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Experimental technique for creating enhanced capacity piles in a centrifuge environment

Leonardo Lalicata[1], Andrew McNamara[1] and Sarah Stallebrass[1]
[1]*Civil Engineering, City, University of London, UK*
Corresponding author**:** Leonardo Lalicata leonardo.lalicata@city.ac.uk

ABSTRACT: The paper describes experimental techniques developed in the geotechnical centrifuge facility at City, University of London to test bored pile foundations with profiled bores designed to increase pile capacity. Improvements were made to existing equipment to ensure accurate measurement of the load displacement response at working loads and potential errors quantified.

Keywords: Pile Foundations; Load-Displacement; Stiff Clays.

1 INTRODUCTION

Researchers at City, University of London are collaborating with Keltbray Piling, on an Innovate UK funded project to develop an enhanced capacity bored cast *in situ* pile. This research builds on work by Gorasia and McNamara (2016) which explored the enhanced capacity of bored cast *in situ* piles with discrete ribs or a rib shaped like a spiral along the length of the pile.

The research at City, University of London consists primarily of a substantial series of centrifuge model tests, 13 tests to date, exploring the influence on the load-displacement response of the piles to changes in the geometry of a novel form of profiling applied to the pile bore. These centrifuge model tests are supplemented by field trials and the results of the tests are being used to develop the profiling equipment used in the field by Keltbray Piling.

2 METHODOLOGY

There were a number of criteria that needed to be fulfilled to ensure that the programme of centrifuge testing complemented the developments and field tests undertaken by Keltbray Piling:

- Centrifuge tests should relate sufficiently closely to the field tests in terms of stress state, pile geometry and soil conditions and yet be well defined and straightforward to analyse.
- Tests should result in consistent load displacement data once allowance has been made for changes in soil properties
- It should be possible to measure displacements and loads accurately at working loads as well as when the pile reaches ultimate capacity.
- The method of profiling the pile bores should be reproducible and the geometry of the indentations representative of those used in the field.

The following sections outline how the test, model preparation equipment, displacement and load monitoring systems were developed to fulfil the above criteria.

3 THE CENTRIFUGE TEST

Bored cast *in situ* piles are commonly used foundations in London, constructed mainly in the London Clay, a stiff overconsolidated marine clay, with a casing provided to support overlying sands and gravels. They are most efficient when they do not extend into underlying unstable strata and the depth of London Clay available is often sufficient to prevent this. In the field tests piles were constructed in the London clay at Southall. Consequently, the centrifuge tests needed to simulate the construction of pile foundations in overconsolidated clay. The overlying strata would not be included in the model to simplify the analysis of the piles and ensure it was straightforward to distinguish the effect of the profiling of the bore which would not be possible in the cased sand and gravel layer. The soil used in the model was created from Speswhite Kaolin clay as discussed below.

The Geotechnical Engineering Research Group at City University makes use of an Acutronic 661 beam centrifuge, described in detail by Schofield and Taylor (1988). The model was tested at 50*g* so that piles representing typical diameters used in the field can be constructed at a sensible size for the purposes of model preparation. To maximise the number of piles tested a “plane strain” strongbox was used of nominal internal dimensions 550 x 200 x 375mm. The piles were bored, profiled and cast, see section 4 at 1*g* and the loading apparatus was then assembled on the plane strain strongbox. Constructing the piles at 1*g* means that the contact between the piles and the surrounding soil is optimised leading to values of the adhesion factor α typically in the region of 0.75 – 1.0 (Gorasia and McNamara, 2016). This eliminates uncertainties that occur in the field due to the softening of the soil near the pile bore and will ensure that increases in capacity caused by profiling will be underestimated by the centrifuge tests.

Once pore pressure equilibrium was reached in flight, see below, the piles were loaded until failure at a displacement rate of 1 mm/min. Due to the high displacement rate, pile loading takes place under undrained soil conditions.

