Installation Behavior of Open Ended and Closed Ended Piles with Torque Application

Pablo Garcia GALINDO
Graduate Engineer, Infrastructure, Arup, Newcastle, UK
Craig DAVIDSON
Research Associate, Civil Engineering, University of Dundee, Dundee, UK
Email: c.s.davidson@dundee.ac.uk
Michael John BROWN
Reader, Civil Engineering, University of Dundee, Dundee, UK

ABSTRACT

Screw piles offer several potential benefits for deployment offshore for renewable energy developments. They are easy to install, have the potential to achieve large capacity and generate low noise and vibration during installation. This latter benefit makes them an attractive alternative to driven piles where there are concerns over the impact of installation on marine mammals. Although screw piles are attractive for offshore deployment, their recent use has been limited to small piles therefore, to allow offshore deployment considerable upscaling of these piles must occur. This increase in size comes with concerns of how they will perform and the requirements for installation. For example, it is well known that the shaft capacity of a driven pile is influenced by plugging or coring behaviour internally. As screw piles are installed by rotation and vertical force, it is necessary to investigate how this installation process effects pile plugging behaviour. As part of a preliminary study, the effect of rotation on plugging and installation capacity behaviour was investigated by 1g small scale model testing in sand. The addition of rotation during installation was seen to give a significant reduction in the pile penetration resistance in both open and closed ended piles.

Key words: *Screw piles, Plugging, Torque, PLR*

1. Introduction

1.1. Overview

Screw piles offer several potential benefits for deployment offshore for renewable energy developments. They are relatively easy to install in a variety of materials, have the potential to generate large tensile and compressive capacity and generate low noise and vibration during installation. This latter benefit makes them an attractive alternative to driven piles where there may be concerns over the impact of their installation on marine mammals for instance (Thomsen *et al.*, 2006). Although screw piles are attractive for offshore use, recent applications have been limited to onshore projects using small piles. Therefore, to allow offshore deployment considerable upscaling of these piles must occur. This increase in size comes with concerns of how they will perform under both axial and lateral loading (Knappett *et al.*, 2014, Al-Baghdadi *et al.*, 2015 Al-Baghdadi *et al.*, 2017[a]) as well as with prediction of the requirements for installation such as the torque (Al-Baghdadi *et al.*, 2017[b]) and vertical force ("crowd force") required. For example, it is well known that the shaft capacity of a driven pile is influenced by plugging or coring behaviour internally and the mode of penetration/plugging may be complicated by rotation (Deeks, 2008). As screw piles are installed by rotation and vertical force it is necessary to investigate how this installation process affects pile plugging behaviour. As part of a preliminary study the effect of rotation on plugging and installation capacity behaviour was investigated by 1g small scale model testing in sand.

2. Experimental testing

2.1. Model pile analogues

Two different pile analogue models were used during this study to various degrees. The piles consisted of mild steel tube of approximately 3mm wall thickness with different outer pile diameters as shown in **Table 1**.

Table 1. Model pile details

Pile	Outer diameter	Length	Surface roughness, R_a
	mm	mm	μm
Pile 1	35	500	0.61-0.64
Pile 2	45	500	0.66

The pile surface roughness (R_a) shown in **Table 1** describes a range of values in the case of Pile 1 and Pile 2 which represents the measurements before and after testing. No distinguishable trend of increasing roughness due to testing was observed.

