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Field and Centrifuge tests to validate a novel type of foundation

Essais en grande échelle et centrifugeuse pour la validation d'un nouveau type de fondation

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ABSTRACT: This paper presents working principles of a novel type of deep foundation. The technology is developed to enhance the geotechnical performance, under vertical load, of rotary bored piles in overconsolidated clay by modifying the geometry of the shaft. The enhancement consists of a local profiling of the shaft wall to create a nodular surface. This is characterised by the shape of the nodules, their vertical spacing, the number at each horizon and finally by the portion of the pile length involved in the enhancement. An extensive experimental study in the geotechnical centrifuge has been carried out to explore the behaviour of the novel type of pile. In each test, internal consistency was achieved by simultaneously testing three enhanced piles and one conventional straight shafted pile. The results show that the geometry changes increased the shaft capacity of the pile by 40% compared to the equivalent straight-shafted pile. The centrifuge tests results have been compared to two full scale pile load tests, one in compression and one in tension. The comparison between the centrifuge test data and the field tests is satisfying; demonstrating the effectiveness of this technology at full scale.

RÉSUMÉ : Ce papier présente les principes de fonctionnement d'un nouveau type de fondation profonde. La nouvelle technologie a été développée pour améliorer les performances géotechniques, sous charges verticales, des pieux forés en argile surconsolidée en modifiant la géométrie de la paroi latérale. L'amélioration consiste d'un remodelage local de la paroi latérale qui crée une surface noueuse. Celle-ci est caractérisée par la forme des nœuds, par leur espacement vertical et le nombre dans chaque niveau et, enfin, par la portion de longueur du pieu améliorée. On a étudié le comportement du nouveau type de pieu en utilisant la centrifugeuse géotechnique dans une étude expérimentale et en même temps extensive. Dans chaque essai, la cohérence interne a été obtenue en testant simultanément trois pieux améliorés et un pieu conventionnel. Les résultats montrent que les modifications apportées à la géométrie de la paroi ont augmenté la capacité latérale de pieu de 40% par rapport au pieu droit conventionnel. Les résultats des essais en la centrifugeuse ont été comparés à deux essais de chargement vertical à grande échelle, l'un en compression et l'autre en tension. La comparaison entre les données des essais de centrifugeuse et des essais à grande échelle est satisfaisante. On peut donc considérer cette technologie efficace même à échelle réelle.

KEYWORDS: piles, axial loading, centrifuge tests, enhanced capacity, shaft resistance

1 INTRODUCTION

Since the introduction of conventional bored piling in the latter half of the 20th century, the industry has seen limited improvements in methodology; with the notable exception of continuous flight auger piling developed in the 1960s. Most piling contractors have experimented with measures aimed at improving bored pile/soil interface friction; although the advantages gained were considered to be outweighed by the disadvantages of the additional time required to profile the pile bore prior to concreting (Ground Engineering, 2003).

An alternative method of increasing pile/soil interface roughness is to profile the shaft walls by creating small impressions that lead to a nodular pile surface. This method creates a novel pile type, which has been termed “impression” pile. The working principles of the impression pile are presented in this paper.

2 IMPRESSION PILE

An impression pile is a novel solution and is defined as a deep foundation with a profiled rotary bored pile shaft; this increases the friction capacity because a shear plane is created along a soil/soil interface, thereby mobilising significantly more soil strength than a conventional pile; which mobilises reduced friction at the pile/soil interface.

2.1 Construction sequence

The profiled shaft is realised by means of a bespoke patented “impression tool” that incrementally dimples the pile bore (Figure 1).

The construction sequence on site is sketched in Figure 2 for a typical soil profile of the London area that includes a made ground layer overlaying a stiff clay deposit:

- The temporary casing is driven through the coarse grained layer,
- The rig bores the hole in the clay soil to the designed length,
- The impression tool is lowered to the toe of the pile using a handling crane,
- Hydraulic jacks push nodular shields out to impress the shaft,
- The shields are retracted and the impression tool is lifted incrementally to each new position whereupon the impressions are created,
- Once the impressions are completed, the impression tool is taken out, the cage is installed and the concrete can be poured; and the temporary casing removed.

