



1st INTERNATIONAL SYMPOSIUM ON SCREW PILES FOR ENERGY APPLICATIONS

WEST PARK, DUNDEE, SCOTLAND | 27-28 MAY 2019

ISSPEA 2019

1st International Symposium on Screw Piles for Energy Applications

West Park, Dundee, Scotland | 27-28 May 2019

Editors

C Davidson, M J Brown, J A Knappett, A J Brennan
Civil Engineering, School of Science and Engineering, University of Dundee, Dundee, DD1 4HN, UK

C Augarde, W Coombs, L Wang
Department of Engineering, Durham University, Lower Mountjoy, South Road, Durham, DH1 3LE, UK

D Richards, D White, A Blake
Faculty of Engineering and Physical Sciences, University of Southampton, University Road,
Southampton, SO17 1BJ, UK

Publisher

University of Dundee
Nethergate, Dundee, Scotland, UK, DD14HN
www.dundee.ac.uk

DOI

10.20933/100001123

The 1st International Symposium on Screw Piles for Energy Applications and this publication were funded by EPSRC grant: Screw Piles for Wind Energy Foundation Systems (EP/N006054/1). Copyright of the individual works contained herein reside with the respective authors. The full proceedings are available with an open access agreement via the University of Dundee Discovery Research Portal.

Although all care has been taken to ensure the quality and integrity of this publication, the publisher, editors and authors do not take any responsibility for damage to persons or property from the use of this publication or any information contained herein.

PREFACE

This volume forms the proceedings of the 1st International Symposium on Screw Piles for Energy Applications (ISSPEA), held at the University of Dundee, 27 – 28th May, 2019.

This conference is the first such event organised at the University of Dundee and was originally designed to be a small event to disseminate the findings of the EPSRC sponsored Supergen WindHub Grand Challenges project: Screw piles for wind energy foundation systems. The impetus to expand the guest list and scope of this event came after discussion with Dr Alan Lutenecker of the University of Massachusetts Amherst who organised the successful 1st International Geotechnical Symposium on Helical Foundations. Unfortunately, the eagerly anticipated 2nd symposium in this series did not occur as planned so it was decided to partially plug this gap in screw pile innovation reporting by expanding the scope and invitees of ISSPEA.

This conference has been organised by the Geotechnical Engineering Research Group at the University of Dundee representing the Screw piles for wind energy foundation systems project partners with academic teams at Durham University and the University of Southampton.

The first ISSPEA provides an excellent opportunity for academics, engineers, scientists, practitioners and students to present and exchange the latest developments, experience and findings in screw pile engineering for renewable energy applications. The proceedings contains 12 papers and 9 extended abstracts with the latter representing the presentations made at the event that were not supported by a full paper. The proceedings contain one invited keynote paper from Alan Lutenecker on the current state-of-understanding of the engineering behavior of screw piles and helical anchors. This paper presents an overview of historical applications of screw piles, with discussions on aspects of their design and behaviour which are both understood and in need of further research, using case studies as examples. Other papers in the proceedings look at a variety of topics including: installation requirements and effects; cyclic behaviour; advanced numerical modelling of screw piles, including the use of DEM and MPM to incorporate installation effects into the models; and screw piles used in industrial applications. It is hoped that this proceedings and symposium will lead to similar future meetings and serve as a useful indicator of the current state of innovation and deployment. It is also hoped the event and proceedings will act as the springboard for new lines of research and development and increased use of screw piles for a variety of applications.

We are grateful to all the authors and reviewers for their efforts in the preparation of the papers.

Finally, the Organisers would like to acknowledge the support and efforts of the Local Organising Committee, paper reviewers and the support of our industrial partners.

*Craig Davidson, Mike Brown,
May 2019, Dundee*

Table of Contents

Screw Pile Research at the University of Dundee M J Brown	1
Screw Piles and Helical Anchors – What We Know and What We Don't Know: an Academic Perspective – 2019 A J Luteneegger	15
Main Findings from Field Studies on Screw Piles in Brazil C H C Tsuha	29
Physical Modelling of Screw Piles for Offshore Wind Energy Foundations C Davidson, M J Brown, A J Brennan, J A Knappett, B Cerfontaine, Y U Sharif	31
A 3D Material Point Method for Geotechnical Engineering L Wang, W M Coombs, C E Augarde	39
Field Tests Assessing the Installation Performance of Screw Pile Geometries Optimised for Offshore Wind Applications D J Richards, A P Blake, D J White, E M Bittar, B M Lehane	47
Performance of Screw Piles in Normally Consolidated Perth Sand E M Bittar, B M Lehane, A P Blake, D J Richards, D J White	55
Linking the Installation Response of Screw Piles to Soil Strength and Ultimate Capacity J P Hambleton, S A Stanier	57
A Critical Review on Design Aspects of Screw Piles for Renewable Energy Devices P V Pavan Kumar, S Patra, S Haldar	59
Rotary Jacking: Models for Installation Resistance and Capacity of Tubular Piles That Support the Upscaling of Screw Pile Technology D J White, A D Deeks	67
Finite Element Modelling of the Uplift Behaviour of Screw Piles in Sand B Cerfontaine, M J Brown, J A Knappett, C Davidson	69
Stress Variation During Installation of Mono-Helix Helical Pile L Thorel, I El Haffar, M Neme Gamarra, J A Schiavon, C H C Tsuha	77

Observations on the Cyclic and Post-Cyclic Response of Screw Anchors in Dry Sand	79
J A Schiavon, C H C Tsuha, L Thorel, I El Haffar	
Static and Cyclic Axial Loading of Single and Multiplate Helical Anchors in Sand	81
J T Newgard, J S McCartney, J A Schneider, D J Thompson	
Effects of Helical Pile Installation on the Lateral Stiffness for Piles in Dense Sand	87
Z H Elsherbiny, M H El Naggar, A Elgamal	
G-PFEM Numerical Assessment of Screw Pile Undrained Capacity	95
L Monforte, M Arroyo, A Gens, M O Ciantia	
Numerically Modelling the Installation and Loading of Screw Piles Using DEM	101
Y U Sharif, M J Brown, M O Ciantia, J A Knappett, C Davidson B Cerfontaine, S Robinson, J Ball	
Physical Modelling of a Helical Pile Installed in Sand Under Constant Crowd	109
A S Bradshaw, R Zuelke, L Hildebrandt, T Robertson, R Mandujano	
Silent Foundation Concept: Helical Piles for Skirt and Pre-Piled Jacket Foundations	117
M Huisman	
Screw Anchor Mooring of a Tidal Energy Platform – an Industrial Approach to R&D	119
A Hunt	
Screw Piles for Floating Wind and Offshore Aquaculture	121
S Powell	

SCREW PILE RESEARCH AT THE UNIVERSITY OF DUNDEE

M J BROWN

Civil Engineering, School of Science and Engineering, University of Dundee, Dundee, DD1 4HN, Scotland, UK
m.j.z.brown@dundee.ac.uk

SUMMARY: This paper gives a brief overview of the research on screw piles that has been undertaken by several members of staff and students at the University of Dundee (UoD) since beginning in 2007. It will give a brief overview of the types and areas of investigation of research projects undertaken and some of the findings of these studies that have helped contribute to current local levels of understanding and the ongoing direction of research. Much of this work has been undertaken in partnership with industry who have been key to the applicability of the findings.

Keywords: aquaculture, centrifuge, DEM, numerical modelling, renewable energy, screw piles.

INTRODUCTION & TIME LINES OF RESEARCH

Research into screw piles at the University began in 2007. These were not your classic steel tube with the helix welded to the outside but cast insitu concrete screw piles. These posed a significant challenge to physical modelling with installation and concreting required to be installed in one operation. This work was initiated by Roger Bullivant Limited (RBL) to allow greater understanding and more efficient design of their widely used CHD (Continuous Helical Displacement)¹ pile in sand. During this work, a 1g rig was developed that could be attached to an Instron UTM that allowed control over both installation and extraction (vertical and rotation control) of a pile injection tool (or bullet) with continuous measurement of load and torque above the pile². On completion of this study the equipment was available and used to service the ever-present need for undergraduate and master's student research projects. Some further work was done on CHD piles (2007-2011) but to make work simpler it was decided to replace the cast insitu pile with modular classic steel piles (2011 onwards). Modular piles were used such that the students could easily explore the effect of helix spacing (s/D) on tension and compressive performance at 1g in sand (to allow ease of preparation and parametric study). Around this time (2012) the Geotechnics Research Group was involved in an EU project on anchoring for wave energy units instigated by Conleth O'Loughlin (UWA). Although the project did not look at screw piles directly it identified their potential for application in offshore renewable energy applications.

As internal projects were starting to create a body of data on geometry variation it was also decided to undertake related projects where both physical and numerical modelling (Plaxis 2D)³ were looked at together to optimise screw pile geometry for in-service performance. Although the soils were well characterised and installation torque and force (crowd) were being

recorded, these elements were not looked at in any real detail.

The real drive to investigate the use of screw piles for use as offshore renewable energy anchors and foundations started in 2013 and was driven by the beginning of a PhD⁴ funded by the Iraqi government where Therar Al-Baghdadi wanted to undertake work on piles and renewable energy applications. An application was also made at the same time to the ERDF for investment in a centre for Marine Renewables Test Centre for Materials & Foundations (Concrete and Geotechnics). As part of this funding it was decided to invest in a centrifuge robot that would have the capability to install piles (push and rotate) and test them vertically and laterally. At the same time Al-Baghdadi began looking at upscaling onshore screw piles for offshore use using 2D & 3D Plaxis^{5,6} and to allow validation, the development of a screw pile rig capable of inflight installation and testing in one operation⁷.

Around the period 2012-2014 it was realised that there was growing interest in using screw piles offshore coming from industry but there as reluctance to take the concept further due to uncertainties in predicting installation requirements and thus concerns over the investment required to develop appropriate installation devices. Based upon the work by Al-Baghdadi⁸ and a perceived growing interest from industry in using screw piles the UoD along with Durham University, DU (previous research partner looking at developing offshore ploughs for renewable energy cable deployment) decided to develop a larger research funding bid. With Durham Energy Institute funding a meeting with industry was held in 2015 to work out the key areas for research. This impetus to work up a larger bid coincided with the call from the EPSRC Supergen Wind Energy Hub, Grand Challenges Call, an obvious target funding source. This funding was awarded in 2016 (UoD, DU and the University of Southampton) and as part of this project it was decided to organise the 1st International Symposium on Screw Piles for Energy Applications (2019) to share early findings from the project and bring together people interested in this specific application of screw piles. This paper will not look at specific outputs from this project as these will be covered elsewhere in the proceedings and presentations given as part of the conference (as well as submitted papers and coming publications).

Since embarking on the EPSRC Supergen project (looking predominantly at screw piles to replace offshore driven piles in jacket structures) the research direction has also grown to include screw piles for anchoring of floating wind and floating wave energy converters (2017, Development of Screw Anchors for Floating marine renewable energy System arrays incorporating anchor sharing. H2020-MSCA-IF-2016)⁹. Further funding has been obtained from EPSRC and RBL (2017) to understand screw pile and CHD pile behaviour in clays and more generally through the use of DEM (Discrete Element Method). The need to create relevant projects for Scottish Government funding for MSc students in Geotechnical Engineering with a particular focus on Scottish Aquaculture has also once again driven research direction. Scottish aquaculture would like to move current salmon production out of sea locks (to avoid sea lice contamination and loch bed biofouling) to offshore deeper water which would require more robust but simple to deploy anchoring solutions. This has led to further work on lateral behaviour, inclined installation, cyclic performance and the effects of rotation on plugging¹⁰ (2014 onwards).

This introduction has outlined the timelines of screw pile research at the University of Dundee. The paper will continue by highlighting the outcomes of the early work that led to EPSRC funding and highlight outcomes from the other parallel studies that may not have been published in the public domain. The paper will not cover the outcomes or look in detail at the outcomes of EPSRC research as this is highlighted elsewhere in the proceedings and presentations made at the conference as well as submitted papers and future planned publications.

SCREW PILE STUDIES

Cast in-situ screw piles (CHD)

Initial work in screw piles began at the UoD in 2007 with a PhD project supported directly by industry (RBL). John Jeffrey developed a 1g screw pile rig capable of perfect pitch matched installation and extraction which was designed to allow cement grout injection with pressure control on removal. This work was undertaken in sand at 1g as an initial trial to develop equipment for use on the centrifuge to allow creation and testing of CHD piles in one operation. The impetus for this project was to improve the understanding of CHD performance and the development of more efficient design where initially design was based upon assuming that the shaft component was only capable of mobilising a proportion of the shaft diameter (D) which was contrary to field testing observations where stiff, high capacity piles were encountered. Unfortunately due to major centrifuge refurbishment works (complete rewire and installation of the earthquake shaker)¹¹ John Jeffrey was not able to move his works to high g testing and concentrated on more detailed 1g model testing with instrumented piles and CPT radial disturbance investigations coupled with comparison the field case study data and numerical modelling¹².

Jeffrey made several findings of value that are now incorporated in CHD design but also wider findings that have value for other pile types and in particular for the vertical compressive capacity of screw piles (Figure 1). These findings were adopted by both Al-Baghdadi⁴ and Davidson et al.¹³ and also in the current research with respect to the variation of insitu conditions due to installation (Figure 2). which would have an effect on inservice performance. This is the current focus of DEM based study¹⁴ and has been incorporated in the modification of FE in attempt to capture installation effects^{4, 9, 12}.

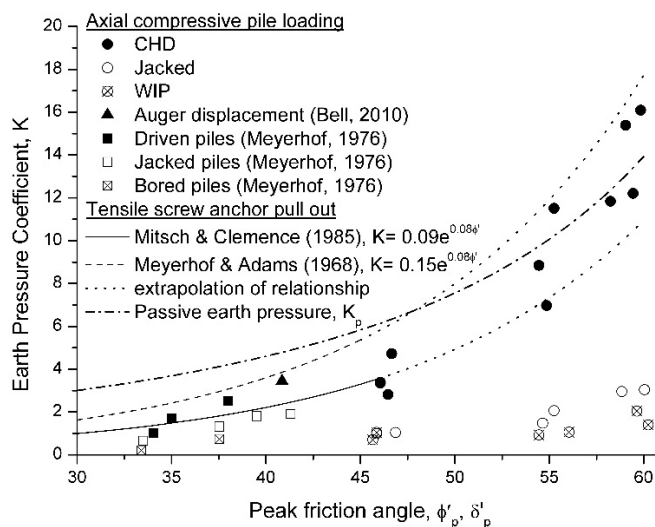


Figure 1: Relationship between the earth pressure coefficient for pile shaft determination and peak friction angle for model CHD piles compared with other model and field study results.²

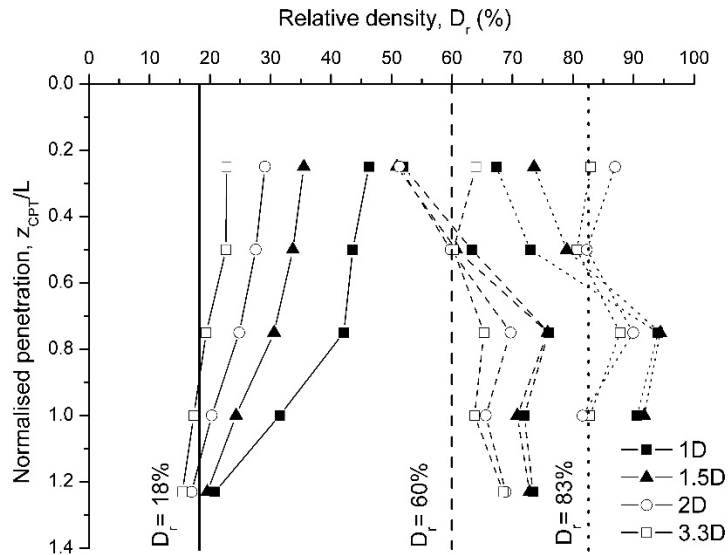


Figure 2: Changes in relative density due to the installation of model CHD piles determined using CPT measurements².

Insights gained from early undergraduate and masters projects

As mentioned in the introduction these studies mainly undertook testing at 1g in sand using the equipment developed by Jeffrey² to test simple classical screw piles with simple modular piles that could vary the spacing between the helix(es), s or change the number of helices. Initially work focused on multiple helix piles as they have the ability to mobilise soil-soil shear and enhanced vertical downward capacity as it was felt that screw piles had seen much attention as anchors but not necessarily to the same degree as piles. A summary of this work was published in 2014 by Knappett et al.³ that focused on the effects of helix spacing (s/D , where D here is the pile core diameter), (Figure 3 & 4), and the helix to core diameter ratio (D_h/D).

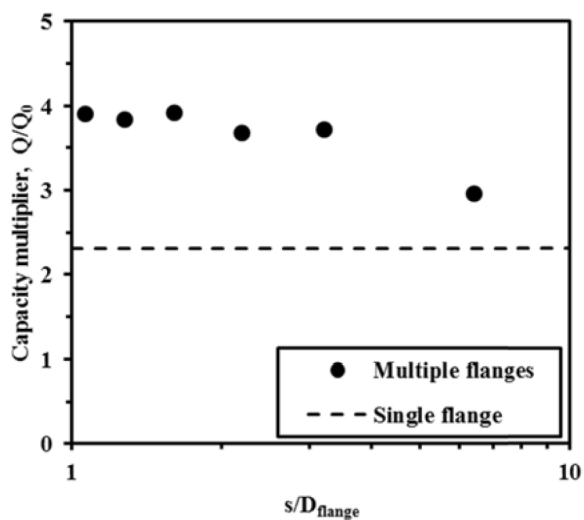


Figure 3: Effect of helix spacing on vertical compressive capacity when compared with a straight shafted pile³

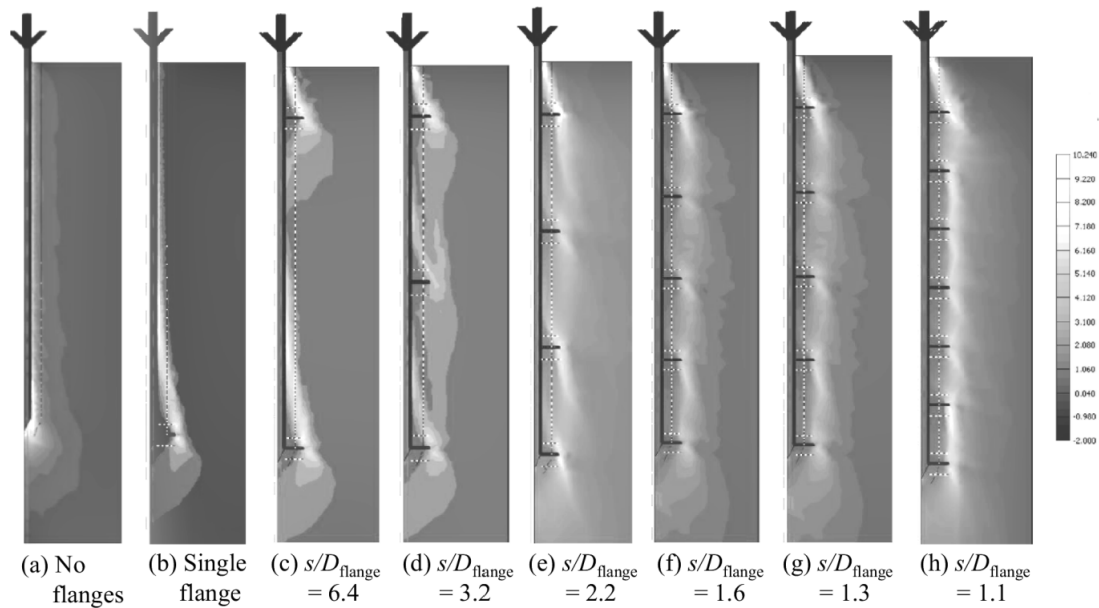


Figure 4: Results of 2D Plaxis modelling showing shear strains in % induced around a helix pile in compression at varying spacing ratios ³

It is apparent from Figure 3 that there is a change in efficiency in compressive capacity when the S/D ratio begins to exceed 3 also there is no significant benefit to installing helix plates closer than this for compressive loading. The research only looked at increasing the helix diameter at a fixed spacing which showed an obvious increase in capacity. For utilisation offshore, the smallest ratio of D_h/D where no significant effect on relative capacity occurs would also seem of interest. This would allow piles to have smaller helix plates which would allow easier stacking, handling and transportation. All of these studies had the problems associated with being at 1g and ignored the effects of installation during numerical modelling.

First PhD study on screw piles to replace driven piles for offshore wind jacket structures

The first full time study of screw piles as replacement for driven piles for offshore wind jacket structures began in 2013 and was undertaken by Therar Al-Baghdadi. Therar wanted to undertake numerical modelling of screw piles and had an interest in renewable energy foundations. With a need for validation of the numerical work (as there were little useful detailed field test case studies in existence for lateral testing) it was also decided to undertake scaled physical modelling at appropriate stress levels. This required the development of a bespoke centrifuge rig with the additional requirement that installation and testing could be undertaken all at an appropriate g level as many previous studies installed at 1g and tested at g , or partially installed at 1g and g ⁷. This limitation was imposed as previous work to investigate this had shown significant difference in-service capacity depending on how realistic installation was simulated. This is confirmed by current DEM studies where very significant detrimental effects on in-service capacity can occur if perfect or self-installation are adopted and self-installing piles are allowed to overflight too much at the end of installation.

Numerical work by Al-Baghdadi focused initially on lateral loading and if pile helix plates could be used near surface to improve the considerable demands placed on piles in jacket structures in terms of lateral behaviour⁶. In fact, it was realised at an early stage in the research that the classic onshore screw pile geometry of the thin core and large helix did not lend itself to the large bending moment demands imposed on the upper elements of a piled foundation and that geometry would need to change significantly to go offshore (larger core diameters to

achieve structural requirements)⁵. Unfortunately, such structural changes lead to greater demands in terms of installation requirements e.g. torque and crowd or vertical installation force (depending on how the pile is installed e.g. pitch matched or self-installed).

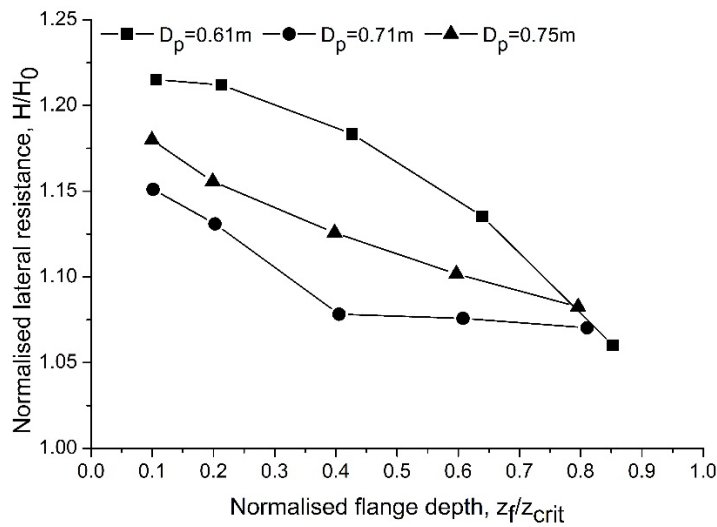


Figure 5: Results of 3D Plaxis simulation to identify the potential of near surface helix plates to deal with lateral loading demands⁶.

Installing large helix plates did assist with increase lateral capacity by up to 22% but these were very large and most benefit was realised near surface where the piles could be subjected to scour. This potential improvement could also be enhanced during compressive loading but would then be further degraded under tensile loading requiring the appropriate design of structural self-weight to avoid this if practical⁵. Undertaking these early numerical studies highlighted how important structural/material design is to the design of a screw pile foundation both during installation and in-service and that to optimise the structural form of a screw pile for offshore use will require insights into particular application and utilisation at the early stages of design and before a particular pile type is selected. This is highlighted in more detail in more recent work^{13, 15}.

Al-Baghdadi explored a wide range of geometrical controls on installation and in-service screw pile performance for piles scaled up for offshore use. What was immediately evident from these pitch matched centrifuge pile installation was that such piles would generate very large torque, and what was unexpected at the time was also very large crowd forces. The latter was unexpected as the recording of crowd is rarely undertaken in the field and no previous discussion of this issue could be found in the literature.

These findings were consistent with the concerns of the offshore renewable energy installation industry (2013-2015) that to allow deployment of screw piles accurate methods of predicting both required torque and now crowd (or vertical installation force) would be required. Based upon offshore GI relying heavily on CPT (rather than SPT onshore) it then seemed logical to attempt to try and use CPT test results to predict screw pile installation requirements. Thus, parallel CPT and screw pile testing was undertaken using a specially designed mini CPT. Development of the CPT torque and crowd predictor (which has its origins in the UWA CPT pile capacity prediction method) seemed to work relatively well for the model situations simulated in different relative density sands for pitch matched installation, at a fixed pitch⁸. This was further improved and tested (Figure 7) for a wider range of pile geometries¹⁶ (and verified in field tests). Further DEM simulation was used to show why this methodology was not sensitive to pitch (at the pitch tested or most likely installation pitches) which is

consistent with the rotational pitch insensitivity seen in pile core plugging studies¹⁰.

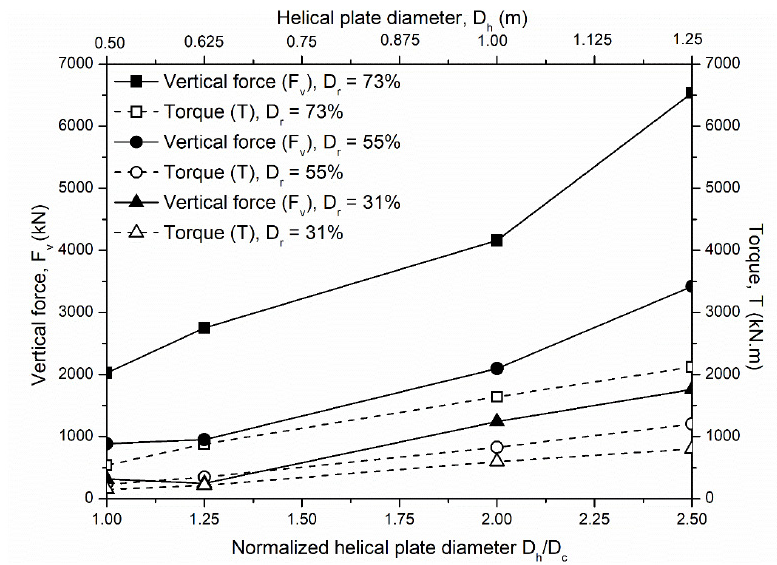


Figure 6: Vertical force and torque for multiple helix screw piles with various helical plate to shaft diameter ratio (D_h/D_c).

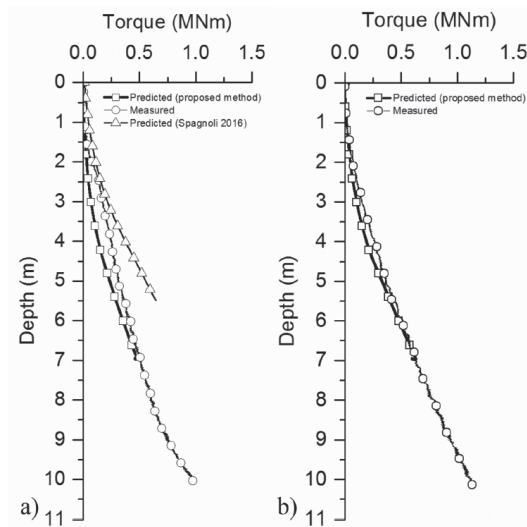


Figure 7: Predicted and measured prototype installation torque from centrifuge tests: a) single helix; b) multihelix screw pile¹⁶.

The work by Al-Baghdadi covered many areas with respect to developing offshore screw piles and formed the basis for an informed application to the EPSC Supergen Wind Hub Grand Challenges call and assisted in focusing the earlier direction of this much bigger project e.g. the need for torque reduction strategies. For example, Figure 8 shows the effect of pile helix to core diameter on pile capacity or the pile capacity torque relationship often adopted to predict pile capacity based upon torque ($K=(Q \times D)/T$, where Q is pile capacity in compression and T is the measured torque). This suggests that the ratio of D_h/D_c is at an optimum between 2 and 3 as per S/D .

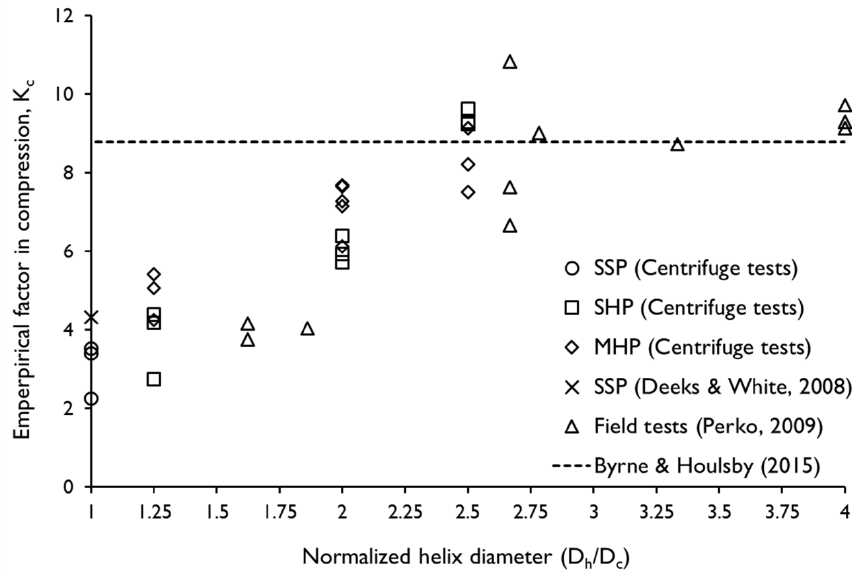


Figure 8: Variation of the empirical factor in compression (K_c) with the normalised helical plate diameter (D_h/D_c) for compression tests.

One additional finding of Al-Baghdadi was that torque during installation in the main was affected by pile core surface area and to a much lesser extent by the helix plate. This would suggest that a direct relationship between screw pile capacity and torque based upon the helix diameter is inappropriate as torque would be controlled by the core diameter and capacity by that of the helix. This is further complicated for a screw pile in uplift where shallow and deep failure capacity mechanisms can occur. This suggests that the form of current torque-capacity relationship should be modified to take account of both the contribution of the core and the helix plates which may vary with spacing ratio. Their application may also be limited for upscaled offshore piles where core shaft area dominates. Current successful application onshore may only be due to the very small core diameters and limited range of dimensions of pile components used. The validity of these relationships is also further complicated by the apparent effect of variability during installation on capacity as discussed later.

Recent and ongoing work

As well as the larger EPSRC funded project that is described in more detail in various papers in the proceedings further funding was obtained in 2017 by Cerfontaine to develop screw anchors for floating marine renewable energy system arrays incorporating anchor sharing. This along with the EPSRC project marked a shift in focus away from compressive performance to tensile screw pile performance with the need to predict tensile capacity for optimised geometries designed to minimise installation requirements. It was quickly discovered through Plaxis modelling of failure mechanisms that multiple helices were not the best approach for near surface shallow embedded anchors¹⁷ and that current onshore uplift capacity design approaches could be non-conservative for the proposed new designs. Similar findings were made experimentally at 1g whilst developing anchors for aquaculture mooring solutions with no apparent gains in capacity seen between a single helix and multiple helices (Figure 9)^{18, 19}. Again, modifications were made to Plaxis modelling to incorporate installation effects informed by previous and ongoing centrifuge modelling¹¹ as well as investigating the effects of soil deformability (Figure 10)⁹.

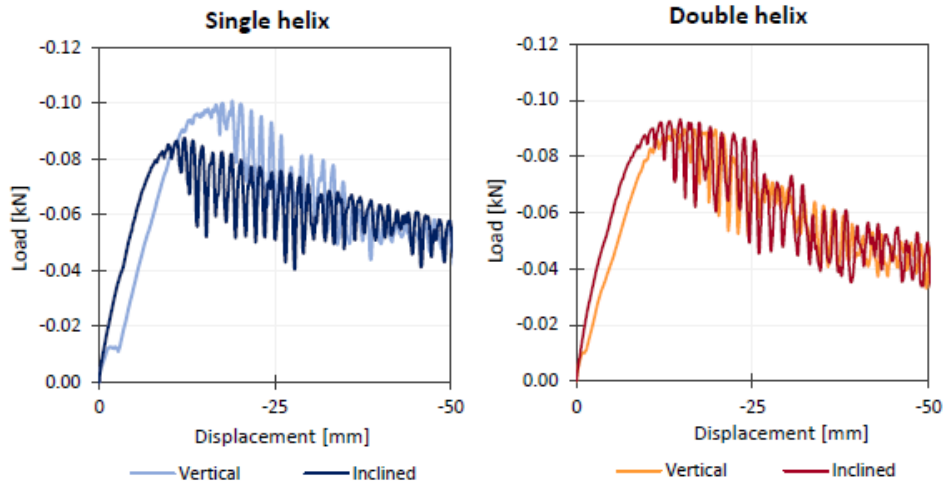


Figure 9: Comparison of vertical and inclined installation of 'single helix' and 'double helix' anchors under 10° load inclination.

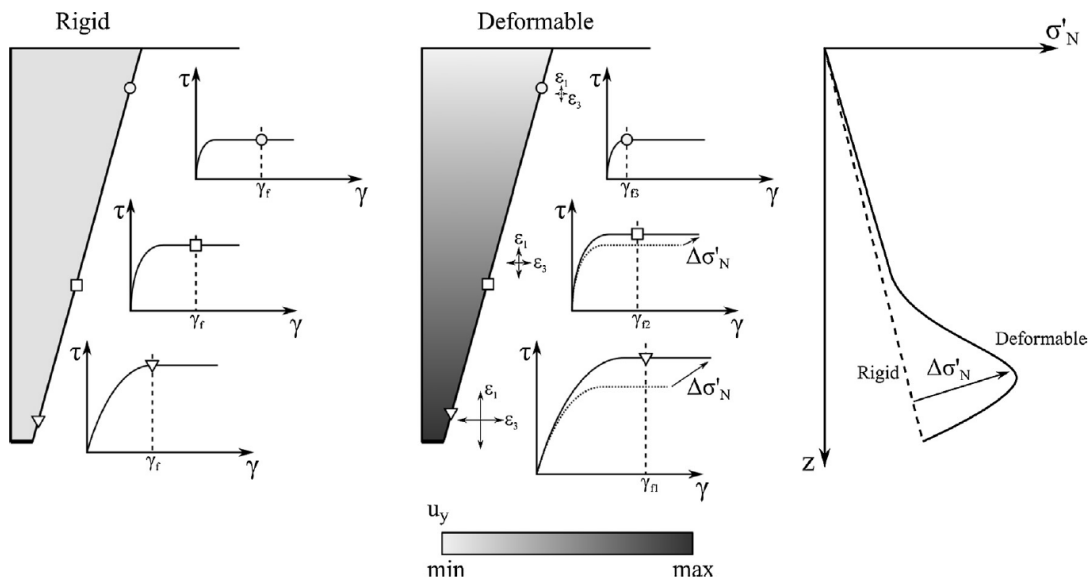


Figure 10: Comparison of idealised shear stress mobilisation between rigid and deformable wedge uplifted by a plate anchor⁹.

What plans for future research direction?

One point of potential real behaviour that we have avoided during centrifuge investigation is whether tubular screw piles plug or not and how this effects installation requirements. This has been avoided due to concerns over scaling of arching and plugging with sand and very small diameter model piles. Therefore, the approach has been to use solid flat ended piles to simulate immediate plugging and a worst-case scenario for installation. Preliminary testing has been and is ongoing with MSc projects at 1g with previous emphasis on the rotation rate (or pitch rate) of various diameter open ended tubular piles in different density soils¹⁰. Pile plugging seemed to be unaffected by rotation in loose soils but appeared to have a greater tendency to plug in dense soil when rotated whereas when not rotated the pile cored and only limited plugging occurred. At the relatively high rate of rotation (or rotational pitch) adopted in these tests torque and pile resistance

during installation seemed generally unaffected by the rate of rotation²⁰. This maybe a useful finding for the wider application of the CPT based installation prediction tool if torque and crowd are relatively insensitive to rotation rates (also verified in DEM).