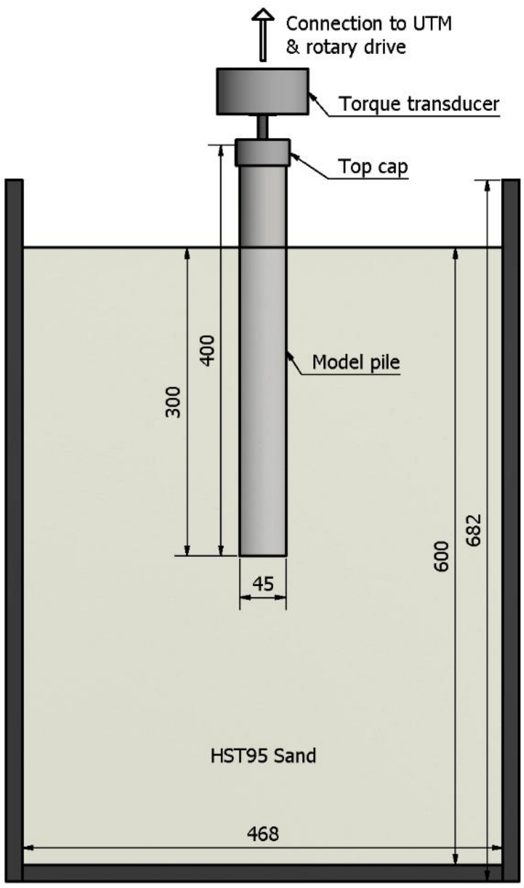

Fig. 1 Typical model pile and test box arrangement (all dimensions in mm, not to scale).

As can be seen in **Fig.1** each pile had a dedicated top cap screwed onto the pile to allow connection to a torque transducer (Novatech F311-Z3862 25kNm) which in turn was mounted on a rotary drive or torque installation system supported on an Instron UTM machine (250kN) with an inline Intsron 10kN load cell which was used to measure vertical forces during installation. Vertical displacement was measured by the Instron UTM. This loading system and its development are described in detail in Jeffrey (2012) and Galindo (2017).

To monitor the depth of the soil plug during the installation of an open-ended pile (OE) the pile top caps were modified to include a Plug Length Ratio sensor (PLR) on the underside of the cap and within the diameter of the pile. The plug length ratio (PLR) is described as the ratio of plug length to pile penetration. The sensor incorporated an infra-red-light emitter and detector calibrated to measure distance (Sharp distance measuring sensor unit, GP2Y0A41SK0F). A bottom cap was also fabricated for each pile which had a tight fit to avoid rotation during installation where a closed ended pile was required (CE).

2.2. Model container and soil

HST95 sand was used for all tests. This fine-grained sand has been extensively characterised in previous studies at the University of Dundee (e.g. Jeffrey *et al*. (2016)). The principal properties of the sand are provided in **Table 2**.

Table 2. Properties of the test sand (HST95)

Property	Value
Critical state friction angle, ϕ' (°)	32
Interface friction angle, δ' (°)*	30
Minimum dry density (kg/m^3)	1487
Maximum dry density (kg/m^3)	1792
D_{10} (mm)	0.10
D_{50} (mm)	0.14

* for dense sand tests at σ_v' =3-7kPa

The sand was tested dry, such that there were no excess pore pressures generated due to rotation. As a result, the tests represent an upper bound on the installation forces that would be required in a 1g model of an offshore pile where the soil is fully saturated.

A box with internal dimensions of 500 x 468mm and 668mm depth was used for all tests (**Fig. 1**). Three sides and the base were made from 16mm thick aluminium, while the remaining side was 14mm thick transparent acrylic. The dimensions of the model pile, installed to 350mm penetration depth, results in minimum pile to box wall diameter ratio of 6.2 and separation of 9.1 pile diameters between the pile tip and base of the box for Pile 1 (which was mainly used in this study), which are in line with previous studies which suggested boundary effects would be negligible (Phillips and Valsangkar, 1987).

Loose sand beds were prepared by stirring the sand to promote high levels of shear deformation, thus achieving critical state and a relative density (D_r) averaging 27%. An air pluviation system, with a slot pluviator, was employed to generate beds of dense sand between 81 and 87% relative density.

2.3. Pile installation and testing procedure

Once the sand bed had been prepared to the correct height it was then loaded into the Instron UTM prior to pile installation. The test pile was connected to the UTM via the torque cell (**Fig. 1**), rotary drive and the additional in-line load cell. The Instron UTM was then set to advance at a rate of 40mm/min and at different rotation rates depending on the test being undertaken (3, 5, 7 & 9RPM). Comparison tests were also undertaken with no rotation (NR). During this process vertical load, torque, pile displacement and internal plug height were continuously monitored by the Instron UTM.