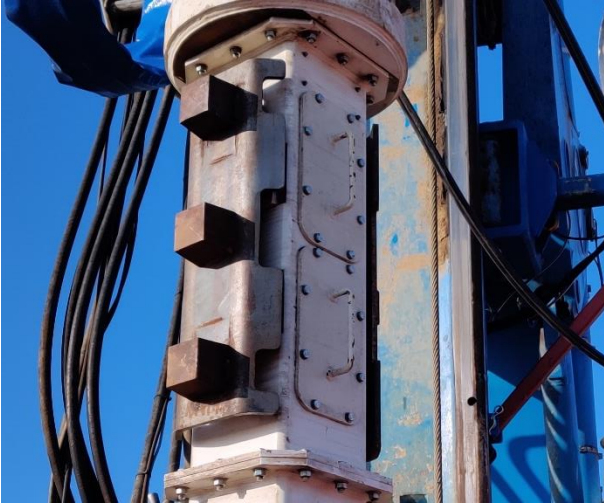


Figure 1. Bespoke Impression Tool from Keltbray Piling (Patent no: P027299GB/JMF/ZJH).

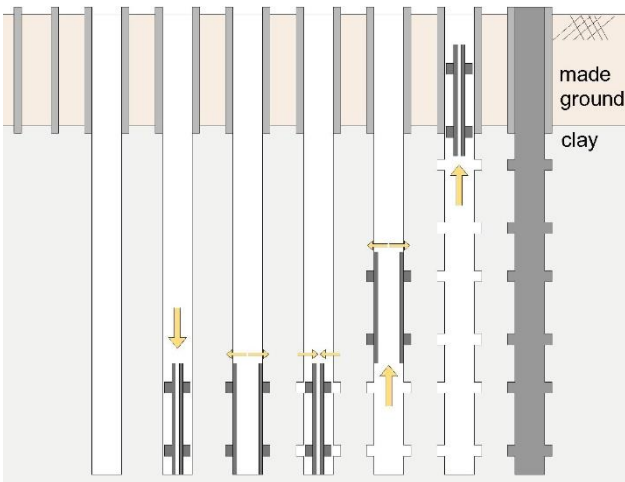


Figure 2. Construction of the impression pile.

In the simplest configuration, four nodules are impressed at a given cross section, spaced at 90° around the axis of the pile, and nodules are aligned in the vertical direction, although other configurations may be used.

Full-scale demonstration trials in London showed that the procedure does not delay the piling programme (Lalicata *et al.*; 2021, Panchal *et al.*; 2021) because the impression tool can be operated from the handling crane. Impressing a 20 m long shaft takes approximately 10 minutes, which is a negligible amount of time especially considering that the impressions would allow the construction of shorter, and eventually smaller, piles.

In the field, the quality of the impressions is monitored by cameras mounted on the impression tool, Figure 3. The visual evidence provides designers with the confidence that impression piles will suitably mobilise the specified design loads.



Figure 3. Impression in the London Clay.

2.2 Geotechnical performance

The impression pile is suited to firm clay soils, such as London Clay, and is generally most effective for carrying axial load. This is because the impressed shaft encourages a failure mechanism to develop beyond the extreme faces of the impressions resulting in more soil-soil shearing, compared with conventional soil-pile shearing on straight shafted piles (Lalicata *et al.*, 2021). The application is limited in very soft clay by the stability of the indentation created, whilst in very firm clay the only limit is the capacity of the jack used to create the indentations.

According to the size of the impressions, and the vertical spacing between them, two failure mechanisms can occur: the block mechanism and the flow around mechanism, Figure 4.