3.1. Preparation and characterisation of the model soil

The Speswhite Kaolin clay used in the tests is prepared from slurry with an initial water content of 120% which is twice the liquid limit. The slurry was created by mixing dry powder and distilled water in an industrial ribbon blade mixer.

The slurry was then carefully poured into the model container and manually stirred to expel the main air bubbles. The model container was previously coated with pump water grease to minimise skin friction. Beneath the slurry there was a filter paper and a 3 mm porous plastic sheet, with an aluminium drainage plate at the base. On top of the slurry a second filter paper and porous plastic sheet were placed and drainage was allowed through holes in the loading plate in the press. The initial slurry height (~575 mm) was much greater than the height of the strongbox (375 mm) requiring the use of an extension in the consolidation stage.

Consolidation was achieved by means of a hydraulic press over a period of 9 days including 1 day of swelling. The models were compressed to a vertical stress of 500 kPa that was then reduced to 250 kPa, inducing an in-flight over consolidation ratio (OCR) that decreases with depth. In flight, the water table was maintained at 10mm below the surface of the clay by means of a standpipe supplied continuously with water from outside the centrifuge and connected to the bottom of the model. The top surface was sealed with a synthetic rubber coating to prevent clay drying during the test. (Panchal et al., 2019; Gorasia and McNamara, 2016). This allows the clay to achieve pore pressure equilibrium with drainage to the base of the model after a period of around 44 hours in flight before the piles are loaded.

At the end of the test, the undrained shear strength was estimated from hand vane tests and water content samples. The water contents were converted to strengths using critical state theory (Wood, 2004). Soil strength measurements for the tests are given in Figure 1. The symbols in the S_u plot are the values derived from water content measurements, while the lines correspond to the hand vane results. In general, the latter give higher strengths. The measurements are largely consistent in the tests. As might be expected, the undrained strength increases slightly with depth as water content reduces.

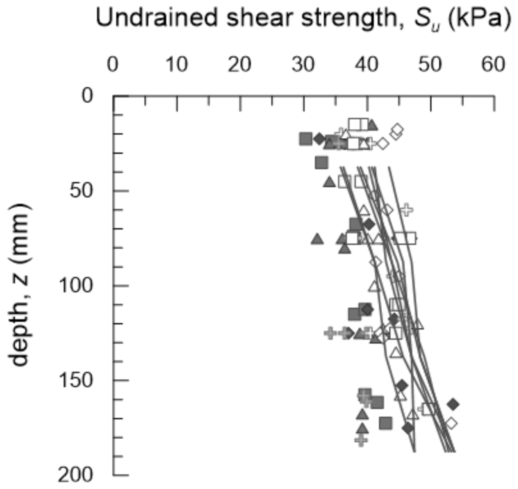

Figure 1. *Undrained shear strength profiles with depth.*

3.2. The experimental apparatus

For each test the soil sample provided up to four testing sites within the rectangular strong box, Figure 2. The piles are positioned at the centreline of the model, 100 mm from the sides, which is far enough to minimise boundary effects (Craig, 1995).

