The Development and Testing of the ScrewSol Rotary Displacement Pile

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ABSTRACT

The paper describes the aims of the research project, the development of the system and the subsequent implementation of a new piling technique. The basic aim of the project was to develop a piling system that would improve the capacity of a bored cast in-situ pile, reduce the material consumption and minimize spoil; to generate unit cost and environmental impact reduction.

The displacement and densification of non-cohesive soils around a pile is beneficial as it enhances the shaft friction capacity and minimizes spoil. The use of traditional bored piling techniques results in a lower unit capacity than an equivalent driven cast in-situ pile.

The fact that driven piles, as with most bored piles, have a smooth or straight shaft means that the transfer of load from the pile shaft to the soil relies upon the relative pile / soil interface friction or adhesion and therefore the capacity of the soil is not maximized.

The ScrewSol piling system described in the paper adopts the benefits of the Continuous Flight Auger piling system. However, the load capacity of the pile is enhanced in non-cohesive soils due to the localized soil densification during pile installation. Furthermore, a regular thread is formed down the pile shaft to enhance load transfer to the soil and reduce material quantities. The results of a number of test piles carried out in a variety of soil types are presented. The data demonstrates that significant pile capacity improvements are achieved with corresponding cost and environmental impact reductions.
BACKGROUND

To understand areas of potential improvement in pile installation systems it is necessary to recognize the strengths and weaknesses in currently adopted systems coupled with ongoing technological improvements in piling equipment.

Conventional bored piles have been successfully constructed for many years. In stable soils exhibiting a degree of cohesion open or dry bores can be formed. The presence of unstable soils necessitates the use of temporary casing or support fluid to stabilize the bore prior to concreting. The use of long temporary casing or support fluid increases the pile cost installation cost. Furthermore, in soils of marginal stability the assumption that a stable dry bore can be formed can expose the pile constructor to significant cost and contract duration risk.

The development of the Continuous Flight Auger (CFA) piling system removes the risks associated with stability of the pile bore and thus the use of the system has become well established worldwide; it may be considered as a mature system. Initial problems associated with the quality of the pile formed have largely been overcome by instrumentation that monitors depth, rotation rate, torque / applied energy, concrete volume, concrete pressure and provides a guide to the rig operator as well as accurate pile records. An example of the pile records is given in Figure 1 along with the basic method of construction and equipment used.

In the early years of CFA piling the available drilling power of CFA piling equipment was somewhat limited which restricted the use of the system to softer soils. This has driven the development of more powerful hydraulic systems to improve the ability to penetrate dense or very stiff strata. However, it should be noted that CFA piles can not normally be through hard man made obstructions, strong rock, boulders, etc.

The bearing capacity of CFA bored piles is generally similar to that of a conventional bored pile although test pile data does highlight some notable differences as follows:

- In stiff clays the CFA pile shaft friction can be higher. This may be due to the short time the clay is exposed and therefore the limited softening that can occur. Another reason may be that with efficient boring tools there is less remolding or disturbance to the walls of the pile shaft and possibly near horizontal asperities formed.

- In stiff clays and weak rocks, where the boring tools are inefficient or the rig has insufficient power poor pile shaft friction can result due to “polishing” of the surface of the pile shaft. The results of two test piles of identical geometry constructed 5 meters apart in London Clay are presented in Figure 2; these demonstrate a 30% reduction in shaft friction resulting from 5 minutes of over-rotation of the auger.

- In non-cohesive deposits the shaft friction is often observed to be 10% to 20% higher than that of an open bored pile provided the rig power and drilling tools are appropriate for the ground conditions. This may be due to some limited soil displacement as the auger penetrates the ground combined with the higher applied concrete pressure.

- In typically loose silty sands where the ground water level is high, the well known phenomenon “flighting” can occur when constructing CFA piles. This results when the ratio of auger rotation to penetration is too high and the auger effectively acts as a screw-feed removing and thus loosening the surrounding soil. The result is to reduce the shaft friction capacity and potentially cause ground settlement.