3. Results and discussion

3.1. Load displacement behavior during installation

Typical results from the installation of Pile 1 are shown in **Fig. 2** and **Fig. 3**. It can clearly be seen from the results that the closed ended (or artificially plugged) pile generates greater resistance to penetration (**Fig. 2** & **Fig. 3**) in the dense sand (12%). There is also an obvious reduction in penetration resistance with the inclusion of rotation for both open and closed ended piles. For closed ended piles the rotation speed appears to have little effect on the penetration resistance where for open ended piles there is a reduction in penetration resistance with increasing rate of rotation. It is also noticeable that the data obtained for the open-ended pile is much "noisier" than that for the closed ended pile especially where rotation is not applied. This is believed to be consistent with plug collapse, followed by coring and the subsequent formation of a new plug on a cyclic basis. Thus, for the non-rotated open-ended pile in **Fig. 3** the pile cores until a depth of 282mm (L/D = 8.1). Based upon the results it would suggest the pile was plugged at least 3 times and was beginning to form another plug at the end of the test.

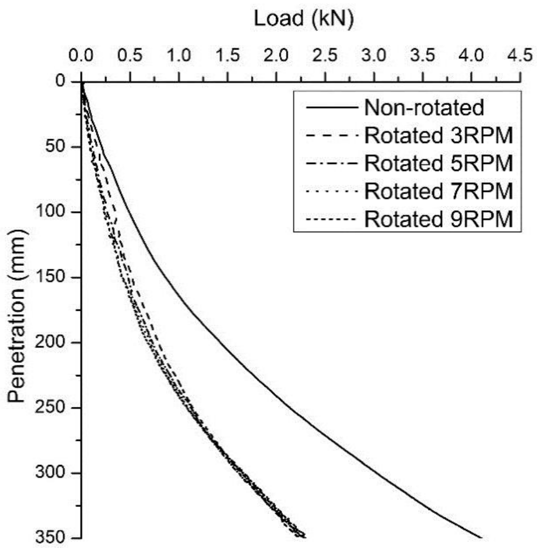

Fig. 2 Load-penetration behavior during installation for a closed ended pile (Pile 1, D = 35mm) installed in dense sand.

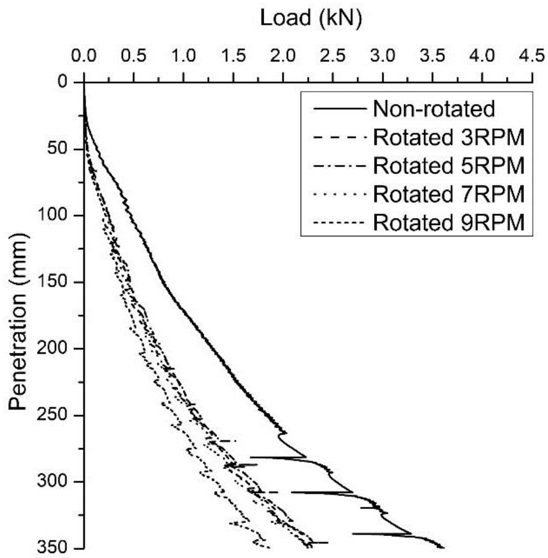

Fig. 3 Load-penetration behavior during for an open ended pile (Pile 1, D = 35mm) installed in dense sand.

Results for the pile with rotation show similar noisy data throughout penetration which might appear to suggest more frequent plugging and collapse (normally associated with loose soils) although this behavior may not be that straight forward as there is the potential for the plug to rotate and lock (rotation coupled or decoupled coring) as well as vertically plug and core as described by Deeks (2008).