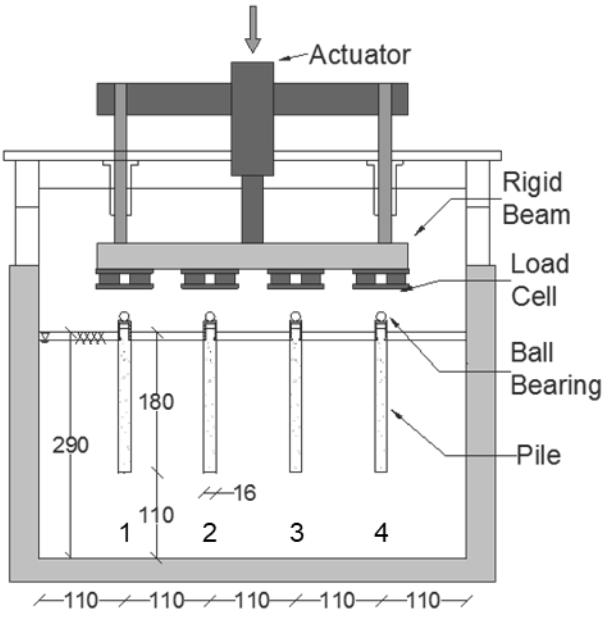

Figure 2. *Model geometry.*

The piles used in tests were 16 mm in diameter and 180 mm long, giving a prototype pile 800mm in diameter 9 m long. The pile length to diameter ratio is small if compared to typical piles used in the field but a reasonable compromise given the need to provide sufficient soil under the base of the piles and the limited depth of clay available. Smaller diameter piles could have been used with a higher *g* level, but this would have made the profiling operation impractical. In addition, the relatively small length of the piles ensures a faster in flight consolidation prior to pile loading.

The piles, are spaced 110 mm apart and loaded simultaneously by means of a rigid beam. The apparatus is devised such that it is possible to obtain independent load and settlement data for each pile. Several pieces of apparatus were designed and developed to improve the experimental technique. These included the loading equipment, the measurements of pile displacement and the guides, jigs and impression tools needed to create the model piles, as discussed below.

4 LOAD-DISPLACEMENT MEASUREMENT

The axial load is applied from the actuator to the piles by means of a rigid reverse T-shaped beam (Taylor *et al.,* 2013). The initial concept was to measure the load whilst assuming that the loading arrangement was sufficiently stiff to ensure that the displacement applied to all piles was the same. Thus, it should have only been necessary to measure displacement on the beam. To reduce the interaction between the beam and the loaded piles the system was stiffened with two silver steel guides (16 mm in diameter) positioned at the extremes of the beam. Each guide travels through a linear bearing 100 mm long and is connected to the other guide above the plate carrying the actuator by a 40 mm thick silver steel plate, Figure 3.

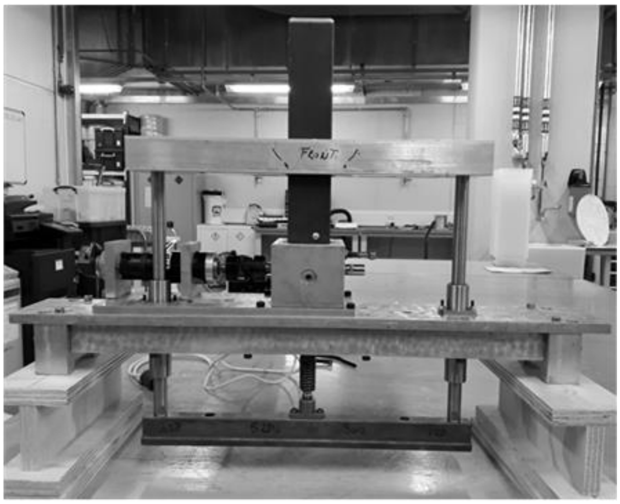

Figure 3. *Loading apparatus.*

Although this resulted in a stiff loading system that would not deflect when loading all piles simultaneously, it was not possible to prevent some movement of the beam if only one pile was loaded, particularly if the pile was at the end of the beam. As it was not feasible to ensure that the beam encountered all piles simultaneously the displacement of the pile heads was monitored independently.

In order to avoid any undesired eccentricity during the loading of the pile, a ball bearing laying on top of a concave plate was used to apply the load, Figure 4(a). Three load cells, sandwiched between two aluminium plates, measured the load on each pile ensuring that errors due to bending in the load cell are eliminated Figure 4(b).