The CFA piling system has many environmental advantages when compared with driven large displacement piles particularly in noise or vibration sensitive areas such as city centers and urban conurbations. However, in terms of load carrying ability driven large displacement piles are generally more efficient. Furthermore, the sensitivity of the CFA pile capacity to the construction technique results in greater uncertainty and thus a naturally increased conservatism being applied to the design. A system that combines the repeatability and load carrying efficiency of driven piles combined with the environmental advantages of the CFA system provides the scope for improvement.

A rotary displacement system can provide significant improvement to the pile bearing capacity whilst avoiding the noise and vibration issues; there is a number of rotary displacement systems used around the world. In countries where ground conditions are highly suitable for such piling systems they are widely used. For example, in Belgium it is estimated that approximately 50% of bearing piles are constructed using rotary displacement methods. However, in other countries their use tends to be limited due to geological conditions, market size, plant availability, less rigorous environmental controls and the low cost of spoil removal. Table 1 contains a number of rotary displacement systems that are used with the following key parameters:

1. Torque represents the rig power / energy provided to install the piles; as the torque required increases the machine size, cost and consumable cost increases. Some systems also require a pull-down force to assist penetration and displacement of the ground.

2. The rotation direction during concreting / extraction influences the quality of the pile base construction and the potential for inclusions within the pile. Rotation in a clockwise direction, as with CFA piles, is the best practice method
that should be adopted. Rotating in an anti-clockwise direction is effectively like back-screwing the auger out of the ground; thus the potential for disturbed ground being left at the pile base is high.

3. The form of shaft constructed influences the pile capacity; a shaft with asperities will result in a higher pile shaft friction than an essentially flat or smooth surface. A “mechanical” interlock between pile and soil will also provide a more reliable pile shaft friction.

4. The use of a lost tip to displace the soil which is then left at the pile base can assist the formation of a good base but represents an additional cost.

AIMS OF THE PROPOSED SYSTEM

The overall aim of the development was to produce a rotary displacement pile with a thread or reproducible asperities down the pile shaft. This would realize the benefits of both load capacity of a driven pile and environmental effectiveness of a CFA pile. With a UK CFA fleet comprising the fully instrumented, tried and tested Soilmec CM48 and CM700 CFA machines with 88.5 KNm and 156.0 KNm torque respectively it would be preferable to use this equipment. This would obviate the need to develop or purchase plant specifically at significant capital cost and would maintain flexibility in the use of the plant. Thus the parameter limits for the system were defined as follows:

1. Installation torque requirement of less than 150 KNm
2. A minimal pull down force to assist auger penetration.
3. Use of current CFA pile installation instrumentation with minor modifications
4. Clockwise rotation during drilling and concreting phases of construction
5. Generation of little or no pile spoil
6. Formation of a robust and regular thread along the pile shaft

TRIALS PERFORMED

A tapered stem boring head, 160mm diameter at the tip increasing to 273mm diameter was manufactured in the plant and fabrication yard in Burscough, England. To this a 330mm diameter flight and cutting tooth to form the thread was attached. Above the tapered boring head 273mm diameter smooth follower tubes were made to facilitate pile construction to depth. Figure 3 shows the assembled equipment on the piling rig prior to use.

Burscough Yard Trials

The initial trials were carried out in the Burscough yard using a Soilmec R622-HD with 180 KNm torque capacity. The prevailing ground conditions are not ideal as they comprise 2.0m of fill overlying a weak to moderately weak sandstone, however, the location meant modifications could be readily made to the prototype equipment. The maximum total penetration achieved was 3.0m i.e. 1.0m penetration into the sandstone. The findings, after some minor changes, were encouraging as:

1. No vertical force or pull down was required by the rig; the tool pulled itself into the ground.
2. The thread was well formed and clearly visible (Figure 3c)
3. The only spoil generated was that which remained on the tapered auger after extraction (Figure 3d).

Project Egg Trials

Within a few miles of the Burscough yard, near Southport, a site was located with more suitable ground conditions that would enable the formation of deeper piles and the subsequent exhumation of the piles constructed. The ground conditions are summarized in Figure 4 but broadly comprise alluvial sands, silts and clays overlying Mercia Mudstone (Marl).