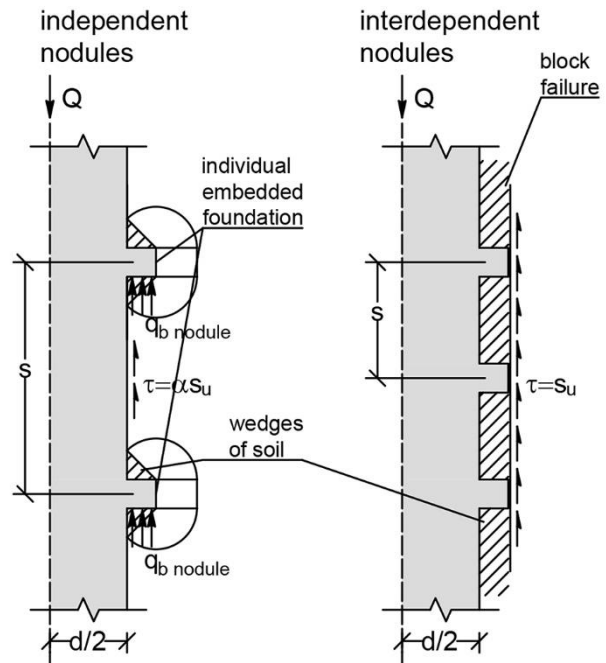


Figure 4. Schematic behaviour of the impression pile (after Panchal *et al.*, 2021).

The extensive parametric experimental study by Lalicata *et al.* (2021) demonstrated that impression pile performance is optimised when the spacing is lower than a critical value and the block failure mechanism is ensured. In this case, the shear planes develop between the impressed extrusions and consequently the failure occurs mainly in the soil. The direct consequence of this is that the mobilised shear strength is close to the undisturbed shear strength of the soil. When the

impression spacing is greater than the critical value, the nodules behave as independent foundations and the soil just flows around them.

3 CENTRIFUGE TESTS

Full-scale trials are expensive, slow to run and subject to the typical uncertainties of *in situ* soil conditions. Therefore, their value is limited in carrying out a comprehensive study of a novel technology.

Centrifuge modelling represents a viable high-quality alternative to address this goal. The increased gravitational field in a centrifuge model allows correct replication of the stress profile in the soil compared with the full-scale prototype (Taylor, 2004). Moreover, the preparation of the soil model and the hydraulic boundary conditions can be carefully controlled thereby providing consistent and repeatable sets of data.

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.
- The method of profiling the pile bores should be reproducible and the geometry of the indentations representative of those used in the field.

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 to ensure that it was straightforward to identify the effect of profiling of the bore. This would not be possible in the case of a sand and gravel layer. The soil used in the model was Speswhite Kaolin clay.

The geotechnical centrifuge at City, University of London was used to undertake the tests. The centrifuge facility and general operations are described in detail by Schofield and Taylor (1988).

The enhanced ultimate capacity of impression piles subjected to a static vertical force was explored in centrifuge tests undertaken at 50g using a homogeneous overconsolidated clay deposit. In each experiment, three impression piles were tested alongside a plain, straight shafted pile to provide a baseline response for comparison purposes. The piles were bored, profiled and cast at 1-g and the loading apparatus was then assembled on the strongbox.

During the centrifuge tests, the water table was maintained at a depth of approximately 10mm below ground level. The top surface was sealed with a sprayed synthetic rubber coating to prevent clay drying during the test. The sample was allowed to come into pore pressure equilibrium and the piles were then loaded until failure at a displacement rate of 1 mm/min.

The complete details of the experimental arrangement and of the test results are given elsewhere (Lalicata *et al.*, 2020; Lalicata *et al.*, 2021). Here only the main results are reported with a particular focus on the method used to analyse the results.

3.1 The Soil

The Speswhite Kaolin clay used in the tests was prepared from slurry with an initial water content of approximately 120%. The samples were compressed to a vertical stress of 500kPa which was then reduced to 250kPa. The undrained shear strength profile, estimated from water content samples taken at the end of the tests, increased slightly with depth as water content reduced.

A linear distribution ($s_u=41.2+0.044z$, with z in mm at the model scale) well describes the distribution of strength in all the tests performed, with the majority of the measurements falling inside a $\pm 10\%$ error band.

3.2 The piles

The test piles were 16 mm in diameter and 180 mm long, replicating a prototype pile 800 mm in diameter by 9 m long. The nodules protruded from the shaft by 1.5mm and were 3mm wide. These dimensions are, respectively, 75mm and 150mm at the prototype scale.