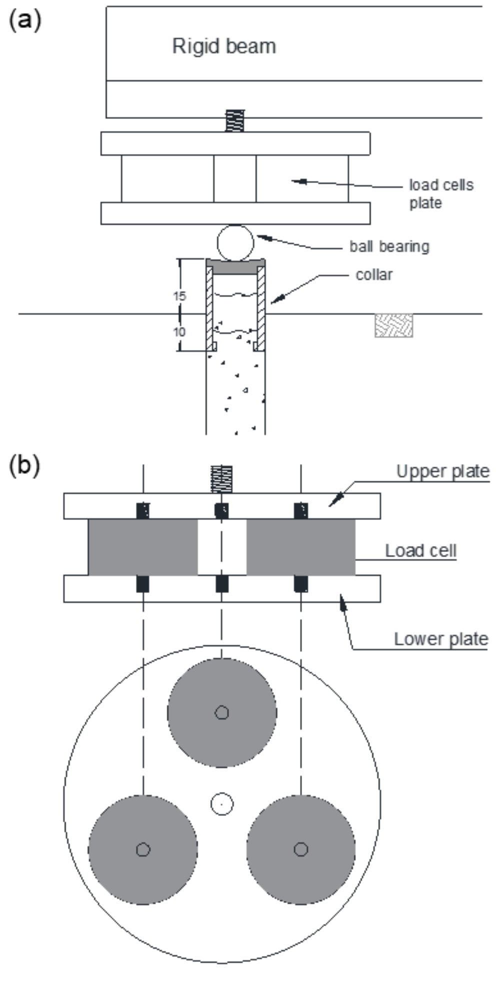

Figure 4. *Load measurement system (a) vertical cross section, (b) detail of the load cells plate.*

Several attempts were made to obtain reliable readings of the head displacement of the pile, the results and the consequences for the response of the pile will be discussed later in the paper. The current measuring system is sketched in Figure 5. A 2 mm thick aluminium plate, 175 mm long and 16 mm wide, is a tight fit to the pile collar and two LVDTs measure the plate displacement at its extremes. The head displacement of the pile is given by the mean value of the LVDT measurements. A 1 mm gap between the plate and the concave dish guarantees that load and displacement are independent readings.

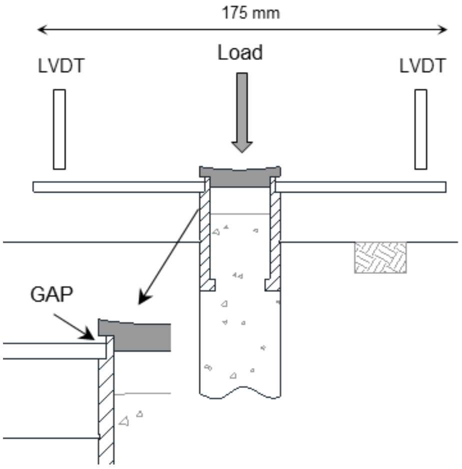

Figure 5. System for the measurement of the head displacement of the pile.

5 MODEL PILES

As noted in Section 3, the piles were cored, profiled and cast at 1*g*. For results to be repeatable it was key that the piles were vertical, a constant length into the clay and the profiling was precisely located and well defined.

The piles were cut using a hypodermic thin walled tube with an external diameter of 16 mm. The tube was mounted onto a brass handle to allow for easy cutting (Gorasia & McNamara, 2016). The verticality and position of the piles was achieved using the system of guides shown in Figure 6 (a). To minimise soil disturbance during boring several precautions were undertaken: the internal part of the tube was sprayed with a lubricant oil and the edge of the tube was sharpened. In addition, the boring was always undertaken in three steps of equal length.

The enhanced capacity piles were created from the plain pile bore. A custom designed tool was inserted into the guide and used to profile the pile bore Figure 6 (b). After profiling, the piles were cast using a 'fast cast' polyurethane resin, Sika Biresin G27 (McNamara, 2001; Gorasia and McNamara, 2016). The pot life of the resin is approximately 3 minutes. Aluminium powder was used as filler in an equal mass ratio with the two components of the resin to ensure that the pile is not buoyant. The mixture was designed to have a good fluidity to fill the profiles. Figure 7 shows some of the exhumed piles and demonstrates the success of the methodology adopted. Several uniaxial compression tests were undertaken to measure the mechanical properties of the resin when set. The resin was found to have a Young's Modulus equal to 1.1 GPa and a yield stress of 35 MPa. These values confirm that the pile behaves as a linear elastic material in the range of the applied loads.