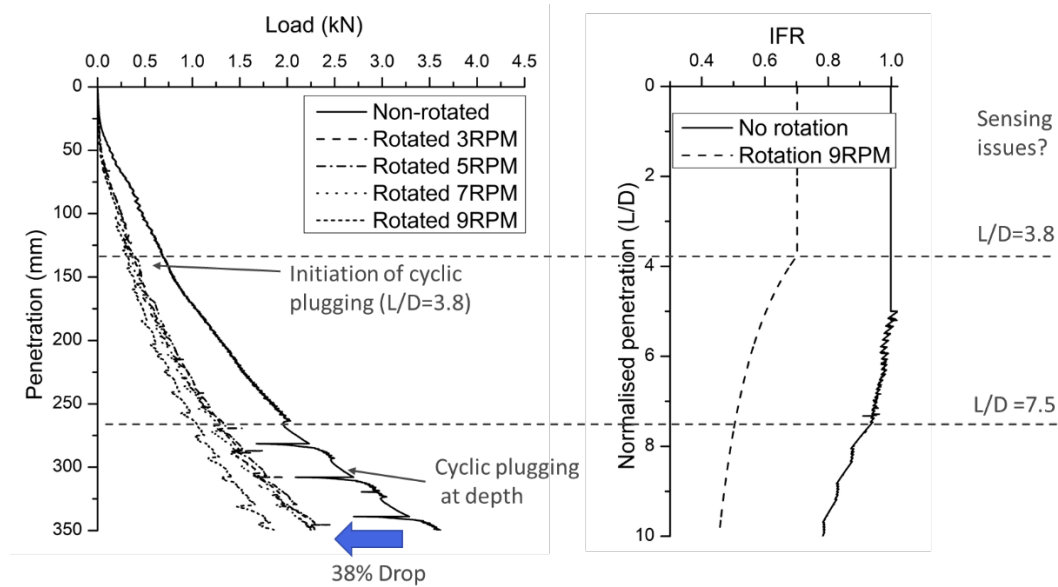


Figure 11: Comparisons of effect of rotation on plugging behaviour for a tubular pile in dense soil¹⁰.

This work will be advanced further through experimental developments to allow better measurement of plug behaviour in terms of height but also rotation during installation.

Current research focus is around the development and use of DEM to gain insights into what controls both screw pile installation requirements and in-service behaviour. DEM is being used as it can simulate both the installation and in-service phase in granular soils and can be calibrated against the centrifuge data previously created. Through investigation of various possible types of installation approach (e.g. pitch matched, self-installation, crowd applied as a proportion of self-weight) it will be possible to determine the most appropriate approach for installation or develop appropriate equipment for installing large screw piles for renewable energy use. But it cannot be forgotten that the installation approach may significantly affect the installation phase and thus render previous correlations of pile capacity to measured installation torque of limited value (Figure 12).

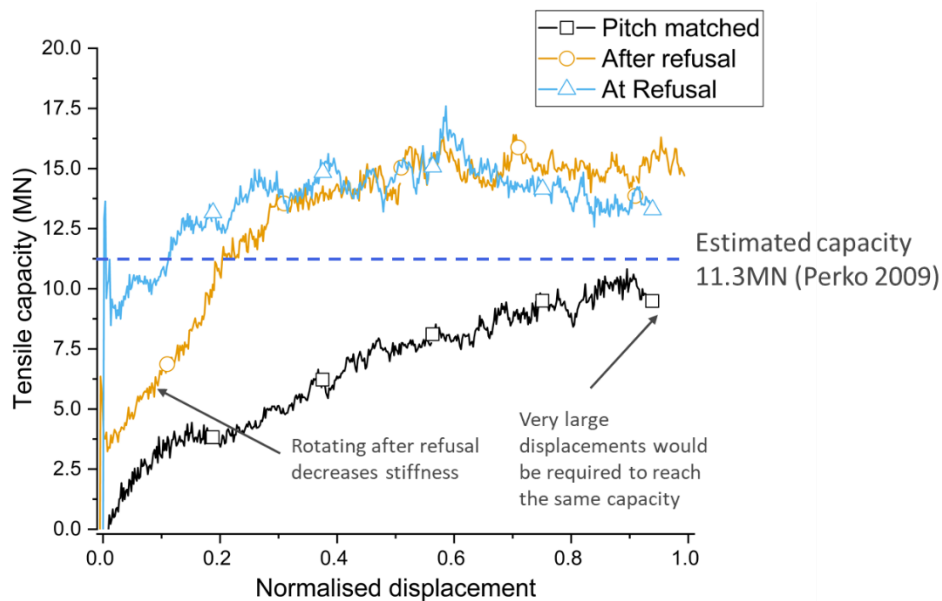


Figure 12: Comparisons of tensile capacity of a pitch matched installation with a “self installing” pile at different stages of installation. Refusal refers to stage at which piles have reducing forward progress during “self-installation”.

ACKNOWLEDGEMENTS

I would like to thank Roger Bullivant Limited (RBL) and particularly Jon Ball for their support help and guidance throughout our many years of work looking at piles. Jon Ball first started supporting my work through his interest in Statnamic pile testing as part of my PhD. We have been friends ever since. RBL and Jon continue support our work through sponsorship of current PhD student Yaseen Sharif. Without RBL’s support we would never have started our work on screw piles. I would like to acknowledge the support of EPSRC for funding over many years that have contributed to our current level of understanding: 2007, EPSRC CASE for New Academics, 2016, EPSRC Supergen Windhub Call 2015: Grand Challenge project with Durham University (Prof Charles Augarde & Will Coombs) and University of Southampton (Prof David Richards) EP/N006054/1. 2017, EPSRC NPIF funded studentship with industry contribution – Screw piles in clay soils. More recently facilities and staff have been supported by the EU through: 2013, ERDF Business Innovation and Growth Call Lowlands and Uplands Scotland ERD Programme 2007-2013 (Priority 1) to create the Marine Renewables Test Centre for Materials & Foundations (LUPS/ERDF/2013/10/1/0075), 2017, EU H2020 Marie Skłodowska-Curie Actions Individual Fellowships SAFS – Development of Screw Anchors for Floating marine renewable energy System arrays incorporating anchor sharing. H2020-MSCA-IF-2016, Grant no. 753156 (08/17-07/19) and 2012, EU FP7, GeoWave Geotechnical and mooring design solutions for the offshore renewable wave energy industry (Euros 1.3M), Capacities FP7-SME-BSG-2011 ‘Research for the benefit of SMEs’. Many colleagues, students, technicians and research partnerships (current Academic Durham University and the University of Southampton, Industry: Cathie Associates, SMD, RBL, InSitu SI) have contributed to the success of our ongoing work. I would like to thank them all.

REFERENCES

1. Jeffrey, J., Brown, M.J., Knappett, J.A., Ball, J. & Caucis, K. (2016) CHD pile performance, Part I: physical modelling. *Proc. Inst. of Civil Engineers: Geotechnical Engineering Journal*, Vol. 169, No. 5, pp. 421-435. DOI: 10.1680/jgeen.15.00131.
2. Jeffrey, J. (2012) Investigating the performance of continuous helical displacement piles. *PhD thesis*, University of Dundee.
3. Knappett, J.A., Brown, M.J., Brennan, A.J. & Hamilton, L. (2014) Optimising the compressive behaviour of screw piles in sand for marine renewable energy applications. *Int. Conf. On Piling & Deep Foundations*, Stockholm, Sweden, 21st-23rd May 2014. Article #1904; publication #100 (IC-2014).
4. Al-Baghdadi, T. (2018) *Screw piles as offshore foundations: Numerical and physical modelling*. PhD thesis, University of Dundee.
5. Al-Baghdadi, T., Brown, M.J., Knappett, J. A. & Humaish, A. (2017) Effects of vertical loading on lateral screw pile performance. *Proc. Inst. of Civil Engineers: Geotechnical Engineering Journal*, Vol 170, GE3. pp. 259-272. DOI: <http://dx.doi.org/10.1680/jgeen.16.00114>.
6. Al-Baghdadi, T., Brown, M.J., Knappett, J. A. & Ishikura, R. (2015) Modelling of laterally loaded screw piles with large helical plates in sand. In V. Meyer (eds) *3rd Int. Symp. on Frontiers in Offshore Geotechnics*. Oslo, Norway. 10 -12 June 2015. Taylor & Francis Group, London. pp. 503-508.
7. Al-Baghdadi, T., Brown, M.J. & Knappett, J. A. (2016) Development of an inflight centrifuge screw pile installation and loading system. In Thorel, L., Bretschneider, A., Blanc, M. & Escofier, S. (eds) *3rd European Conference on Physical Modelling in Geotechnics (Eurofuge 2016)*, Nantes, France. 1-3 June 2016. pp. 239-244.
8. Al-Baghdadi, T., Brown, M.J., Davidson, C., Knappett, J., Brennan, A., Wang, L., Coombs, W.M., Augarde, C.E., Richards, D. & Blake, A. (2017) CPT based design procedure for installation torque prediction for screw piles installed in sand. *8th Int. Conf. on Offshore Site Investigation & Geotechnics (SUT OSIG)*, 12-14th Sept., 2017, London, UK. Vol. 1. pp. 346-353.
9. Cerfontaine, B., Knappett, J.A., Brown, M.J. & Bradshaw, A.S. (2019) Effect of soil deformability on the failure mechanism of shallow plate or screw anchors in sand. *Computers and Geotechnics*. Vol. 109 pp. 34-45. DOI: doi.org/10.1016/j.compgeo.2019.01.007. ISSN: 0266-352X.
10. Garcia Gallindo, P., Davidson, C. & Brown, M.J. (2018) Installation behaviour of open ended and closed ended piles with torque application. *Proceedings of the 1st International Conference on Press-in Engineering 2018*, 19-20th September 2018, Kochi, Japan. International Press in Association, Japan. pp. 379-386.
11. Brennan, A.J., Knappett, J.A., Brown, M.J., Bertalot, D., Loli, M. & Anastasopoulos, I. (2014) Dynamic centrifuge modelling facilities at the University of Dundee and their application to studying seismic case histories. *8th Int. Conf. On Physical Modelling in Geotechnics ICPMG'14*, Perth, Western Australia, 14-17th Jan 2014. pp. 227-233.
12. Knappett, J.A., Caucis, K., Brown, M.J., Jeffrey, J. & Ball, J. (2016) CHD pile performance, Part II: numerical modelling. *Proc. Inst. of Civil Engineers: Geotechnical Engineering Journal*, Vol. 169, No. 5, pp. 436-454. DOI: 10.1680/jgeen.15.00132. ISSN 1353-2618.
13. Davidson, C., Brown, M.J., Cerfontaine, B., Knappett, J.A., Brennan, A.J., Al-Baghdadi, T., Augarde, C., Coombs, W., Wang, L., Blake, A., Richards, D.J. & Ball, J.D. Feasibility of screw piles for offshore jacket structures, Part I: Physical modelling. *Geotechnique*. Under consideration.

14. Sharif Y, Brown M J, Ciantia M O, Knappett J A, Davidson C, Cerfontaine B, Robinson S and Ball J. (2019) Numerically modelling the installation and loading of screw piles using DEM. *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications*, Dundee, Scotland, 27 – 28 May 2019. University of Dundee.
15. Davidson, C., Al-Baghdadi, T., Brown, M.J., Knappett, J., Brennan, Augarde, C.E., A., Wang, L., Coombs, W.M., Richards, D. & Blake, A. (2018) Centrifuge modelling of optimised screw piles for offshore wind energy foundations. *Proc. 9th International Conference on Physical Modelling in Geotechnics (ICPMG 2018)*. 17-20th July 2018, London, UK. Taylor & Francis Group, London, UK. pp. 695–700.
16. Davidson, C., Al-Baghdadi, T., Brown, M.J., Knappett, J., Brennan, Augarde, C.E., A., Coombs, W.M., Wang, L., Richards, D., Blake, A. & Ball, J. (2018) A modified CPT based installation torque prediction for large screw piles in sand. *4th International Symposium CPT'18 - Cone Penetration Testing*. 21-22 June 2018, Delft, Netherlands. CRC Press. pp. 255-261.
17. Cerfontaine, B., Knappett, J.A., Davidson, C., Brown, M.J., Brennan, A.J., Al-Baghdadi, T., Augarde, C., Coombs, W., Wang, L., Blake, A., Richards, D.J. & Ball, J.D. Feasibility of screw piles for offshore jacket structures, Part II: Numerical modelling. *Geotechnique*. Under consideration.
18. Horvath, A. (2018) *Examining inclined installation of screw anchors scaled up for offshore renewable energy deployment*. MSc Thesis. University of Dundee. Dundee, UK.
19. Caton, A. (2016) *Examining the behaviour of screw anchors under varying load inclinations*. MSc Thesis. University of Dundee. Dundee, UK.
20. Garcia Galindo, P. (2017). *Installation behavior of open and closed ended piles in sand while applying torque*. MSc Thesis. University of Dundee, Dundee, UK

SCREW PILES AND HELICAL ANCHORS – WHAT WE KNOW AND WHAT WE DON'T KNOW: AN ACADEMIC PERSPECTIVE – 2019

A J LUTENEGGER

University of Massachusetts, Amherst, Ma. 01003 USA
lutenegg@ecs.umass.edu

SUMMARY: Screw piles and helical anchors have been used in Civil Engineering for over 175 years. While they were used extensively during the mid to latter half of the 19th Century, their use declined through the first half of the 20th Century. In the past 20 years considerable advances have been made around the world to expand our understanding of the behavior of screw piles and helical anchors in a variety of soils, partly because of the renewed interest in their application in a variety of design situations. This technology may be the fastest growing market in foundation engineering around the world. However, there are still some gaps in our knowledge and our understanding. A review of the current state-of-understanding of the engineering behavior of screw piles and helical anchors is presented with specific examples largely from full-scale field load tests. Areas that are still in need of research are also presented.

Keywords: field tests, helical anchors, review, screw piles,

INTRODUCTION

A screw pile or helical anchor consists of a central steel shaft with one or more helical plates welded to the shaft at specified intervals. They have been used over the past 175 years to support buildings, bridges, towers and other structures much in the same way that other foundation or anchor systems are used.¹ Screw piles and helical anchors are typically a factory manufactured foundation/anchor system with predetermined dimensions. The performance is dependent not only on the soil conditions at a particular site, the direction of loading, specific geometry and quality of the installation.

Explosion of Knowledge Through Technical Publications

Much of the current understanding of the behavior of screw piles and helical anchors is based on research conducted in the decade between the late 1970s through the late 1980s. Both field and laboratory research established modes of failure for shallow and deep single- and multi-helix screw piles and helical anchors in fine-grained and coarse-grained soils. In the past 20 years there has been an expansion of research around the world on a range of topics related to screw piles and helical anchors. Figure 1 shows the history of publications appearing in technical journals and conference proceedings during the period 1970–2018. However, even with this increase in activity, there are still gaps in some fundamental topics that need attention if the profession is to develop a better understanding of behavior and reach a maturity level comparable to other types of deep foundations. In more recent years, a welcome addition to the literature has been published

A J. Luteneegger. *Screw piles and helical anchors – what we know and what we don't know: an academic perspective – 2019. Proceedings of the 1st International Screw Pile Symposium on Screw Piles for Energy Applications*, Dundee, Scotland, 27 – 28 May 2019.

cases involving large scale screw piles and helical anchors, a return to early historical use.

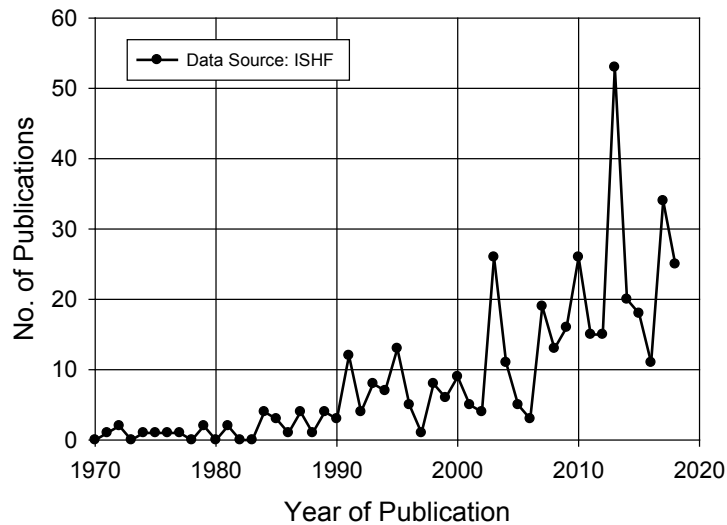


Figure 1: History of publications related to screw piles and helical anchors.

PART-1: Our Current Understanding – “What We Know”

The current state of our understanding of the basic behavior of screw piles and helical anchors is good. In general, the fundamental aspects under axial loading have been established. There are several distinct areas that make up our current understanding.

The Contribution of Helical Plate to Capacity

It should now be recognized by most engineers that under axial compression or tension the distribution of load is a function of the specific geometry of the screw pile or helical anchor in a given soil. In uniform soil, the contribution of the helical plate(s) to load capacity varies with the size of the plate and shape and size of the central shaft for round-shafts. The relative importance of a single helical plate to ultimate load capacity can be illustrated by a simple parametric analysis.

We may consider a set of helical piles with the same diameter helical plate (12 in.) attached to round central shafts of different diameter. In a uniform soft clay with $s_u = 500$ psf (25kPa) and assume undrained behavior for shaft resistance, the total undrained load capacity in compression and the capacity derived from the helical plate may be determined, as shown in Figure 2. Expressed another way, the percentage of the ultimate capacity developed by the plate is shown in Figure 3. Since the total capacity varies with shaft length, two lengths are shown. Naturally, there is no shaft with a diameter of 0; this is purely hypothetical. This simple analysis shows that the influence of the helix diminishes rapidly, as the shaft diameter increases and the pile reverts to a plain pile and load capacity is picked up by the pipe shaft as the shaft diameter increases. In this analysis, when the helix diameter and pipe diameter are the same, this represents a plain pile.

A similar analysis performed by varying the shaft diameter while holding the helical plate diameter constant is shown in Figure 4. The relative load capacity increases as the ratio D_H/D_S increases. While these results are for an ideal uniform soft clay, similar parametric analyses can be performed for uniform sand. Results would show similar results, although the

percentage contribution of the helical plate will be different because of the difference in developing side resistance on the pipe as compared to end bearing on the helix. Effectively, the pipe shaft takes on more importance as the diameter increases. For a very long pile the behavior is close to a plain pile with no helix. At the serviceability state, say $Q_{ult}/2$, a higher percentage of load is taken by the pipe shaft.

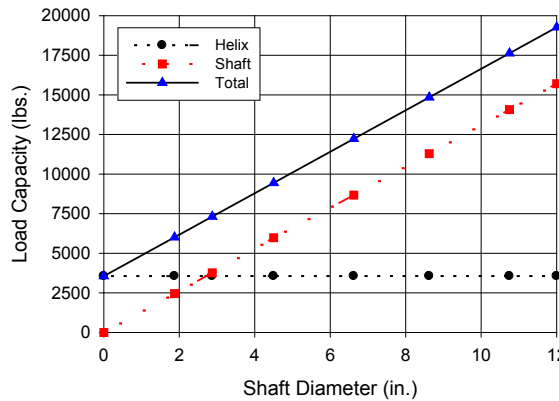


Figure 2: Influence of helix on load capacity in soft clay.

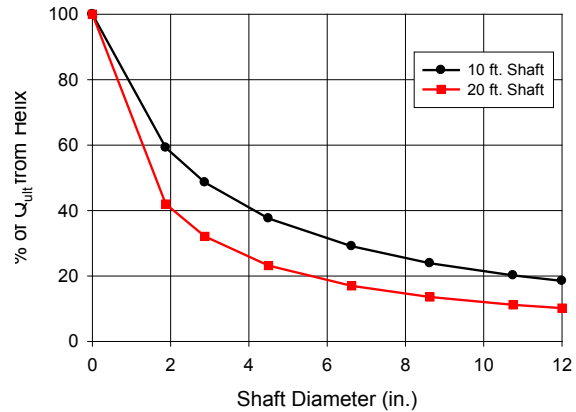


Figure 3: Relative contribution of helix to capacity.

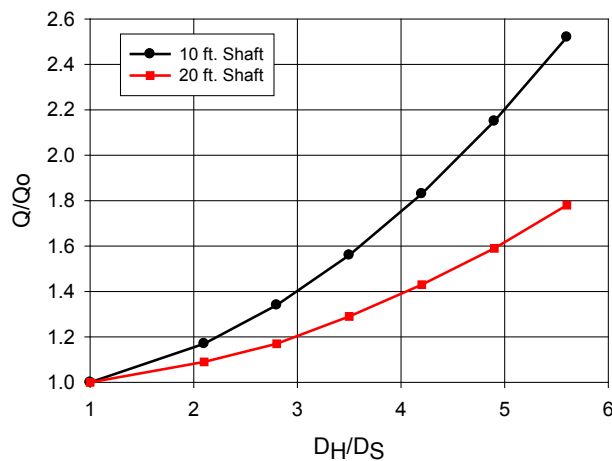


Figure 4: Increase in relative load capacity as a function of D_H/D_S .

Spacing of Helical Plates

For at least 30 years, it has been known that the relative spacing of helical plates along the central shaft of colinear multi-helix screw piles and helical anchors influences behavior. Two modes of failure have been suggested; 1) Perimeter Shear between adjacent plates, and 2) Individual Plate Bearing. It is generally recognized that the ultimate load is developed as a transition from Perimeter Shear (PS) mode of failure to Individual Plate (IP) mode of failure as the relative helix spacing increases and helical plates become independent of adjacent plates. In clays, the transition occurs at a relative helix spacing of about 1.5 helix diameters, as shown by theoretical analysis² and about 2.5 helix diameters as shown by field tests.³ Figure 5 shows results of field tests on multi-helix anchors in clay in which the relative helical spacing was systematically changed. Similar results have been obtained by the Author in sand. Figure 6 shows a comparison between load capacity with $S/D_H = 1.5$ as compared to $S/D_H = 3$ for a number of anchors in both clay and sand.

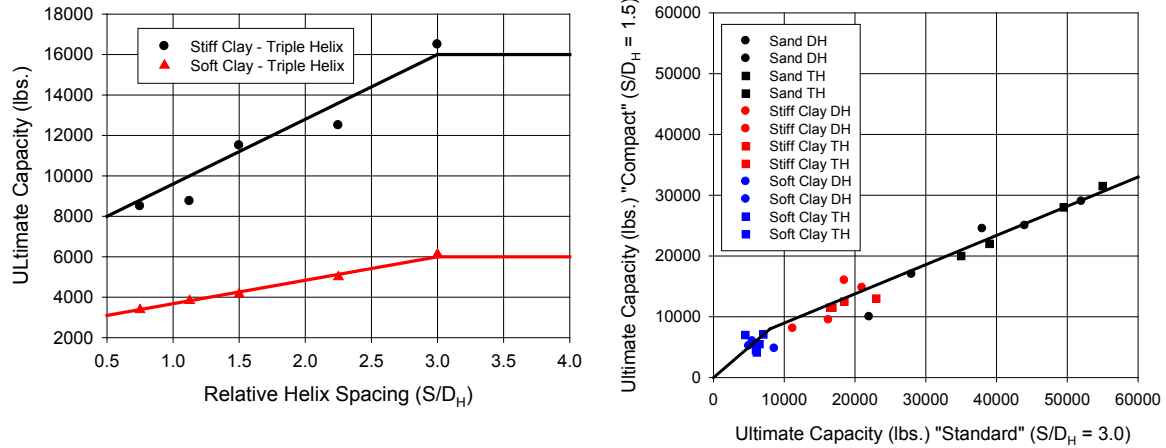


Figure 5: Influence of helix spacing on capacity in clay. **Figure 6:** Load capacity for $S/D_H = 1.5$ vs. $S/D_H = 3.0$.

Normalized Behavior

Load tests using different geometry of screw piles and helical anchors in the same soil show normalized behavior. That is, the load-displacement behavior may be expressed in non-dimensional terms by dividing the load by the failure load (taken as the load producing a displacement of 10% of the diameter of the average helical plate) and the displacement by the failure displacement (10% of the average helix diameter). Figure 7 shows results obtained in clay that illustrate this behavior. The engineer can use this behavior to predicted load-displacement behavior for any size pile/anchor using the results from a single test and predict the displacement at the serviceability state.

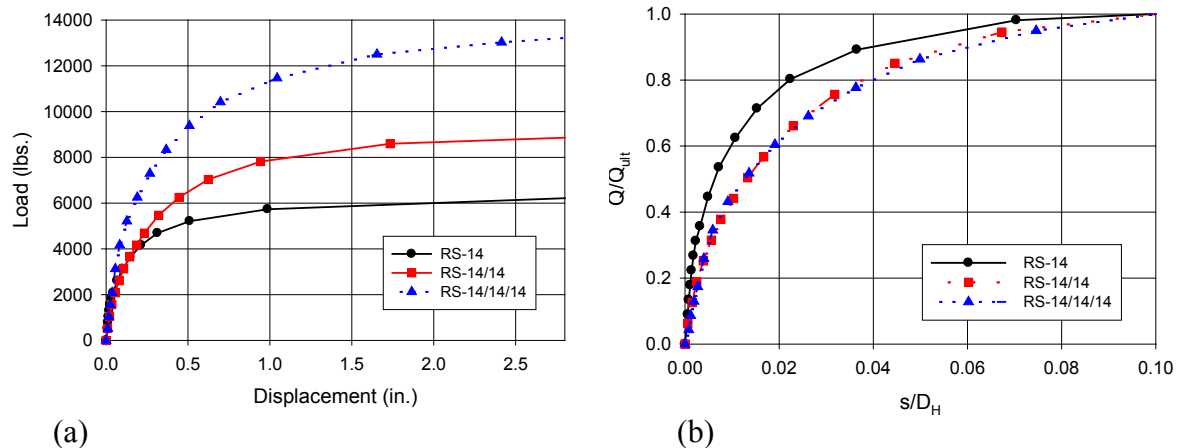


Figure 7: a) Load-displacement behavior; b) Normalized load-displacement behavior.

Efficiency of Colinear Screw Piles and Helical Anchors

It is now understood that the efficiency of colinear multi-helix screw piles and helical anchors is less than 100%. That is, trailing helical plates do not develop the same capacity as the lead helix. Efficiency, E , of colinear multi-helix piles/anchors with the same diameter plates is defined as:

$$E = [Q_{ultMH} / (N \times Q_{ultSH})] \times 100\% \quad (1)$$

where: Q_{ultMH} = ultimate capacity of a multi-helix pile/anchor; Q_{ultSH} = ultimate capacity of a single-helix pile/anchor; N = number of helical plates

Equation 1 is strictly not correct since the addition of more plates will not increase the load capacity proportionally but depends on the relative percentage contribution that a plate

can provide, which depends on both the plate and shaft geometry. However, load test data from square-shaft anchors provided by a manufacturer of screw piles and helical anchors were interpreted by the Author in terms of Efficiency, using Eq. 1. The results are shown in Figure 8 and include 5 different sets of tests in medium stiff clay with helices ranging from 8 in. to 15 in. diameter.

Figure 9 shows additional results obtained by the Author in both stiff and soft clay for both square-shaft and round-shaft helical anchors. The trend of these data suggests that this reduced efficiency is real and should be taken into account in design. Similar results have been obtained in sands.^{4, 5, 6}

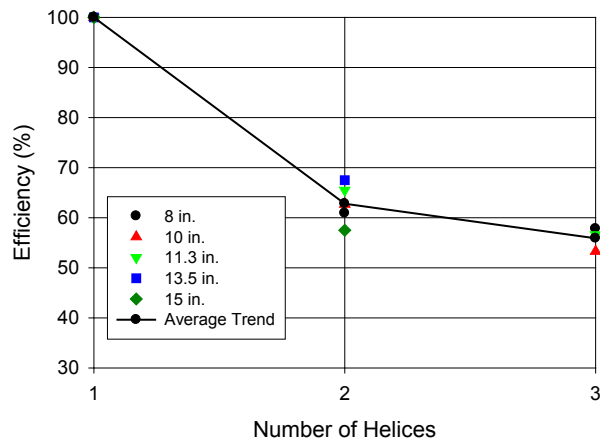


Figure 8: Efficiency of square-shaft multi-helix anchors in stiff clay.

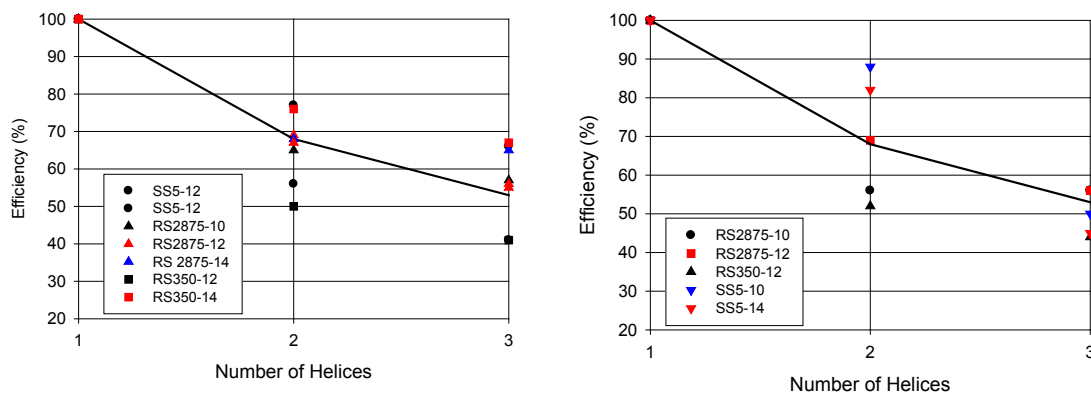


Figure 9: Efficiency of multi-helix anchors in stiff and soft clay.

Available data show that the capacity of each successive plate is reduced progressively by the preceding disturbance. While the 1st plate has 100% Efficiency, trailing plates will have reduced Efficiency because of progressive disturbance, as will be discussed later.

Recognition of Installation Disturbance

The discussion of Efficiency in the previous section suggests that this behavior is related to progressive disturbance during installation, which is likely to occur even with high quality installation. The degree of disturbance and influence on behavior depends on the type and geometry of the pile, the method of installation and the soil conditions. Lutenegger et al.⁷ presented results of field vane tests conducted directly over the top of helical anchors which showed a reduction in undrained shear strength as compared to the undisturbed soil.

The results indicated that double-helix and triple-helix anchors produce more disturbance than a single-helix anchor. This means that in clays having additional plates will likely produce

more soil disturbance and a greater reduction in strength, producing an anchor which has a combined plate efficiency of less than 100%, as previously shown. That is, the mobilized strength available to develop load capacity decreases progressively with additional plates.

It has been established that installation of helical piles/anchors in clay produces varying degrees of disturbance and a corresponding reduction in undrained shear strength. The reduction in shear strength may be related to the quality of installation for a given soil. It is useful to consider how the quality of installation can affect disturbance and load capacity of a pile/anchor.

“Perfect” installation of a screw pile or helical anchor would result in the advance of one pitch distance for each complete revolution of the shaft and plate. So for example if the pitch of each helical plate is 3 in. then the “perfect” advance would be 4 revolutions per ft. of advance. By contrast, it is more likely that most field installations occur in a more “Imperfect” manner. That is, the number of rotations of the helical plate for each unit of advance is greater than the “Perfect” case and in some extreme cases may even approach no advance. “Imperfect” installation produces substantial disturbance to the soil simply because the helical plate is now acting partially as an auger and is in effect simply churning the soil. Different degrees of imperfect installation can occur depending on the geometry of the pile/anchor, the subsurface conditions encountered and the skill of the installer.

A simple quantitative measure of the installation quality that can be obtained during installation and can be used as a quality control measure on the Contractor's work. The Installation Disturbance Factor, IDF, can be defined as the ratio of actual measured installation to the “Perfect” installation:

$$IDF = (R)/(A/P) \quad (2)$$

where: R = measured number of Revolutions per unit of advance; A = ideal number of Revolutions per unit of advance; P = Pitch of helical plate

Figure 10 shows a comparison of the Installation Torque and the Advance for the two 2.875 in. round-shaft anchors installed in a medium stiff clay (Sensitivity = 5). Initially, the Installation Torque is similar, but after a depth of about 5 ft. it can be seen that the torque developed by the two anchors starts to diverge. This is the result of the larger number of rotations required for Anchor-A as compared to Anchor-B. As the number of rotations increases, the torque decreases as the soil is remolded. Results of load tests performed on these two anchors are shown in Figure 11 and demonstrate the influence of disturbance (poor quality installation) on capacity.

The results presented in Figure 11 suggest that in clays there is a link between the quality of the installation and the reduction of undrained shear strength resulting from rotation and installation of the anchors. Even the best installation produces a reduction in shear strength. The degree of reduction in strength is complex but is clearly related to the quality of installation and soil conditions (e.g., Sensitivity).

One approach to quantify the effect of installation disturbance is to consider the available undrained shear strength, i.e., what percentage of the undisturbed shear strength is still available for developing load capacity after installation? Logically, as the Installation Disturbance Factor increases, the soil becomes more disturbed and less strength is available. A simple conceptual framework was presented by Lutenecker et al.⁷

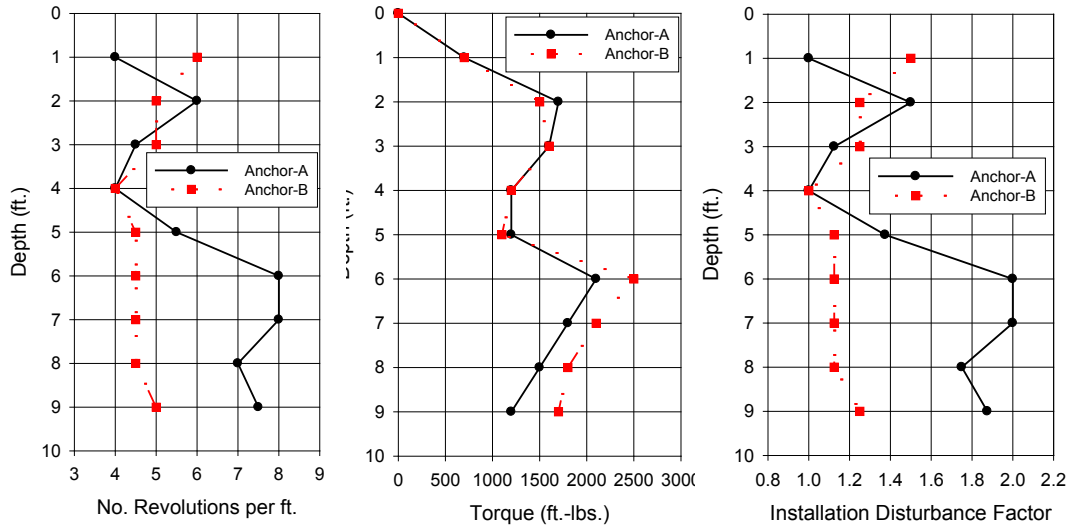


Figure 10: Advance, torque and installation disturbance factors for two round-shaft anchors.

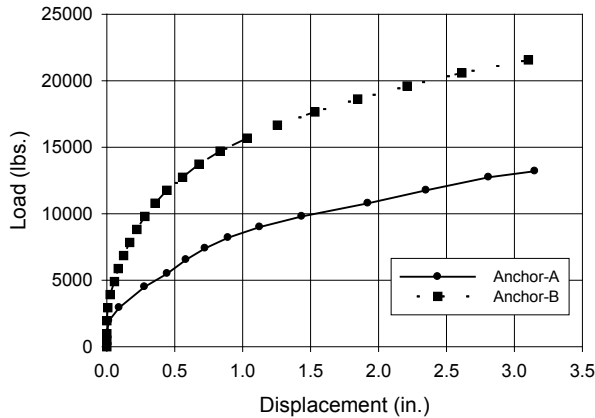


Figure 11: Comparison of load-displacement behavior of two round-shaft anchors.