The impression tool was miniaturised to create the impressions at the model scale, Figure 5, and was designed to be versatile such that different spacing and positions of the impressed zone could be easily tested.



Figure 5. Small scale impression tool.

After profiling, the piles were formed using a ‘fast cast’ polyurethane resin, Sika Biresin G27 (McNamara, 2001; Gorasia and McNamara, 2016). Aluminium powder was used as filler in an equal mass ratio with the two components of the resin to ensure that the pile was not buoyant. The mixture was designed to have a good fluidity to fill the profiles and to produce a pile with appropriate values of stiffness, strength and weight. In these experiments, the capability of creating high quality impression piles was prioritised with respect to the reproduction of the pouring/curing process of the concrete. Figure 6 shows some of the exhumed piles with well shaped and well vertically aligned nodules; even at such a small scale.

Contrary to what happened in the field, in a centrifuge test the quality of the impression can always be determined at the end of the test. Therefore, it is possible to gain great confidence in the results obtained, especially when the geometrical parameters of the impression pile are varied by a small amount.

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. Model piles showing the different spacing between nodules (after Lalicata *et al.*, 2021).

4 FIELD TESTS

Preliminary full-scale tests have been carried out at a site in Southall, West London to understand the implications of profiling the shaft on the ultimate capacity of the piles.

The ground conditions comprised 1.5m Made Ground and 5.5m River Terrace Gravels overlying London Clay. The undrained shear strength of the clay was defined as $s_u = 100 + 5z$, where z was the distance below the top of the London Clay strata measured as 25mOD.

4.1 Compression test

Two series of tests have been undertaken. The first was a compression tests on two similar piles, one impressed and the other straight shafted. The impression and straight shafted test piles were instrumented with strain gauges and constructed as 900mm diameter piles, nominally 22.5m in length. Temporary casings were necessary to support the made ground and granular material overlying the clay. These were 9.5m long segmental 1000mm diameter and were sealed into the top of the London Clay, as illustrated in Figure 7, and removed during concreting. Cubic shaped impressions, 100·100·70mm, were formed into the pile bore with a spacing of approximately 500mm. Four levels of strain gauges were installed on the piles at 31.3mOD, 23.3mOD, 19.3mOD, 15.3mOD, 10.8mOD.

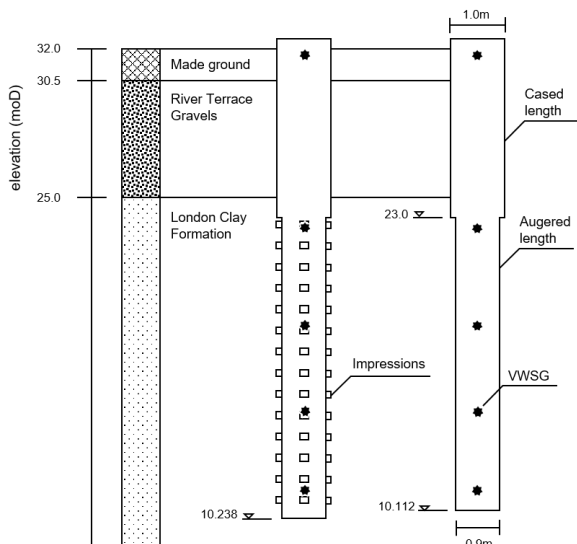


Figure 7. Southall compression test (after Panchal *et al.*, 2021)

The load settlement curves are presented in Figure 8. Although the impression pile displaced less compared to the conventional pile, neither pile achieved a complete failure because the 10MN structural capacity of the loading frame was reached first. The thick coarse layers overlying the London Clay, in which the impressions were formed, obscured the effect on the nodules although their influence can be seen more clearly at depth in Figure 9. In the London Clay, owing to the presence of the nodules, the impression piles mobilised on average ~60% more skin friction than was mobilised with the straight shafted pile.