Initial construction trials were performed prior to the installation of eight piles to a depth of 7m for load testing. To provide comparative data, four of these piles were standard 500mm diameter CFA piles (C1 to C4) and the remainders were 350/500mm diameter ScrewSol piles (S1 to S4). Anchor / reaction piles were also constructed to facilitate testing. (Ref. Figure 4). Furthermore, the testing regime was designed to test both the response to compression and tension loads.

The installation of the piles was carried out with a Casagrande C50 / B18 rig (Ref. Figure 5) but the actual peak torque monitored was 75 KNm for the ScrewSol piles; this compares to an observed peak torque of 65 KNm to install the CFA piles. The ScrewSol pile installation required no pull down force to assist penetration and the only pile spoil produced was that on the boring head. Some initial construction trials were carried out and these ScrewSol piles were pulled out of the ground and cleaned in order to assess the quality of the thread produced; as can be seen in Figure 5, a robust and regular thread has been produced.
The test piles were subjected to a standard loading regime with extended hold periods; the overall test duration was 12 hours. The load tests results presented in Figure 6 demonstrate that the capacity of the 350/500mm diameter ScrewSol pile is the same as the 500mm diameter CFA pile of the same depth; this is true both in tension and compression. Whilst the pile capacity may be the same, this represents an improvement in real terms as there is a very small quantity of spoil to remove from site and the volume of concrete used is reduced by more than 30%. The high water table and loose silty nature of the soils is considered to have resulted in their displacement but, with limited passive resistance, densification of the deposits around the pile shaft has not occurred.

Le Havre Trials

The trials at Le Havre, France were part of a large European funded research project, TOPIC. The test programme included the installation of a number of piling techniques including CFA (TC-C2 & A1), driven cast-in-situ (BM-C1 & A4), French displacement system (D2A-C4, C3 & A2), CFA with thread (TCE-B1 & A3) and ScrewSol (Scr-B2 & B3) piles. Ground conditions comprised medium dense silty sand reclamation fill overlying natural soft clay and fine silty sand; a summary is presented in Figure 7. The ground water table is found at a depth of 3.0m.

The CFA and ScrewSol piles were installed with a locally available Llamada rig with a torque capacity of 250 KNm. (Ref. Figure 8); the peak torque observed whilst installing a 350/500mm diameter pile to 10.5m depth was 180 KNm. Piles were also installed to 15.0m depth. After the standard static load testing procedure had been completed on the piles the opportunity was taken to exhume the upper section of the piles.

The static load test results are presented in Figure 9 for both the 10.5m and 15.0m long piles. Adopting the somewhat arbitrary definition of ultimate pile capacity as 10% of the pile diameter, the ultimate capacity of the 10.5m long piles is 1900 KN and 2700 KN, for the CFA and ScrewSol piles, respectively. The capacity of the 15.0m ScrewSol pile could not be tested above 4000 KN due to the structural capacity of the 350mm diameter core of the pile; at this load the axial stress applied to the pile is in excess of 41MPa. Based upon the aforementioned approach the estimated ultimate pile capacities are 3200 KN and 4500 KN for the CFA and ScrewSol piles respectively. The test data demonstrates that a 40% to 45% enhancement in bearing capacity is achieved using the ScrewSol method when compared to the CFA method in the medium dense fine sands at the test site.

The quality of the pile formed is not only demonstrated by the applied load but also the exhumed part of the pile constructed below the ground water table in unstable soil (Ref. Figure 8). The latter is an important aspect to confirm in the trial as it further confirmed the robustness of the concreting process and the value of forming the thread adjacent to the concrete discharge point.

FURTHER TESTS PERFORMED

Having both gained the confidence of the operation teams and tested the viable new piling system, the time had come to cautiously exploit the system in the market place. To provide the necessary confidence in different ground conditions extended static load testing to demonstrate the ultimate bearing capacity or factor of safety was carried out. The results from a couple of these project sites are described below.