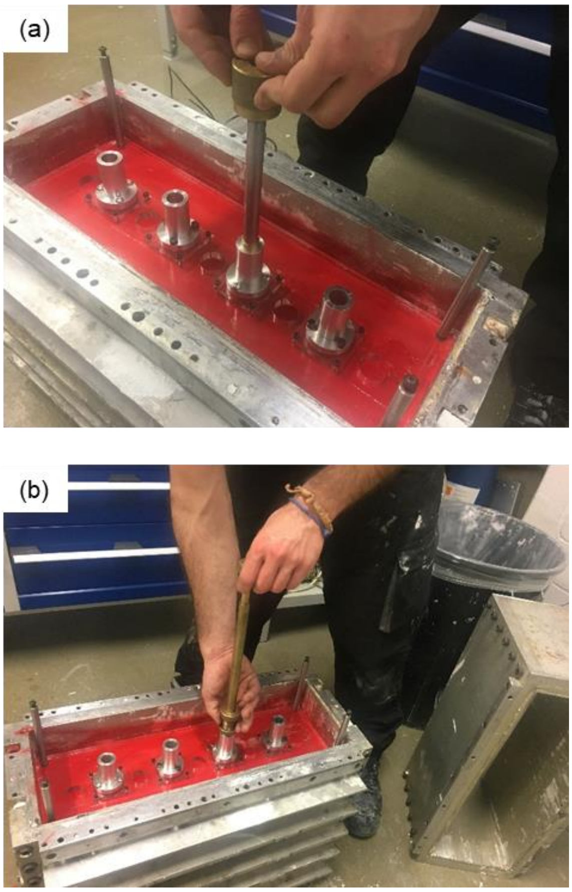

***Figure 6.** (a) guide for pile boring, (b) impression.*

***Figure 7.** Exhumed model piles some with profiled bores*

These values also allowed the pile-soil stiffness ratio to be estimated from standard relationships between soil stiffness and strength. For a low plasticity, heavily overconsolidated clay such as that used here, the stiffness/strength ratio is typically given by E_u/S_u =300 leading to relative stiffness ratio, between pile and soil of approximately 90. Therefore, the pile is expected behave as a compressible pile with most of the interaction concentrated in the upper part of the shaft as might be expected of a full length pile used in the field tests.

6. ANALYSIS OF RESULTS

6.1 Repeatability

Figure 8 shows data from all tests on straight-sided model piles interpreted in a consistent manner to give the ultimate capacity of the pile. These ultimate capacities have been plotted against undrained shear strength calculated using both water content measurements and vane test data. In general, the ultimate loads correlate well with undrained strengths calculated from water content data and show a slight increase in ultimate load with undrained strength as would be expected.

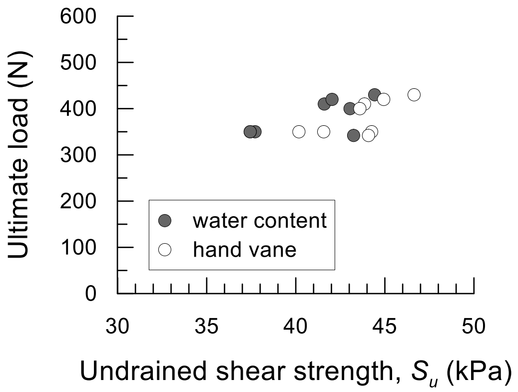

Figure 8. *Ultimate load of all straight sided model piles plotted against the undrained shear strength at z=L/2=90 mm, where L is the length of the pile.*

6.2 Pile-beam- pile response

The typical evolution with time of displacement and load for a set of four straight-sided and profiled piles are presented in Figure 9(a) and Figure 9(b) respectively. The dashed line represents the imposed displacement. For each pile, the displacement is given by the average of the LVDTs and the load is the sum of the LCs measurements. The piles are displaced over a time interval of 2.5 minutes that approximately corresponds to the accuracy of the collar installation into the bore (± 1 mm), given that the displacement rate of the beam should be 1 mm/min. Inspection of the displacements, Figure 9 (a), shows that in the early stages of loading, the pile head displacements are different from those imposed.