Torque to Capacity Ratio

For over 40 years it has been suggested empirically that the ultimate load capacity, Q_{ult} , is related to the installation torque, T , more or less independent of loading direction, soil type, helical size and number and shaft size and shape. The installation torque is often used to estimate load capacity based on the assumption that a relationship exists between installation torque and load capacity. In fact, the relationship between Q_{ult} and T is a complex one and not easily evaluated, except by careful field installation monitoring and careful load testing.

The basic premise behind correlations relating installation torque to ultimate capacity is that both Q_{ult} and T are a function of the specific geometry of the pile/anchor and soil properties, i.e., soil strength. Therefore, a logical and reasonable conclusion is that we expect a relationship between ultimate capacity and installation torque; i.e.:

$$Q_{ult} = TK_t \quad (3)$$

Unfortunately, both the installation torque and the ultimate load capacity may be influenced by a number of factors that are not generally accounted for in the simple form of Eq. 3 making any correlation between torque and capacity tenuous. K_t is not a constant but varies with a number of factors. It is somewhat naïve to think that a single parameter model

works effectively for all configurations and soils.

For example, there is still some confusion about defining the ultimate capacity from a field load test. Suggested methods of interpretation vary widely, e.g., Davisson, Fuller-Hoy; Brinch Hansen; Chin; Kulhawy L₁-L₂, etc. In some cases however, there is a lack of detailed site characterization information so that even high quality field load tests are difficult to evaluate in terms of soil characteristics. In order to accurately compare measured behavior to predicted behavior or to validate design methods and /or K_t . Lutenecker⁸ listed a summary of factors that might influence the correlation between Q_{ult} and T into two broad categories: 1) factors influencing the field measurement of installation torque; and 2) factors influencing the determination of ultimate load capacity.

However, many of the reported comparisons between installation torque and capacity show wide variations. For example, Hoyt & Clemence⁹ compared results of a large number of field tension load tests in different soils using assumed values of K_t which were applicable at that time. The accuracy between observed and calculated values (ratio of measured to computed capacity) ranged from about 0.3 to 4.5, suggesting considerable scatter in the accuracy of any individual value of K_t .

Lutenecker⁷ showed that a simple model of the undrained behavior of plain pipe piles (i.e., with no helical plate) in compression in clay shows that the value of K_t decreases as the pipe diameter increases as:

$$K_t = 2/D \quad (4)$$

where: K_t = Torque-to-Capacity factor (ft^{-1}); D = pipe shaft diameter (ft.)

This relationship is shown in Figure 12. Several studies have shown a similar trend for round shaft helical piles.^{10,11,12,13} Adding one or two helices to a pile/anchor does not significantly affect this trend.

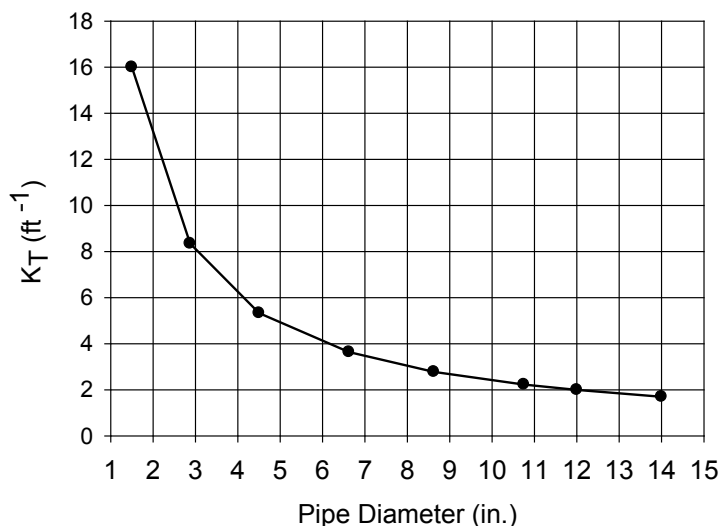


Figure 12: Theoretical variation in K_t with pipe shaft diameter for plain pipe piles.

An example of how a single factor may influence the measurement of torque can be illustrated by using some tests recently performed by the Author. Helical anchors with a single 12 in. dia. helical plate attached to a 2.875 dia. central shaft were fabricated with a helical pitch of 3, 4 and 6 in. The anchors were installed at a site consisting of 5 m (15 ft.) of sand overlying

clay. Figure 13 shows the installation torque and IDF for these three anchors. Load tests showed essentially the same ultimate load capacity for all three anchors in the sand (at 10 ft.) and the clay (at 20 ft.) giving different K_t factors for each of the anchors.

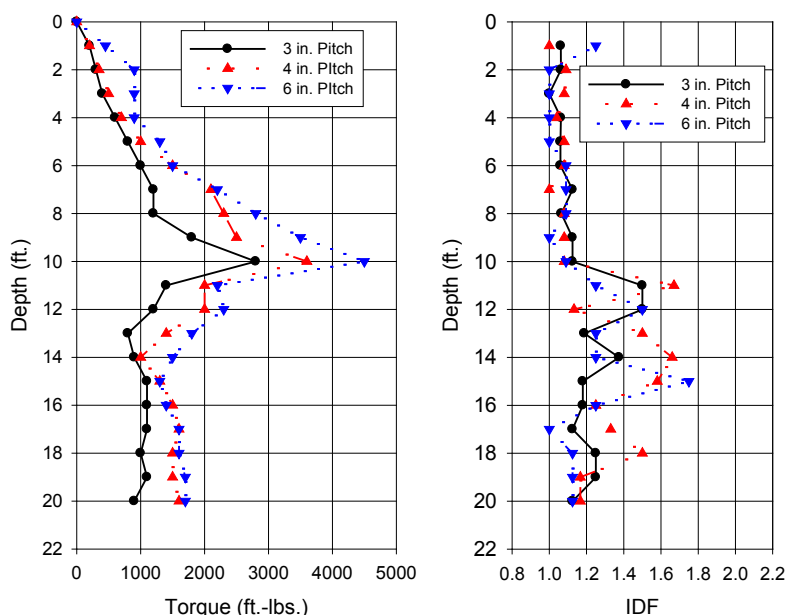


Figure 13: Installation torque and IDF for single-helix round-shaft anchor with pitch of 3, 4 and 6 in.

PART- II – Areas Needing More Work – “What We Don’t Know”

Even though our current understanding is good, there are still some areas that need additional attention and that may have significant impact on our understanding and application over the next decade.

Aging Effects

There have been essentially no detailed data reported on the influence of aging on behavior of screw piles and helical anchors. It is well known that setup and aging occurs when driven piles are installed in both clays and sands. Very little is known on the aging effects on screw piles and helical piles. A delay time in load testing may influence the interpretation of ultimate load capacity and aging may influence the value of K_t , since T is measured during installation.

Recent tests conducted by the author on a series of single-helix round-shaft anchors in stiff (L.I. = 0.4) and soft (L.I. = 1.0) clay are shown in Figure 14. These results represent fresh tests performed on individual adjacent anchors. Figure 15 shows results from different tests performed in stiff and soft clay and suggest that there is little increase from aging in the soft clay but substantial aging in the stiffer clay. More tests are needed in clay and sand to help establish and isolate the aging of the shaft vs. aging of the helical plate(s).

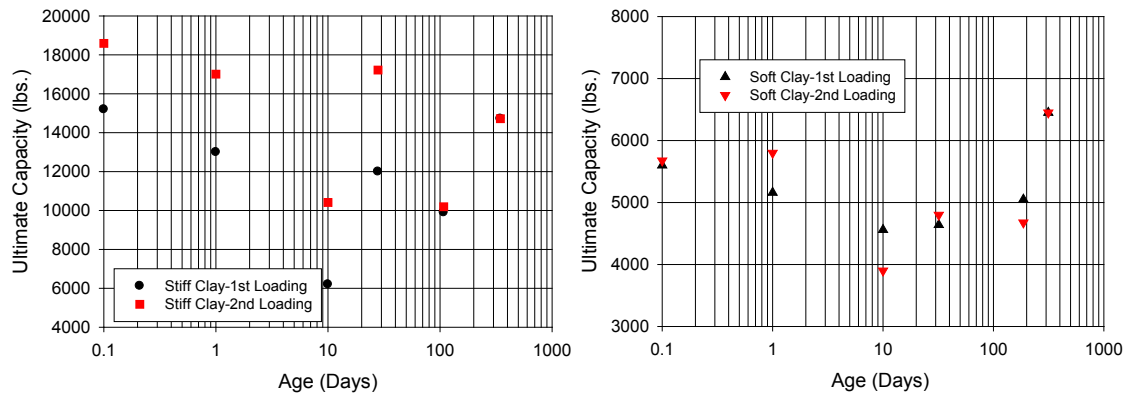


Figure 14: Influence of aging on load capacity in stiff and soft clay.

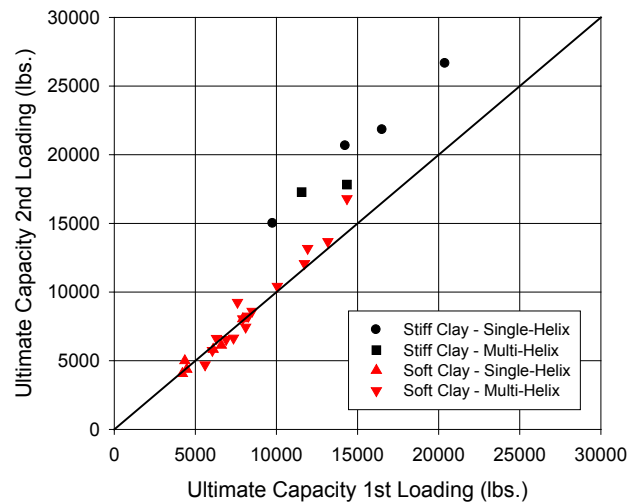


Figure 15: Influence of 180 day aging on load capacity in stiff and soft clay.

Loading Rate Effects

As with other types of deep foundations, the behavior of screw piles and helical anchors may depend on the rate of loading. This may be expected to be more important in clays than in sands. Figure 16 shows results obtained in clay from two helical anchors installed in a clay and loaded at different rates. Figure 17 shows results of axial tension tests conducted on a series of single-helix round shaft helical anchors installed in stiff and soft clay in terms of time to reach failure (load at displacement = 10% helix diameter). Different rates of loading were used for each anchor. The first series of tests were performed 8 days after installation. After testing the anchors were unloaded and allowed to rest for 180 days. Repeat tests were then performed on each anchor using the same loading rates. After the second series of tests had been performed, the anchors were advanced to a depth of 20 ft. into softer clay and the tests were repeated; i.e., an initial series of tests were performed 7 days after installation and then a repeat series of tests were performed after 180 days.

As far as the Author knows, there are no other similar results available in the literature. There is a need for additional field tests in other soils to determine the degree of influence of loading rate on pile/anchor behavior so that this can be taken into account in design.

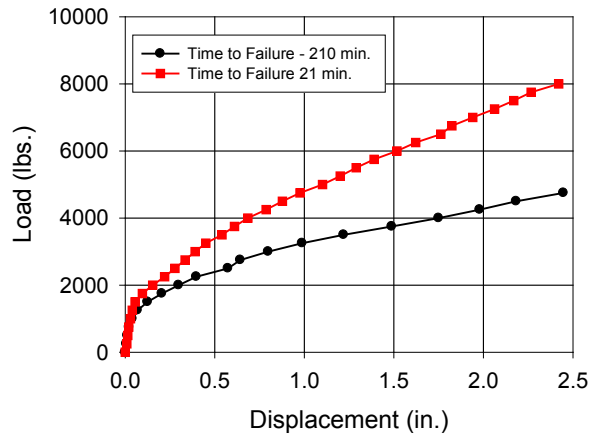


Figure 16: Influence of loading rate on behavior.

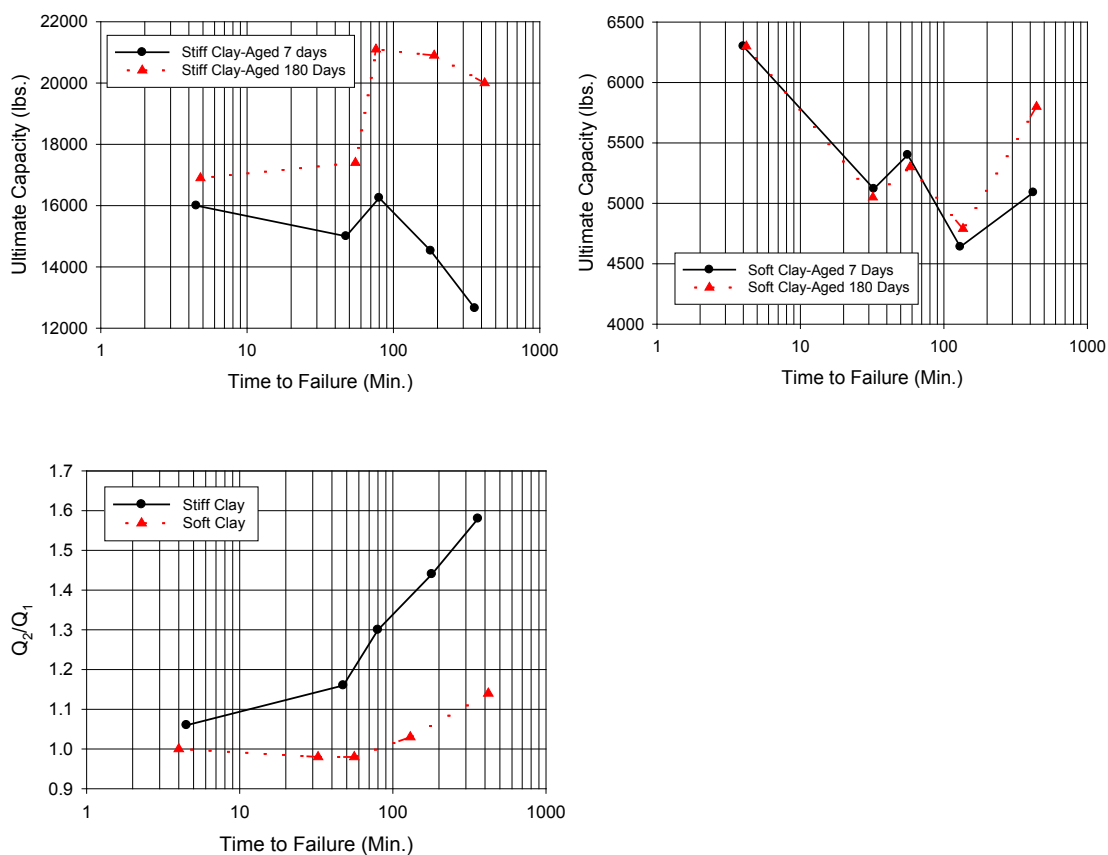


Figure 17: Influence of loading rate and aging on behavior.

Group Effects

There may be occasions in which a group of helical anchors may be considered as an alternative to a single anchor. There have been only a few studies investigating group behavior and the influence of anchor spacing on group behavior. Early tests reported by Radhakrishna^{14,15} for testing involving double-helix anchors in sand and clay. Lutenegger¹⁶ presented results of single-helix group anchors in stiff clay and soft clay with different anchor spacing as shown in Figure 18. Additional work is needed on group behavior of both single-helix and multi-helix piles/anchors in clay and sand.

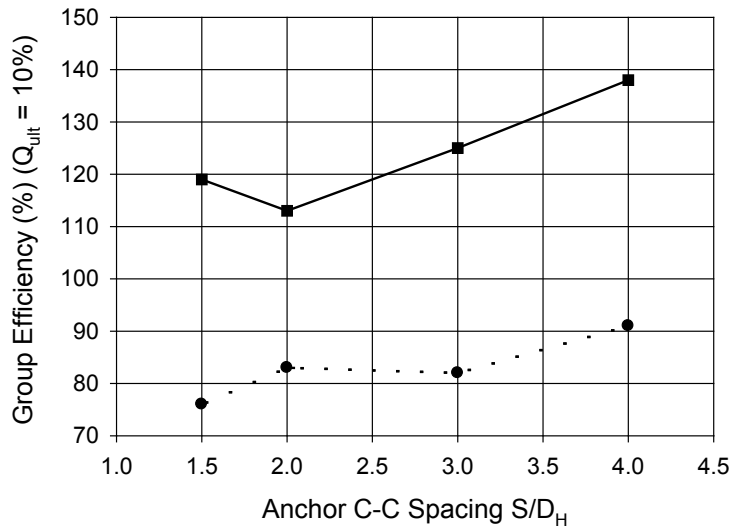


Figure 18: Group effects of single-helix anchors in stiff and soft clay.

Accounting for Installation Disturbance in Design

In 1950 Prof. A. Skempton¹⁷ presented a valuable discussion to the paper of Wilson¹⁸ on the behavior of screw piles in clays noting that for multi-helix screw-piles it was important to recognize that the clay beneath the upper screws had been partially remolded by the passage of the first screw and suggested that it might be reasonable to assume that the average shear strength of the clay between plates would be equal to:

$$c_{p2} = c - [1/2(c - c_r)] \quad (5)$$

where: c_{p2} = operational undrained shear strength; c = peak undrained shear strength; c_r = remolded undrained shear strength

This suggestion by Skempton shows the potential importance of evaluating Sensitivity of the clay, often not performed in routine site investigations. Additional field tests are needed in a range of soils to evaluate Skempton's approach.

Design in Sands

Many studies and published design manuals suggest a simple design model for screw piles and helical anchors in sand. The ultimate load capacity is often stated as:

$$Q_{ult} = A_H(q'N_q) \quad (6)$$

where: A_H = area of the helical plate; q' = effective overburden stress; N_q = deep foundation bearing capacity factor

This is similar to methods used for determining the end bearing of piles in sand but requires evaluating N_q using an interpreted friction angle that may be difficult to establish. As with driven piles in sands, other alternative design approaches to estimate load capacity, for example, using CPT results offer an attractive alternative. Additional field tests in well documented sands with tests on different size screw piles and helical anchors are needed to help define appropriate design parameters.

Long-Term Loading Under Sustained Load – Creep

There are no detailed published results of field tests on the creep behavior of screw piles and helical piles under long-term sustained loading. The creep behavior at different levels of applied load (as a percentage of the ultimate load) is not known. This appears to be another important area in which field tests in both sand and clay at well-characterized sites are needed.

Long-Term Slow Loading in Clays – Drained Behavior

Most available field test results of screw piles and helical anchors in clay represent quick load tests; generally interpreted as undrained behavior. The only field tests that the author is aware of in which tests were conducted very slowly in clay, over a period of several days, are those presented by Mooney et al.¹⁹ The drained behavior of screw piles and helical anchors in clays has not been investigated in any detail.

SUMMARY

What are the prospects for screw piles and helical anchors in the near future? Based on the Author's observations and conversations with engineers and researchers around the world the following areas are likely to drive short-term future trends:

1. There appears to be continued growth in use of large size pipes and helical plates for both compression and tension loading around the world, especially for support of bridges and other heavy structures.
2. As occurred in other areas of deep foundations, there are likely to be expanding development of digital automated and wireless installation monitoring equipment for logging of depth, torque, crowd, advance, and speed. The technology exists and is used in other areas; the demand from engineers must grow. In order to be attractive, it must be low cost and seamless so the installation is not disrupted and the equipment can be used on routine work.
3. There may be continued interest in high strain testing in lieu of traditional static load testing on some projects to provide economical design verification and to correlate with installation data. The equipment must be simple and low cost and limitations vs. advantages of high strain testing clearly understood by the Engineer.

Parametric and numerical studies are useful for rapid evaluation of individual variables that might influence behavior. The author is a strong proponent of full-scale field tests on real soil. Full scale does not imply large size, but includes all sizes of screw piles and helical anchors being used in the industry. Even though the cost can be considerable, the measured behavior is more reliable. Many published case histories lack even the most basic of information, for example, time between installation and testing or basic soil characterization. In order to be beneficial to the industry a case history of field behavior must have detailed site characterization.

REFERENCES

1. Lutenegger, A.J. Historical Development of Iron Screw-Pile Foundations: 1836 – 1900. *International Journal for the History of Engineering and Technology*, Vol. 81, No. 1, pp 108-128, 2011. Merifield, R.S. The Ultimate Uplift Capacity of Multi-Plate Helical Type

- Anchors in Clay. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 137, No 7, pp 704-716, 2011.
2. Lutenecker, A.J. Cylindrical Shear or Plate Bearing? – Uplift Behavior of Multi-Helix Screw Anchors in Clay. *Contemporary Issues in Deep Foundations*, ASCE, pp 456-463, 2009.
3. Clemence, S.P., Crouch, L.K., and Stephenson, R.W., Prediction of Uplift Capacity for Helical Anchors in Sand. *Proceedings of the 2nd Geotechnical Engineering Conference*, Cairo, pp 332-343, 1994.
4. Lutenecker, A.J., Behavior of Multi-Helix Screw Anchors in Sand. *Proceedings of the 14th Pan-American Conference on Geotechnical Engineering*, 6 pp, 2011.
5. Tsuha, C.H.C., Aoki, N., Rault, G., Thorel, L. and Garnier, J., Evaluation of the Efficiencies of Helical Anchor Plates in Sand by Centrifuge Model Tests. *Canadian Geotechnical Journal*, Vol. 49, pp. 1102-1114, 2012.
6. Lutenecker, A.J., Erikson J., and Williams, N., Evaluating Installation Disturbance of Helical Anchors in Clay from Field Vane Tests. *Proceedings of the 39th Annual Deep Foundations Institute Annual Meeting*, 10 pp, 2014.
7. Lutenecker, A.J., Factors Affecting Torque Correlations of Screw-Piles and Helical Anchors. *Proceedings of the 1st International Symposium on Helical Foundations*, pp 211-224, 2013.
8. Hoyt, R.M. and Clemence, S.P., Uplift Capacity of Helical Anchors in Soil. *Proceedings of the 12th International Conference on Soil Mechanics and Foundation Engineering*, Vol. 2, pp 1019-1022, 1989.
9. Deardorff, D. A., Torque Correlation Factors for Round Shaft Helical Piles. *Proceedings of the 32nd Deep Foundations Institute Annual Conference*, 20 pp, 2007.
10. Sakr, M., Relationship Between Installation Torque and Axial Capacities of Helical Piles in Cohesionless Soils. *Journal of the Performance of Constructed Facilities*, ASCE, Vol. 29, No. 6, 2015.
11. Padros, G., Dinh, B.L., Li, B. and Schmidt, R., Predicted and Measured Compressive Capacity and Torque of Large Helix Diameter Screw Piles in Stiff and Very Stiff Cohesive Soils. *Proceedings of GeoManitoba*, 6 pp, 2012.
12. Harnish, J. and El Naggar, M., Large-Diameter Helical Capacity – Torque Correlations. *Canadian Geotechnical Journal*, Vol. 54, pp 968-986, 2017.
13. Radhakrishna, H.S., Helix Anchor Tests in Stiff Fissured Clay. *Ontario Hydro Research Division Research Report 75-123-H*, 34 pp, 1975.
14. Radhakrishna, H.S., Helix Anchor Tests in Sand. *Ontario Hydro Research Division Research Report 76-130-K*, 33 pp, 1976.
15. Lutenecker, A.J., Axial Uplift of Square-Shaft Single-Helix Helical Anchor Groups in Clay, *Proceedings IFCEE 2018*, Orlando, Florida, 2018.
16. Skempton, A.W., discussion of The Bearing Capacity of Screw Piles and Screwcrete Cylinders. *Journal of the Institution of Civil Engineers – London*, Vol. 34, No. 5, pp 374-386, 1950.
17. Wilson, G., 1950. The Bearing Capacity of Screw Piles and Screwcrete Cylinders. *Journal of the Institution of Civil Engineers – London*, Vol. 34, No. 5, pp. 4-73.
18. Mooney, J.S., Adamczak, S.Jr., and Clemence, S.P., Uplift Capacity of Helix Anchors in Clay and Silt. *Uplift Behavior of Anchor Foundations in Soil*, ASCE, pp 48-72, 1985.

MAIN FINDINGS FROM FIELD STUDIES ON SCREW PILES IN BRAZIL

C H C TSUHA

Department of Geotechnical Engineering, University of São Paulo, São Carlos, Brazil

SUMMARY: The purpose of this presentation is to provide a quick overview of the main findings on the performance of screw piles obtained from field investigations, carried out by researches of the University of São Paulo, and from observations made during the fieldwork of a large number of transmission line towers in Brazil during the last ten years.

The behaviour of screw piles started to be studied in a doctoral thesis at the University of Sao Paulo in 2004, due to the need of a better understanding of this new type of foundation in Brazil, which began to be used at this time to support power transmission line and telecommunication towers. A few years later, the use of screw piles increased significantly for this type of application. This occurred because this type of foundation offers several advantages for the construction of extensive and numerous transmission lines in Brazil, as follows: resist compressive and tensile loads; is easily transported to remote sites, can be installed at a batter angle (case of guy wire anchors); rapid installation with small equipment; eliminate concrete and formwork; the pile capacity is correlated to the final installation torque; etc.

The transmission lines in Brazil are usually very extensive, since the centers of power consumption are often far from the most hydroelectric plants. As consequence, the construction and maintenance of transmission lines is abundant in this country. Therefore, in the face of a significant increase in the use of this non-conventional type of foundation, the power transmission industry required more studies on this subject. For this reason, with the support of the industry, a series of new researches on this subject were carried out after 2010 at the Department of Geotechnical Engineering at the University the Sao Paulo.

To complement and assist in elucidating the pile foundation responses observed in field tests, physical modelling investigations were carried out at the IFSTTAR centrifuge in France in a cooperation with University of Sao Paulo. Therefore, the combination of field investigations and reduced models tests under controlled conditions contributed to clarify different questions of screw piles design over the last years.

Some different aspects investigated by masters and doctoral students at the University the Sao Paulo, and observed from several fieldwork that will be showed in the presentation are: installation forces, torque-capacity correlations, effect of the number of helices on the pile performance, effects of installation on pile capacity, uplift capacity x compression capacity, load-displacement response, opened x closed-ended piles, axial cyclic loading, screw piles improved with cement injection, corrosion, etc. The findings presented are useful for practitioners and academics interested in screw piles.

The existing results to the present time and also some new issues observed in the field indicate that there are still other aspects of screw pile foundations to be investigated. Therefore, the new research projects that are developed at the University the Sao Paulo, due to the demand of the practical application, will quickly be described at the end of the presentation.

PHYSICAL MODELLING OF SCREW PILES FOR OFFSHORE WIND ENERGY FOUNDATIONS

C DAVIDSON, M J BROWN, A J BRENNAN, J A KNAPPETT,
B CERFONTAINE, Y U SHARIF

Civil Engineering, School of Science and Engineering, University of Dundee, Dundee, DD1 4HN, Scotland, UK

SUMMARY: Using existing design methodologies, a series of screw piles were designed to meet the loads required for an upper-bound design scenario of a steel jacket supported offshore wind turbine in deep water. The installation torque and force were measured from centrifuge tests of 1/80th scale models of the screw piles in very dense sand. Results indicate that the installation requirements are significant and may be beyond the capabilities of existing conventional installation equipment. Optimisation of the screw pile design was successful in reducing the installation force and torque by 34 and 17% respectively over the non-optimised design variant. Accurate prediction of the installation torque is critical and can be achieved using correlations with cone penetration test data.

Keywords: centrifuge, installation force, installation torque, screw piles.

INTRODUCTION

Screw piles, which have been in use for over 180 years¹, offer a number of advantages as foundations in numerous applications such as, for light poles, underpinning of structures, and anchors for guy lines. These advantages include: superior axial capacity, being extractable and reusable, and minimal noise and vibration during installation. The piles are installed by combining rotatory and axial forces typically supplied by a drive unit attached to small plant machinery which screw the pile into the soil. These advantages have led many to suggest the application of screw piles in the marine environment where recent concern has led to the introduction of restrictions regarding operational noise during installation of foundations². As the offshore energy sector continues to expand, especially with the rapid growth of offshore wind farms, the loads acting on foundations are increasing as structures become larger, taller and move into progressively deeper water. Such progress leads to greater costs resulting from noise mitigation of the dynamic installation of conventional straight-shafted piles and monopile foundations which are becoming ever larger and require more energy to install. Thus, an innovative solution is required, prompting research into the installation and performance of screw piles suitable for the loading conditions encountered offshore.

DEVELOPMENT OF PHYSICAL MODELLING OF SCREW PILES AT UOD

Physical modelling of screw piles at the University of Dundee (UoD) has been ongoing since 2007, when research began in to cast-in-situ screw piles with 1g physical experiments³. Further 1g tests investigated the influence of changing the helix spacing to shaft diameter ratio on the

failure mechanism generated during axial loading of multi-helix piles⁴. Results from this study are in agreement with observations from full scale tests. 1g modelling effects (e.g. dilation of sand at low vertical effective stresses) led to the development of equipment to perform tests of model screw piles in the geotechnical centrifuge at the University of Dundee. Al-Baghdadi developed a dual-axis actuator capable of installing and axially loading screw piles in one continuous flight of the centrifuge⁵. Creating a stress field representative of prototype conditions at all stages of a screw pile test is important, as installation of the screw pile at 1g does not effectively model soil displacement and resulting changes in stress, which are critically important factors in the performance of the pile under axial loads.

Further development and refinement of the testing equipment (or screw pile rig) is ongoing and includes some notable alterations⁶. The presence of instrumentation in a system which includes rotary motion leads to difficulties concerning the routing of wiring, which in this case included the cable for the combined torque transducer and loadcell used to measure the installation requirements and axial capacity of the test piles. Clearly a wireless system offers an elegant solution for the data acquisition, but since the use of batteries to supply the power is precluded in the centrifuge, this solution was not attainable. Therefore, the initial solution was to simply allow the cable to wind itself onto the loadcell as it rotated⁵. This was difficult to control in the high-g environment and thus an 8 channel slipring was added to the system, above the loadcell. This solution has since been refined further by incorporating a 24 channel slipring inside the shaft supporting the loadcell which has the added benefits of increasing the maximum length of screw pile which can be tested, reducing the bending moments acting on the system, and allowing for instrumentation of the test piles⁶.

The screw pile rig in its various forms has been used to complete a multitude of tests of various screw pile designs in sand. These tests have focussed on the installation requirements and behaviour of large scale screw piles in an effort to develop designs suitable for use in the offshore energy sector.

SCREW PILES DESIGNS

Al-Baghdadi⁷ tested a series of screw piles which were not specifically intended to generate particular axial capacities, but were used to systematically investigate the behaviour and trends associated with altering certain geometric aspects such as the number of helices and their diameter in varying relative densities of sand.

Following on from this work, the Author, has conducted an experimental programme of centrifuge tests of screw piles designed to sustain the expected loads acting on the foundation of a jacket supported Offshore Wind Turbine (OWT). Given that screw piles are not a current foundation solution offshore, a worst-case design approach was used to determine an upper-bound approximation of the expected magnitude of imposed foundation loads, the resulting necessary screw pile design and its installation requirements. Steel jackets are expected to be used to support OWTs in intermediate water depths between 40m, below which monopile foundations currently dominate, and 80m, above which floating structures are likely to be deployed. Currently, the deepest water in which a jacket supported OWT is situated, is 56m at the Beatrice Offshore Wind Farm, Scotland⁸. To estimate the loads acting on a single pile at each corner of a four-legged steel jacket, supporting an 8MW OWT in 80m water depth, calculations were made to determine the self-weight and environmental loads using methods prescribed by the DNV⁹ with the parameters reported in Davidson et al.⁶. The calculated loads from this procedure shown in Table 1 are significant and include a factor of safety of 1.35 as used by an industrial project partner in their commercial design work for the offshore energy sector. Storm level wind and wave conditions were used in-line with the worst-case approach

to the design scenario.

Table 1. Loads acting on screw pile (negative value indicates tensile load)

Load Direction	Upwind	Downwind
Horizontal (MN)	6.28	6.28
Vertical (MN)	-26.14	34.85

Table 2. HST95 sand material properties¹⁰.

Property	Value
Grading description	Fine
Effective particle size, D_{10} (mm)	0.09
Average particle size, D_{50} (mm)	0.14
Critical state friction angle, ϕ'_{crit} (°)	32
Typical interface friction angle, δ'_{crit} (°)	24
Angle of dilation*, ψ (°)	16
Maximum dry density, ρ_{max} (kN/m ³)	17.58
Minimum dry density, ρ_{min} (kN/m ³)	14.59

* As measured at 80% relative density¹⁰.

Using available published screw pile design methods, three initial screw piles were designed which satisfied the design loads in terms of lateral and axial loading for a foundation in homogenous very-dense sand (see Table 2 for properties of the HST95 sand). An iterative design approach was necessary since for example, increasing the shaft diameter to accommodate the lateral load leads to higher installation torque, which in turn requires a minimum wall thickness and diameter of the shaft to resist the torque, which has an effect on the lateral, axial and structural capacities of the pile.

The following sources were used to calculate the appropriate capacities: tensile resistance from the multi-helix method in Das and Shukla¹¹; Perko¹² for compressive capacity; analytical methods in Fleming et al.¹³ for the lateral capacity, with no contributions from the helices considered; installation torque from Al-Baghdadi et al.¹⁴. This design process highlighted that the tensile capacity was a critical component of the screw pile design, requiring the uppermost helix to be located as deeply as possible to generate sufficient resistance. Consequentially, the predicted compressive capacity was above the design requirement. This led to an effort to optimise the design for all aspects, resulting in the screw pile shown in *Figure 1* which has a partially reduced shaft diameter and a lower helix with a smaller diameter than the upper helix. The lateral capacity of the pile is the main factor in determining the diameter of the upper section of the shaft of the pile. Thus, below the depth at which no further lateral resistance is generated, the shaft diameter can be reduced to a minimum diameter and wall thickness which still satisfies the structural requirements of the pile. This optimised design was predicted to meet the required axial and lateral loads while also offering a reduction in the volume of material and of the installation torque when compared to the initial non-optimised double-helix design of *Figure 1*.

From the design process and the need to embed the uppermost helix as deep as possible, it was also noted that a single-helix design could offer the best solution by meeting the design loads and reducing installation requirements. All three screw pile designs and their geometry are given in *Figure 1* and Table 3.

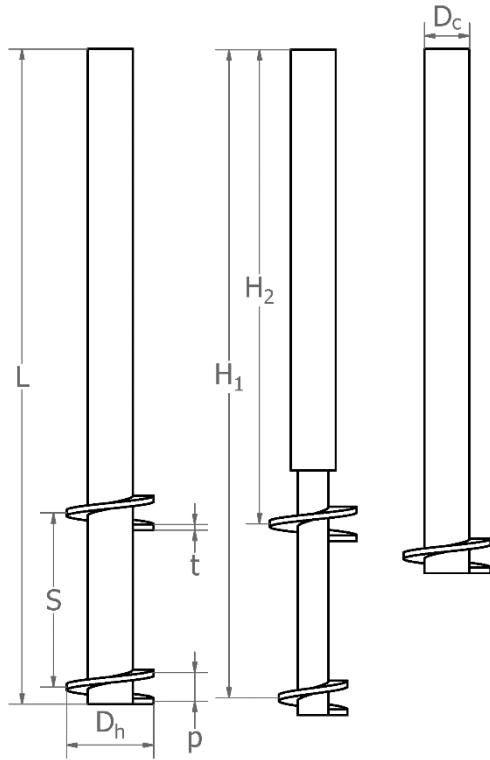


Figure 1. Screw pile designs used in centrifuge tests. Left: uniform double-helix, middle: optimised double-helix, right: uniform single helix. See Table 3 for description of symbols and dimensions.

Table 3. Screw pile dimensions in metres at prototype scale (mm at model scale of 1/80th).

