High shear capacity ribbed piles

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Abstract: Ribbed bored piles are known to give increased shaft capacity in comparison to conventional straight shafted bored piles. The commercial benefit of greater pile capacity is cheaper foundations. Significant environmental benefits will also accrue from the use of efficient foundations that are able to carry higher load, leading to less excavation and spoil removal requiring disposal, and reduced concrete in construction. Moreover, redevelopment of urban sites often requires removal of existing deep foundations owing to clashes in position of old and new foundations. Higher capacity piles offer potential for greater flexibility in foundation layout owing to their reduced size, making them easier to install around existing piles. This paper describes a series of tests conducted using the City University London Geotechnical Centrifuge. The tests show that concentrically ribbed piles can provide an increase in capacity of about 30% when compared with plain piles. Furthermore, ribbed piles provided a greater capacity than that of a pile with a diameter equal to that of the rib diameter.

Keywords: Bored pile, ribs, pile capacity, centrifuge modelling.

1 BACKGROUND

In 2002 Expanded Piling and Arup Geotechnics agreed to co-operate and jointly funded a programme of research consisting of a limited number of full scale field trials, undertaken by Expanded Piling and supported by numerical analyses conducted by Arup Geotechnics. The field trials involved construction of several ribbed piles which in turn required preliminary development work on a special tool used for profiling the shaft. The analyses and tests yielded promising results and suggested that pile capacity could be increased by 30% - 40%. The project was featured in an article in Ground Engineering, the magazine of the British Geotechnical Association, in December 2003.

Conventional pile capacity is known to be sensitive to the construction process. 'Over auguring' during pile excavation appears to reduce pile capacity because the soil at the concrete/soil interface is extensively disturbed and remoulded. Pile test data have shown that subjecting concrete to extended vibration during placing can result in an increased pile capacity when compared to standard practice.

Whilst the technique of providing a mechanically rough pile/soil interface has demonstrated increased shaft capacity in the field, and this has been confirmed by numerical analyses, there is a need to test a wider range of geometries in various soil conditions to establish how the additional capacity that such piles offer is derived.

2 INTRODUCTION

The past decade has seen the construction of buildings and infrastructure increase rapidly, resulting developers building larger structures in more confined spaces. As buildings increase in height with varying design, shape and structure, one aspect remains constant, their foundations, which invariably involve some sort of piling. It is therefore necessary for these foundations to carry larger loads as

designers plan for more extravagant structures. To accommodate greater loads engineers have no option but to bore deeper and wider piles, at closer spacing. Eventually, this becomes unfeasible.

Given the obvious potential for commercial exploitation of this, a fundamental study of the factors affecting behaviour at the pile shaft/soil interface has been undertaken. In order to understand how increases in pile capacity can be optimised and to develop guidelines for the important factors affecting design and construction of high capacity piles.

This paper describes a series of centrifuge experiments conducted at 50g in over consolidated speswhite Kaolin clay, using model plain bored pile versus piles with profiled shafts.

3 APPARATUS AND MODEL

Each test consisted of three testing sites within the soil container; two of the sites were used for piles and the third for a T-bar penetrometer. Since the soil container was a cylindrical tub, it was decided to locate each test site on a pitch circle diameter of 240mm. Thus ensuring that each site is sufficiently far away from the boundaries of the tub, but also from adjacent test sites, so as to minimise any influence they may have on each other.

The piles used were nominally 16mm in diameter by 180mm in length, at 50g this scales to 800mm diameter by 9m long pile. For the ribbed piles the shaft diameter remained constant at 16mm, the ribs protruded outwards

3.1 Pile cutting apparatus

The straight shafted pile was cut using hypodermic tube with an external diameter of 16mm and wall thickness of 0.5mm. The hypodermic tube had been mounted onto a knurled brass handle, to allow for easy cutting, as shown in Figure 1.



Figure 1. Straight shafted pile cutting tool.

Figure 2. Rib cutting tool.

The pile cutting tube was guided using collars to maintain a high positional tolerance and verticality; the guide system is discussed below. 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 to move more freely inside the tube, and a sharpened edge on the tube. Moreover, the boring of the pile took place 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. The rib profiling tool is shown in Figure 2.

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.

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



Figure 3. Pile cutting plates and guide collars.