This is particularly true for the first two piles (4 and 1) that are at either end of the loading beam. For pile 4 the displacement curve is concave at the beginning and then, as the beam touches pile 1, the concavity changes and the trend become parallel to that. This is likely to be related to some small (~1/400 of rotation) rocking of the beam due to the temporary asymmetry of the loading and the relatively high stiffness of the piles. The other piles (2 and 3, in the central position) loaded last, displace with approximately the same loading rate as that imposed. That is because the external piles have "balanced" the beam by applying roughly the same reaction and because piles 2 and 3 are closer to the centre of the beam, where the effect of rocking is lower. This behaviour is not affected by the configuration of the straight-sided and profiled piles.

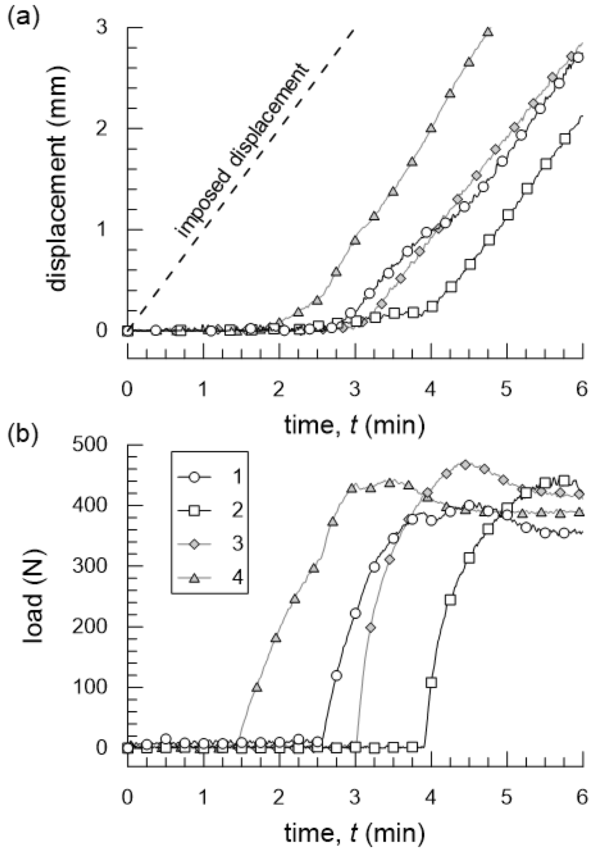

Figure 9. *Evolution with time of: (a) displacements of the piles, (b) loads of the piles*

The consequence of this effect is depicted in Figure 10(a) and Figure 10 (b) that show the load-settlement response for an external (1) and an internal pile (3) respectively. In each figure, the measured load-settlement curve is compared with the one that would be obtained assuming that the pile displacement was equal to that imposed. The underestimation of the initial pile stiffness in the latter case is apparent in both cases: 63% for pile 1 and 43% for pile 3. The difference reduces in the second case as the pile is loaded after piles 4 and 1 and it is closer to the centre of the beam. It is thus clear that in order to obtain reliable measurements at low deformation levels (i.e. working load) it is critical to measure the head displacement of the pile directly. However, the value of the failure load is unaffected by errors in the displacement measurements.