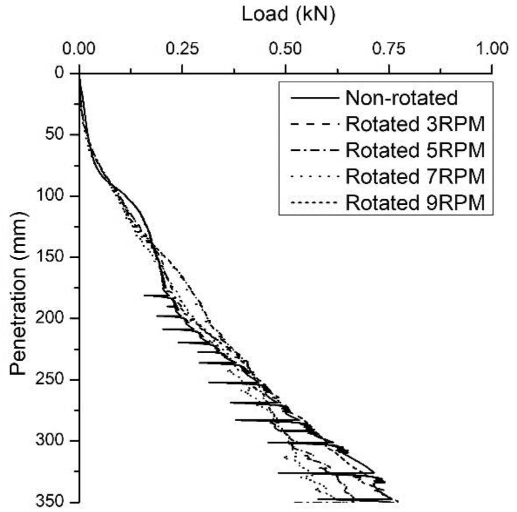

Fig. 4 Load-penetration behavior during for an open ended pile (Pile 1, D = 35mm) installed in loose sand.

Table 3. Maximum installation load results summary for Pile 1 in dense soil.

Test	Max. axial load kN	Reduction factor	Average reduction factor
Closed ended			
NR	4.103	-	-
3RPM	2.242	0.546	0.557
5RPM	2.290	0.558	
7RPM	2.292	0.559	
9RPM	2.311	0.563	
Open ended			
NR	3.615	-	-
3RPM	2.326	0.643	0.616
5RPM	2.458	0.680	
7RPM	2.263	0.626	
9RPM	1.867	0.517	

The behavior for the same pile installed in loose sand is seen in **Fig. 4** and is quite different from that seen in dense sand where the non-rotated pile seems to show very frequent plug formation and collapse and is similar to the 3RPM rotated case suggesting similarities in the plug formation behavior. Again, the pile resistance reduces with rate of rotation. The observed reductions in installation forces are summarized in **Table 3 & 4** where the reduction factor is the maximum resistance from the rotated pile divided by that from the non-rotated pile.

Table 4. Maximum installation load results summary for Pile 1 in loose soil.

Test	Max. axial load kN	Reduction factor	Average reduction factor
Closed ended			
NR	1.285	-	-
3RPM	0.749	0.583	0.517
5RPM	0.640	0.498	
7RPM	0.692	0.539	
9RPM	0.576	0.448	
Open ended			
NR	0.762		-
3RPM	0.778	1.021	0.88
5RPM	0.665	0.873	
7RPM	0.641	0.841	
9RPM	0.623	0.818	

3.2. Plug behaviour

It was hoped that by including the PLR sensor that detailed insights would be gained into the plugging mechanisms. Unfortunately though, it was found that using soil in the pile as the reflector reduced the output from the sensor and useful results were not obtained until the sand was relatively close to the sensor. This is shown as a vertical line in **Fig. 5** and **Fig. 6** at low penetrations when the sand in the plug was at the furthest distance from the sensor. This vertical line does not necessarily reflect the true PLR and should be viewed with some caution. Also, variable noisy results were obtained during rotational tests due to the changing target point for the sensor meaning that the data had to be smoothed and this resulted in loss of information with respect to detailed points at which plugging occurred.

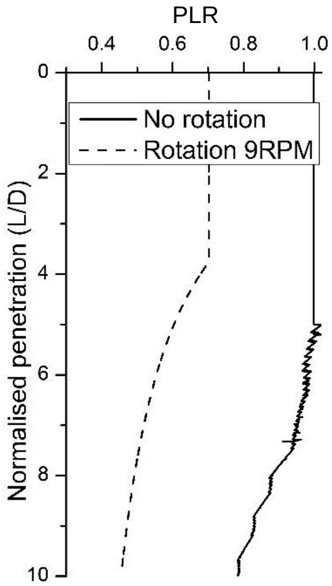

Fig. 5 Plug behavior during penetration in dense sand (Pile 1, D = 35mm).

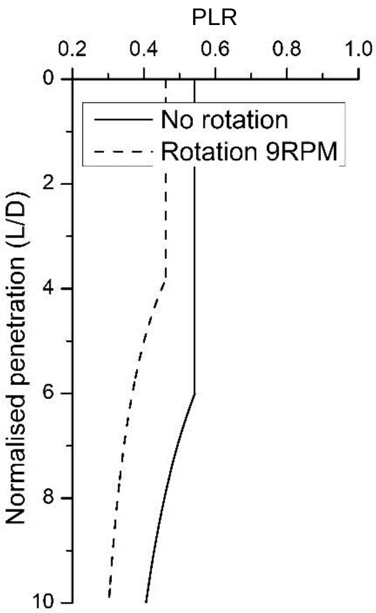

Fig. 6 Plug behavior during penetration in loose sand (Pile 1, D = 35mm).