3.2 Pile loading

The pile cap is the component of the foundation that provides the connection in between the superstructure and substructure. Pile caps can be designed to only transmit specific types of load. In the case of these tests, which are designed to study the axial capacity of the foundation, it was necessary for the pile cap to only transfer vertical loads, and hence not horizontal loads or moments. The pile cap had been designed to achieve this, see Figure 4.



Figure 4. Pile cap detail.

Figure 5. Load cell with loading pin.

The load cells were fitted with a bull nose loading pin, which sat in a matching recess in the pile cap as shown in Figure 5.

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, which two LVDT legs rested on. 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 10mm 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 8mm linear bearings and matching shafts were provided.

The screw jack, manufactured by Zimm was capable of providing 5kN of axial force, and had a maximum stroke of 250mm 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 15Nm of torque.

3.3 Pile geometries

This paper presents a number of centrifuge tests with concentrically ribbed piles. In each test a 16mm (800mm at prototype) plain pile was also used in order to provide a control. The rib outstands and heights were constant for all tests (1.5mm or 75mm at prototype) and therefore the only variation between the tests was the distance between the ribs. Figure 6 show the range of tested pile geometries.



Figure 6. Range of pile test geometries.

3.4 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 without excessive exotherm whilst providing good resistance to shrinkage and fast setting. This study led to the conclusion that a suitable material would 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; the exotherm was also measured

and found to be within acceptable limits. A mixture of 100g of filler to 100g of resin resulted in 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.

Some preliminary tests of the Sika Biresein G27 resin were conducted to check the viability of the resin for the proposed tests. A simple resin delivery system was used, whereby an 8mm nylon hose was attached to a funnel, the hose assisted in delivering the resin to the bottom of the pile bore.

The resin to filler mixture was found to give a density approximately equivalent to water. As this would be unrepresentative a mixture of 2 parts resin to 3 parts filler was used which was found to have a density of approximately 1800kg/m^3 , whilst this was not the same as concrete it was significantly closer.

The piles were cut, profiled and cast on the lab floor, immediately after removal of the sample 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 8mm diameter tube to ensure the resin was delivered to the bottom of the pile bore.

3.5 T-bar penetrometer

An instrumented T-bar penetrometer based on Stewart & Randolph (1991) to profile the undrained shear strength of the soil in flight, but after pile driving, was used. The penetrometer consisted of a 7mm diameter rod connected to a hollow tube, via a short length of thin walled hypodermic tube, to which the strain gauges were attached. The T-bar used four strain gauges in a full bridge circuit to compensate for bending and only measured axial strain whilst simultaneously compensating for temperature changes, lead wire resistance and Poisson's ratio effects. A brush on neoprene coating applied to the strain gauges provided protection from dirt and moisture (Figure 7).



Figure 7. T-bar penetrometer.

From the force on the T-bar, the shear strength was estimated using the following simple expression:

$$\frac{P}{S_{\mu}d} = N_b \tag{1}$$

Where:

$$\begin{split} P &= \text{force per unit length acting on the cylinder (kN).} \\ d &= \text{diameter of the cylinder (m).} \\ S_u &= \text{undrained shear strength of the soil (kPa).} \\ N_b &= \text{bar factor.} \end{split}$$

Randolph and Houlsby (1984) recommend that an intermediate value for Nb of 10.5 could be adopted for general use. Figure 8 shows measured undrained shear strength against depth for several tests.



Figure 8. Measured undrained shear strength.

3.6 Sample preparation

The clay samples for the tests were prepared from slurry at a water content of approximately twice the liquid limit, as per standard practice, which for speswhite kaolin is 120%. Clay was recycled from previous tests where possible. Consolidation took place over a 9 day period, including 1 day of swelling. McNamara (2001) found that after approximately one week the vertical movement of the ram was negligible. The consolidation load was incrementally increased to a maximum of 500kPa over the period of three days and kept constant for a further 5 days. At this point the sample was allowed to swell to 250kPa a day before model making.

A consolidation pressure of 500kPa followed by swelling to 250kPa gives an over-consolidation ratio variation with depth as shown in Figure 9, and therefore a variation of K_0 with depth as shown in Figure 10, calculated using Equation 2 after Mayne and Kulhawy (1982)



 $K_0 = (1 - \sin \phi') OCR^{\sin \phi'}$

The consequent theoretical vertical and horizontal total and effective stresses are shown in Figure 11.