Parameter		Uniform double-helix	Optimized double-helix	Uniform single-helix
Length, L		13 (162.5)		10.24 (128)
Core diameter, D_c	Upper	0.88 (11)		0.88 (11)
	Lower	0.88 (11)	0.60 (7.5)	0.88 (11)
Helix diameter, D_h	Upper	1.70 (21.25)		1.70 (21.25)
	Lower	1.70 (21.25)	1.34 (16.75)	
Pitch, p	Upper	0.56 (7)	0.56 (7.5)	0.56 (7.5)
	Lower			
Thickness, t	Upper	0.11 (1.4)	0.11 (1.4)	0.11 (1.4)
	Lower			
Helix spacing ratio, S/D_h		2	2	-
Helix depth, H	Upper (H_2)	9.06 (113.25)	9.06 (113.25)	-
	Lower (H_1)	12.46 (155.75)	12.46 (155.75)	9.91 (123.88)

EXPERIMENT SETUP AND TEST PROGRAMME

The screw pile rig was designed to be operated at 50g in the centrifuge, but operating with a scaling factor of 50 was not possible as this would have led to larger model piles and unsuitable boundary conditions. However, it is possible to conduct the centrifuge tests in a total stress environment and scale accordingly to match the saturated effective stress conditions¹⁵ of the geometry of the screw piles presented above. Thus, a scaling factor of approximately 1/80th is possible while operating the centrifuge at 50g, allowing for smaller piles and maintaining suitable separation from the boundaries of the model container as shown in Figure 2. Conducting the tests with dry sand also speeds up the testing, allowing for more tests in a shorter timescale.

The model screw piles were manufactured at the University of Dundee by machining the single piece screw piles from a larger diameter solid piece of EN1A steel. This process created

a solid shafted pile with precise dimensions. The solid shaft again represents worst-case conditions of a plugged shaft and the flat tip style was envisaged to be the easiest to manufacture for full scale screw piles.

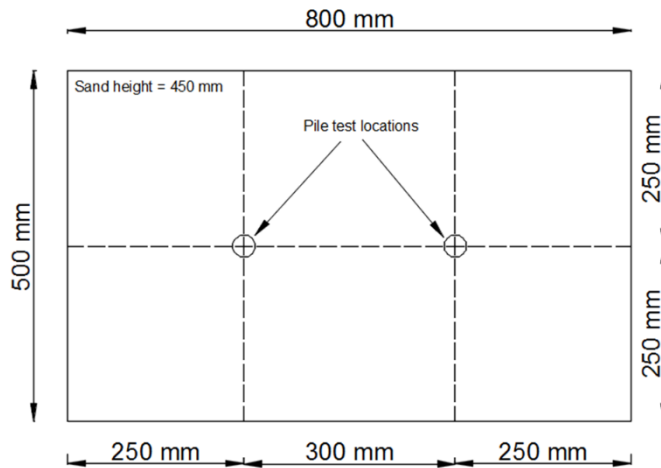


Figure 2. Plan locations of the centrifuge pile tests in the sand container.

The soil container used in all tests, filled with a homogenous dry HST95 sand bed 430mm deep at 84% relative density, allowed for two tests to be completed in each sand bed. The centrifuge was stopped and the box turned around between tests. Continuous measurement of the force, torque and displacement was made during the investigation of the installation requirements of all three piles, which were installed at 21mm/min and 3RPM, giving a perfectly pitch matched installation as recommended by Perko¹². A Cone Penetration Test (CPT) was also performed in a different flight of the centrifuge, in sand prepared to the same relative density to gather cone resistance (q_c) data¹⁶.

RESULTS AND DISCUSSION

The measured installation torque and force for the three pile designs are shown at prototype scale in Figure 3. The observed values of installation torque and force are significant, with a maximum of 7.5 MNm and 20.2 MN respectively. To contextualise these values, a large onshore screw piling system utilising a torque head mounted on an excavator is only capable of generating a vertical force of 257 kN and torque of 250 kNm. More powerful equipment is available in the form of track mounted, hydraulic powered casing rotators, which after some modification to allow their use for installing screw piles, can generate up to 5 MNm of torque and 1.2 MN of force. It is unclear if this system could be adopted in the deep water offshore environment. It is apparent from the results that the optimisation of the screw pile design was successful in reducing both the installation torque and crowd, with reductions of 17% and 34% respectively over the uniform, non-optimised design which is in line with results reported by Morais and Tsuha¹⁷ between their piles with uniform and partially reduced shaft diameters. Furthermore, optimization of the screw pile design reduced the surface area and volume of the screw pile by 11 % and 18 % respectively, which could present a substantial saving of material and costs across a large array of turbines, while still achieving the in-service structural and performance requirements. The additional torque and force required to install the second helix of the uniform double-helix design is apparent in Figure 3 when compared to the values for the single-helix design.

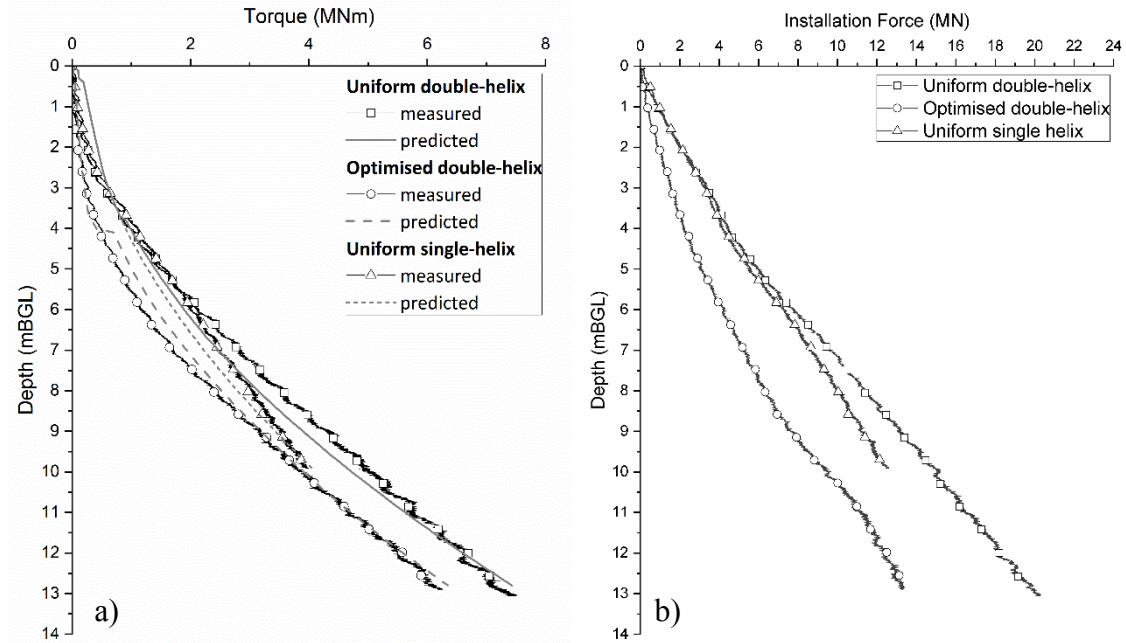


Figure 3. a) Measured and predicted installation torque and b) measured installation force from centrifuge tests at prototype scale.

The magnitude of the installation force for these screw pile designs in relation to the available vertical force from the relevant installation equipment is significant and methods of reducing these requirements should be investigated. Current understanding of the force needed to install a particular screw pile is lacking, with only one single design method available¹⁸. Furthermore, it is uncommon in the onshore screw pile industry to measure the installation force, although for torque prediction and quality control the author considers that this should be routine. A robust method for predicting the installation force is necessary and should consider all aspects of the screw pile geometry and soil properties.

Data from the tests was also used to refine previous work which had developed a CPT q_c based method to predict the installation torque of screw piles, by calculating the resistance on the pile shaft and tip and the lower surface, outer perimeter and leading edge of the helices¹⁴. The updated method includes modifications to the previous method such as, the removal of reduction factors applied to the base and shaft components, addition of an interface shear component to the tip and the use of the full value of q_c for the tip¹⁶. From Figure 3a it is evident that the revised method performs well in predicting the torque for the range of screw pile designs tested and may serve as an important design aid in the development of screw piles for the energy sector.

CONCLUSIONS

Structures in the offshore wind energy industry require large foundations to sustain the significant loads generated by the self-weight of the equipment and the harsh environmental conditions. Consequentially, screw piles, which have been suggested as a possible foundation solution, designed to sustain these loads require substantial torque and force during installation. Centrifuge tests of screw piles designed to support such large loads were conducted to measure the installation torque and force requirements. It was found that optimisation of the screw pile design through reduction of the diameter of lower part of the shaft and lowermost helix can yield a reduction in torque and force of 17% and 34% respectively. CPT based predictions of the installation torque of the screw piles in the centrifuge tests was demonstrated to be accurate and

reliable across screw piles with various designs.

The importance of the installation force was presented and it is recommended that further studies be conducted to investigate ways of reducing this and the installation torque levels to enable the development and use of screw piles for offshore wind energy.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of EPSRC (Grant no. EP/N006054/1: Supergen Wind Hub Grand Challenges Project: Screw piles for wind energy foundations) and the Iraqi Ministry of higher Education of Scientific Research (MOHESR). This project has also received support from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 753156. Elements of this work were undertaken using facilities developed as part of the ERDF-funded Scottish Marine & Renewables Test Centre (SMART) at the University of Dundee.

REFERENCES

1. Lutenecker AJ (2014). Historical development of iron screw-pile foundations: 1836–1900. *The International Journal for the History of Engineering & Technology*. 81(1):108–28.
2. Bruns B, Stein P, Kuhn C, Sychla H, Gattermann J. (2014). Hydro sound measurements during the installation of large diameter offshore piles using combinations of independent noise mitigation systems. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Melbourne, Australia: Institute of Noise Control Engineering.
3. Jeffrey J R, Brown M J, Knappett J A, Ball J, Caucis K. (2016) CHD pile performance: part I – physical modelling. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*. 169(5):421 – 35.
4. Knappett J A, Brown M J, Andrew J B, Hamilton L. (2014). Optimising the compressive behaviour of screw piles in sand for marine renewable energy applications. *DFI/EFFC 11th International Conference on Piling and Deep Foundations*. 21 – 23 May; Stockholm, Sweden: Deep Foundations Institute.
5. Al-Baghdadi T A, Brown M J, Knappett J A. (2016). Development of an inflight centrifuge screw pile installation and loading system. *3rd European Conference on Physical Modelling in Geotechnics (EUROFUGE 2016)*. 1 – 3 June; IFSTTAR Nantes Centre, France.
6. Davidson C, Al-Baghdadi T A, Brown M J, Brennan A J, Knappett J A, Augarde C, Coombs W, Wang L, Richards D, Blake A, Ball J. (2018) Centrifuge modelling of screw piles for offshore wind energy foundations. *9th International Conference on Physical Modelling in Geotechnics (ICPMG 2018)*. 17 – 20 July; City, University of London, London, UK: Taylor Francis Group.
7. Al-Baghdadi T A. (2018). *Screw piles as offshore foundations: Numerical & physical modelling*. [PhD]. Dundee, UK: University of Dundee.
8. Beatrice Offshore Wind Farm Ltd (2019). *Offshore construction complete 2019* [15th May 2019]. Available from: <https://www.beatricewind.com/single-post/2019/05/15/Offshore-construction-complete>.
9. DNV. (2007). Recommended Practice DNV-RP-C205: Environmental Conditions and Environmental Loads. Høvik, Norway: DNV.

10. Al-Defae A H H. (2013). *Seismic performance of pile-reinforced slopes*. [PhD]. Dundee, UK: University of Dundee.
11. Das B M, Shukla S K. (2013). *Earth anchors*. USA: J. Ross Publishing; 2013.
12. Perko H A. (2009). *Helical piles: a practical guide to design and installation*. Hoboken, USA: John Wiley & Sons.
13. Fleming K, Weltman A, Randolph M, Elson K. (2008). *Piling engineering*. 3rd ed. Abingdon, UK: Taylor and Francis.
14. Al-Baghdadi T A, Davidson C, Brown M J, Brennan A J, Knappett J A, Augarde C, Coombs W, Wang L, Richards D, Blake A. (2017). CPT-based design procedure for installation torque prediction for screw piles installed in sand. *Offshore Site Investigation and Geotechnics: Smarter Solutions for Future Offshore Developments: Proceedings of the 8th International Conference*. 12 – 14 September; London, UK. London, UK: Society for Underwater Technology.
15. Li Z, Haigh S K, Bolton M D. (2010). Centrifuge modelling of mono-pile under cyclic lateral loads. *7th International Conference on Physical Modelling in Geotechnics*. 28th June – 1st July; Zurich, Switzerland: CRC Press.
16. Davidson C, Al-Baghdadi T A, Brown M J, Brennan A J, Knappett J A, Augarde C, Coombs W, Wang L, Richards D, Blake A, Ball J. (2018). A modified CPT based installation torque prediction for large screw piles in sand. *4th International Symposium on Cone Penetration Testing (CPT'18)*. 21 – 22 June 2018; Delft, Netherlands. London, UK: CRC Press.
17. Morais T S O, Tsuha C H C. (2014). A New Experimental Procedure to Investigate the Torque Correlation Factor of Helical Anchors. *Electronic Journal of Geotechnical Engineering*. 19(P):3851-64.
18. Ghaly A, Hanna A. (1991). Experimental and theoretical studies on installation torque of screw anchors. *Canadian Geotechnical Journal*. 28(3):353 – 64.

A 3D MATERIAL POINT METHOD FOR GEOTECHNICAL ENGINEERING

L WANG, W M COOMBS, C E AUGARDE
Department of Engineering, Durham University, UK

SUMMARY: The Material Point Method (MPM) is a promising numerical method for simulation of large deformation problems in geotechnics. Software for 3D analysis using the MPM is under development at Durham University with applications in geotechnical engineering. This paper introduces some recent advances in this software for modelling the behaviour of screw piles for offshore wind turbine foundations as part of a larger EPSRC-funded research project in collaboration with the universities of Dundee and Southampton. This software has been validated using a model of a shear vane test and has also been used to compute torque and vertical force requirement for screw pile pull-out and rotation. In future, the software could be used to optimise the geometry of screw piles in different seabed conditions.

Keywords: accuracy, material point method, screw pile, 3D analysis

INTRODUCTION

Screw (or helical) piles are a promising foundation solution for offshore wind, in particular they could be deployed under each leg of jacket sub-structure (as shown in Figure.1 in intermediate water depths and form part of a geotechnical engineer's *toolkit* of foundation solutions for offshore wind energy systems¹⁻³. One benefit of using screw piles is their low noise during installation, reducing the impact on the ocean and subsea ecological environment. Compared to the hydraulic impact driving for installation of a monopile, as commonly used for an offshore wind turbine foundation, the installation of a screw pile is much quieter as they can simply be *screwed* into the seabed. Screw piles have been widely used in onshore geotechnical engineering projects, e.g. building foundations, motorway signs/gantries. However, to extend the use of screw piles to offshore engineering, where the nature and magnitude of the in-service loads are considerably more onerous compared to onshore applications, we need to optimise the geometry of the screw pile for minimising installation resistance and maximising in-service loading capacity. The research presented in this paper is linked to the EPSRC-funded project “Screw piles for wind energy foundation systems”, grant number EP/N006054/1, led by the University of Dundee. Key aims of the project are: (i) to improve our understanding of the mechanics for installation of a screw pile and (ii) to determine the installation torque and vertical force requirements of full-scale screw piles in different soil conditions. To facilitate achieving these aims, the research team

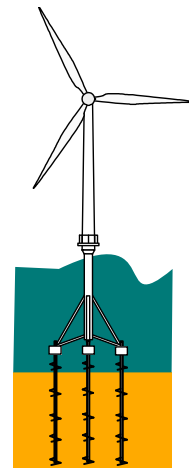


Figure 1:
Envisaged use of screw piles for offshore wind.

at Durham University have developed a novel numerical program to simulate the installation process.

The material point method (MPM) has been selected in this research because of its ability to model large deformation geotechnical engineering problems^{4,5}. The MPM uses a set of points to represent the physical domain and to track the deformation, while a background mesh is used to compute the mechanical relationship between points. As demonstrated by a simple shear problem in Figure 2 after each increment of deformation, Δu , the background grid is reset to its original deformed shape. This avoids issues associated with mesh distortion in conventional finite element analysis. However, the MPM method suffers from a number of issues, including: cell crossing instabilities, accuracy of integration and projection between material points and the background grid, volumetric locking⁶ amongst others.

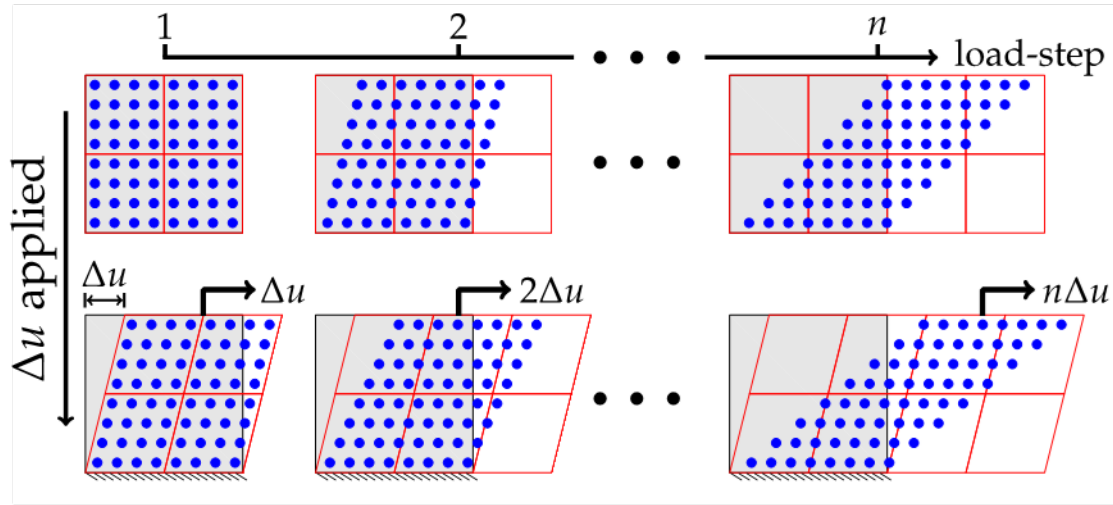


Figure 2: Demonstration of the original MPM via the simple shear problem

Over the duration of the EPSRC-funded research project, we have developed a number of novel strategies for improving the accuracy and efficiency of the MPM and have addressed a number of the above problems. However, our initial investigations using the latest MPM approaches to model rotational soil deformation around piles found that the original MPM predicts more physically realistic deformation (and torque requirements) than the latest advanced domain-based* approaches⁷. Therefore, the present MPM program is based on the original MPM. However, there are several challenges associated with using the original MPM to model screw pile installation, namely: (i) discretisation of the complex geometry of the soil around the screw pile and (ii) stress concentration next to the pile. Unlike most of the geotechnical MPM community who uses regular, or structured, background meshes (and also normally in 2D), we used a locally refined 3D tetrahedral mesh to solve these problems. However, using a tetrahedral mesh leads to additional problems: (iii) difficulty (in terms of computational cost) in locating material points in the background mesh, and (iv) volumetric locking, which affects accuracy of the simulation results. Our solutions to these two problems are detailed in⁸. In this paper, the MPM program with the strategies of [8] is referred to as *present MPM*, while without these strategies it is referred to as *standard MPM*. This paper presents the effect of the volumetric locking in two geotechnical examples, and discusses what we have learnt about mechanics for the installation of the screw pile from these simulations.

* The domain-based MPMs were introduced to overcome, or at least reduce, the issues associated with sudden transfer of stiffness and force as a material point crosses between background grid elements. However, the domains themselves are susceptible to distortion under certain deformation modes.

NUMERICAL EXAMPLES

This section presents some numerical examples using a large deformation elasto-plastic MPM formulation (see [9] for details of the large deformation framework). All of the analyses use a linear elastic, perfectly plastic constitutive model with a von Mises yield surface and associated plastic flow. The von Mises yield function can be expressed in the following form

$$f = \rho - \rho_y$$

where ρ_y is the yield strength of the material and $\rho = \sqrt{2J_2}$, $J_2 = s_{ij}s_{ij}/2$, $s_{ij} = \tau_{ij} - \tau_{kk}\delta_{ij}/3$. τ_{ij} is the Kirchhoff stress tensor and δ_{ij} is the Kronecker delta tensor.

Vane shear test

Prior to modelling a screw pile a simpler problem is used for validation. The shear vane test is a standard geotechnical test to obtain soil strength information. In the test, the vane, as shown in Figure 3, is pushed into the ground and rotated. The torque-rotation response can be used to define the soil strength with a simplified analytical relationship. In the simulation, we have cylindrical soil cut by the vane. The size of the vane is, radius $r_v = 0.05\text{m}$, height $4r_v$, and the thickness of the vane blade is $0.1r_v$. The radius of soil is $3r_v$ and its height is $8r_v$, while the height of the mesh is $9r_v$. The top of vane is coincident with the soil surface. The material parameters of the soil are shown in Table 1. The vane rotation is simulated by applying a rotational displacement boundary condition on the soil surfaces, next to the vane blade. At each step, an incremental rotation $\Delta\theta = 5 \times 10^{-5}\text{rad}$ is applied. A “moving mesh” strategy is employed such that the whole mesh is rotated with the vane. The torque computed in the simulation against rotation is plotted in Figure 3, and clearly shows that the present MPM, unlike the standard MPM, avoids volumetric locking.

Table 1. Material parameters

Young's modulus	Poisson's ratio	Yield strength
100 MPa	0.3	$\sqrt{3} \times 10^4 \text{ Pa}$

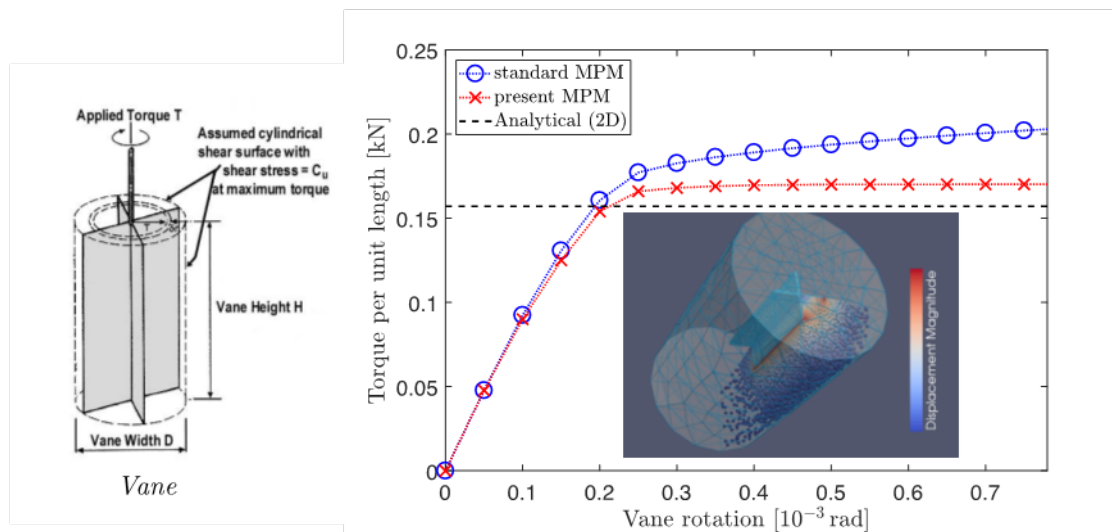


Figure 3: Vane shear test geometry and torque versus rotation response.

Screw pile

This section presents simulations for pull-out and rotation of a screw pile. In the simulations, the screw pile is placed in the cylinder of soil (rather than modelling the full installation process). The geometry, mesh and material points are shown in Figure 4. The physical domain is discretised into 220,368 linear tetrahedral elements with 39,980 nodes. The mesh is locally refined around the pile in order to accurately model the pile geometry and capture the resultant stress gradients around the pile as it is displaced. One material point per initially filled element is used. The material properties are shown in Table 1.

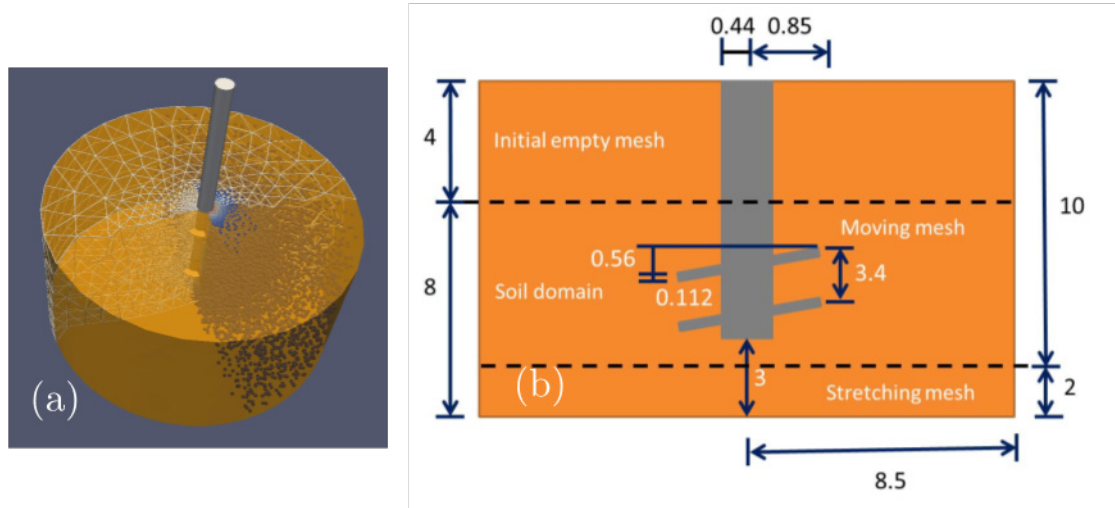


Figure 4: The geometry, partial mesh and partial material points in the simulations of a screw pile are shown in (a). Dimensions of the model (in meters) are shown in (b).

Pull out

The boundary conditions for the pull-out simulation include: fixed base, roller on the outer cylindrical surface and vertical displacement on the pile. Notably, a no-slip condition is assumed between the pile and the soil allowing the imposed vertical displacement boundary condition to be applied directly to the soil next to the pile.

As seen in the cross-section of the physical domain, Figure 4(b), the mesh is partitioned into different regions along the axis of the pile. As indicated by the dimensions on the left of the figure, the bottom part of height 8m contains soil, but the top part of height 4m is initially empty. As the pile is pulled up, some material points will move into elements in this empty mesh. The mesh is also partitioned to implement the moving mesh strategy. As indicated by the dimensions on the right of the figure, the lower 2m of the mesh will be stretched while the other part of mesh will rigidly translate with the pile. This moving mesh strategy guarantees that the background mesh around the pile will always coincide with the pile as it is pulled out of the soil body.

Some of the simulation results are shown in Figure 5. The axial normal component of stress in (c) with the present MPM is smoother than that with the standard MPM in (b). This shows the advantage of the present MPM in reducing stress oscillations. The stress distribution in (c) shows that the soil above the helices is compressed and that below is stretched. The axial force on the pile plotted against the displacement in (d) shows that the standard MPM predicts an erroneous increase in force due to volumetric locking while the present MPM gives a more physically reasonable response.

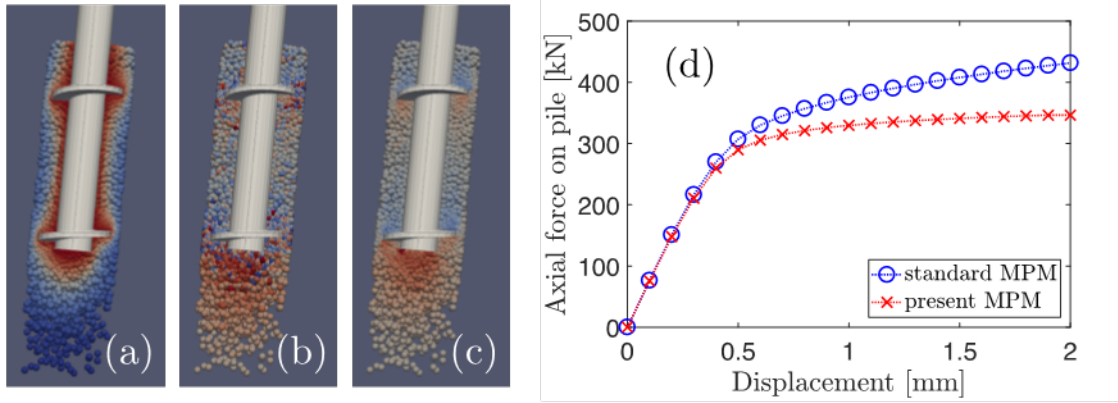


Figure 5: Pile pull-out: (a) axial displacement, (b)&(c) axial normal component of the Cauchy stress with the standard MPM and present MPM, respectively, and (d) axial force versus displacement.

Rotation

The boundary conditions for the rotation simulation are: fixed base, roller on the outer cylindrical surface and rotational displacement on the pile. The moving mesh strategy is that the background mesh rotates with the pile such that the geometry of the pile is maintained throughout the analysis.

Some of the simulation results are shown in Figure 6. Consistent with the rotational boundary condition, the displacement magnitude reaches a maximum at the edge of helices, as shown in (a). The numerical analysis allows us to understand the stress state in the soil around the helices, for example the shear component σ_{xz} of the stress in (b) has negative value below helices on the left and positive value on the right. Figure 6(c) shows the shear stress distribution linking the radial and circumferential coordinates, $\sigma_{r\theta}$. This figure allows us to observe a clear failure line between part of the soil body that rotates rigidly with the pile and the rest of the domain (also seen in (a)). The failure zone is close to the edge of the helices and then narrows to a minimum distance from the pile approximately halfway between the two flights. The torque versus rotation behaviour in Figure 6(d) shows that the transient part of the response is very short with the pile quickly reaching a steady state after yield.

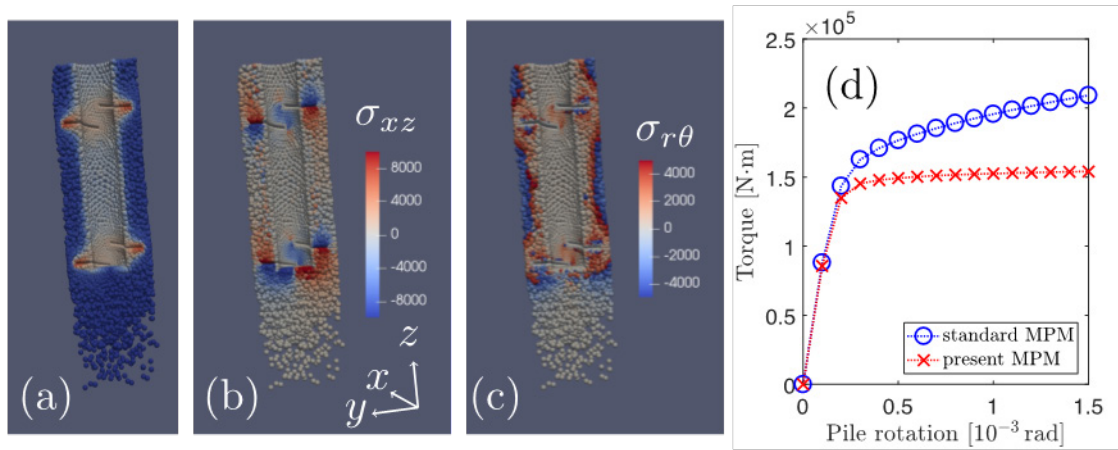


Figure 6: Pile rotation: (a) magnitude of the displacement, (b) shear component of the Cauchy stress, (c) radial-circumferential shear Cauchy stress, (d) torque against the pile rotation.

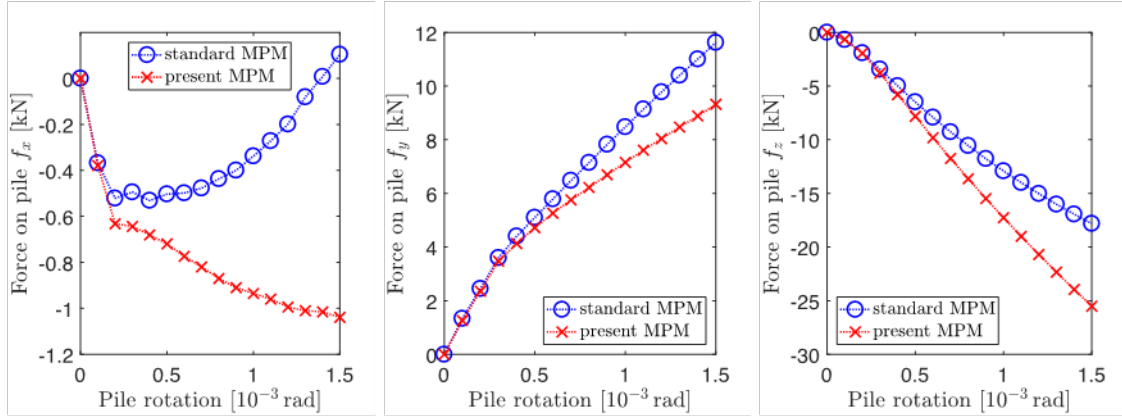


Figure 7: Pile rotation: Cartesian force components.

The force on the pile shown in Figure 7 shows that the magnitude of f_z is larger than the other components. This force provides part of the driving force on the pile penetration into the soil. The force in y direction is also not small because the end of helices are on the plane with normal direction of y-axis. The force in x direction is the smallest. It is interesting to see that, after yield, the force change in x direction changes slope in different ways from the prediction of two methods.

REMARKS

The purpose of this paper is to showcase a very small part of the research at Durham which is developing the Material Point Method for the analysis of challenging geotechnical problems. Here we have shown some of the work undertaken as part of a wider research project on screw piles, led by Dundee University. Given the audience, we have presented only brief details of the numerical techniques, followed by a validation example and some simple modelling of a screw pile. To a practitioner, the screw pile model may appear crude and the simulations somewhat limited in scope, however, the modelling undertaken here is a step on the way to modelling of screw pile installation, capturing the changes induced in the soil state, something beyond the scope of any standard finite element method. Development of reliable complex computational modelling methods requires careful validation and checking at each stage.

ACKNOWLEDGEMENTS

We are grateful for the support by the UK Engineering and Physical Sciences Research Council grant No. EP/N006054/1.

REFERENCES

1. Byrne B W and Houlsby G T. Helical piles: an innovative foundation design option for offshore wind turbines. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 373(2035):20140081, 2015.
2. Al-Baghdadi T A, Brown M J, and Knappett J A. Development of an inflight centrifuge screw pile installation and loading system. In *Proceedings of 3rd European Conference*

- on *Physical Modelling in Geotechnics (Eurofuge 2016)*, pages 239--244. IFSTARR, Nantes, France, 2016.
3. Al-Baghdadi T A. *Screw piles as offshore foundations: Numerical and physical modelling*. PhD thesis, University of Dundee, 2018.
 4. Ceccato F, Beuth L, Vermeer P A, and Simonini P. Two-phase material point method applied to the study of cone penetration. *Computers and Geotechnics*, 80:440--452, 2016.
 5. Andersen S and Andersen L. Modelling of landslides with the material-point method. *Computational Geosciences*, 14(1):137--147, 2010.
 6. Coombs W M, Charlton T J, Cortis M, and Augarde C E. Overcoming volumetric locking in material point methods. *Computer Methods in Applied Mechanics and Engineering*, 333:1-21, 2018.
 7. Wang L, Coombs W M, Augarde C E, Brown M J, Knappett J A, Brennan A, Davidson C, Richards D, and Blake A. On the use of the material point method to model problems involving large rotational deformation. *6th European Conference on Computational Mechanics and 7th European Conference on Computational Fluid Dynamics*. Glasgow, UK, 11-15 June. CRC Press, Taylor & Francis Group, 2018.
 8. Wang L, Cortis M, Coombs W M, Augarde C E, Brown M J, Knappett J A, Brennan A, Davidson C, Richards D, and Blake A. On implementation aspects of implicit MPM for 3D analysis. In *Proceedings of 2nd International Conference on the Material Point Method for Modelling Soil-Water-Structure Interaction*, Cambridge, United Kingdom, 8 – 10 January, 2019.
 9. Charlton T J, Coombs W M, and Augarde C E. iGIMP: An implicit generalised interpolation material point method for large deformations. *Computers & Structures*, 190:108--125, 2017.

