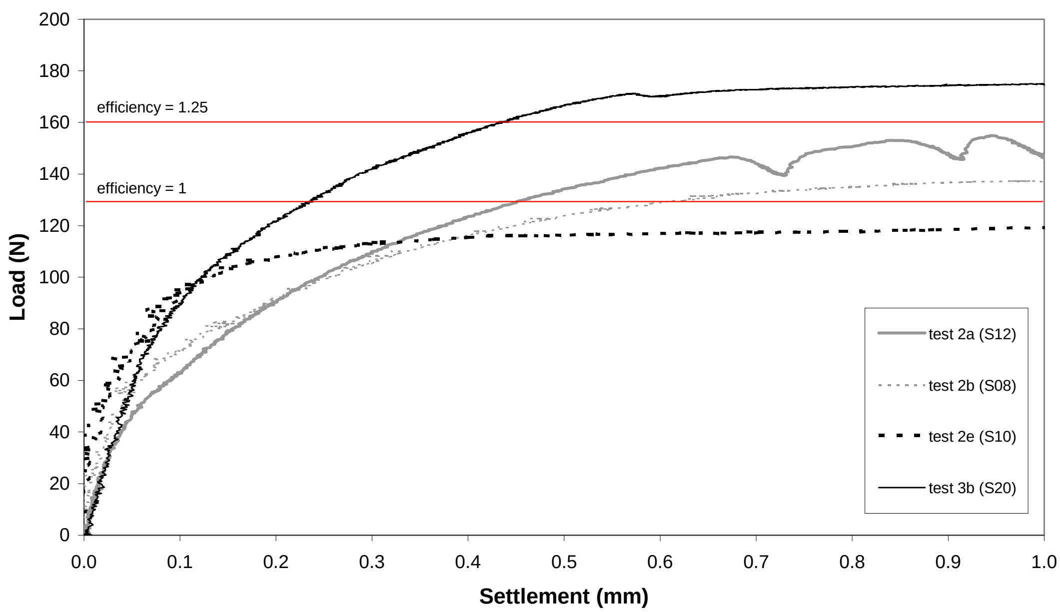


Figure 10. Results from perimeter group tests (square groups)

5 CLOSING REMARKS

Apparatus has been designed and commissioned that allows accurate installation of closely spaced groups of model micropiles at 1 g and allows multiple pile groups to be installed in a single clay sample. Generally, the tests have worked well and the data generated so far is consistent.

The results suggest that the capacity of a linear group is not affected by the pile-to-pile spacing, between 1.25 and 3.0 d. The results also indicate that both linear groups and perimeter groups show efficiencies greater than one and suggest that there is a 'group effect' contributing to the capacity of the foundation. Further testing will take place to confirm the group efficiencies and also to compare with existing literatures which present conflicting findings to these test results.

The next stages of work will involve testing different arrangements of perimeter groups with the aim of increasing the group effect to enhance the capacity and efficiency.

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