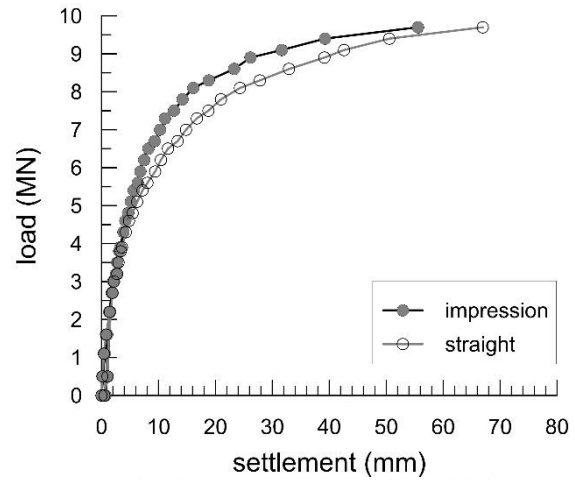


Figure 8. Load settlement curves at Southall (modified from Panchal *et al.*, 2021).

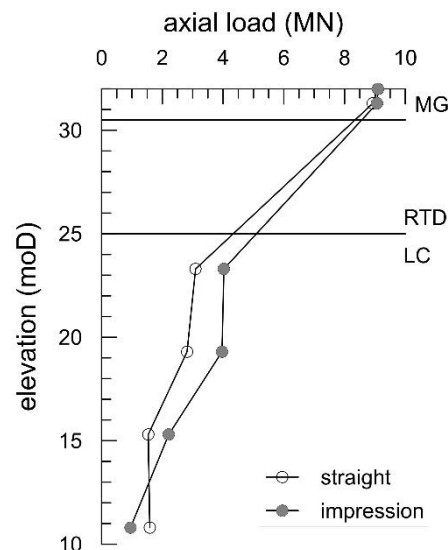


Figure 9. Load profiles at Southall.

4.2 Tension tests

The second test was a tension test on two 760mm diameter piles. The piles were bored to a design toe depth 24m below platform level. Tension bars were positioned in the piles to coincide with the openings in the tension test frame. In order to reduce the influence of the gravel layer on the load settlement response, a dummy reinforcement cage 9m long, wrapped with beamform, was lowered into the bore and the centre backfilled with pea shingle before removing the casings. The reacting length of the piles was approximately 15m which was completely embedded in the London Clay formation, Figure 10. The nodules were flat head cylinders 110mm in diameter embedded 70mm into the soil. The vertical spacing was approximately 700mm. The portion of the pile that was impressed was estimated as being 13m from the pile construction log.

Figure 11, reports the load settlement curves of the tension tests. As recorded in the test log, the measured settlements are not entirely reliable due to other simultaneous operations at the construction site. However, in this case, the increase in capacity of the impression pile is clearly around 30%.

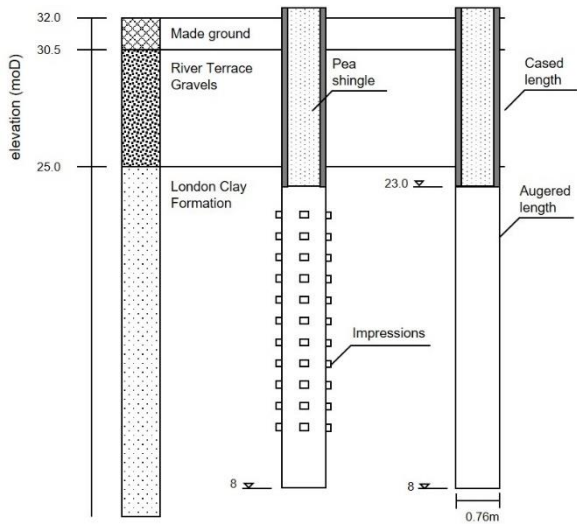


Figure 10. Southall tension test.

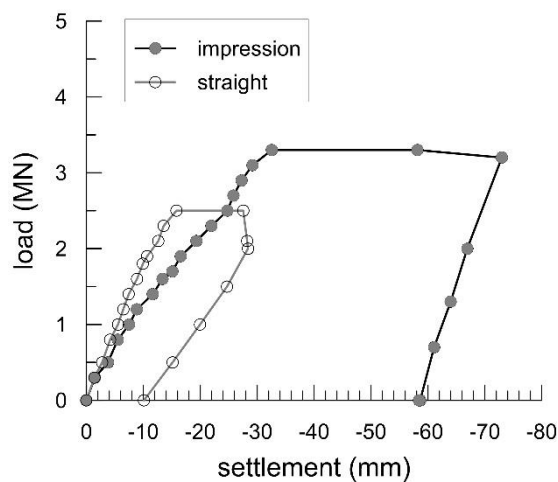


Figure 11. Tension test at Southall.