FIELD TESTS ASSESSING THE INSTALLATION PERFORMANCE OF SCREW PILE GEOMETRIES OPTIMISED FOR OFFSHORE WIND APPLICATIONS

D J RICHARDS, A P BLAKE, D J WHITE

Geomechanics Research Group, Faculty of Engineering and Physical Sciences, University of Southampton, UK

E M BITTAR, B M LEHANE

Department of Civil, Environmental & Mining Engineering, University of Western Australia, Australia

SUMMARY: This paper describes the first phase of a field testing campaign to assess the installation performance of screw pile geometries optimised for future offshore wind applications. The tests were conducted in medium dense aeolian siliceous sand at University of Western Australia's Shenton Park Field Station. Single helix, double helix, closed-ended and open-ended pile configurations were tested. Different combinations of installation torque, thrust and pitch were investigated to gain a better understanding of the torque-thrust-pitch interaction, which is important to maximise the practical applicability of screw pile technology at the scale required for offshore wind applications. The results of the tests will be used to validate analytical and numerical techniques under development within the Supergen Wind screw pile project involving the Universities of Dundee, Durham and Southampton.

Keywords: Field testing, installation, load capacity, load test, piling, rotary piling, sand, screw pile.

INTRODUCTION

Over 80% of offshore wind turbines installed in European waters are supported by driven monopile foundations¹. Wind turbines are being installed in ever increasing water depths and subject to increasingly challenging environmental and geotechnical conditions. The transition to deeper waters has seen an almost two-fold increase in monopile diameter from 4 m in 25 m water depth² to 7.8 m in 41 m water depth (Veja Mate Wind Farm, German North Sea).

It has been predicted that piled steel jackets will become the foundation system of choice for turbines deployed in water depths exceeding 50 m. Indeed, turbines at the Beatrice Wind Farm in the Moray Firth, UK are installed in water depths of up to 55 m and supported by steel jackets with four 2.2 m diameter tubular driven piles at each corner³. Wind farms supported by steel piled jackets require at least three times more piles than those supported using monopiles which results in longer installation times and subsequently increased costs. In addition, concerns over the effects of pile driving noise and vibration on marine life have already led to effective bans on offshore pile driving or the requirement for expensive mitigation systems such as the deployment of piling bubble curtains⁴.

Screw piles are being considered as an alternative to driven monopiles to support offshore wind turbines^{5,6,7}. Screw piles are steel tubes with one or more helical elements fabricated on the shaft that are rotated (screwed) into the ground. In onshore practice a hydraulically driven torque head is used for installation, mounted on a 360° excavator with vertical force (“thrust”) applied by the boom of the excavator. Historically, they have been used to support seaside piers, bridges and lighthouses⁸. Modern applications of screw piles include foundations for solar panel farms, residential and commercial buildings, motorway signs and gantries, and transmission towers. Screw piles possess good tensile and compressive capacity and offer three main advantages over driven piles; (i) higher capacity to weight ratios, (ii) lower installation noise and vibration, and (iii) more rapid installation. Hence, screw piles have the potential to be a more attractive foundation solution for offshore wind farms compared to plain driven piles⁹.

Onshore screw piles typically comprise of one or two helical plates (helices) welded to a shaft and their application generally involve much lower lateral loads than those associated with offshore wind turbines, resulting in typical helix (D_h) to core diameter (D_c) ratios (D_h/D_c) of 1.5 to 8⁸. To meet the demands of the loads applied to wind turbines in the offshore environment, screw pile geometries will require substantial enhancement⁵. For example, numerical analyses by Al-Baghdadi et al.¹⁰ showed that D_h/D_c will need to be significantly reduced to satisfy the structural bending moment capacity requirements for offshore applications. Knappett et al.¹¹ and Al-Baghdadi¹² indicated that higher capacity to weight ratios could be achieved through optimising D_h/D_c and the vertical spacing between helices (S) to D_h ratio (S/D_h). It has been identified that these geometric enhancements could increase the associated installation torque and thrust to unprecedented levels that will exceed the capabilities of existing offshore plant⁵. Consequently, screw pile design for offshore wind applications could potentially be governed by installation requirements rather than by in-service loading¹³.

Model tests conducted by White et al.¹⁴ on non-helical piles installed in sand via rotary jacking (an action similar to screwing) showed that an inter-dependency exists between torque, crowd (vertical force) and pitch during installation, which would also apply to the shaft of a helical pile.

A field testing campaign is underway by the University of Southampton, within the EPSRC-funded Supergen Wind project on helical piles, which is led by the University of Dundee. The aim of first phase of the campaign was to assess the installation performance of screw pile geometries optimised for future offshore wind applications. The testing was undertaken in sand at the University of Western Australia’s Shenton Park Field Station. The primary aim of the campaign was to gain a better understanding of the torque-thrust-pitch interaction, which is important to maximise the practical applicability of screw pile technology at the scale required for offshore wind applications.

TEST SITE

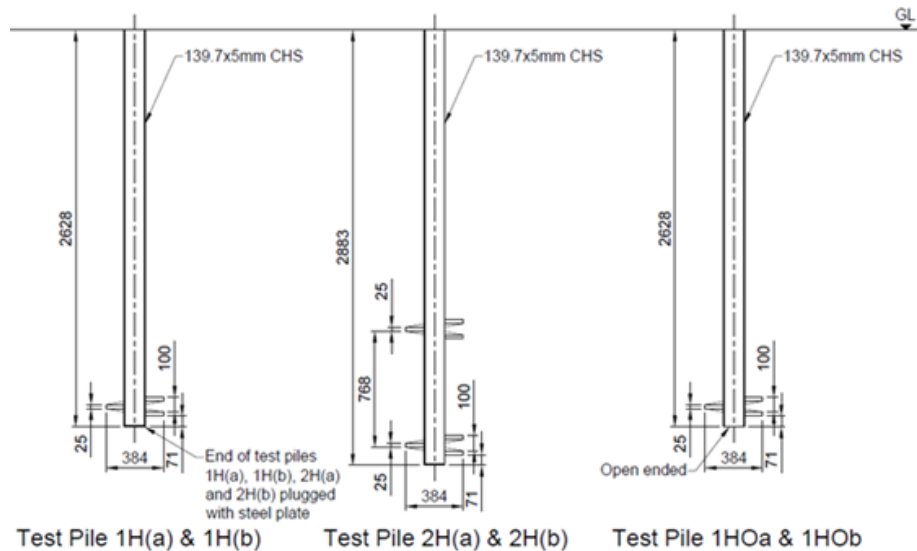
The Shenton Park Field Station is a 67 hectare research site operated by The University of Western Australia (UWA) located within the Spearwood Dune system in a geomorphologic region known as the Perth Basin. The stratigraphy at the site comprises a 5 to 7 m thick deposit of medium dense aeolian siliceous sand overlying weakly cemented Pleistocene Tamala Limestone. The site has been previously characterised through in situ and laboratory testing (Table 1)¹⁵ and used for field testing of driven piles in sand^{16,17}. Cone penetration testing (CPT) was conducted at four locations within close proximity to the pile test locations immediately before the present test program.

Table 1: Sand properties at Shenton Park Field Station¹⁵

Parameter	Symbol	Value
Particle sizes	D ₅₀	0.43+/-0.02mm
	D ₆₀	0.47+/-0.02mm
	D ₁₀	0.21+/-0.01mm
Fines content	FC	< 5%
Bulk unit weight	ρ_b	1670 kg/m ³
Moisture content	w	3.2-3.8%
Saturation ratio	S _r	< 15%
Maximum voids ratio	e _{max}	0.81+/-0.01
Minimum voids ratio	e _{min}	0.45+/-0.01
Relative density	I _d	45+/-10%

TEST PILES

The field tests involved six test piles (illustrated in Figure 1): (i) two identical closed ended single helix piles (1Ha and 1Hb); (ii) two identical open ended single helix piles (1HOa and 1HOb); and (iii) two identical closed ended double helix piles with a (2H). All piles had helix and shaft diameters of 384 mm and 139.7 mm respectively, and a helix pitch of 100 mm.

**Figure 1:** Test pile geometries (all dimensions in millimetres)

MEASUREMENT

Torque (T), thrust (V) and angular rotation (θ) were measured during pile installation with a ProDig® Intelli Tork® measurement system (model C441-S400 Wi-Fi - S/N 119637, Figure 2). The instrument measured torque and thrust using strain gauges and rotation with magnetometers. The rated maximum T and V of the instrument are 81.4 kNm and 4.4 MN respectively. The instrument is capable of sampling at a rate of 10 Hz using a 24-Bit ADC giving T and V resolutions of $4,852 \times 10^{-9}$ kNm and 256×10^{-6} kN respectively. Measurement data was transmitted in real time via an on board 2.4 GHz wireless transmitter to the Intelli-Tork® App operating on an Android Smartphone.

Verification of the calibration of the Torque and Thrust sensors within the Intelli Tork

device was performed in the heavy structures laboratory at UWA. Torque calibration involved incrementally applying bending moment (0 to ~20 kNm) with an electrically powered chain block mounted to a gantry crane at an eccentricity of 1 m from the centre of the Intelli-Tork while measuring load with a pre-calibrated tension load cell positioned in line with the lever arm beam and the chain block (Figure 2). Thrust calibration was performed by incrementally applying compressive load (0 to ~30 kN) in a press to the Intelli-Tork system arranged with a pre-calibrated compression load cell.



Figure 2: IntelliTork torque calibration setup

METHODOLOGY

The test piles were installed using a tracked excavator (Figure 3) with a mass of ~9 t (including torque motor and couplers) and capable of applying a maximum thrust of ~22 kN. The torque motor generated a maximum torque and angular velocity of 100 kNm and 15 rpm respectively. The Intelli-Tork was connected in line with the torque motor and pile head (Figure 3). Torque, thrust and angular velocity were controlled manually by the excavator operator. Graduations marked at 100 mm intervals on the surface of each test pile were observed by an “off-sider” during installation. When a graduation reached ground level (GL) the off-sider triggered a button in the Intelli-Tork App which assigned a depth value to the recorded data, this action was repeated for every 100 mm depth increment.



Figure 3: Installation arrangement

RESULTS AND DISCUSSION

The results of six screw pile installations are summarised in Table 2. Figure 4 and Figure 5 show torque and thrust profiles (respectively) plotted against depth for each installation.

For all installations, torque did not exceed 1 kNm (0.07 to $0.1T_{\max}$) over the initial ~ 0.7 m ($1.8D_h$) of pile (tip) penetration. Beyond 0.7 m the torque increased rapidly and consistently stabilised close to the final embedment depth. This rapid increase in torque is attributed to the helix beginning to mobilise significant soil shear strength. Between ~ 0.3 to ~ 1.0 m (0.8 to $2.6D_h$) the thrust applied by the tracked excavator was backed-off to approximately zero as the helix began generating enough thrust to overcome the soil resistance acting on the pile shaft. This ability of the helix to pull the shaft into the ground is a feature that may avoid substantial reaction force (which is difficult to provide subsea) being required to install screw piles in an offshore environment.

The peak torques were 10.1 and 9.8 kNm (open ended single helix piles), 10.7 and 8.6 kNm (closed ended single helix piles) and 15 and 13 kNm (closed ended double helix piles). There was no significant difference between the torque required to install the open ended and closed ended single helix piles. Measurements taken following installation of the open ended piles indicate that the both piles plugged at 570 mm below ground level. The peak torque required to install the closed ended double helix piles was 1.5 to 1.7 times higher than that required for the single helix piles.

Figure 6 shows pitch profiles plotted against depth for each installation together with the “perfect pitch”, $p_{\text{perfect}} = 24.1$, which is defined here as the ratio of the circumference of the outer edge of the helix (i.e. $c = 2\pi D_h$) to the helix pitch, p_h (i.e. vertical height from the bottom to top of a 360° helix). During the initial stage of the installation, the pitch was much higher than the perfect pitch, generally ranging from 70 to 120. During the main phase of installation, the pitch progressively reduced and typically varied from 30 to 50 –consistently higher than

the perfect pitch.

These tests were completed two months prior to the present event, and full analysis of the results is currently underway. The outcomes of this field testing will support the EPSRC Supergen Wind project, ref. EP/N006054/1, led by the University of Dundee in collaboration with the Universities of Durham and Southampton.

Table 2: Summary of installation results

Test	Pile	Max. torque, T_{\max} (kNm)	Max. thrust, V_{\max} (kN)	Avg. pitch, p (-)
1	1HOa	10.1	6	46.3
2	1HOb	9.8	7	41.5
3	1Ha	10.7	6	54.1
4	1Hb	8.6	6	58.9
5	2Ha	15.0	13	53.6
6	2Hb	13.0	17	74.2

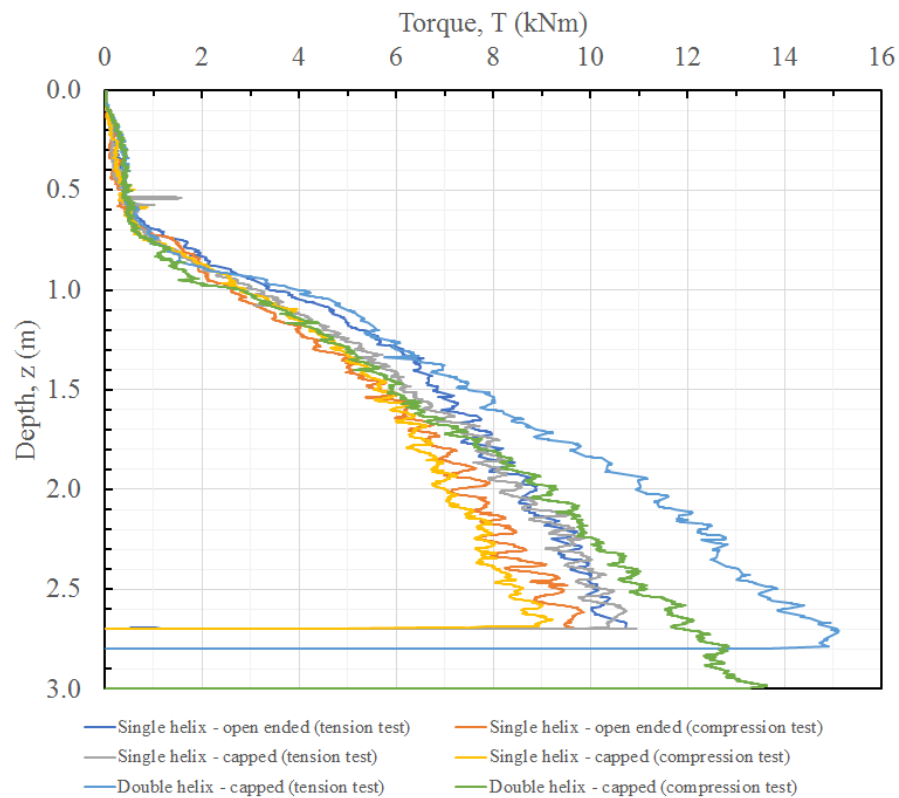


Figure 4: Profiles of installation torque

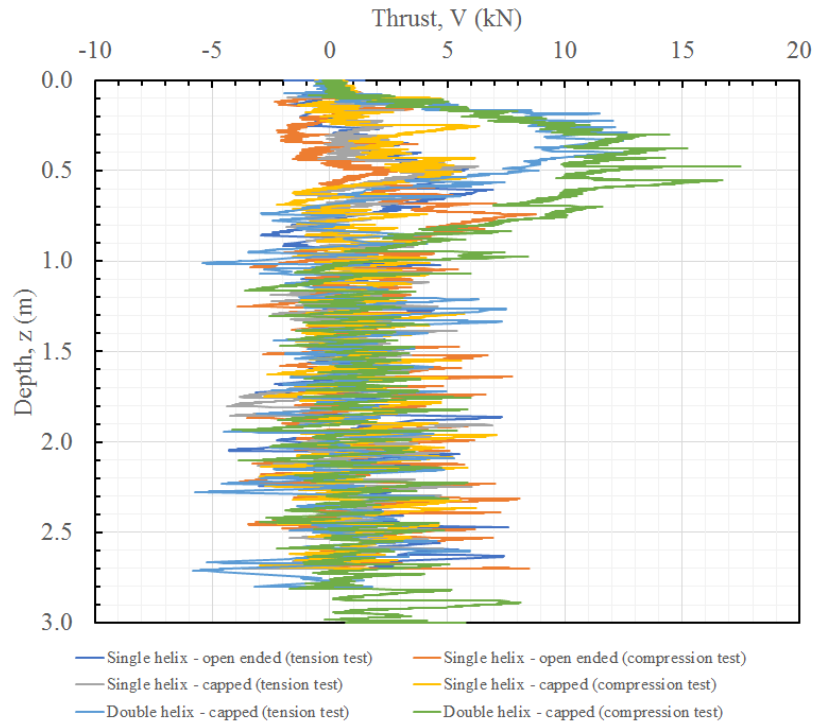


Figure 5: Profiles of controlled installation thrust

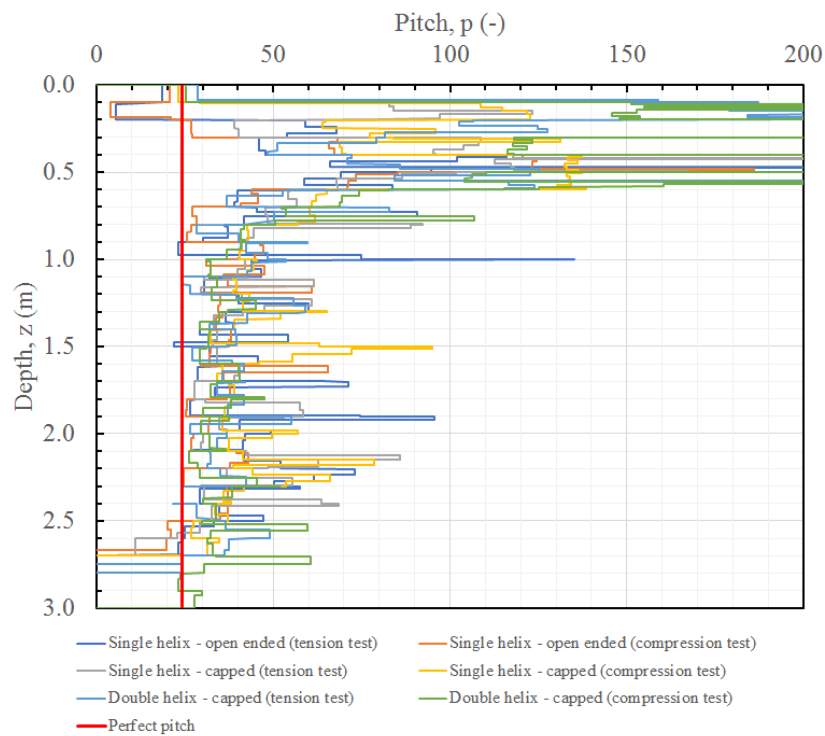


Figure 6: Profiles of installation pitch

REFERENCES

1. WindEurope Business Intelligence. (2017). *The European offshore wind industry: Key trends and statistics 2016*. <https://windeurope.org/>.
2. LeBlanc, C., Houlsby, G. T. and Byrne, B. W. (2010). Response of stiff piles in sand to

- long-term cyclic lateral loading. *Géotechnique*, 60(2), pp. 79-90.
3. Beatrice Offshore Windfarm Ltd. (2017). *Beatrice Offshore Wind Farm Piling Strategy*. Online, pp. 109.
4. Bruns, B., Stein, P., Kuhn, C., Sychla, H. and Gattermann, J. (2014). Hydro sound measurements during the installation of large diameter offshore piles using combinations of independent noise mitigation systems. *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, Melbourne, Australia, Vol. 249, pp. 5629-5638.
5. Davidson, C., Brown, M. J., Cerfontaine, B., Al-Baghdadi, T. A., Knappett, J. A., Brennan, A., Augarde, C., Coombs, W., Wang, L., Blake, A. P., Richards, D. J. and Ball, J. D. (2019). Feasibility of screw piles for offshore jacket structures, Part I: physical modelling. *Géotechnique*. Submitted for review.
6. Davidson, C., Al-Baghdadi, T. A., Brown, M., Brennan, A., Knappett, J., Augarde, C., Coombs, W., Wang, L., Richards, D., Blake, A. and Ball, J. (2018a). A modified CPT based installation torque prediction for large screw piles in sand. In *4th International Symposium on Cone Penetration Testing*. CRC Press, Delft, Netherlands, pp. 255-261.
7. Davidson, C., T.A., A.-B., M.J., B., Brennan, A., A., K. J., Augarde, C., Coombs, W., Wang, L., Richards, D., Blake, A. and Ball, J. D. (2018b). Centrifuge modelling of screw piles for offshore wind energy foundations. In *9th International Conference on Physical Modelling in Geotechnics*, Taylor Francis Group, University of London, London, UK, Vol. 1, pp. 695-700.
8. Perko, H. A. (2009). *Helical piles: a practical guide to design and installation*. Hoboken, USA, John Wiley & Sons.
9. Byrne, B. W. and Houlsby, G. T. (2015). Helical piles: an innovative foundation design option for offshore wind turbines. *Philosophical Transactions of the Royal Society A*, 373(2035).
10. Al-Baghdadi, T. A., Brown, M. J., Knappett, J. A. and Ishikura, R. (2015). Modelling of laterally loaded screw piles with large helical plates in sand. In *Frontiers in Offshore Geotechnics III*, CRC Press, pp. 503–508.
11. Knappett, J. A., Brown, M. J., Andrew, J. B. and Hamilton, L. (2014). Optimising the compressive behaviour of screw piles in sand for marine renewable energy applications. In *DFI/EFFC 11th International Conference on Piling and Deep Foundations*. Deep Foundations Institute, Stockholm, Sweden.
12. Al-Baghdadi, T. A. (2018). *Screw piles as offshore foundations: Numerical & physical modelling*. PhD thesis, University of Dundee, Dundee, UK.
13. Morais, T. d. S. O. and Tsuha, C. d. H. C. (2014). A new experimental procedure to investigate the torque correlation factor of helical anchors. *Electronic Journal of Geotechnical Engineering*, 19(2014), pp. 3851-3864.
14. White D.J., Deeks A.D. & Ishihara T. (2010). Novel piling: axial and rotary jacking. *Proc. 11th Int. Conf. of the Deep Foundations Institute, Geotechnical Challenges for Urban Regeneration*. London.
15. Anusic, I., Lehan, B. M., Eiksund, G. R. and Liingaard, M. A. (2018). Field study on the effects of impact frequency on the axial and lateral capacity of driven piles in sand, *Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*, Madrid, Spain, 17th-22nd June 2018, OMAE2018-78428.
16. Xu, X. (2008). *Investigation of the end bearing performance of displacement piles in sand*. PhD thesis, The University of Western Australia, Perth, Australia.
17. Schneider, J. A (2007). *Analysis of piezocone data for displacement pile design*. PhD thesis, The University of Western Australia, Perth, Australia.

PERFORMANCE OF SCREW PILES IN NORMALLY CONSOLIDATED PERTH SAND

E M BITTAR, B M LEHANE

Dept of Civil, Environmental & Mining Engineering, University of Western Australia

A P BLAKE, D J RICHARDS, D J WHITE

Geotechnics Group, Faculty of Engineering and Physical Sciences, University of Southampton

SUMMARY: The bearing capacity of these piles is typically estimated using the individual bearing or cylindrical shear analytical methods. The individual bearing method considers failure occurring at each individual helix and the total axial pile resistance in compression or tension is the sum of the capacities of the individual helixes plus shaft friction. On the other hand, the cylindrical shear method assumes that a cylindrical shear failure surface, connecting the uppermost and lowermost helixes are formed. Therefore, the axial capacity is calculated from the shear friction along the cylindrical surface and the pile shaft, and bearing resistance above the top helix for uplift and from the bearing resistance below the bottom helix for compression loading.

Furthermore, CPT-based direct methods and empirical torque correlations for predicting the capacity of screw piles loaded in static axial tension and compression are frequently used.

This work investigates various these method for calculating the bearing capacity of screw piles in normally consolidated sands, both in tension and compression condition. To achieve that, single helix and double helix screw piles were installed at The University of Western Australia field station in Shenton Park, measuring torque and axial loading applied during installation to then be subjected to load tension and compression tests.

The presentation shows the results of static tension and compression tests on single and double helix screw piles installed in the dune sand at Shenton Park. These results are contrasted whit analytical and direct methods aforementioned.

Additionally, results from a separate series of uplift tests on piles with an enlarged base in the same sand deposit are also presented. The capacities predicted using existing analytical approaches are compared with both sets of test data. The same test data are also backanalysed using the finite element method to provide insights into the influence of the installation method on the uplift capacity.

The research concludes by showing that the use of typical bearing capacity factors N_q can lead to overestimates the compressive bearing capacity and a better approximation for the base capacity can be obtained by CPT-based direct methods. Moreover, one of the analytical methods developed for anchors uplift capacity studied showed a satisfactory estimation over the studied screw piles. The shaft friction of the installed screw piles exhibited small influence in the total capacity of them, this might be because they were installed at depths of approximately 2.6m to 3m.

Keywords: screw piles, uplift capacity, normally consolidated sands.

LINKING THE INSTALLATION RESPONSE OF SCREW PILES TO SOIL STRENGTH AND ULTIMATE CAPACITY

J P HAMBLETON

Department of Civil and Environmental Engineering, Northwestern University, Illinois, USA

S A STANIER

Department of Engineering, University of Cambridge, Cambridge, UK

SUMMARY: A perceived advantage of screw-type foundations is the ability infer aspects of foundation performance from quantities measured or observed during installation, such as torque and advance rate. For example, a concept widely used in practice is to correlate installation torque to ultimate capacity. This notion of “torque-capacity correlation” has already proven to be exceptionally useful as a field verification technique despite the absence of validated models that relate key variables of interest, such as installation torque, axial (crowd) force, geometrical parameters, and soil strength.

This presentation provides an overview of previous work by the co-authors and collaborators¹⁻⁶ on analytical, numerical, and physical modelling of screw piles. Focus is on modelling of the installation process and relating the quantities measured or controlled during installation to the ultimate capacity and soil strength. Attention is given almost exclusively to saturated clay as a particular soil type amenable to simplified analysis. The analytical model for a single-helix pile developed by Hambleton et al.⁴ by analyzing the stresses and resultant forces acting on the screw pile during installation (Figure 1) is considered as a means of directly relating the undrained shear strength to the installation torque T , crowd force N , plate pitch p , plate diameter D , shaft diameter d , installation depth H , and surface roughness. This relationship between undrained shear strength and the remaining variables is used to highlight the possibilities and limitations of inferring soil properties from the installation response or, in other words, regarding the installation process as a technique for *in situ* soil testing, and thus capacity prediction. The connection between the installation variables and ultimate capacity—and the sensitivity to crowd force in particular, a quantity that is typically not measured during field installations—is also discussed. The theoretical predictions are compared against data obtained from small-scale laboratory experiments⁶, which supports some aspects of the theoretical modeling while challenging others.

Readers interested in full details of the work described in this presentation are referred to the full paper being considered for publication in the *Proceedings of the 44th Annual Conference on Deep Foundations*⁷ and to the original publications by the co-authors and collaborators¹⁻⁶.

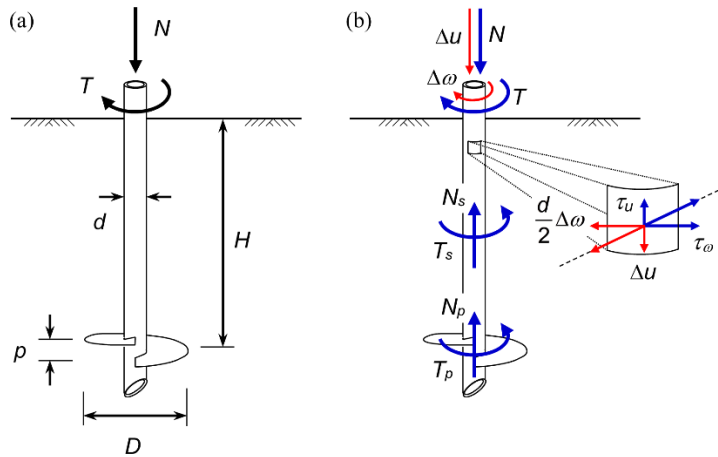


Figure 1: Schematic of a single-helix screw pile: (a) key variables; (b) stresses and resultant forces generated on the shaft and helical plate during installation⁴. Variables Δu and $\Delta \omega$ denote the rate of axial displacement and rotation, and subscripts “s” and “p” are used to indicate the axial forces and torques mobilized along the shaft and helical plate, respectively. Quantities τ_u and τ_θ respectively denote the axial and angular shear stresses mobilized along the shaft. (Reproduced with permission from the Australian Geomechanics Society.)

REFERENCES

1. Hird, C. C., & Stanier, S. A. (2010). Modelling helical screw piles in clay using a transparent soil. *Proceedings of the 7th International Conference on Physical Modelling in Geotechnics*, Zurich, 28 June-1 July, pp. 769-774.
2. Stanier, S. A. (2012). *Modelling the Behaviour of Helical Screw Piles*. PhD thesis. University of Sheffield.
3. Stanier, S. A., Black, J. A., & Hird, C. C. (2013). Modelling helical screw piles in clay and design implications. *Proceedings of ICE-Geotechnical Engineering*, 167(5), 447-460.
4. Hambleton, J. P., Stanier, S. A., Gaudin, C., & Todeshkejoei, K. (2014). Analysis of installation forces for helical piles in clay. *Australian Geomechanics*, 49(4), 73-79.
5. Todeshkejoei, C., Hambleton, J. P., Stanier, S. A., & Gaudin, C. (2014). Modelling installation of helical anchors in clay. *Proc. 14th International Conference of the International Association for Computer Methods and Advances in Geomechanics*, Kyoto, 22-25 September, pp. 917-922.
6. Todeshkejoei, K. (2019). *The Mechanics of Screw Piles in Clay*. PhD thesis. University of Newcastle, Australia.
7. Hambleton, J. P., & Stanier, S. A. (2019). Linking the Installation Response of Screw Piles to Soil Strength and Ultimate Capacity. *Proceedings of the 44th Annual Conference on Deep Foundations*, Chicago, 15-18 October, (under review).

A CRITICAL REVIEW ON DESIGN ASPECTS OF SCREW PILES FOR RENEWABLE ENERGY DEVICES

P V PAVAN KUMAR, S PATRA, S HALDAR

School of infrastructure, IIT Bhubaneswar, Jatni, Odisha, India, 752050
pvk11@iitbbs.ac.in, shantanu@iitbbs.ac.in, sumanta@iitbbs.ac.in

SUMMARY: Screw piles could potentially be a cost-effective, easy to install and low carbon footprint alternative to the conventional foundation for renewable energy devices, e.g., wind turbines and solar panels arrays. In this paper, an extensive review is carried out to study the available design procedures and methods for prediction of the lateral capacity of the screw pile. A comparison of existing design methodologies and their limitations in estimating screw pile capacity is presented. The state of the art design approaches for screw piles along with the installation effect is discussed in detail. The influence of type and strength of soil, geometry (shaft diameter, helix diameter, helix spacing, etc.) and material properties of the screw pile on its performance were also investigated for different loading conditions

Keywords: Combined loading, installation effect, lateral load, screw pile

INTRODUCTION

Screw piles have been in use for over 170 years¹ in different applications like transmission towers, light poles, excavation bracing, etc.². According to International Building Code (IBC) 2009³ a screw pile is defined as a “manufactured steel deep foundation element consisting of a central shaft and one or more helical bearing plates and is installed by rotating it into the ground”. The first time, it was used by Alexander Mitchell for the foundation of the structure at the Maplin Sands light-house⁴. Presently, screw piles are gaining popularity as an effective alternative to the conventional type of foundations particularly for energy devices like wind turbines and solar panels. The screw pile foundation has several advantages over conventional foundations including: easy and quick installation, does not produce spoil, little noise, and can be installed in sites with limited access^{1,5}. Screw piles are considered to be cost-effective as they require less labour, do not require specialized equipment when installed for small scale onshore applications, and can be reused. In reality, screw piles are often subjected to combined axial and lateral loads where the lateral loads may be contributed either from wind or earthquakes or unbalanced earth pressures, or load eccentricity, etc., or combination of any of these⁶. The behavior of screw piles under axial loads are well defined in the literature, but limited studies are available on their lateral performance⁶ particularly for wind turbine application where they are subjected to a significant amount of wind loads⁷. The lateral performance of upscaled screw piles for offshore wind turbine is investigated by several researchers^{2,7}. However, their performance of relatively small scaled screw piles for onshore wind turbines has not yet been studied. Apart from the wind turbines, onshore solar panels are also subjected to a significant amount of wind loads. Hence, such foundation should be designed for the uplift⁸ as well as lateral loads⁹.

PERFORMANCE OF SCREW PILE UNDER LATERAL LOADING

Past studies suggest significant progress on the prediction of the axial capacity of screw piles but the study on the lateral behavior of screw piles are inadequate⁶. The initial studies^{10,11} to predict the lateral behavior of helical piles was based on mathematical models and small scale model tests.

Theoretical methods

Puri et al.¹⁰ proposed a mathematical models for flexible screw pile subjected to lateral loads and moments based on Matlock and Reese's elastic theory. For flexible pile the embedded length was considered to be greater than 4 to 5T for sand and 4 to 5 R for clay. The following equations were proposed to determine the load-deformation behavior in sand (Eq. 1) and clay (Eq. 2)¹⁰.

$$y = C_u [A_y (PT^3 / EI) + B_y (MT^2 / EI)] \quad (\text{sand}) \quad (1)$$

$$y = C_u [A_y (PR^3 / EI) + B_y (MR^2 / EI)] \quad (\text{clay}) \quad (2)$$

where y = lateral deflection at ground level, C_u = coefficient determined from the experimental correlation, A_y = deflection coefficient for lateral load, B_y = deflection coefficient for moment, P = lateral load at ground level, M = moment applied at ground level, T = relative stiffness factor $(= (EI / \eta_h)^{1/5})$, where η_h is the subgrade modulus for sand, E = Young's modulus of pile, I = moment of inertia of the pile, R = relative stiffness factor $(= (EI / K)^{1/4})$, where K is the subgrade modulus for clay).

A_y and B_y are Matlock and Reese¹² function of non-dimensional depth ($Z = X/T$) for cohesionless soils and Davisson and Gill¹³ function of non-dimensional depth (where $Z = X/R$) for clays. These factors are same as ordinary piles. The coefficient C_u incorporates the effect of helix on the pile performance and was determined (to be approximately equal to 3.0) by correlation with the observed behavior from model tests.

Prasad and Rao¹¹ proposed a theoretical model for rigid screw pile in clay to determine its ultimate lateral load carrying capacity. The model considered static equilibrium of forces due to lateral resistance on the pile shaft, bearing and uplift resistance offered by the soil, and frictional resistance on top and bottom of the helical plates. Figure 1 shows the typical loads acting on the screw pile when subjected to lateral load¹¹. The following equations were proposed to determine the ultimate lateral capacity (H_u) of rigid screw pile in clay.

$$H_u = c_u d (18X - 10.5d - 9L) \quad (3)$$

where, c_u = undrained strength of soil, d = diameter of shaft, L = embedment length, X = depth of point of rotation from ground level and can be obtained from taking the moment of all forces about the ground surface.

In the above method, the lateral resistance was calculated based on Poulos and Davis¹⁴, bearing pressure by Skempton's method¹⁵ and uplift pressure based on Das¹⁶. Since the proposed model was validated using small scale laboratory tests data of 18 nos., further study is required that may involve full-scale testing before enforcing into practice.

Similar to the above study, the ultimate lateral capacity of screw pile in sand was determined by Mittal et al.¹⁷. However, the major difference is that the proposed method did not consider the passive resistance offered by the soil below the point of rotation. In addition, the shaft resistance was determined using Broms method¹⁸ (with a slight modification to

incorporate the effect of increase in the flexural rigidity on account of presence of helix), the bearing resistance of helix by Rogers method¹⁹ and uplift resistance based on Chattopadhyay and Pise²⁰.