(2)



3.7 Centrifuge model testing

Model preparation typically took two hours from removal of the soil sample from the consolidation press to centrifuge spin up.

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 50g 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 0.25mm/min for at least 12 minutes or 3mm of settlement, whilst the T-bar was driven at a rate of 60mm/min to a depth of approximately 200mm.

4 TEST RESULTS

The results of a series of 9 tests are reported. Each test consisted of a plain pile for control and a profiled pile.

4.1 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 12 shows the average load/settlement curves of the tests for both piles. The data shows good consistency between the two piles, the maximum error observed was less than 5%. This was then reasonably assumed to be the maximum error in any future tests.



Figure 12. Load settlement curves for verification tests.

4.2 Main test series

Figure 13 shows normalised load/settlement curves for the main series of tests. 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 circumventing any inconsistencies within the soil sample.

The data shows that a 10mm rib spacing provided the greatest increase in capacity when compared to a plain pile. This increase in capacity is then shown to decrease as the rib spacing is increased to 15mm. With a rib spacing of 20mm the load at the lower displacement range was less than that of a plain pile, but this quickly recovered and at a displacement of 3mm the normalised load was some 20% greater. A pile with rib spacing of 40mm was shown to mirror the behaviour of the 20mm spaced pile. The load at the lower displacements was higher than that of a plain pile, and at a displacement of 4mm the normalised load was 20% lower.

The test series also included a 19mm plain pile, which was bored in the same way as the ribbed piles (using a blank plate on the rib cutting tool), to ensure a consistent pile/soil interface. The normalised load settlement data of this test is also shown in Figure 13. Surprisingly, the 10mm spaced pile and to some extent the 15mm spaced pile performed better than a pile with a diameter equivalent to the rib diameter.

Following completion of the tests the piles were removed from the model and it was consistently apparent that there was less adhesion between the straight shafted pile and the soil then with the ribbed pile.



Figure 13. Normalised load settlement curves.

5 DISCUSSION

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

- 1. The Chin (1970, 1971) Failure Method, where failure is defined as the inverse slope of a load/settlement against settlement graph.
- 2. 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.
- 3. 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 0.14mm/kN.
- 4. 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.

The results of these analyses are present in Table 1 below. It is clear that at failure the 10mm ribbed pile was clearly the most optimised spacing, with a 34% improvement over the plain pile. This is also evident from the normalised load settlement curves which show the 10mm spaced ribbed pile has a 36% improvement over the plain pile at a settlement of an 4mm.

Pile	Chin	BS8004:1986	Fuller & Hoy	Brinch Hasen	Average (N)	Improvement
	Method (N)	Method (N)	Method (N)	Method (N)		over plain pile
10mm spaced	653.12	589.97	574.52	589.84	601.86	+34%
15mm spaced	608.94	513.54	550.91	549.82	555.80	+33%
20mm spaced	513.68	485.46	485.46	474.74	483.14	+20%
40mm spaced	405.09	419.03	390.34	440.10	413.64	-14%

Table 1. Summary of pile test analysis.

Whilst the 10mm 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 10mm spaced ribs to the 19mm 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 19mm plain pile was clearly inferior to the pile with 10mm 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.

Work currently being undertaken involves the use of a plane strain box and Perspex window. Piles cut in half longitudinally are placed against the window. By loading the piles in this way it may be possible to gain a better understanding of the flow of soil around the piles rib, this will likely provide insight as to the reason for increased capacity.

6 CONCLUSION

It is clear from the significant number of tests reported that an increased ultimate bearing capacity can be achieved by the modifying the profile of the pile shaft.

The tests conducted involved casting model piles into a sample of over consolidated Kaolin clay and comparing the results of a constant rate of penetration test with that of an equivalent plain pile. The results that were obtained were remarkably consistent and they showed a significant increase in the piles ultimate bearing capacity; especially when closer rib spacing was used.

The ribbed piles capacity was shown to be reduced with a large rib spacing (40mm) but consistently increase as the rib spacing was reduced. Furthermore, the difference between the improvement in the 10mm and 20mm spaced ribs was only 1%. This suggests an optimum spacing has been found since the additional work required to install closer spaced ribs only increased the piles improvement by a small amount. A wider range of geometries will need to be tested to verify this.

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