5 A METHOD TO EVALUATE THE PERFORMANCE OF THE IMPRESSION PILE

On the basis of the experimental evidence gathered from the centrifuge tests, Lalicata *et al.* (2021) proposed a failure mechanism based on an upper bound solution that is able to capture the main aspects of the impression pile behaviour and allows the enhanced shaft resistance to be computed. This calculation method considers explicitly the resistance provided by the nodules and the remainder of the shaft, providing solid agreement with experimental data. The authors also acknowledge that, for values of spacing lower than critical, the effective spacing is practically irrelevant on the performance of the impression pile. The most crucial factors are the number of nodules in the cross section, the protruding length of the nodules into the soil and their width.

Lalicata *et al.* (2021) reported that it is reasonable to neglect the actual positioning of the impressions, and instead assume that the shear mechanism is circular in plan and is offset from the pile bore with an equivalent diameter, d_{eq} , over the impressed length of the pile. For simplicity, the method assumes that value of the adhesion factor along the shaft of the equivalent circular pile is that of the soil-pile interface. In principle, a unit value of α could be used to compute the shear strength acting on the equivalent cylinder, leading to a lower value of d_{eq} . The choice of using a typical value of α has been made to guarantee the continuity with current design methods, alternative choices are obviously possible.

The equivalent diameter method is an idealisation, useful for design purposes, of the enhancement produced by the nodules. As detailed in Lalicata *et al.* (2021), the real failure mechanism includes the shaft resistance developed along the vertical blocks, the shear resistance at the soil-pile interface between those blocks and the base resistance of the blocks. All these components make it difficult to directly evaluate the effectiveness of the impression while varying the geometrical (critical length, dimensions and number of the nodules) and the mechanical parameters (soil pile adhesion factor). The equivalent diameter concept is derived from the complete analytical solution but has the advantage of readily providing a way of estimating the effectiveness of the impressions as a function of the layout of the nodules and the adhesion factor.

The capacity of the impression pile, $Q_{u,imp}$, can be calculated as:

$$Q_{u,imp} = Q_{s,eq} + Q_{s,out} L_a + Q_b - W \quad (1)$$

where the shaft capacity is divided into two terms: $Q_{s,eq}$ which is the shaft capacity in the impressed portion of the pile; termed the active length L_a . and $Q_{s,out} L_a$ which is the shaft capacity of the non-impressed length. The base capacity Q_b and the self-weight of the pile W are the same as that of a standard pile. $Q_{s,out} L_a$ is also calculated in a standard fashion, but it applies only to the remaining length of the shaft, $L-L_a$. $Q_{s,eq}$ is therefore:

$$Q_{s,eq} = \pi \cdot \alpha \cdot s_u \cdot d_{eq} \cdot L_a \quad (2)$$

Within this conceptual scheme, the equivalent diameter method can also be used to back analyse the performance of the impression pile. To do this, the active length L_a , must be known as well as the shear strength profile and the soil-pile adhesion factor α . If only the load-settlement at the head of the pile is available, such as in the centrifuge tests for instance, the following procedure is followed:

- The various factors contributing to the ultimate capacity of the impression pile, $Q_{u,imp}$, must be evaluated.
- The equivalent shaft capacity inside the active length is calculated from eq. (1).
- Finally, the value of the equivalent diameter is evaluated from eq. (2).

If the strain gauge measurements, inside the portion of the pile which has been impressed are available, then the equivalent diameter can be readily evaluated by applying eq. (2) where the shaft capacity is taken as the difference between the readings at two different strain gauge depths.

The procedure has been applied to some of the centrifuge tests reported by Lalicata *et al.* (2021) and the field tests summarised above. In the centrifuge tests and the tension test at Southall the equivalent diameter has been evaluated from the measured ultimate capacity at the head of the pile with the procedure described above. For the compression test at Southall the strain gauge analysis, reported in Figure 9, has been used.