Broughton Test Piles

A large CFA piling contract was underway at a site in Broughton, England for an airplane wing manufacturing facility with further works planned. The ground conditions, whilst variable, were well defined as summarized in Figure 10 for the area of the test piles. As the founding strata comprised glacial clay a standard static load test regime with extended hold periods at 600KN, 900KNand 1200KNwas adopted; the overall test period was 8 hours. It was decided to maximize the data generated by performing tension and compression test piles in with comparison with CFA piles. Some initial construction trial piles were installed and exhumed as can be seen in Figure 11. The test piling procedure adopted was essentially the same as at the Project Egg Trials, however, all piles were installed to a depth of 12.0m with the exception of CFA pile C4 which was only 11.0m long. The pile layout is given in Figure 10.

The test results presented in Figure 12 indicate that the capacity of the 350/500mm diameter ScrewSol piles (S1 to S4) are the same as a 500mm diameter CFA piles (C1 to C4) in tension and compression. The response to load is that the ScrewSol pile is less stiff than the CFA pile due primarily to the higher concrete stress and resulting increase in elastic shortening. Furthermore, the end bearing effect of the threads would require larger displacements to mobilize the shaft friction. At the working load capacity of 600 KN the actual pile head settlement difference is less than 1mm between the ScrewSol and CFA piles; for the vast majority of foundations this is insignificant.

Production piles were installed successfully for a Fire Station on the site. The pile spoil generated at ground level was limited to that on the boring head; however, it is believed that the glacial clay would have undergone a degree of heave during pile construction but that this was masked by the overlying, highly compressible, soft organic alluvial deposits. Central tension steel was installed in all piles. It is worthwhile noting that the project required careful planning of the pile
construction sequence to avoid damage to recently cast piles by the rig or by soil displacement during boring; such planning and sequencing as required for driven cast in-situ piles is advocated.

**Exeter Test Piles**

Ground conditions on the site at Exeter, England comprise 5.0m of fill and stiff clay over sandstone with an unconfined compressive strength (UCS) in the range of 5 MPa to 10 MPa (Ref. Figure 13). The pile bearing capacity was heavily dependent on the formation of a good pile base as the piles were expected to extend only 1.5m below the sandstone surface or “rockhead”. Expendable preliminary pile tests were installed and the reaction system designed to facilitate loads of up to 2250 KN; significantly beyond the contractual requirements. A standard static load testing procedure was adopted to meet Client requirements.

As can be seen from the static load test data, the near linear pile head settlement response to load and stiff response indicates that settlement is predominantly due to elastic compression of the concrete. The vast majority of the load capacity is generated from the 1.5m socket in the sandstone; the results are a good demonstration of the formation of a good combined friction and end bearing in the sandstone using the ScrewSol system. Ground surface heave was observed when installing some of the piles which should be expected when displacing consistently dense or compact soils where significant improvement in density at shallow depth is not possible. A central steel bar was installed in all piles and the works were programmed such that adjacent piles were not constructed during the same day.

**CONCLUSIONS**

The data and observations from the trials, test piling and projects carried out in a number of different strata types have shown the ScrewSol rotary displacement piling system to be robust with soil displacement and a regular thread formed in all cases. The cost effectiveness has been proven by virtue of the projects awarded in competitive tender scenarios.

As may be expected with any displacement pile the benefits of the system are dependant on the strata type. From a bearing capacity point of view the greatest benefits are realized in medium dense sands where an increase in ultimate shaft friction of 40% to 45% can be realized. In loose sands and clays the primary advantage of the system is the reduction in material consumption. However, in such materials the potential for “flighting” or “polishing” that can occur when using CFA methods are removed due primarily to the formation of the thread down the pile shaft. Table 2 provides a broad assessment, based upon current experience, of the efficiency and limitations of the system in different strata types.