Fig. 5 confirms that the non-rotated pile generally cored until an L/D of 7.5, as observed in **Fig. 3**, which would be expected for an open ended pile in dense sand (Kikuchi *et al*. 2008). In contrast, the rotated pile appears to have been partially coring or cyclic plugging/coring throughout the test but due to the problems with the transducer, no further insight is gained into if the pile is plugging vertically, rotationally or both. A PLR of 0.46 was noted at the end of the test with behavior more normally associated with loose soil.

In the loose soil, the pile appeared to display partial plugging or cyclic plugging/coring but this occurred for the non-rotated and rotated piles with PLRs of 0.41 and 0.30 respectively. It is clear from both **Fig. 3** and **Fig. 5** that the use of rotation during installation has the ability to modify the core failure mechanism and lead to lower overall (internal and external) pile skin frictional resistance.

3.3. Torque measurements

The measurements of torque during penetration were relatively "noisy" as seen In **Fig. 7**. It is thought that this is due to problems of verticality of the loading and connection arrangement rather than electrical noise. To aid comparison of the data, the results were fit using a third order polynomial fit with typical results shown in **Fig. 8**. In general, the results showed that there was no significant change in installation torque in a certain sand density between the varying tests in terms of whether or not the piles were open or the speed they were installed. The results of maximum measured torque (rather than smoothed torque) are summarized in **Table 5** and compared with the corresponding maximum vertical penetration forces. As would be anticipated the torque in the loose sand are lower than those in the dense sand (**Table 5**).

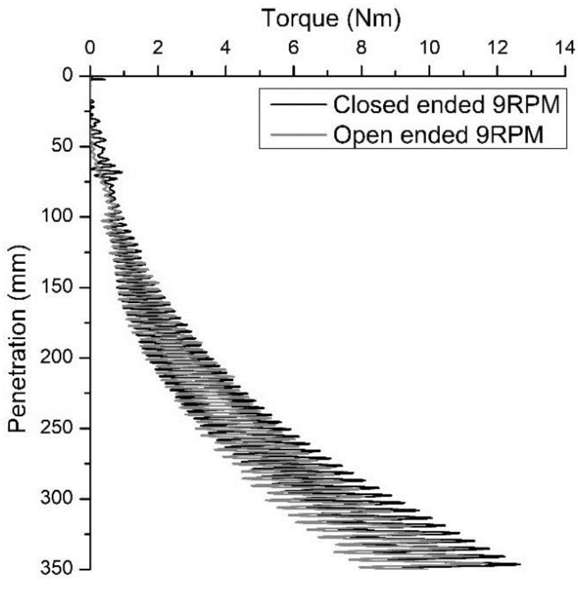

Fig. 7 Torque measured during installation of open ended and closed ended piles in dense sand (Pile 1, D = 35mm).

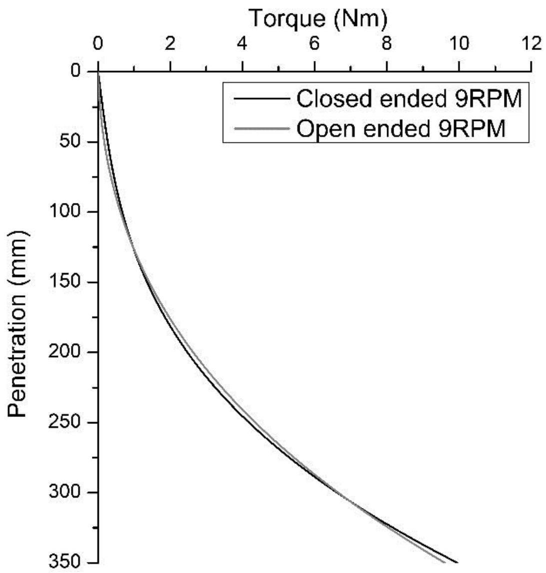

Fig. 8 Smoothed torque measured during installation of open ended and closed ended piles in dense sand (Pile 1, D = 35mm).