The back-calculated equivalent diameter over the actual diameter of the pile ratio is presented in Figure 12 as a function of the adhesion factor. The nodule embedment to diameter ratio is comparable between the centrifuge model tests and the full-scale tests. All data in Figure 12 refers to piles with four nodules over the cross section. The centrifuge test data clearly show that the equivalent diameter, and consequently the effectiveness of the impressions, reduces as the adhesion factor increases. The compression test at Southall is aligned with the centrifuge data while the tension test has a smaller equivalent diameter than

expected. This could be related to the previously mentioned uncertainties over the values of the active length and the embedment of the nodules. It is also worth mentioning that the soil properties in the centrifuge tests are less uncertain compared to those in the field owing to the controlled preparation of the model soil.

Overall, the results in Figure 12 show that the preliminary field trials and the centrifuge data are comparable; once some allowances for the soil properties and quality of the impressions are made on the field data.

The d_{eq}/d ratio reflects the increase in the shaft capacity inside the active length only. The overall increase in capacity of a pile under compressive load will be lower owing to the contribution of the base resistance.

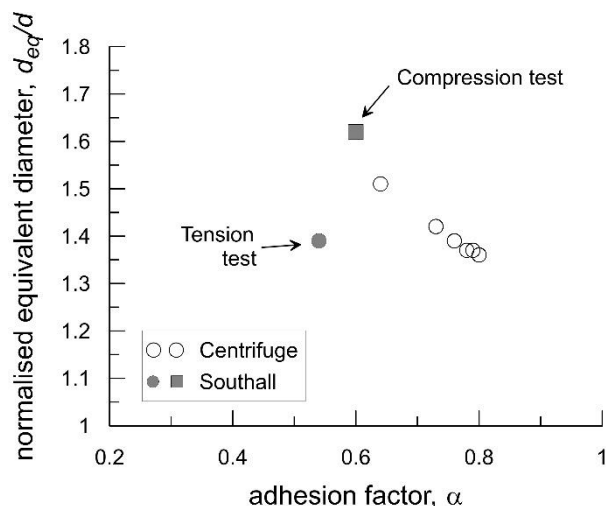


Figure 12. Back calculated equivalent diameter values from the centrifuge and field tests.

6 CONCLUSIONS

The working principles of the impression pile technology are presented in this paper. This novel type of deep foundation allows for an enhanced interface strength; of approximately 40%. The solution is developed for rotary bored piles in overconsolidated clays such as London Clay.

The nodular surface moves the shear planes away from the shaft of the pile resulting in a tendency for soil-soil shearing and this is regarded as the major achievement of the impression piles, while the larger shaft surface has a secondary influence on the enhanced capacity.

The equivalent diameter concept is used to compare the results from the centrifuge tests and the field tests. In this framework, the shaft capacity of the impression pile is divided in two terms: one inside the portion of the pile impressed and the other on the remainder of the shaft. The latter is the same as a straight shafted pile. The equivalent diameter framework neglects the actual layout of the nodules in the impressed area and considers a cylindrical failure surface along an equivalent diameter, larger than the actual diameter of the pile. The equivalent diameter is derived from the complete analytical solution and accounts for the geometry of the nodules, their layout and the soil-pile adhesion factor.

The comparison between the centrifuge test data and the field tests is satisfying, especially when the allowance for the mechanical properties of the soil and the geometry of the impressions is considered for the field data. The way the centrifuge tests are prepared greatly reduces the uncertainties on both the soil resistance and the construction of the piles. The same high level of confidence is generally not available on site. The results show that the effectiveness of the impressions tend to reduce for increasing values of the adhesion factor as the relative weight of the soil-soil shearing reduces and the

secondary geometrical effects remain. This is a promising finding as the adhesion factor in the field usually ranges between 0.3 and 0.7. Consequently, the gain in capacity observed in the centrifuge tests may represent the lower bound of the potential increase in capacity of a full scale pile, once reliable impressions can be made.

7 ACKNOWLEDGEMENTS

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