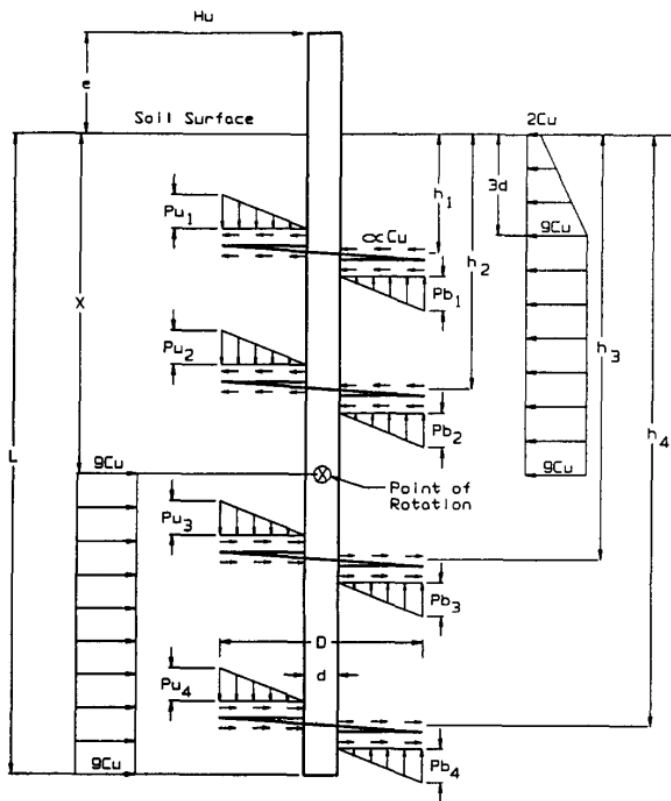


Figure 1: Forces acting on the pile subjected to lateral load¹¹

Field tests

The field tests on laterally loaded screw piles are scarce with only a few exceptions^{9,21,22}. Sakr⁹ conducted field tests to study the lateral behavior of screw piles installed in two sites: Site 1 comprised of silty clay with varying shear strength (undrained shear strength varying from 43 to 150 kPa) whereas Site 2 had two layers of alluvial deposit of silt and sand mixture. In their study, the effect of shaft diameter and number of helix on the lateral load capacity of the screw pile was studied. The effect of shaft diameter on the lateral load capacity of screw pile installed at Site 1 was observed to be significant (34% increase in pile capacity for 47% increase in diameter). However, for the same site soil condition, marginal increase (4% - 6%) in the lateral resistance was noted for the double helix as compared to the single helix. Since the results were based on a limited number of tests (5 nos.), no specific conclusion could be made for the effect of installation and number of helix for silty sand (Site 2). Hence, further study is required for cohesionless soil.

Sakr²² conducted field tests for both single helix and double helix piles in oil sand (natural mixture of sand water and bitumen). The installation of a double helix pile in sand required higher torque (around 17% to 29%) compared to the single helix piles²². The authors concluded that the double helix pile capacity is slightly lower compared to that of the single helix pile. This is because of higher soil disturbance caused during pile installation for double helix pile.

Elkasabgy and Naggar²¹ carried out field tests on double helix screw piles installed in cohesive soil. The ultimate lateral load capacity of the piles was determined based on lateral deflection corresponding to 1.02% (Prakash and Sharma²³) and 2.05% (according to industrial application) of helix diameter for two different embedment length (L) of pile. The modulus of subgrade reaction (K) obtained experimentally was found to be lower than that of analytical

value found using the intact soil strength parameter. The authors proposed that a “disturbance factor” should be used for accurate prediction of lateral loads to consider the effect of strength reduction of soil due to the disturbance caused by the installation of screw piles.

Field tests like Cone penetration test (CPT) could be one of the potentially useful techniques to predict the lateral pile capacity of screw pile. Cone penetration test (CPT) is useful in obtaining the soil characteristics along the depth and has been employed in the past to determine the lateral capacity of the normal piles. Lee et al.²⁴ proposed a correlation between the lateral soil resistance and cone penetration resistance for simple piles installed in sand. However, no specific solutions exist to estimate the lateral load capacity for screw piles using CPT results and need to be studied.

Laboratory tests

Small scale laboratory tests are very useful in predicting the lateral capacity of screw piles. Several researchers conducted laboratory tests to know the lateral behavior of screw piles^{10,11,25,26}. Puri et al.¹⁰ conducted 1-g laboratory tests on reduced scale screw piles (1/4th scaled) in sand for varying numbers of helix (i.e. single-helix, two-helix, and three-helix). The lateral load capacity of the screw pile mainly governed by the interaction between the shaft and the soil and the effect of number of helices on the lateral capacity of screw pile was observed to be negligible¹⁰.

Prasad and Rao¹¹ conducted model tests (1-g laboratory tests) to determine the lateral capacity of screw piles installed in clay with 2 and 4 numbers of helices. It was observed that the capacity of the helical piles increased to 1.2 - 1.5 times higher than that of the straight shaft piles and as the number of helical plates increased (2 to 4), the lateral capacity also increased (about 25%). However, the effect of installation on the lateral capacity of screw piles may play an important role but completely neglected in the above studies^{10,11} as screw piles were assumed to be wished-in-place.

Abdrabbo and Wakil²⁶ studied the performance of screw piles in sand subjected to lateral loads based on small scale 1-g laboratory tests. The effect of the pile parameters such as depth of top helix from the ground surface, the spacing of helix, number of helices, and helix diameter on the lateral capacity of the screw pile was also investigated considering the pile wished-in-place. For a single helix pile, the improvement ratio was found to be linearly increasing with the increase in helix to shaft diameter (D/d) ratio where improvement ratio is defined as the ratio between the ultimate load of helical pile to that of a plain pile. For a single helix pile, the most efficient depth of helix was found between 1/3 to 1/2 the embedment length (L). For multiple helix, the optimum performance of the screw pile was observed for 2 number of helices considering the effective spacing ($S/d = \text{spacing to shaft diameter ratio}$) equal to 1 (or $S/D = \text{spacing to helix diameter ratio} = 0.133$) and depth of top helix is $L/2$. For 2 nos. of helix, the most efficient spacing of helix (S/d) was found to be 3 and the improvement ratio increases nonlinearly up to $L/L_r = 0.9$ (where L_r = length of reference pile) and becomes insignificant thereafter. The improvement in the ultimate lateral load capacity of a helical pile could be 2.42 times that of a straight shaft pile based on the model tests data²⁶. However, the ultimate loads were measured with respect to an arbitrary displacement of 2.5% of the pile diameter and no clear reference was presented in this regard. Pitch of the helix and the installation effect has a substantial effect on the lateral capacity of the pile²⁵ but not considered in the above studies^{10,11,26}.

Ding et al.²⁵ performed small scale 1-g laboratory tests to determine the influence of pitch of the helix on the lateral capacity for single helix pile in sand considering the installation effect. Based on model tests data, they have proposed the following empirical relations (Eq. 4) to predict the ultimate lateral capacity of a screw pile

$$H_u = \frac{\gamma d L^3 K_p}{2(e + L)} \left(1 - \frac{p}{9d} \right) \quad (4)$$

where K_p = passive earth pressure coefficient, e = eccentricity of the applied lateral load with respect to the ground level, p = pitch of helix, L = embedment length

The above relationship considered the effect of pitch of helix and is an improvement over the empirical relations proposed by Mittal et al.¹⁷. It was found that the effect of pitch of helix resulted in a reduced lateral capacity of the screw pile due to a greater disturbance of the surrounding soil²⁵. The equation (3) provided by Ding et al.²⁵ is useful for predicting the ultimate load for shallow embedded piles. For deeper embedment length the results might not be useful. Another drawback of the study²⁵ is that the effect of the number of helices is not considered which is an important parameter and should be addressed.

Numerical study

Numerical techniques enable one to conduct a detail parametric study of screw piles and provide cost-effective, faster solution as compared to the lab tests or field tests. Several numerical techniques have been employed by many researchers^{2,27-30} to study the behavior of screw piles. Al-Baghdadi et al.²⁷ presented the lateral behavior of screw pile installed in sand using three-dimensional finite element analysis considering. In their study, the effect of helix diameter and the effect of placement of helix on the lateral performance of screw pile were analysed. Near-surface placement of helix gives 22% greater lateral capacity as compared to a normal pile corresponding to 10% deflection of pile diameter. However, the increase in the helix diameter has a moderate influence on the pile capacity. The study was limited to a single helix pile and considered the pile to be wished-in-place. Therefore, further study is needed that considers multiple-helix and the effect of pile installation.

For large deformation problem such as pile installation, the finite element method fails mainly due to the mesh distortion effect which could be avoided by employing advanced numerical techniques like material point method (MPM). Phuong²⁹ used MPM to study the installation of plain piles. Wang et al.²⁸ considered installation of screw pile using MPM which could be subsequently transferred to standard finite element package for the in-service performance prediction. On the other hand, the discrete element method permits realistic modelling of discrete soil particles by capturing the macroscopic particle contact mechanics. Hence, could be extended (available for lateral capacity of normal piles³⁰) to study the lateral behavior of screw piles.

PERFORMANCE OF THE SCREW PILE UNDER COMBINED AXIAL AND LATERAL LOADING

The performance of screw piles under combined lateral loading is very important particularly considering the foundation for wind turbines where the environmental loads (wind loads) act in addition to the dead load. However, few studies are available on screw piles subjected to combined loading with the only exception of the work of Al Baghdadi et al.² where the behavior of a screw pile under combined vertical and lateral loads was numerically investigated using PLAXIS 3D for varying diameters and spacing of the helices. The lateral capacity corresponding to a deflection of 10% of the shaft diameter significantly enhanced under compressive load (about 46% increase was observed as compared to no axial load when subjected to 80% of ultimate axial compressive load). However, the lateral capacity reduces under axial tension (approximately 11% increase was observed as compared to no axial load when subjected to 80% ultimate axial

tension). The major drawback of the study was that the screw pile was modelled as wished-in-place and did not consider the effect of installation of the pile.

CONCLUSIONS

This paper presents a detailed review of the lateral performance of screw piles. The review focuses on the available theoretical and empirical relations to estimate the ultimate lateral load carrying capacity of the screw pile. The review also concentrates on the effect of pile parameters and the effect of installation on the lateral capacity of the screw pile. It is observed that the increase in the pile cross-section has a greater effect on the lateral capacity than the increase in the number of the helices. The effect of the number of helices and helix spacing on the pile capacity is not clearly understood and also needs further numerical validation. Installation of screw pile slightly reduces the lateral pile capacity in cohesionless soils for double helix pile than for single helix pile due to the soil disturbance. However, in cohesive soils, the double helix pile shows little increase in its lateral capacity than single helix pile. The theoretical models available were validated against the laboratory tests and requires further verification from field tests. The field tests were mostly carried out for single and double helix piles. Use of CPT results in estimating the load carrying capacity of the screw pile will be beneficial and should be addressed. Based on the performance of the screw pile it is indicated from the literature that they can be used as an effective alternative to the conventional foundations for wind turbines and solar panels.

REFERENCES

1. Tsuha C H C. Physical Modelling of the Behaviour of Helical Anchors. In *3rd European Conf. on Physical Modelling in Geotechnics (EUROFUGE 2016)*. IFSTTAR Nantes Centre, France, 1st-3rd June 2016.
2. Al-Baghdadi T A, Brown M J, Knappett J A and Al-Defae A H. Effects of vertical loading on lateral screw pile performance. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, Vol. 3*, Feb 2017, pp 259-272.
3. International Code Council. *International Building Code*. Washington, D.C. 2009.
4. El-sawy M K. *Seismic Performance of Steel Helical Piles*. Electronic Thesis and Dissertation Repository 4999, The University of Western Ontario, Ontario, Canada, 2017.
5. Perko H A. *Helical piles: a practical guide to design and installation*. John Wiley & Sons; October 2009.
6. Sakr M. Lateral resistance of high capacity helical piles—case study. In *Proceedings of the 63rd Canadian Geotechnical and 6th Canadian Permafrost Conference*. Calgary, Alberta. September 2010, pp 12-16.
7. Byrne B W and Houlsby G T. Helical piles: an innovative foundation design option for offshore wind turbines. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, Vol. 373, February 2015, 20140081.
8. Lutenecker A J. Foundation Alternatives for Ground Mount Solar Panel Installations. In *Geotechnical and Structural Engineering Congress 2016*, 14th-17th February 2016, pp 1873-1885.
9. Sakr M. Helical piles-an effective foundation system for solar plants. In *The 64th Canadian Geotechnical Conference and Pan-AM CGS*, Toronto, Ontario. October 2011, pp 2-6.

10. Puri V K, Stephenson R W, Dziedzic E and Goen L. Helical anchor piles under lateral loading. In *Laterally Loaded Deep Foundations: Analysis and Performance*. January 1984. ASTM International.
11. Prasad Y V and Rao S N. Lateral capacity of helical piles in clays. *Journal of geotechnical engineering*. Vol. 11, November 1996, pp 938-941.
12. Matlock H. and Reese L C. Generalized Solutions for Laterally Loaded Piles. *Transactions of the American Society of Civil Engineers*, Vol. 127, 1962, pp 1220-1247.
13. Davisson M T and Gill H L. Laterally loaded piles in a layered soil system. *Journal of the Soil Mechanics and Foundations Division*, Vol. 89, May 1963, pp 63-94.
14. Poulos H G and Davis E H. *Pile foundation analysis and design*. John Wiley and Sons, New York, 1980.
15. Skempton, A. W. "The bearing capacity of clays." *Proc., Build. Res. Congr. Vol. 1*, 1951, pp 180-189.
16. Das B. M. Model test for uplift capacity of foundation in clay. *Soils and Foundations*, Vol. 18, June 1978, pp 17-24.
17. Mittal S, Ganjoo B and Shekhar S. Static equilibrium of screw anchor pile under lateral load in sands. *Geotechnical and Geological Engineering*. Vol. 5, September 2010, pp 717-725.
18. Broms B B. Lateral resistance of piles in cohesionless soils. *Journal of the Soil Mechanics and Foundations Division*. Vol. 3, May 1964, pp 123-158.
19. Rogers W. *Manual of screw pile foundations*. Energy Structures Inc, Houston, Texas, 2002.
20. Chattopadhyay B C and Pise P J. Breakout resistance of horizontal anchors in sand. *Soils and Foundations*, Vol. 26, December 1986, pp 16-22.
21. Elkasabgy M A and El Naggar M H. Lateral performance of large-capacity helical piles. In *IFCEE 2015 International Association of Foundation Drilling Deep Foundation Institute Pile Driving Contractors Association*, American Society of Civil Engineers, March 2015.
22. Sakr M. Performance of helical piles in oil sand. *Canadian Geotechnical Journal*. Vol. 9 August 2009, pp 1046-1061.
23. Prakash S and Sharma H D. *Pile foundations in engineering practice*. John Wiley & Sons, July 1990.
24. Lee J, Kim M and Kyung D. Estimation of lateral load capacity of rigid short piles in sands using CPT results. *Journal of geotechnical and geoenvironmental engineering*, Vol. 136, July 2009, pp 48-56.
25. Ding H, Wang L, Zhang P and Le C. Study on the Lateral Bearing Capacity of Single-Helix Pile for Offshore Wind Power. In *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*, June 2018, pp 1-6.
26. Abdrabbo F M and El Wakil A Z. Laterally loaded helical piles in sand. *Alexandria Engineering Journal*, Faculty of Engineering, Alexandria University, Vol. 4, 2016, pp 3239–3245.
27. Al-Baghdadi T A, Brown M J, Knappett J A and Ishikura R. Modelling of laterally loaded screw piles with large helical plates in sand. In *Frontiers in Offshore Geotechnics III: Proceedings of the 3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015)* Vol. 1, 2015, pp 503-508. Taylor & Francis Books Ltd.
28. Wang L, Coombs W M, Augarde C E, Brown M, Knappett J, Brennan A, Richards D and Blake A. Modelling screwpile installation using the MPM. *Procedia Engineering*, 175 January 2017, pp 124-132.

29. Phuong N, van Tol A F, Elkadi A S K and Rohe A. Modelling of pile installation using the material point method (MPM). *Numerical Methods in Geotechnical Engineering*, May 2014, pp 271-276.
30. Duan N, Cheng Y P and Liu J W. DEM analysis of pile installation effect: comparing a bored and a driven pile. *Granular Matter*, Vol. 20, August 2018.

ROTARY JACKING: MODELS FOR INSTALLATION RESISTANCE AND CAPACITY OF TUBULAR PILES THAT SUPPORT THE UPSCALING OF SCREW PILE TECHNOLOGY

D J WHITE

Geomechanics Group, Faculty of Engineering and Physical Sciences, University of Southampton

A D DEEKS

Norwegian Geotechnical Institute

SUMMARY: The installation and in-service performance of a screw pile depends on the resistance offered by both the helix and the shaft. Models for the resistance of the shaft can be developed by extending conventional solutions for the axial shaft resistance on conventional piles. This presentation describes model tests in which non-helical piles are installed into sand via rotary jacking – a screw-type action – and then load tested. The research was prompted by the development in Japan of large scale onshore rotary jacking machines. These machines have torque and thrust capacities of >1 MNm and >3 MN respectively, and are used to install steel tubular piles with diameters of >1.5 m, for earth retention systems and building foundations. The power of these machines significantly outstrips the capacity of conventional onshore screw pile installation plant, and offer an illustration of the potential upscaling of screw pile technology for offshore applications.

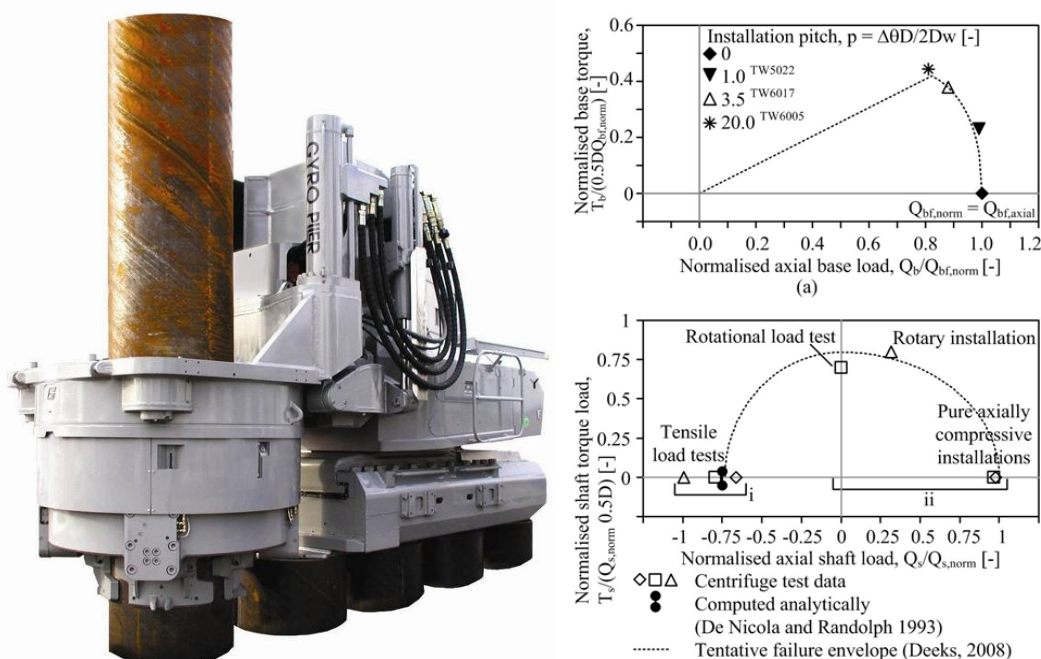


Figure: Large scale rotary jacking machine (left); Combined axial force – torque envelopes (right).

The model test results support a new analytical approach for shaft resistance during rotary jacking based on failure envelopes for the axial-torsional capacity of the pile. This approach provides a new basis for predicting and linking the installation and in-service responses of the shaft element of screw piles. These models are useful as screw piles are upscaled to offshore applications. They provide a basis to quantify the interaction between the forces created by the shaft and the helix, and allow the pitch and dimensions of a screw pile to be optimised to maximise the in-service capacity within limits of available installation force and torque.

FINITE ELEMENT MODELLING OF THE UPLIFT BEHAVIOUR OF SCREW PILES IN SAND

B CERFONTAINE, M J BROWN, J A KNAPPETT, C DAVIDSON

Department of Geotechnics, University of Dundee, Fulton Building, Dundee DD1 4HN UK
bcerfontaine@dundee.ac.uk

SUMMARY: In this paper a simplified procedure to incorporate some installations effects into the numerical finite element modelling of screw pile uplift is presented. The procedure consists of the approximation of the installation phase through 1) the application of a compression loading corresponding to successive embedment depths, 2) the use of modified soil properties over a disturbed zone. Pre-defined failure mechanisms are added to introduce some weakened zones due to either soil disturbance or strain-localisation. The results of numerical simulations are compared to a centrifuge test undertaken at the University of Dundee. The simulation considering an inclined failure mechanism and the simulated installation better captures the uplift capacity and initial stiffness.

INTRODUCTION

Screw piles have three main advantages that make them particularly suitable for offshore anchoring and foundations¹. The environmental disturbance generated during their installation, that can be damaging for marine mammals (noise, vibrations), is limited as the pile is screwed into the soil during its installation. A significant uplift capacity can be mobilised as the helix acts as an embedded plate. Finally, they can be easily removed from the soil by applying the reverse procedure, restoring the seabed back to its initial conditions.

The uplift capacity is a critical feature for several offshore applications, such as floating wind turbines² or jacket foundations³. The prediction of the screw pile uplift capacity is largely based on criteria developed for plate anchors⁴. However, these methods do not incorporate any installation effects, while recent studies have shown that the installation can modify the failure mechanism^{5,6} and reduce the uplift capacity.

The deployment of offshore screw piles will necessitate a significant upscaling of the onshore typical designs and the applicability of relatively small-scale based methods to large geometries is unknown. Finite element modelling is a relatively simple tool to simulate a large number of configurations but does not allow the modelling of the entire installation process. This would require more advanced numerical methods such as MPM⁷ or DEM⁸, which are computationally intensive and require specialised expertise, not always available.

The objective of this paper is to develop a simplified methodology to incorporate some installation effects into the finite element modelling of screw piles. The installation effects of two different possible failure mechanisms (cylindrical⁹ or conical³) are assessed and numerical results are compared with experiments undertaken in the centrifuge at the University of Dundee³.

INSTALLATION DISTURBANCE

The installation of piles inherently generates some disturbance, as the piles replace the soil previously in place. The soil disturbance consists of a change of the soil structure (e.g. density, anisotropy) and/or a change of the stress field around the pile. This disturbance results from the combination of several physical phenomena, as reported in Figure 1. Their relative importance and magnitude strongly depend on the installation method (e.g. following a true helical movement -pitch-matched- or not), but also on the geometry of the pile (e.g. helix and shaft diameters).

The crowd force applied to install the pile influences the soil far below the pile tip, generating settlement and increasing the vertical stress, as illustrated in Figure 1(a)(1). When the pile tip reaches a given depth, it creates some cavity expansion⁸ and moves the soil laterally, increasing vertical and lateral stress, as shown in Figure 1(a)(2) and demonstrated through DEM simulations¹¹. Afterwards, the soil particles are moved upwards, downwards or remain at the same depth, depending on the helix pitch, as described in Figure 1(a)(3), loosening the soil just above the helix. Finally, some cavity expansion occurs, decreasing the lateral and vertical stress fields after the helix movement. Some relative displacement between the helix and the soil particles holds, due to the soil shearing, as represented in Figure 1(a)(4).

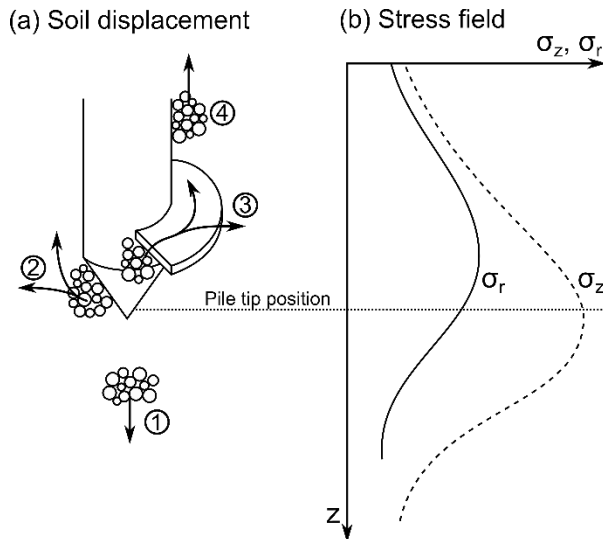


Figure 1: Idealisation of the disturbance induced by the screw pile installation on the (a) soil displacement and (b) vertical σ_v or radial σ_r stress field around the pile

The physical and strength properties of the soil disturbed due to the installation process are likely to affect the behaviour of the pile, while loaded. The tensile capacity of the pile is expected to be the more affected, as all density disturbance is located above the helix. While the tensile failure mechanism is usually assumed to be a conical soil wedge⁸, a highly disturbed cylindrical volume of soil located above the helix has been observed by Schiavon et al.⁸ and it was assumed failure occurred along a cylindrical failure surface. In the following both failure mechanisms are investigated, and results are compared to a centrifuge test.

NUMERICAL PROCEDURE

A numerical procedure has been recently proposed¹¹ to incorporate some simplified installation effect into the finite element simulation of screw pile uplift behaviour in sand. It has been compared against centrifuge tests and was shown to provide results consistent with centrifuge

test results. The original two-stage procedure is illustrated in Figure 2 and only incorporates a stress field disturbance, i.e. there is no significant modification of porosity or soil strength.

The first stage of the procedure (Figure 2(a)) consists in identifying the failure mechanism of the considered screw pile assumed wished-in-place in an undisturbed soil. The magnitude of the shear strain along the failure mechanism is also inspected. It could be expected that some strain-softening should take place at large shear strain (above a given threshold), although the HSsmall model used does not simulate it.

In the second stage, interface elements are defined along the position of the observed failure mechanism (Figure 2(b)). The constitutive law assigned to these interface elements allows a reduction of the shear strength along a ‘softening zone’, close to the edge of the pile, where the shear strain is beyond a given threshold. The length of this softening zone was set up to two helix diameters D_h . The stress field is modified by considering the crowd force applied during installation (Figure 2(c)). Five successive steps representative of increasing penetration depth H are simulated. The plate elements corresponding to the pile geometry at a given depth are activated and the corresponding crowd force is applied, then reduced to zero.

The procedure can be extended easily to incorporate a cylindrical failure mechanism, as shown in Figure 2(b). In this case, interface elements are defined vertically. The properties of this interface as well as the disturbed volume of soil enclosed are defined to be at critical state, to be consistent with a large soil disturbance.

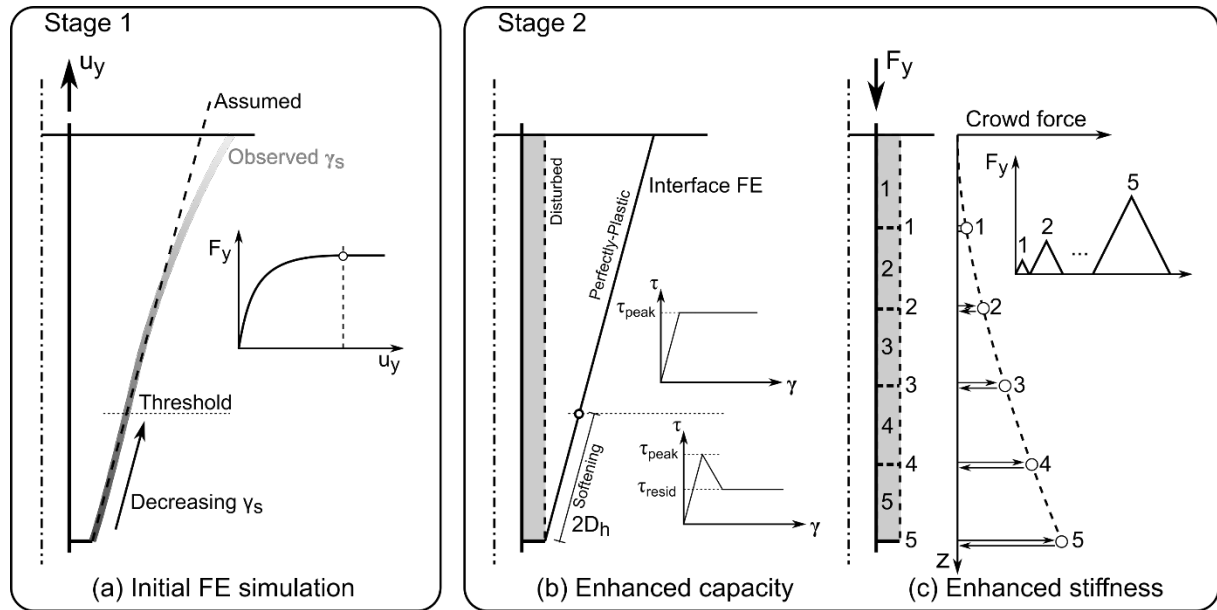


Figure 2: Summary of the two-stage procedure for the simulation of the uplift capacity of screw piles, incorporating a simplified modelling of the installation effects.

RESULTS AND DISCUSSION

The example simulated in the following consists of a screw pile embedded in saturated dense sand ($D_r \approx 84\%$) at the relative embedment ratio H/D_h equal to 5.9. The main soil parameters are given in Table 1 and more detailed information about the tests and simulations can be found in^{11,12}.

Table 1: HSsmall soil parameters of the HST95 sand, relative density (D_r), peak friction and dilatancy angles (ϕ_p , ψ_p), cohesion (c'), total unit weight (γ_{tot}), secant reference modulus (E_{50}^{ref}) and material parameter m .

D_r [%]	ϕ_p [°]	ψ_p [°]	c' [kPa]	γ_{tot} [kN/m ³]	E_{50}^{ref} [MPa]	m [-]
84	45.8	17	1	20.3	51.5	0.52

Figure 3(a) compares experimental result (Centrifuge) to the simulation of a wished-in-place pile (No mechanism) or incorporating only a pre-defined failure mechanism (Cylindrical or Conical, stage 2(b)). The vertical uplift load F_y corresponding to the wished-in-place simulation overpredicts the centrifuge capacity, which was also observed for the other geometries considered in¹¹ at deeper embedment or in a medium-dense sand. Considering a conical pre-defined failure surface leads to a slight underestimation of the capacity, while the cylindrical surface grossly underpredicts the capacity. In all cases, the stiffness is not correctly captured.

Figure 3(b) compares centrifuge and numerical results after the full numerical procedure has been applied, namely a compression load has been applied at several depths. This case shows an improvement of the prediction for both cases (stiffness and capacity). However the conical mechanism is still the best approximation of the experimental results.

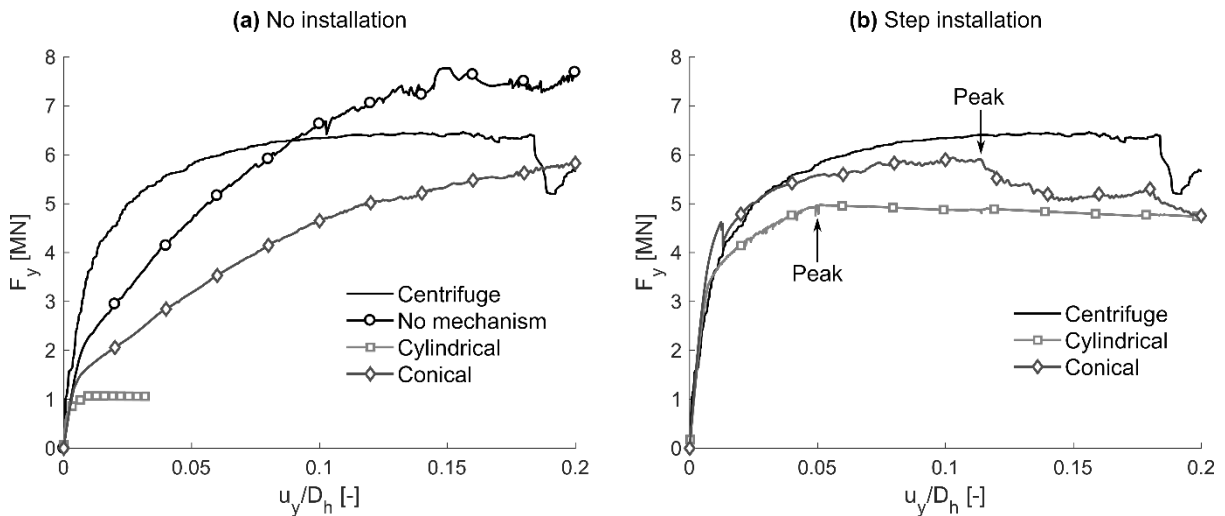


Figure 3: Comparison of centrifuge tests with uplift simulation of a shallow screw pile ($H/D_h = 5.9$) (a) Considering stage 1 simulation (no mechanism) or a pre-defined mechanism (cylindrical or conical); (b) Considering a pre-defined mechanism (cylindrical or conical) and installation effects

The vertical displacement u_y and plastic points corresponding to the maximum uplift force (peak in Figure 3) are depicted in Figure 4. This figure shows that the failure mechanisms active at the end of the simulation are the ones that were predefined (a wedge and a cylinder respectively), although the conical failure mechanism departs slightly from the linear pre-defined shape while approaching the surface. In addition, the displacement field clearly exhibits that the vertically moving soil is not monolithic, but a gradient of displacement exists due to the soil compressibility. This soil compressibility induces an increase in lateral stress which in turns enhances the maximum shear stress available along the failure mechanism (with respect to the initial stress distribution), as discussed in¹³.

The step procedure used to simulate installation applies a compression force of increasing magnitude at different fixed depths. The volume of soil affected by this load is mainly located directly below the helix and extends laterally as a function of the load magnitude, i.e. it is greater at greater depth. The normal stress distribution along the pre-defined failure mechanism in Figure 5 illustrates how the stress distribution is affected after the installation and during uplifting (at peak uplift force).

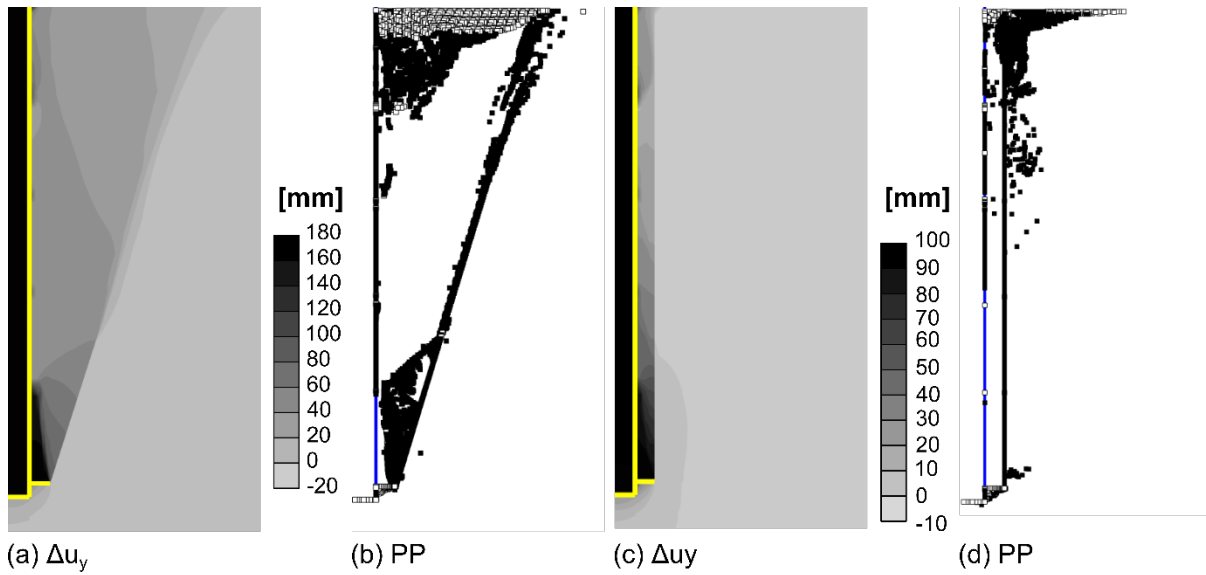


Figure 4: Comparison of vertical displacement Δu_y and plastic points PP for pre-defined (a-b) conical failure mechanism and (c-d) cylindrical failure mechanism. Results are given at peak, depicted by an arrow in Figure 3(b).