For screw piles it is often common to relate the pile capacity (Q_c) to the torque (T) during installation by a simple k factor (tension and compression typically have different k values). To create a dimensionless form of this, Byrne & Houlsby (2015) introduced the screw pile helix diameter (D_h) to this relationship:

$$K_c = \frac{Q_c \times D_h}{T} \quad (1)$$

Work by Al-Baghdadi (2018) though showed that the greatest contribution to the torque came from the pile core rather than the helix plates and therefore it would suggest that a direct relationship between screw pile capacity and torque based upon the helix dimeter is inappropriate as torque would be controlled by the core diameter and capacity by the helix. This is further complicated for a screw pile in uplift where shallow and deep failure mechanisms can occur. This suggests that the form of equation 1 should be modified to take account of both the contribution of the core and the helix plates which may vary with spacing ratio.

The average value of k_c (k factor in compression loading) obtained is below the value of 8 suggested by Byrne & Houlsby (2015) for screw piles and reflects the additional contribution of the helix plates and optimization of the number and spacing of these, which Al-Baghdadi (2018) showed was also affected by the ratio of pile core to helix diameter.

Table 5. Summary of installation torque requirements and torque factor in dense sand (Pile 3, D = 35mm).

Test	Max torque Nm	k_c	Average k_c
Closed ended			
3RPM	11.586	6.77	6.78
5RPM	10.857	7.38	
7RPM	12.152	6.60	
9RPM	12.682	6.38	
Open ended			
3RPM	11.822	6.89	6.44
5RPM	12.160	7.07	
7RPM	12.768	6.20	
9RPM	11.642	5.61	

Table 6. Summary of installation torque requirements and torque factor in loose sand (Pile 3, D = 35mm).

Test	Max torque Nm	k_c	Average k_c
Closed ended			
3RPM	3.371	7.78	6.66
5RPM	3.095	5.56	
7RPM	3.640	7.83	
9RPM	3.322	5.46	
Open ended			
3RPM	4.026	7.48	6.53
5RPM	3.695	6.43	
7RPM	3.621	6.75	
9RPM	3.985	5.47	

It is interesting to note that the average k_c values shown in **Tables 5** and **6** do not vary significantly with pile tip arrangement or relative density suggesting that pile capacity and torque for a straight shafted pile are both simply controlled by the surface area in contact with the soil.

3.4. Failure mechanism observations

During the testing it was noted that depending on whether the pile was rotated or not, different external surface failure mechanisms were observed. For example, in **Fig. 9** for a closed ended pile (Pile 2) a single low diameter surface breach of the failure mechanism is noted at 71.7mm (1.6D/2) from the pile. When the pile is then installed with rotation, a series of surface mechanisms appear (**Fig. 10**) of increasing diameter moving away from the pile which are not present during installation of the non-rotated pile (final mechanism 97-154mm or 2.8-4.4D/2 from the pile). This would suggest that in the non-rotated pile the surface mechanism develops at a shallow depth driven by an end bearing mechanism as the overburden stress is low but as depth increases, this mechanism is suppressed by either the effect of the overburden or the increased vertical stress close to the pile due to the skin friction. In the rotated case it is as if the effect of overburden or stress increase due to the skin friction is removed (or suppressed) allowing the mechanisms to propagate to the surface throughout penetration. This is similar to the mechanism differences noted between 1g and centrifuge tests by Mikasa & Takada (1973). As the tests here were only undertaken at 1g under low stresses it may be that this behavior would not be significant at prototype scale, but results show that the inclusion of rotation even effects the failure mechanism for a closed-ended pile. However, it is unclear if this is at the shaft, pile tip or a combination of both.