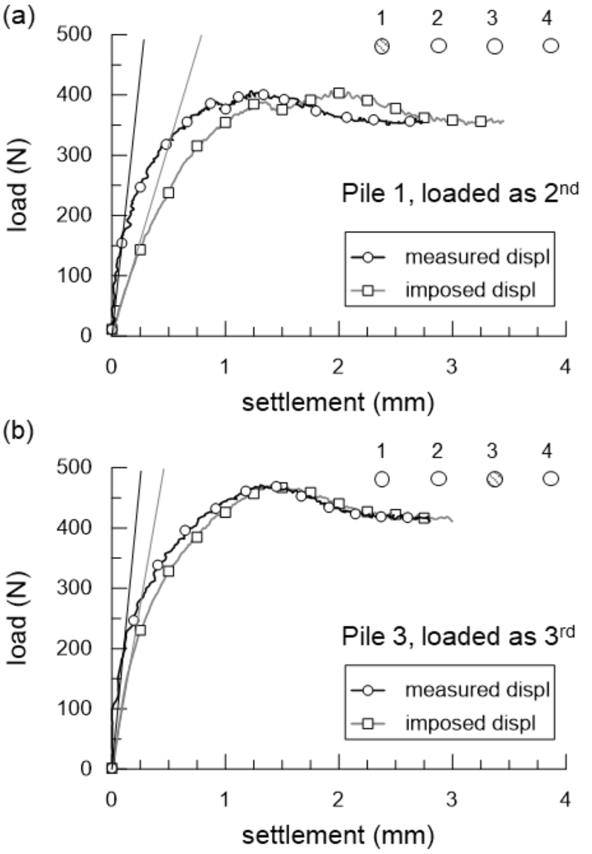

Figure 10. *Direct measures of pile displacement compared with that expected from the beam movement: (a) external pile, (b) central pile.*

7 CONCLUSIONS

A series of centrifuge tests have been designed to characterise the increase in pile capacity obtained by profiling the bore of a bored cast *in situ* pile. In addition to pile capacity the tests also needed to measure changes in load displacement response at working load, which required accurate measurement of both load and in particular displacement at displacements of less than 0.2mm. The aim was to produce a substantial series of tests that would form a parametric study to be compared to a limited number of field tests.

Apparatus has been developed that loads four piles always including a straight unprofiled pile for comparison. The loading system, despite being modified to improve its rigidity, did not provide a sufficiently accurate or reliable means of measuring the displacement of the pile head and consequently a system was developed to measure these displacements separately. The consequence of measuring the pile head movements directly compared to measuring the displacement of the loading beam has been quantified.

Compromises in the modelling of the overall pile geometry have been discussed and it has been established that the soil/pile stiffness used ensures that the pile will respond as a compressible pile even though it is comparatively short. It has been shown that consistent measurements of pile capacity can be obtained if changes in undrained strength are accounted for, demonstrating that the methodology for the preparation of the soil bed and the construction of the piles provides repeatable results that can be used to generate data for a parametric study of the influence of the profiling on pile behaviour.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

Craig, W.H. 1995. Geotechnical centrifuges: past, present and future. In Geotechnical Centrifuge Technology (Taylor RN (ed.)). Blackie Academic and Professional, Glasgow, UK, ch. 1, pp. 1–19.

Gorasia, R.J. and McNamara A.M. 2016. High-capacity ribbed pile foundations. Proceedings of the Institution of Civil Engineers: Geotechnical Engineering, **169**(3): 264–275.

McNamara, A.M. 2001. Influence of Heave Reducing Piles on Ground Movements Around Excavations. PhD thesis, City University, London, UK.

Panchal, J.P., McNamara, A.M., Halai, H. and Divall, S. 2019. Centrifuge modelling to determine the influence of pile stiffness on pile capacity. Proceedings of the XVII ECSMGE-2019 Geotechnical Engineering foundation of the future. doi: 10.32075/17ECSMGE-2019-0036.

Schofield, A.N. and Taylor R.N. 1988. Development of standard geotechnical centrifuge operations. In Centrifuge 88 (Corte JF (ed.)). Balkema, Rotterdam, the Netherlands, pp. 29–32.

Taylor, R.N., Rose, A.V. and Gorasia, R.J. 2013. Pile and Pile Group Capacity: Some Findings from Centrifuge Tests. International Journal of Geo-Engineering, **5**(2), 5-15.

Wood, D.M. 2004. Geotechnical modelling. New York: Spon Press.