In all cases, the installation procedure increases the lateral stress along the location of the failure mechanism (even before the uplift starts), as shown in Figure 5(Initial). The conical failure mechanism continuously moves away from the shaft while approaching the soil surface, i.e. it moves away from the area where the stress magnitude was increased. On the contrary, the cylindrical failure mechanism is continuously located where the stress increase has been the greatest. Subsequently, the maximum shear stress that can be mobilised at failure increases and the enhanced capacity is fivefold the one which does not consider any installation.

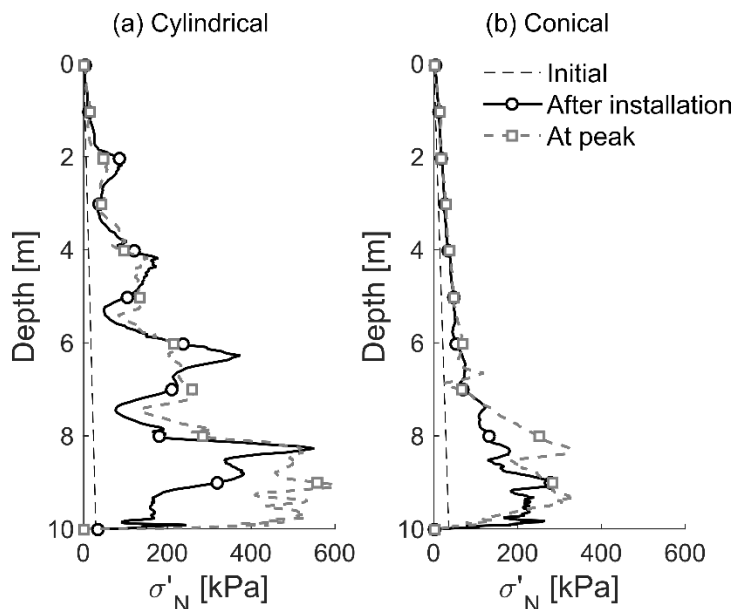


Figure 5: Normal stress distribution along the failure mechanism at different time steps in case along a pre-defined (a) cylindrical or (b) conical failure mechanism

CONCLUSION

Screw piles have been recognised as a promising technology for the foundations and anchoring of offshore and marine renewable energy devices. Experience and design method are available

from onshore applications, but a significant upscaling is necessary for offshore applications. However, no standard simulation method is currently able to simulate the installation effects onto screw pile uplift behaviour.

The screw pile installation generates a disturbed zone around the anchor where the soil density is modified due to the penetration of the helix and the shaft. The stress field around the pile is also modified due to the cavity expansion generated by the shaft penetration and the relatively large crowd force applied during installation.

This paper introduces a simplified procedure to take into account some installations effects into the numerical simulation of screw pile uplift. The crowd force is applied in several steps, corresponding to successive screw pile depths. The soil properties corresponding to a disturbed zone are modified to introduce the helix disturbance. A pre-defined failure mechanism is finally added into the mesh to consider a weakened zone due to the helix disturbance (cylindrical mechanism) or strain localisation (conical mechanism).

Simulations considering a conical failure mechanism are shown to better predict the anchor uplift capacity, but also the initial stiffness, when compared to centrifuge tests.

ACKNOWLEDGEMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 753156. The authors would also like to acknowledge the support of EPSRC (Grant no. EP/N006054/1: Supergen Wind Hub: Grand Challenges Project: Screw piles for wind energy foundations).

REFERENCES

1. Byrne BW, Houlsby GT. Helical piles: an innovative foundation design option for offshore wind turbines. *Philos Trans R Soc A Math Phys Eng Sci.* 2015;373(February):1–11.
2. Bachynski EE, Kvittem MI, Luan C, Moan T. Wind-Wave Misalignment Effects on Floating Wind Turbines: Motions and Tower Load Effects. *J Offshore Mech Arct Eng.* 2014;136(4):041902.
3. Davidson C, Brown MJ, Cerfontaine B, Al-Baghdadi T, Knappett J, Brennan A, et al. Feasibility of screw piles for offshore jacket structures, Part I: physical modelling. (submitted for consideration in) *Géotechnique.* 2019;
4. Ghaly A, Hanna A, Hanna M. Uplift behaviour of screw anchor in sand, I dry sand. *J Geotech Eng.* 1991;117(5):773–93.
5. Schiavon JA, Tsuha CHC, Thorel L. Scale effect in centrifuge tests of helical anchors in sand. *Int J Phys Model Geotech.* 2016;16(4):185–96.
6. Cerfontaine B, Knappett J, Brown MJ, Davidson C, Al-Baghdadi T, Brennan A, et al. Feasibility of screw piles for offshore jacket structures, Part II: numerical modelling. (submitted for consideration in) *Géotechnique.* 2019;
7. Wang L, Coombs WM, Augarde CE, Brown M, Knappett J, Brennan A, et al. Modelling Screwpile Installation Using the MPM. *Procedia Eng.* 2017;175:124–32. Available from: <http://dx.doi.org/10.1016/j.proeng.2017.01.040>
8. Zhang N, Arroyo M, Ciantia MO, Gens A, Butlanska J. Standard penetration testing in a virtual calibration chamber. *Comput Geotech.* 2019;111(March):277–89. Available from: <https://doi.org/10.1016/j.compgeo.2019.03.021>
9. Perez ZA, Schiavon JA, Tsuha CHC, Dias D, Thorel L. Numerical and experimental

- study on the influence of installation effects on the behaviour of helical anchors in very dense sand. *Can Geotech J.* 2018;55:1067–80.
10. Deeks AD, White DJ. *An investigation into the strength and stiffness of jacked piles in sand*. Ph D, Cambridge Univ Cambridge, UK. 2008;(July):1–390.
11. Sharif YU, Brown MJ, Ciantia MO, Knappett JA, Davidson C, Cerfontaine B, et al. Numerically modelling the installation and loading of screw piles using DEM. In: *Proceedings of the International Symposium on Screw Piles for Energy Applications*. Dundee, UK; 2019.
12. Giampa J, Bradshaw A, Schneider J. Influence of Dilation Angle on Drained Shallow Circular Anchor Uplift Capacity. *Int J Geomech.* 2017;17(2):4016056. Available from: [http://dx.doi.org/10.1061/\(ASCE\)GM.1943-5622.0000725](http://dx.doi.org/10.1061/(ASCE)GM.1943-5622.0000725)
13. Cerfontaine B, Knappett JA, Brown MJ, Bradshaw AS. Effect of soil deformability on the failure mechanism of shallow plate or screw anchors in sand. *Comput Geotech.* 2019;109(May):34–45.

STRESS VARIATION DURING INSTALLATION OF MONO-HELIX HELICAL PILE

L THOREL, I EL HAFFAR

Ifsttar GERS Department, Geomaterials & Models in Geotechnics Laboratory, Bouguenais, France

M NEME GAMARRA

IFSTTAR GERS Department, Geomaterials & Models in Geotechnics Laboratory, Bouguenais, France and Universidad La Republica, Montevideo, Uruguay

J A SCHIAVON

Department of Geotechnical Engineering, Aeronautics Institute of Technology, São José dos Campos, Brazil and Department of Geotechnical Engineering, University of São Paulo, São Carlos, Brazil

C H C TSUHA

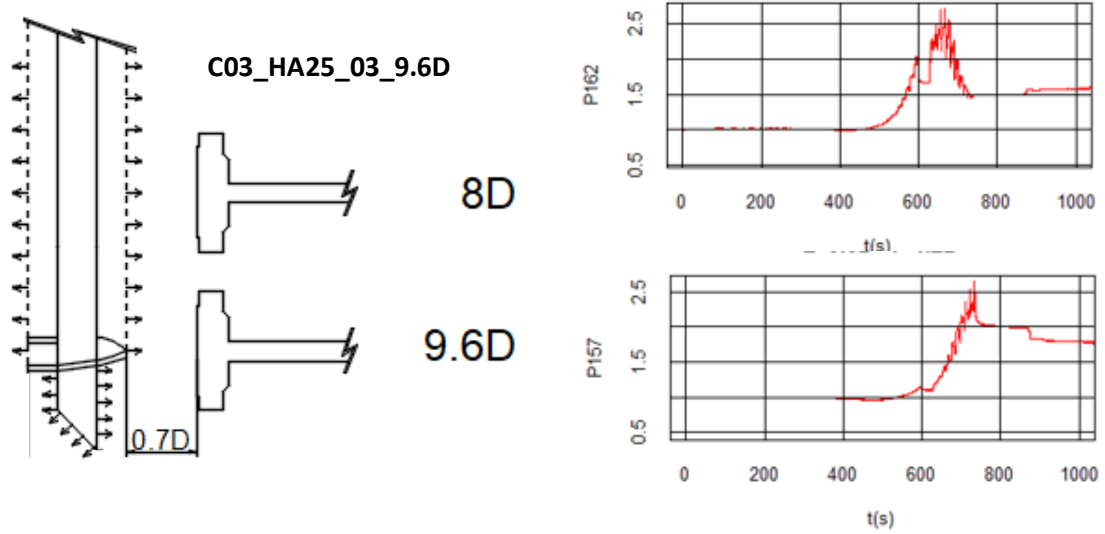
Department of Geotechnical Engineering, University of São Paulo, São Carlos, Brazil

SUMMARY: When a mono-helix helical pile is installed in a dense sand, the progressive screwing of the pile generates displacement of the sand grains. A cylindrical volume of sand is remoulded above the helix, as it has been shown previously¹.

A series of centrifuge tests has been performed in saturated sand in order to study the behaviour of helical pile. In the vicinity of mono helix piles, stress and pore pressure sensors have been pre-installed in order to follow the variation of stresses during the installation, the monotonic loading and the cyclic loading.

During the installation, performed at an angular velocity of 5.3 RPM, on an helix of $D = 25$ mm of diameter and with a pitch of 7 mm, the remoulding process generates dilatancy, and so an increase of the horizontal stresses.

The results show that the stress field is modified both vertically and horizontally during the phases of installation. On the figure below, the total stresses, measured with Kyowa sensors located at an horizontal distance of $0.7 D$ from the disturbed cylinder of soil, and at depth respectively of $8 D$ and $9.6 D$, are presented as normalised by the initial stress. It is shown that the horizontal stress is increased by about 2.5, and maintained at least at a ratio of 1.5, even after the helix has moved deeper.



REFERENCES

1. Schiavon J.A., Tsuha C.H.C., Thorel L. 2016. Scale effect in centrifuge tests of helical anchors in sand. *Int. J. Physical Modelling in Geotechnics* ISSN 1346-213X <http://dx.doi.org/10.1680/jphmg.15.00047>

OBSERVATIONS ON THE CYCLIC AND POST-CYCLIC RESPONSE OF SCREW ANCHORS IN DRY SAND

J A SCHIAVON

Dep of Geotech. Engineering, Aeronautics Inst. of Technology, São José dos Campos, Brazil
Department of Geotechnical Engineering, University of São Paulo, São Carlos, Brazil

C H C TSUHA

Department of Geotechnical Engineering, University of São Paulo, São Carlos, Brazil

L THOREL, I EL HAFFAR

Ifsttar GERS Department, Geomaterials & Models in Geotechnics Laboratory, Bouguenais, France

SUMMARY: A variety of applications for screw anchors requires safe operation under repeated loads arising mainly from environmental changes. Previous studies on other types of anchors and piles have highlighted the potential for excessive displacement accumulation, bearing and shaft capacity degradation or even complete anchor pull-out to occur with cycles. For screw anchors, however, the literature is still scarce, and few guidelines are validated. To address this issue, a comprehensive experimental campaign was undertaken in the Ifsttar geo-centrifuge in which a set of cyclic tests simulated screw anchors under different intensities and number of loading cycles. The model anchors were installed in very dense sand beds and subjected to different loading conditions (monotonic, cyclic and post-cyclic). First, an evaluation of scale effects on the uplift capacity was carried with different sizes of anchors. For the cyclic tests, the main aspects investigated were installation forces, soil disturbance due to anchor installation, axial load-displacement response under cyclic loading, cyclic displacement accumulation, cyclic stability, changes in the post-cyclic axial capacity. The observations from the current investigation draw attention to three topics of major significance: (i) the effect of pre-failure and pre-loading on the anchor uplift behaviour; (ii) displacement accumulation with cycles; (iii) increase or reduction of post-cyclic tensile capacity due to cyclic loading. For the first topic, the proposition of some design guideline is difficult since this effect is dependent on the soil type, and more tests are needed to confirm the trends observed in current study. The other two topics have been rarely addressed and little information is available to provide support for decisions in design of screw anchors. The main observations of the current study are: (a) anchor behaviour was governed by helix bearing resistance, and no degradation of helix bearing capacity was noticed with cycles; (b) most of degradation of shaft resistance was noticed in the first 100 cycles; (c) A more significant rate of displacement accumulation occurred for the first 100-300 cycles, but the accumulation does not ceased up to 3000 cycles (maximum tested); (d) no catastrophic anchor failure was observed for the cyclic loading conditions and numbers of cycles performed, however, the accumulated displacements generated during the cycles may reach the serviceability limit state; (e) For cyclic loading conditions that caused accumulated displacements (U_{acc}) larger than 10% of the helix diameter (D) after 1000 cycles (failure criteria), negligible degradation of the post-cyclic uplift capacity was noticed, however, in some cases of low mean load and $U_{acc} < 10 \% D$ after 1000 cycles, some degree of degradation of the post-cyclic uplift capacity occurred.

STATIC AND CYCLIC AXIAL LOADING OF SINGLE AND MULTIPLATE HELICAL ANCHORS IN SAND

J T NEWGARD, J S MCCARTNEY

University of California San Diego, La Jolla, CA, USA

J A SCHNEIDER

United States Army Corps of Engineers, St. Paul, MN, USA

D J THOMPSON

Naval Facilities Engineering and Expeditionary Warfare Center, Port Hueneme, CA, USA

Disclaimer: The views expressed are those of the authors and do not necessarily represent those of the U.S. Army Corps of Engineers

SUMMARY: A series of four static and four cyclic uplift tests were performed on 152 mm diameter single and multiplate helical anchors embedded approximately 5.5 diameters in a high friction angle sand. Multiplate anchors had approximately 10% higher static uplift capacity but showed negligible accumulation of displacement after 10,000 one-way cycles at approximately 20% of the static capacity. Under the same cyclic loading conditions, single plate anchors accumulated uplift displacements of approximately 6% to 10% of the diameter at 10,000 cycles. After cyclic loading, one of the single plate anchors was re-installed to its initial installation depth and showed similar cyclic performance for a follow on cyclic loading sequence.

Keywords: Capacity, cyclic, long term loading, multiplate, uplift.

INTRODUCTION

Previous research has indicated that multiplate helical anchors may accumulate less displacement than single plate anchors under cyclic load for a constant installation depth and constant cyclic load amplitude². This may result from an increase in static resistance from the additional plate, or differences in the mechanism of displacement accumulation between the two anchor types. An experimental program was performed to compare static capacity and cyclic accumulation of displacements for one single plate and two double plate anchor types for a constant cyclic amplitude.

ANCHORS AND TEST PROGRAM

Three helical anchors (shown in Figure 1) were analysed in this study:

- 1) a 152 mm single plate anchor, 35 mm shaft, 22 mm to 48 mm pitch variable pitch, and a 5 mm plate thickness

- 2) a double plate anchor with 152 mm top and bottom plates, 33.5 mm shaft, 30 mm constant pitch, and 5 mm plate thickness
- 3) a double plate anchor with a 254 mm top plate and a 152 mm bottom plate, 48 mm shaft, 30 mm constant pitch, and a 5 mm plate thickness

For the two double plate anchors, the upper plate is 508 mm ($3.3D$) above the lower plate where D is the lower plate diameter. Static and cyclic axial loading tests were conducted on the helical anchors in a 1.5 m wide by 1.5 m deep by 25 m long concrete trench. Sand was compacted into the trench in 152 mm lifts with a vibroplate, followed by bottom-up saturation which occurred over approximately 1 week. The first trench (Trench 12) was prepared on 14-15 April 2015, and testing was performed between 23 and 29 April 2015. The second trench (Trench 13) was prepared on 30 April 2015, and testing was performed between 12 and 26 May 2015. Helical anchors were installed under rate controlled conditions using dead weight and a winch. The winch rate and the rotation rate were specifically matched to the pitch of each anchor to minimize the required vertical force during installation. In all cases the vertical advancement rate was approximately 10 mm/s.

The test program is summarized in Table 1. In addition to the tests listed below in Trenches 12 and 13, a static test on a 152 mm diameter anchor performed in a different trench (Trench 8) reported by Newgard et al.⁵ is included in this table, and the new results in this study are discussed in light of results from that paper to provide additional insight on helical anchor cyclic response.

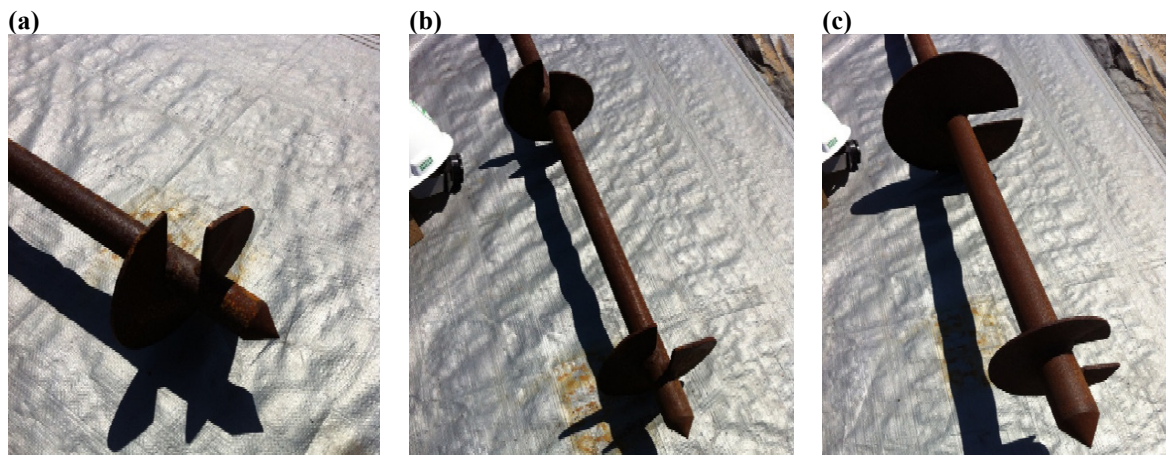


Figure 1: Photographs of anchors used in this study (a) 152 mm single plate (b) 152-152 double plate (c) 152-254 double plate

SOIL CHARACTERIZATION

The sand investigated in this study is referred to as Golden Flint sand ($e_{\max} = 0.847$; $e_{\min} = 0.487$; $C_u = 1.61$; $C_c = 1.13$) and is classified as SP according to the Unified Soil Classification Scheme (USCS). Miniature (2 cm^2) cone penetration tests (mCPTs) were performed to characterize the density, friction angle, and dilation angle of the sand⁶. Figure 2 summarizes the average mCPT tip resistance and inferred soil properties for Trenches 12 and 13 that were tested in this study, as well as Trench 8, tested by Newgard et al.⁵. The soil layers in each trench are similar in character with similar behaviour with depth and lateral extents. No significant increases in mCPT tip resistance were observed during the duration of the anchor tests.

The inferred soil properties in Figure 2 were based on a calibrated relative density correlation developed in Schneider et al.⁶ linked to laboratory triaxial tests through the Bolton

¹ stress dilatancy relationship with parameters $Q = 9.5$, $R = -0.68$, $\beta = 0.64$. Friction and dilation angles were assessed at the in situ vertical effective stress, which is close to the mean effective stress at failure for helical anchor uplift in sand³. The friction angle of the sand ranged from 36° to 51° and is considered a high friction angle sand.

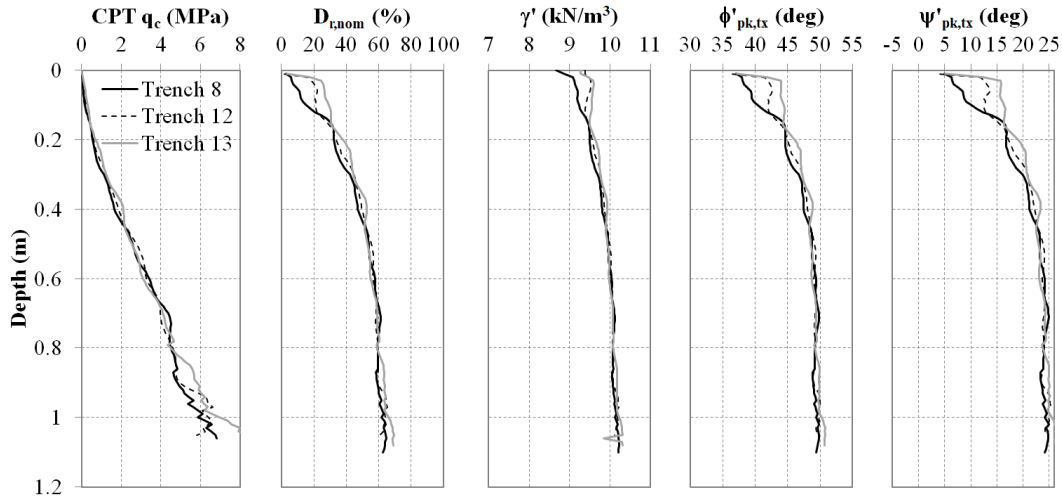


Figure 2: Average CPT tip resistance and inferred soil properties for Trenches 8, 12, and 13

Table 1. Summary of testing program and results.

Trench	Test	Diameter (mm) ^a	Inst. Depth (mm)	Test Type	Inst. Torque (N-m) ^b	Mean Max Load ^c (N)	Mean Min Load ^c (N)	Cycles	Resistance at Failure, R_f (N)	Tip Depth at Failure, z_f (mm)
8	2	152	840	Static	96	--	--	--	4550	827
12	7	152	831	Cyclic	108	1011	-17	17803	4566	803
12	8	152	830	Static	135	--	--	--	4841	820
13	3	152 / 152	836	Cyclic	160	1019	-6	15347	4570	824
13	4	152 / 152	840	Static	173	--	--	--	5073	831
13	5	152 / 254	844	Cyclic	285	1005	-11	12684	4816	840
13	6	152 / 254	852	Static	303	--	--	--	5024	847
13	7	152	835	Static	95	--	--	--	4294	819
13	8	152	835	Cyclic	130	1004	-21	39083	--	--
13	8re	152	834	Cyclic	-- ^d	992	-9	41800	5384	804

^a Double plate anchor notation formatted as [bottom plate diameter / top plate diameter]

^b As measured over the last $\frac{1}{2}$ diameter (of bottom plate) in depth

^c Sign convention is positive in uplift/tension, negative for downward/compression

^d Anchor was only re-installed approximately 25 mm deeper to reach its initial depth before cycling

STATIC UPLIFT TESTS

Eight new static uplift tests are presented in this paper, four of those performed after a period of cycling. The results of these tests are included in Table 1. Resistance at failure (R_f) was defined

as the maximum sustained load the anchor could resist without pulling out of the sand layer. An anchor test may have resulted in three possible failure conditions; (i) static loading to failure (S) or (ii) failure during cycling (C); or (iii) failure during a post-cyclic static test (PC). Within this test series the cyclic load level was low enough in all cases to preclude failure during cycling (C).

The load displacement-profiles for static uplift tests are shown in Figure 3. The average static uplift capacity for single plate anchors was 4562 N, with a coefficient of variation of 6%. The average static uplift capacity for double plate anchors was 5048 N, 11% higher than the single plate anchor tests, with a coefficient of variation of less than 1%. It is inferred that for this case of shallow uplift, the upper plates were entirely within the failure wedge³ and did not provide significant additional resistance. The cause of the additional 10% increase in capacity requires additional analysis. It is of interest to note that while each of the anchors had similar capacity, the installation torque was significantly higher for the multiplate anchors. The 152/152 anchors required approximately 1.6 times the installation torque of a single plate anchor, and the 152/254 anchors required approximately 3.0 times the installation torque of a single plate anchor to install.

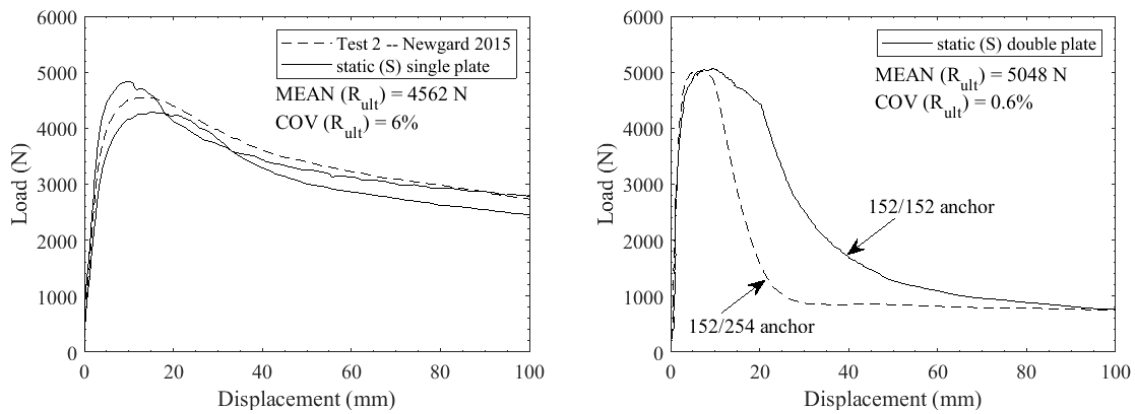


Figure 3: Comparison of load-displacement profiles for single and multiplate anchors

CYCLIC PERFORMANCE

Each cyclic test lasted for at least 10,000 load cycles, the cycles were load controlled, and the load limits were constant throughout the program. The load limits are defined via ζ_b and ζ_c :⁴

$$\zeta_b = \frac{Q_{\max}}{R_{\text{ult}}} \quad (1)$$

$$\zeta_c = \frac{Q_{\min}}{Q_{\max}} \quad (2)$$

In these expressions, Q_{\min} is the mean minimum cyclic load (i.e. compression loading) and Q_{\max} is the mean maximum cyclic load (i.e. uplift loading). R_{ult} is the capacity under static uplift, taken here as the average value of the single plate, or multiple anchors. The load limits were held the same in all tests – the anchors were loaded to approximately 20% of R_{ult} in uplift with no compressive loads applied. Based on LeBlanc et al.⁴, a pair of empirical equations that predict the accumulation of displacements (w) due to cyclic loading are given in Equations 3 and 4:

$$T_b = f(\zeta_b) = \frac{1}{a} (\zeta_b)^c \quad (3)$$

$$\frac{w}{D} = T_b \cdot T_c \cdot N^d \quad (4)$$

where a , c , and d are empirical fitting parameters. Newgard et al.⁵ suggested values of $a = 40$; $c = 1.7$; $d = 0.4$ for uplift of helical anchors in high friction angle Golden Flint sand; N = cycle number; D = anchor diameter; w = vertical displacement; and $T_c = 1$ for one-way cyclic loading (all tests in this study). These parameters tend to also match single plate anchor anchors at the lower cyclic stress ratios tested in this study.

The repeat tests of the 152 mm single plate anchor (Test 12-7 and 13-8) exhibited accumulated displacements within 3 mm of each other after about 17,000 cycles, indicating reliable reproducibility of results. Both the 152 / 152 mm (Test 13-3) and the 152 / 254 mm (Test 13-5) double plate anchors essentially did not move during the entirety of cycling. The apparent accumulation of compressive displacements for multiplate anchors ($-w/D$ in Figure 4), may have resulted from a slight temperature drift in instrumentation for the overnight tests.

After cycling, the 152 mm single plate anchor (Test 13-8) was re-installed (Test 13-8re) approximately 25 mm to reach its initial depth before cycling, and then cycled again. The displacements accumulated at the same rate during both tests. This suggests a potentially valuable maintenance strategy wherein the anchor is re-installed periodically, perhaps after severe storm loading, to mitigate accumulated displacements.

As is evident from Figure 4f, which provides fits to the data via the model detailed by Equations 3 and 4, the double plate anchors accumulate less displacement than the single plate anchors. The model fits and the test data for each cyclic test are shown in Figure 4a-4e. The mechanism of the double plates' increased resistance to cyclic loading requires further study. Because the 152 / 152 mm double plate anchor required much less torque to install than for the 152 / 254 mm double plate anchor, and it did not accumulate displacements during cycling, it may be considered to be the best performing anchor in this study.

CONCLUSIONS

Single and double plate anchors have been tested under static uplift and long term axial cyclic loading in sand. While the double plate anchors required approximately 1.6 to 3 times the installation torque, they exhibited only approximately 10% higher static uplift capacity. However, minimal cyclic displacements were accumulated for the multiple plate anchors at a cyclic stress ratio of 20%. Despite higher torques, the 152 / 152 mm multiplate anchor was most efficient in terms of cyclic performance in this study.

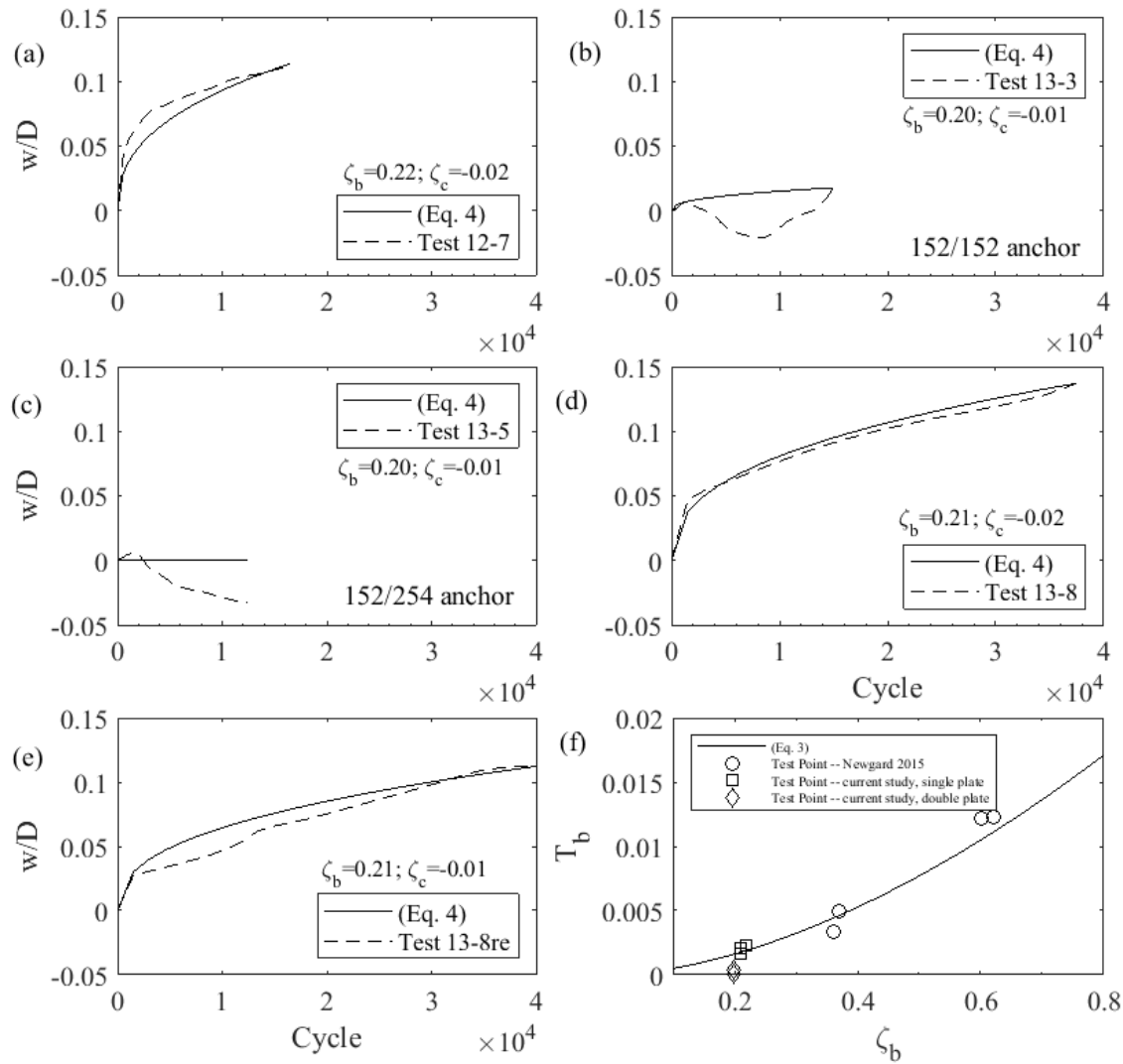


Figure 4: Measured and estimated displacements for long term cyclic tests (a) through (e); and single plate and multi-plate T_b parameters compared to results from Newgard et al.⁵ (f)

REFERENCES

1. Bolton M D. The strength and dilatancy of sands. *Géotechnique*, Vol. 36 (Issue 1), January 1986, pp 65-78.
2. Cerato A B and Victor R. Effects of helical anchor geometry on long-term performance for small wind tower foundations subject to dynamic loads. *Journal of the Deep Foundations Institute*, Vol. 2 (Issue 1), 2008, pp 30-41.
3. Giampa J R, Bradshaw A S and Schneider J A. 2016. Influence of dilation angle on drained shallow circular uplift capacity, *ASCE Int. J. of Geomechanics*, 17(2): 11pp.
4. Leblanc C, Houlsby G T and Byrne B W. Response of stiff piles in sand to long-term cyclic lateral loading. *Géotechnique*, Vol. 60 (Issue 2), February 2010, pp 79-90.
5. Newgard J T, Schneider J A and Thompson D J. Cyclic response of shallow helical anchors in a medium dense sand. *Proc. of Frontiers in Offshore Geotechnics III*, Oslo, Norway, June 2015. CRC Press, London, 2015, pp 913-918.
6. Schneider J A, Giampa J R, Bradshaw A S and Newgard J T. 2016. Calibrating CPT relative density and strength correlations for a laboratory fine sand, *Proc. 5th Int. Conf. Site Characterisation*, Brisbane, 449-454.

EFFECTS OF HELICAL PILE INSTALLATION ON THE LATERAL STIFFNESS FOR PILES IN DENSE SAND

Z H ELSHERBINY

Senaltek Engineering Group Ltd., Calgary, AB, Canada
z.elsherbiny@senaltek.com

M H EL NAGGAR

Department of Civil and Environmental Engineering, The University of Western Ontario,
London, Ontario, Canada

A ELGAMAL

Department of Structural Engineering – University of California San Diego, San Diego,
California, USA

SUMMARY: Design engineers and owners are sometimes hesitant to utilize helical piles as a foundation solution for applications where the lateral stiffness of the pile is an important design consideration. Such applications include foundations for wind turbines and equipment sensitive to vibrations, foundations for vibrating machinery, and foundations for tall structures. The main concern in these applications is that the installation of helical piles, especially with multiple helices, would cause disturbance to the soil around the pile and hence reduces its lateral resistance. This paper provides an insight into the effects of pile installation on the static and dynamic lateral stiffness of helical piles installed in dense sand. The information provided are the results of a full-scale field testing of instrumented single helix and double-helix piles and tested under monotonic and low-strain dynamic lateral loads.

Keywords: helical pile, installation disturbance, weak-zone

INTRODUCTION

Helical piles are made of a central steel shaft with one or more discontinuous helical plates welded to the shaft. The helical pile is installed into the ground by applying torque to its head and an axial downward force, called crowd, applied at the top of the pile via a motorized torque head. Circular shaft steel pipes are very common in Canada due to their large torque capacity. The diameter of the helical plates, for such piles, typically ranges between 2 to 4 times the diameter of the shaft.

The installation of closed-ended helical piles, same as driven piles, displaces a volume of soil to accommodate the installed pile. This action results in disturbance to the soil fabric and microstructure and alters the native in-situ soil stresses and density around the installed piles. The resulting disturbance could affect the soil resistance to the pile movement and hence may adversely impact the pile stiffness and capacity. It is particularly important to quantify the effects of pile installation on the stiffness of helical piles for applications where the lateral

Z H Elsherbiny, M H El Naggar, A Elgamal. *Effects of helical pile installation on the lateral stiffness for piles in dense sand. Proceedings of the 1st International Screw Pile Symposium on Screw Piles for Energy Applications*, Dundee, Scotland, 27 – 28 May 2019.

stiffness of the pile is of great importance to the design. Therefore, this study investigates the effects of helical pile installation on its lateral stiffness.