The main advantages of the ScrewSol system may be summarized as follows:

1. It can be installed using a standard instrumented CFA rig.
2. The construction method is the same as that for a CFA pile with only additional control applied to the lift speed and rotation during the concreting phase.
3. Only spoil on the boring head, from depth, is brought to the surface; a significant advantage on contaminated sites.
4. Concrete consumption is reduced when comparison is made with CFA pile solution.
5. The density of the soil around the pile and thus shaft friction and performance can be improved.
6. The effective pile diameter is enhanced due to a regular thread being formed down the pile shaft.
7. The thread improves the pile / soil load transfer and reduces drilling sensitivity.
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FIGURE 1  Basic CFA piling method and instrumentation
Notes on Construction

<table>
<thead>
<tr>
<th>Pile Diameter (mm)</th>
<th>Pile Depth (m)</th>
<th>Peak Load (KN)</th>
<th>End Bearing* (KN)</th>
<th>Shaft Friction* (KN)</th>
<th>Adhesion Factor, $\alpha$</th>
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<td>As normal Bachy Soletanche Ltd operating procedures</td>
<td>500</td>
<td>20.5</td>
<td>2825</td>
<td>350</td>
<td>2475</td>
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<td>With over-rotation of the auger prior to concrete pumping</td>
<td>500</td>
<td>20.5</td>
<td>2220</td>
<td>350</td>
<td>1870</td>
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* Analysis of test pile results carried out using W.G.K. Fleming (1992) method

FIGURE 2 The effect of over-rotation during CFA pile construction
FIGURE 3  Burscough plant yard trials

(a) Theoretical pile shaft geometry

(b) Tapered auger and follower tube fitted to rig

(c) Thread formed in cohesive made ground

(d) Spoil remaining on boring head only
FIGURE 4 Project Egg trials – Ground conditions & layout
(a) Pile installation using C50 / B18 rig  
(b) No spoil on completion of boring  

(c) Pile exhumation  
(d) Cleaned off pile with threads  

FIGURE 5 Project Egg trials – Installation and exhumation
FIGURE 6  Project Egg trials – Load test results
FIGURE 7 Le Havre trials – Ground conditions & layout
(a) Pile installation using a Llamada rig

(b) Pile exhumation

FIGURE 8 Le Havre trials – Installation and exhumation
FIGURE 9  Le Havre trials – Load test results
FIGURE 10 Broughton test piles – Ground conditions & layout
FIGURE 11 Broughton test piles – Exhumed piles
FIGURE 12 Broughton test piles – Load test results

(a) CFA and ScrewSol tension test results

(b) CFA and ScrewSol compression test results
FIGURE 13 Exeter test piles – Ground conditions & test results

(a) Sandstone compressive strength and quality

(b) Soilmec CM700 rig installing piles

(c) Test pile results
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<tr>
<th>Pile Type</th>
<th>Torque (KNm)</th>
<th>Extraction direction</th>
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<tr>
<td>Olivier</td>
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<td>CHD</td>
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<td>Anti - Clock</td>
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<td><strong>Aim</strong></td>
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<td><strong>Clockwise</strong></td>
<td><strong>Threaded</strong></td>
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**TABLE 1** Comparison of Different Rotary Displacement Piling Systems
<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Strength Range</th>
<th>Improvement in:</th>
<th>Comments</th>
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<td>Local Soil</td>
<td>Shaft Load Transfer</td>
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<td>Strength</td>
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<td></td>
<td></td>
<td></td>
<td>Too loose to gain significant soil improvement</td>
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<td>Sandy Gravels</td>
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<td>✓</td>
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<td>Too loose to gain significant soil improvement</td>
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<td></td>
<td></td>
<td></td>
<td>Ideal</td>
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<td>Clays</td>
<td>Cu = 20 – 40</td>
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<td></td>
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<td>Potential for heave</td>
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<td>High torque, clay pre-sheared during drilling &amp; potential for heave</td>
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<tr>
<td>Weak Rock</td>
<td>UCS &lt; 5 MPa</td>
<td>×××</td>
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<td></td>
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<td>High torque, early refusal &amp; potential for heave</td>
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Key: ✓✓✓ = Greatly Improved, ✓ = Limited Improvement, × = No Benefit, ××× = Potential Reduction

TABLE 2 Assessment of ScrewSol System in Primary Strata Types