For the open-ended pile, no significant surface heave or mechanism was noted when the pile was installed without rotation. When rotation was used the surface heave only appeared as one failure mechanism when the pile had reached quite a significant depth (final mechanism 115-143mm or 3.3-4.2D/2 from the pile). Thus suggesting the rotated piles had plugged, and again due to rotation, it was easier for the piles when rotated to develop a mechanism that extended to the soil surface.

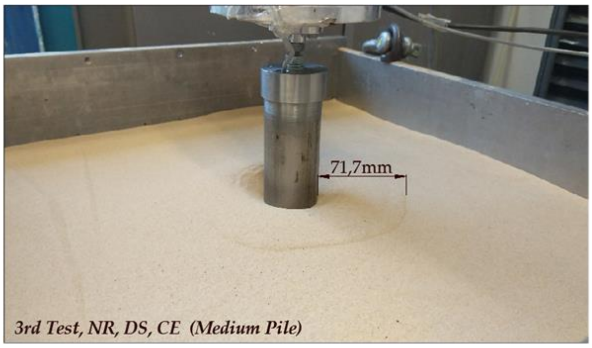

Fig. 9 Surface mechanism for the non-rotated closed ended pile installed in dense sand (Pile 2, D=45mm).

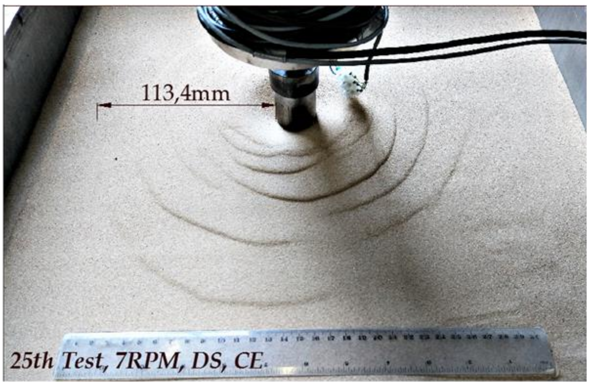

Fig. 10 Surface mechanism for the rotated pile closed ended installed in dense sand at 7RPM (Pile 1, D=35mm).

Fig. 11 Surface disturbance for the non-rotated open ended pile installed in dense sand (Pile 1, D=35mm).

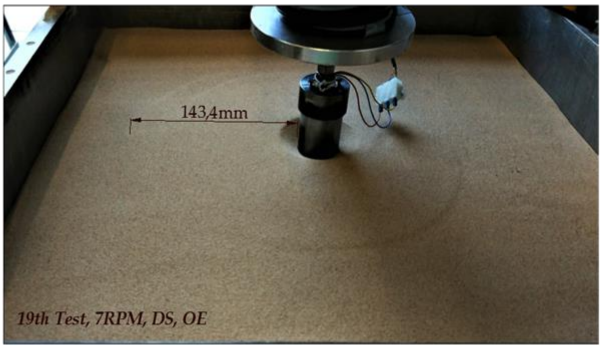

Fig. 12 Surface mechanism for the rotated open ended pile installed in dense sand (Pile 1, D=35mm).

4. Concluding remarks

The use of rotation during the installation of straight shafted piles installed in loose and dense sand has been seen to give a significant reduction in penetration resistance both for open and closed ended piles. The speed of rotation used here did not show a significant effect on the results but there may be a tendency for resistance to reduce with increasing rate of rotation. The closed ended piles reduced resistance by 44%, while 38% was obtained for open-ended piles. In loose soil these reductions were significantly smaller when the pile was open ended (48% closed-ended and 12% open-ended).

An IR based light sensor was used to measure internal plugging and determine PLR during the test. The outputs from this were significantly reduced due to the poor reflective properties of the sand and further development is required with this technology. In dense soil the pile cored when not rotating and displayed partial or cyclic plugging behavior when rotated. Similar behavior was noted in the loose sand whether or not the pile was rotated.

In contrast the measured torque seems unaffected by pile configuration and the ratio between penetration resistance and torque was unaffected by pile configuration or soil density.

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