Foundations for many structural applications are designed to certain acceptance criteria such as to limit deflection and vibration response, and to avoid resonance with frequency of exciting forces. Such applications include wind turbines in which a proper foundation design would ensure that the wind turbine's dominant natural frequencies are away from the exciting forcing frequencies. Accurate estimate of natural frequencies requires an accurate representation of pile stiffness.

The research presented herein investigates the effect of disturbance on the lateral performance of single and multi-helix piles installed in dense sand by comparing actual performance to estimated performance from the literature by varying the soil strength and stiffness parameters.

BACKGROUND

Disturbance mechanisms

There are multiple disturbance mechanisms associated with helical piles installation which can be categorized into: installation disturbance; fabrication disturbance; and geometrical disturbance.

Installation disturbance can be categorized into inherent (unavoidable) and accidental (preventable) disturbances. Inherent installation disturbance results from the shearing of the soil structure by the helical plates, following a spiral path, as the pile advances into the soil. Accidental installation disturbance is typically caused by either lack of installation experience, unfavourable soil conditions such as inclusions of cobbles and boulders, or a combination of both. This type of disturbance can be avoided provided that there is a rigorous quality control program in place and is administered by experienced personnel.

The quality of pile installation can be assessed by the continuous monitoring of the rate of pile advancement, and the pile verticality during installation. The rate of pile advancement through the soil must be maintained at one helix pitch per full revolution. If the advancement rate is higher, it indicates that the applied crowd force is greater than the soil shear and bearing resistance and will result in great disturbance to the soil along and below the pile. If the advancement rate is lower, it indicates that the pile is spinning in place causing great disturbance to the soil along the pile. Piles in such cases must be rejected unless otherwise proven satisfactory by means of load testing. Pile verticality must be maintained throughout the installation otherwise a gap between the pile shaft and the surrounding soil will form at the ground surface. This type of disturbance can be alleviated by backfilling the gaps with properly compacted soil or non-shrink cementitious material.

Fabrication disturbance results from the way the pile is constructed, such as spacing between helices, helix shape, helix edges, shaft straightness, and shaft splicing. These disturbance factors can be avoided by administering rigorous fabrication quality standards and quality control program. For piles with multiple helices, it is important to ensure that all the helices follow the same shearing spiral path as they advance through the soil. This can be satisfied by ensuring that all helices have the same pitch and that the spacing between the helices is a whole multiple of the helix pitch.

The helix shape can also affect the level of soil disturbance. True helix shape is where the leading and trailing edges are parallel to each other and any radial line passing through the shaft's centre and across the helical plate is perpendicular to the pile shaft. True helix shape produces the lowest disturbance compared to other types of helical shapes. Similarly, bevelled leading edge of helical plate (i.e. knife-edged) and straight shaft also reduce the level of

disturbance. Finally, flush welded shaft splices produce less disturbance in the soil around the shaft compared to mechanical coupling splices which extend beyond the shaft diameter.

Geometrical disturbance refers to the soil disturbance caused by the pile geometry such as the shape of the shaft (square or circular) and the number of helices. Square shaft piles produce more soil disturbance compared to circular shaft piles. Consequently, the shaft resistance of square shaft piles is typically ignored in the design. Moreover, multiple helices produce more soil disturbance compared to single helix piles.

Degree of disturbance

The degree of disturbance depends on the type of soil and the disturbance mechanisms discussed in the previous section. There are two methods in the literature used to evaluate the degree of disturbance: direct and indirect. The direct method evaluates the soil disturbance via direct measurements of soil strength and stiffness parameters before and after disturbance. The indirect method estimates the degree of soil disturbance by comparing the actual pile performance with theoretical models such as comparing experimentally established p-y curves with published values in the literature¹.

Elkasabgy and El Naggar^{2,3} and Elkasabgy et al.⁴ investigated the axial and lateral low-strain dynamic performance of single helical piles and driven steel piles installed in clay till. Utilizing the indirect method, they reported a decrease in piles lateral stiffness due to the disturbance caused by the helices along the pile shaft during pile installation. They also reported similar disturbance caused by the installation of driven steel piles in the same soil. They concluded that the effect of installation disturbance on pile stiffness for structured and cemented soils, such as clay till, is significant. The effect is manifested by a reduction in the low-strain shear modulus of the soil around the shaft, as well as the creation of gaps around the shaft near the ground surface. They proposed considering an annular zone with reduced stiffness (weak zone) around the pile shaft to account for reduction in shear modulus when estimating the pile stiffness. They suggested diameter of the weak zone to be equal to the diameter of the largest helix and recommended some reduction factors for the soil shear modulus within the weak zone.

Lutenegger et al.⁵ conducted a series of field vane tests near the shafts of single-helix and multi-helix piles installed in a stiff over-consolidated clay crust overlaying normally consolidated clay layer. The vane tests were performed before and after the installation in an attempt to quantify the level of installation disturbance through direct measurement of undrained shear strength of the soil before and after disturbance. They concluded that the installation disturbance caused a reduction in the soil strength parameters; multi-helix piles produce greater disturbance compared to single-helix piles; and that the degree of disturbance is related to soil sensitivity and the quality of installation. Lutenegger and Tsuha⁶ conducted a series of compression and tension load tests on single and multi-helix piles in cohesive, cohesionless, and structured soils. They relied on the ratio of the uplift to compressive load capacity, of piles with same geometry and installed in the same soil, to indirectly evaluate the degree of disturbance. The main assumption employed is that the uplift capacity of a helical plate should be the same as its compressive capacity provided that the helical plates are deeply embedded and that shaft contributions to the capacity are negligible. They concluded that the degree of disturbance is negligible on the capacity of single and multi-helix piles in stiff clays; and that structured soils suffer the greatest disturbance which tend to lessen with an increase in the relative density of the structured soil.

Pérez et al.⁷ studied the effects of installation disturbance on the uplift capacity of single-helix piles installed in very dense sand by means of centrifuge testing and numerical modelling. They identified two zones of installation disturbance around the piles: the first zone with a diameter equal to the helix diameter with the most disturbance; and a less disturbed zone around

zone 1. They concluded that the installation disturbance in very dense sand resulted in a reduction in the uplift capacity and stiffness of the piles. This is manifested by the reduction in the breakout factors estimated from the numerical analysis when compared to values in the literature. They also concluded that the embedment ratio of the helix required to ensure a deep failure mode increased as a result of the disturbance when compared to values in the literature for deep embedment ratio corresponding to undisturbed soil strength parameters.

FULL-SCALE TESTING

The test setup, test layout, and site description are discussed in detail in Elsherbiny et al.⁸. A summary of the site description is provided herein for convenience.

Pile geometry

Two identical single-helix piles (SH-1 and SH-2) and two identical double-helix piles (DH-1 and DH-2) were tested under lateral static, and dynamic loads at the Englekirk Structural Engineering Center facility at the University of California San Diego.

The single-helix and double-helix piles were installed within 5m of each other such that the soil properties at each pile location may be considered the same. The central pile shaft was made of a welded steel pipe (ASTM A500, Grade B) with diameter equal to 114.3mm and a wall thickness equal to 8.6mm. Single-helix piles consisted of 254mm diameter helical plate and double-helix piles consisted of a top 254mm diameter helix and a bottom 203mm diameter helix with a helix spacing of 762mm. All piles had an overall pile length equal to 3.96m. Piles SH-1 and SH-1 were tested under static monotonic load and piles SH-2 and DH-2 were tested under low-strain dynamic loading. The piles projected 0.305m above grade and the lateral load on the piles was applied 0.270m above grade.

Test site description

A summary of the site description is provided herein. Site was backfilled to 9m depth with uncontrolled granular fill a number of years prior to the testing. The soil was a mix of sand, silt, and gravel. The top crust was dry and naturally cemented silty sand. Two CPT soundings (CPT-1 and CPT-2) with low-strain shear wave velocity measurements were conducted at the site. The negligible pore water pressure measurements indicate a dry or moist, but not saturated, soil. The high ratio of sleeve friction (f_s) to cone tip resistance (q_t) is indicative of large horizontal stresses due to soil backfilling activity. The friction angle, as interpreted from the CPT logs, for the top 0.5m ranged between 47° and 57°, and between 45° and 38° for soil below that elevation. The low-strain shear wave velocity (V_s) was found to be an average of 900m/s for the top 1.5m at CPT-1 and an average of 300m/s below 1.5m, while V_s measured at CPT-2 showed a gradual increase in V_s with depth with an average of 300m/s. Typical V_s for dense and very dense sand range between 250 to 350m/s. In addition, V_s measurements are typically not accurate near the surface. Therefore, V_s measurements at CPT-1 for the top 1 to 1.5m are not considered reliable. The installation torque was recorded at 0.3m increments and the torque profiles with depth are presented in Figure 1. All piles had similar installation torque profiles which indicates similar soil strength properties at all pile locations.

RESULTS

In this study, the disturbance effects are indirectly evaluated using different methods. The installation torque profiles for single and double-helix piles were compared to evaluate the effect

of a second helix on the disturbance. In addition, the measured load-displacement performance was compared with values estimated using the p-y method. Finally, the measured dynamic response was compared with response calculated using the elastic continuum method as presented by Novak⁹ and implemented in the software DYNA6.1¹⁰.

Installation torque

The installation torque profile is shown in Figure 1. The installation torque has to overcome the soil frictional resistance along the pile shaft and helices, and bearing along the leading edge of the helical plates.

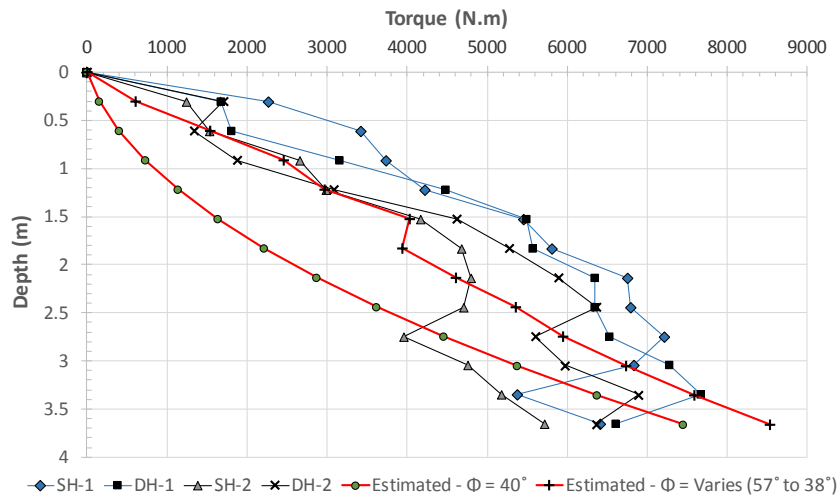


Figure 1: Installation torque variation with depth

As the pile advances, the helix cuts through the native soil resulting in disturbed soil along the shaft. Hence the installation torque corresponds to disturbed soil strength parameters along the pile shaft. Therefore, the installation torque for a single helix pile is expected to be higher than the torque for the double-helix pile, but considering the additional shearing resistance on the second helix. However, this was not observed from the measured torque profiles. Piles SH-1 and DH-1 were located close to each other and thus their torque profiles are very similar. Similarly, SH-2 and DH-2 had very similar torque profiles due to their proximity to each other.

The torque profile can be estimated using the frictional forces mobilized along the shaft and helices. The estimated torque profile of a single helix-pile is calculated, as shown in Figure 1, considering two cases: a uniform sand with $\Phi = 40^\circ$; and non-uniform sand based on CPT predictions of Φ (i.e. varying from 57° at the ground surface to 38° at the bottom of the pile). By comparing the measured torque profile with the estimated one it can be shown that the measured torque corresponds to an average friction angle not less than 40° which indicates that there was no installation disturbance.

Static lateral load test

The static lateral load-displacement curves for SH-1 and DH-1 are shown in Figure 2. It is expected that the double-helix piles would have lower stiffness as well as capacity compared to single helix piles. As can be noted from Figure 2, the load-displacement curves are linear up to 20mm of displacement followed by a non-linear region up to 50mm with no apparent failure. SH-1 and DH-1 perform nearly identical in the linear region and then deviate slightly where SH-1 seems to be stiffer than DH-1 in the non-linear region. Since the initial linear portion of the curve is controlled by soil stiffness parameters and the non-linear portion of the curve is

controlled by soil strength parameters, this indicates that perhaps the stiffness of the soil was the same for both piles regardless of the number of helices but the strength for soil around DH-1 was slightly reduced.

The measured results are compared in Figure 2 with the calculated response using the p - y approach utilizing a uniform Φ ranging between 40° to 60° and employing the Reese et al. sand model (11). It is observed from Figure 2 that the calculated response for $\Phi = 40^\circ$ is much softer than measured and a good agreement is reached as Φ approaches 60° . Therefore, it could be assumed that installation disturbance for helical piles in dense sandy soils has no negative effects on the static performance of the piles.

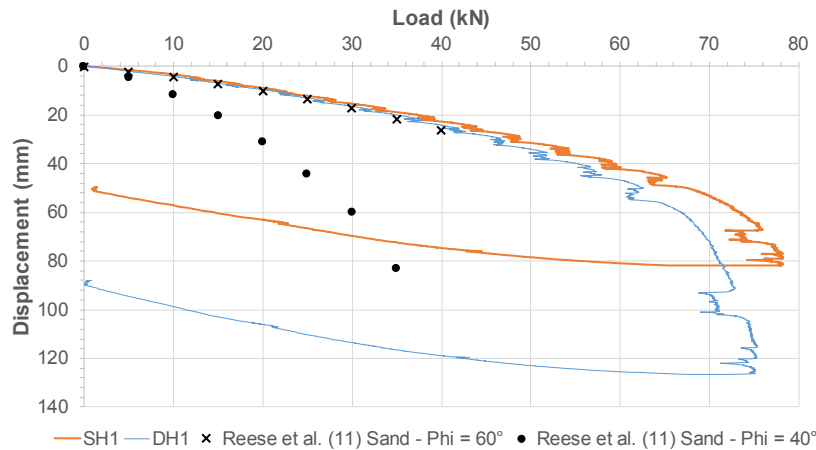


Figure 2: Static load-displacement curve for SH-1 and DH-1

Dynamic lateral load test

Figure 3 shows the average measured low-strain dynamic response versus loading frequency. As it is clearly demonstrated in Figure 3, single and double-helix piles exhibited almost identical responses, which indicates that single and multi-helix piles have the same stiffness.

The program DYNA6.1¹⁰ was employed to evaluate the low-strain dynamic response of the piles. The program calculates the vibration amplitude based on the continuum approach and considering plane strain conditions⁹. The solution is limited to linear elastic pile and soil materials. This approximation is representative for cases where the applied loads on the pile result in low shear strain amplitude in the soil⁹.

Using a uniform shear wave velocity profile along the depth equal to 300m/s, the calculated response was found to be much lower than the measured response as shown in Figure 3. Even though it was concluded that soil disturbance due to pile installation had negligible effect on the static performance, a small soil gap is sufficient to reduce the dynamic low-strain stiffness. Soil heaving and small gaps were observed during pile installation.

To account for the effect of the observed gap on the calculated response, the pile projection is increased from 305mm to 650mm. The calculated response for this case is in excellent agreement with measured response as shown in Figure 3. It is believed that the amount of soil heave, and hence the depth of soil gap, due to first helix penetration is a function of the helix diameter and therefore it would be reasonable to assume that the top 1 to 1.5 helix diameter will not provide lateral support to the pile in low-strain steady state loading conditions. It is worth noting that by reducing V_s to 200m/s the calculated response is still far from the measured values which indicates that soil disturbance had no effect on the measured V_s values as obtained by the SCPT tests.

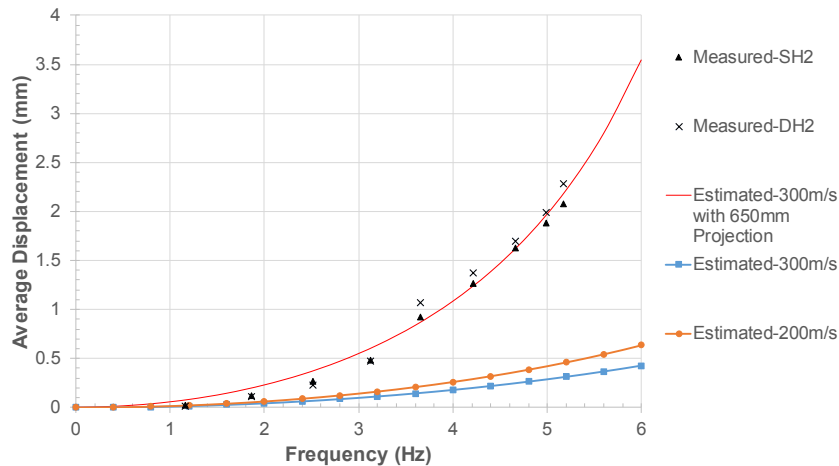


Figure 3: Average measured dynamic response versus estimated theoretical dynamic response

CONCLUSION

Helical piles with single and multi-helix configurations installed in dense sand appeared to have the same static performance as well as dynamic stiffness.

By comparing the measured static performance to calculated performance using available theoretical models, it is found that the effects of installation disturbance appear to be negligible. Therefore, no reduction in the soil strength or stiffness parameters should be accounted for in the pile design parameters. However, the installation disturbance manifested by the formation of a gap between the pile shaft and soil can cause a reduction in dynamic stiffness of helical piles. This effect can be mitigated by backfilling any formed gaps with compacted or non-shrink cementitious grout.

ACKNOWLEDGEMENT

Partial funding for this research was provided by the US National Science Foundation (Grant No. OISE-1445712).

REFERENCES

1. Elkasabgy, M. and El Naggar M.H. Lateral performance and p-y curves for large-capacity helical piles installed in clayey glacial deposit. *ASCE Journal of geotechnical and Geoenvironmental Engineering*. 2019.
2. Elkasabgy M, El Naggar MH. Dynamic response of vertically loaded helical and driven steel piles. *Canadian Geotechnical Journal*. 2013 Mar 27;50(5):521-35.
3. Elkasabgy M, El Naggar MH. Lateral Vibration of Helical and Driven Steel Piles Installed in Clayey Soil. *Journal of Geotechnical and Geoenvironmental Engineering*. 2018 Jun 27;144(9):06018009.
4. Elkasabgy M, El Naggar MH, Sakr M. Full-scale vertical and horizontal dynamic testing of a double helix screw pile. In *Proceedings of the 63rd Canadian Geotechnical Conference*, Calgary, Alta 2010 Sep (pp. 12-16).
5. Lutenege AJ, Erikson J, Williams N. Evaluating installation disturbance of helical anchors in clay from field vane tests. In *Proceedings of the 39th Annual Conference on Deep Foundations* 2014 (pp. 129-138).

6. Lutenegeger AJ, Tsuha CH. Evaluating installation disturbance from helical piles and anchors using compression and tension tests. In *XV Panamerican Conference on Soil Mechanics and Geotechnical Engineering*, Buenos Aires. 2015 Dec 11 (pp. 373-381).
7. Pérez ZA, Schiavon JA, Tsuha CD, Dias D, Thorel L. Numerical and experimental study on influence of installation effects on behaviour of helical anchors in very dense sand. *Canadian Geotechnical Journal*. 2017 Dec 2;55(8):1067-80.
8. Elsherbiny Z, El Naggar MH, Elgamal A. Helical piles foundation for wind turbines: Full-scale testing of a single helical pile in sand. In *Proc., 3rd Int. Conf. on Performance-Based Design in Earthquake Geotechnical Engineering*. London: International Society of Soil Mechanics and Geotechnical Engineering-Technical Committee 2017.
9. Novak M. Dynamic stiffness and damping of piles. *Canadian Geotechnical Journal*. 1974 Nov 1;11(4):574-98.
10. El Naggar, M.H., Novak, M., Sheta, M., El Hifnawi, L., and El Marsafawi, H. *DYNA 6 - a computer program for calculation of foundation response to dynamic loads*. GRC, Western. 2015.
11. Resse LC. *Handbook on Design of piles and Drilled Shafts Under Lateral Loads*. US Department of Transp. 1984.

G-PFEM NUMERICAL ASSESSMENT OF SCREW PILE UNDRAINED CAPACITY

L MONFORTE, M ARROYO, A GENS

Universitat Politècnica de Catalunya (UPC), Barcelona (Spain) - Department of Civil and Environmental Engineering
lluis.monforte@upc.edu

M O CIANTIA

Civil Engineering, School of Science and Engineering, University of Dundee, Dundee, DD1 4HN, Scotland, UK

SUMMARY: This contribution describes a preliminary parametric analysis of the factors affecting the pull-out resistance of screw-piles in undrained conditions. The numerical simulations rely on the Particle Finite Element method, a method known for its capabilities to tackle large deformations and rapid changing boundaries at large strains. A total stress analysis –assuming a quasi-incompressible elastic model along with a Tresca plastic model- is used to simulate the clayey soil behavior. Contact constraints are imposed to the solution with a penalty approach. As a first step, a two-dimensional geometry is used and the pile resistance to pullout and penetration is assessed.

INTRODUCTION

The fast growth of offshore developments poses new challenges and increases the demand for cost-effective and reliable foundation solutions. Screw piles (or helical piles) have been proposed as a potential innovative alternative foundation in offshore environments. This kind of foundation is capable supporting large uplift loads. Examples of its application include the support of pipelines and the foundations for transmission towers^{1,2}.

The optimization of the geometry of the screw pile has been historically addressed by experimental means and also through the use of quite simplified analytical solutions. Although much insight is gained from such analyses, a number of basic features of the problem are left aside. Consequently, nowadays, numerical models are predominant. The Finite Element method (FEM) allows to accurately simulate the non-linear behavior of clayey soils using well-honed tools of continuum mechanics (field equations, constitutive material descriptions). However, advanced variants of FEM are required in order to avoid mesh tangling and distortion when the interaction between various deformable or rigid bodies is included.

One such advanced variant is the Particle Finite Element Method (PFEM), which is here employed to simulate the screw piles in clayey soil. The work is structured as follows: first, the numerical method is outlined; after presenting a validation analysis (the simulation of the insertion of a pile) some preliminary results are highlighted; finally, some conclusions are drawn.

NUMERICAL MODEL

The Particle Finite Element Method is characterized by a particle discretization of the domain: every time step a finite element mesh – whose nodes are the particles – is constructed using a Delaunay's tessellation and the solution is evaluated using this mesh with well-shaped, low-order elements. The continuum is modeled using an Updated Lagrangian formulation^{3,4}. Additionally, *h*-adaptive routines are employed to obtain a better discretization of the domain. New particles are introduced in areas where large plastic dissipation is generated. These zones must be refined because the number of particles may become too low to obtain an accurate solution. On the contrary, due to high shear deformations, particles may locally concentrate in the same region of the domain. To overcome the difficulties that may follow from that, particles that are closer than a characteristic distance are removed.

Numerical simulations have been carried out by means of the numerical code G-PFEM⁵, specially developed for the analysis of large strain contact problems in geomechanics. The code is able to accurately simulate the interaction between fluid-saturated porous media and rigid structures using low-order elements for efficiency. Techniques to alleviate volumetric locking are required: in this work, a mixed stabilized formulation⁶. The code is capable of handling coupled problems within quasi-static⁷ or fully dynamic settings⁸. However, in this preliminary study only a relatively simple axisymmetric undrained total-stress model is employed. This approach is reasonable, as the loading of piles in clayey soils occurs at a relatively high velocity compared with the hydraulic properties of clay and undrained conditions prevail.

Model set-up

All the numerical simulations reported in this work share the same constitutive parameters. The soil is assumed to obey a Tresca yield criterion and a quasi-incompressible elastic model, with a Young modulus $E = 2980$ kPa, Poisson's ratio $\nu = 0.49$ and undrained shear strength $S_u = 10$ kPa, which results in a rigidity index of $I_r = G/S_u = 100$.

The pile is considered completely rigid; this hypothesis is approximate enough due to the high ratio between the pile Young's modulus and that of the soil. The contact constraints are imposed in the solution using a Penalty Method. This includes an inbuilt tension cut-off, since no tensions are allowed at the soil-structure interface. The tangential part of the contact is modelled employing the so-called elastic-plastic analogy and, as customary in total stress analyses, the maximum allowable contact tangential stress is taken as a fraction α of the undrained shear strength of the soil.

At the beginning of the simulations, the pile is wished-in-place; thus, installation effects are not considered here. The soil initial state is characterized by a total pressure equal to $p = 200$ kPa and null deviatoric stresses $q = 0$ ($K_0 = 1$). Therefore, at the top boundary a load of 200 kPa is applied. Both displacement components are restricted at the bottom boundary, whereas only the horizontal component is imposed at the vertical boundaries.

Validation analysis: penetration of a simple pile

To showcase the possibilities of the method, results of the penetration of a pile are first presented. Two different cases are presented, one assuming a completely smooth interface and the other with an adhesion equal to half the undrained strength or $\alpha = 0.5$.

Figure 1 presents the main result of interest, namely the bearing capacity factor, N_c , defined as:

$$N_c = \frac{q^{tip} - \sigma_{v0}}{S_u}$$

where q^{tip} is the total tip force divided by the projected area of the pile whereas σ_{v0} stands for the initial total vertical stress. It is clear that after a normalized penetration of one radii, both cases reach a stationary state. Little influence of the contact roughness is visible in the results: for the smooth case, the mean bearing capacity factor is 8.97 whereas a value of 9.33 is obtained for the rough case. The obtained end bearing capacity factor assuming a smooth interface, $N_c = 8.97$, is in very close agreement with the traditional value proposed by Skempton⁹, $N_c = 9$. Figure 2 illustrates for the smooth case how the failure mechanism accompanies the pile, by plotting incremental plastic shear strain at several penetration depths (ranging from 1 to 5 radii).

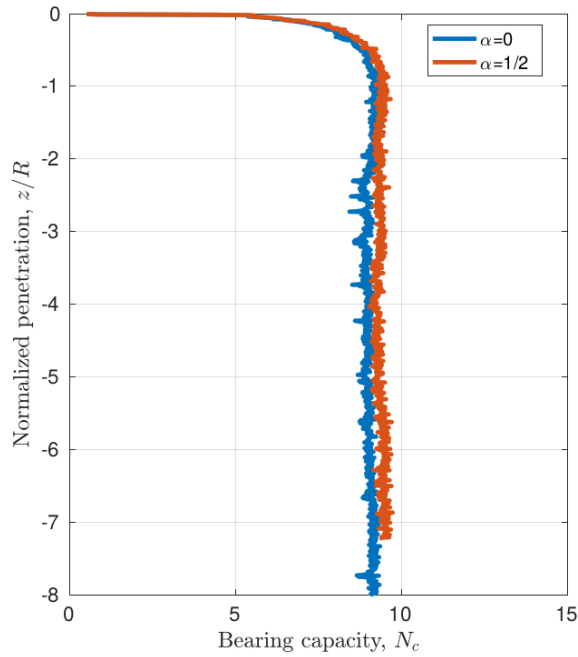


Figure 1: Closed-ended pile. Normalized penetration curve for the smooth and rough cases.

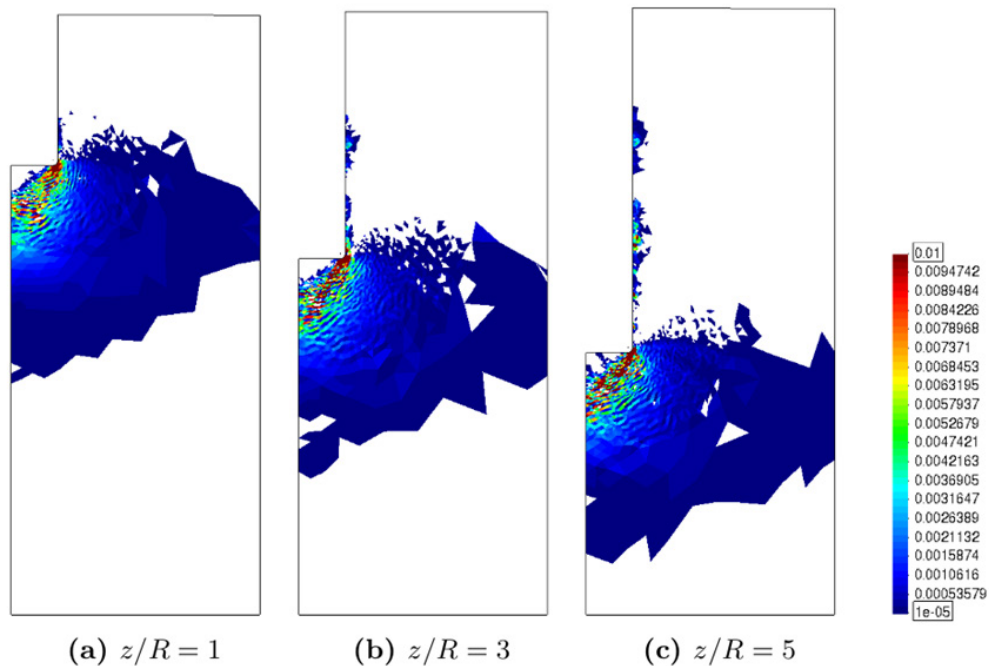


Figure 2: Closed-ended pile. Smooth interface. Incremental plastic shear strain.

RESULTS AND DISCUSSION

Once the accuracy of the developed numerical framework has been demonstrated, screw piles may be confidently simulated. Two different geometries are assessed with one and two helices (see Figure 3). In both cases a pull-out vertical displacement equal to 0.5 times the radius of the pile is imposed at the head of the pile.

Figure 4 reports the load-displacement curves, where the pile displacement has been normalized by the radius of the pile whereas the load is normalized by the projected area of the pile. At zero displacement a pressure of 200 kPa has to be supplied to neutralize the effect of the initial stress state. For the single helix case, the pile rapidly reaches a steady state with a limit resistance of around 240 kPa. Meanwhile, for two helices, the limit resistance is around 450 kPa with slower resistance mobilization. Three different bearing capacity factors are also presented: for the tip of the pile (introduced previously), and for each individual helix, (defined as the total vertical force acting on their surfaces divided by the projected area and normalized by S_u). Bearing capacity at the tip is negative; in contrast to the analysis of pile penetration the soil fails in an inverse mode. In the pile that only has one helix, the bearing capacity factor of the helix is close to 12. In contrast, in the case with two helices this capacity factor is of around 9.

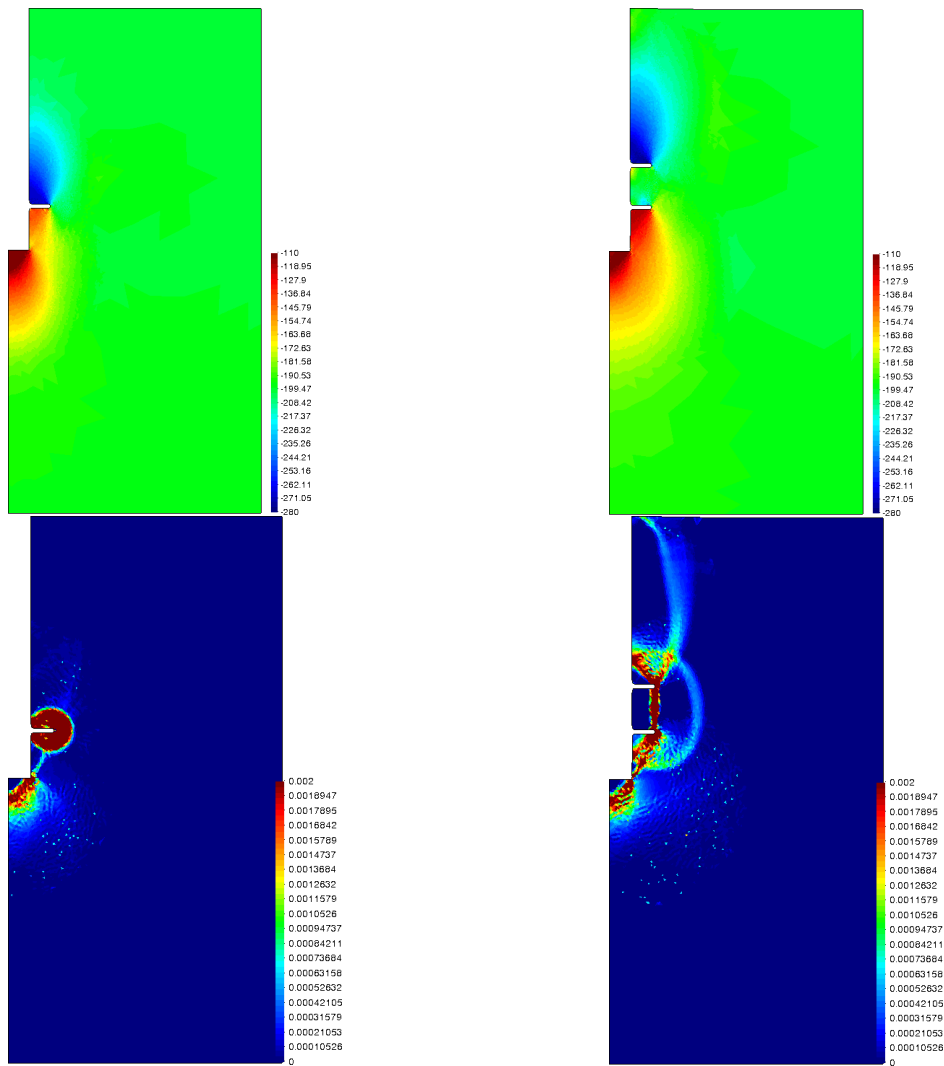


Figure 3: Total vertical stress [in kPa] (top) and incremental plastic shear strain (bottom) for cases with one (left) and two helices (right)

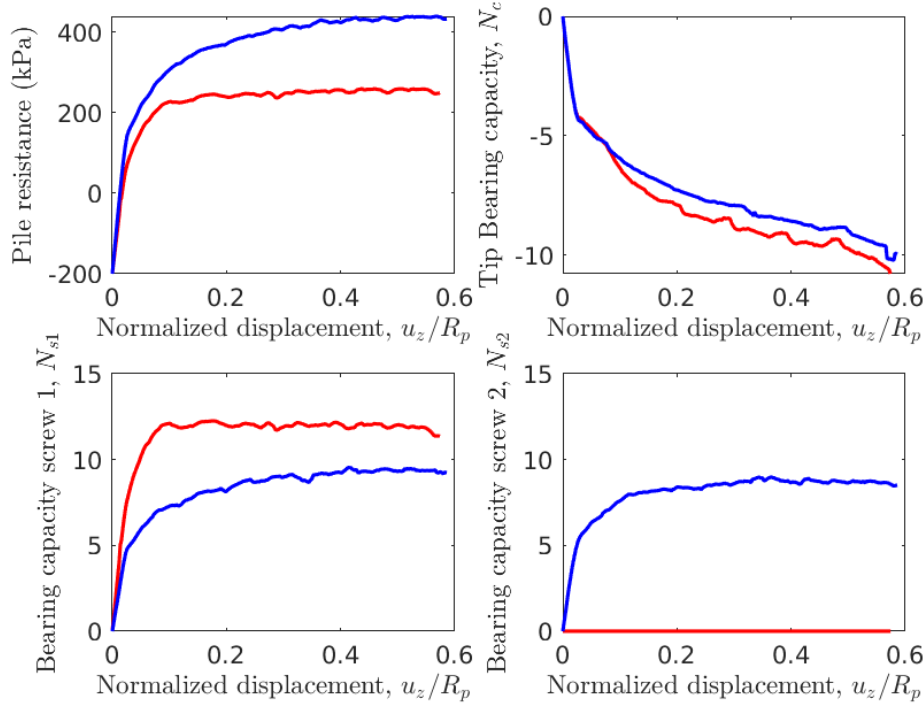


Figure 4: Evolution of the pile resistance, tip bearing capacity and bearing capacity factor of each screw in terms of the normalized uplift. Results for the geometry with two plates are depicted in blue.

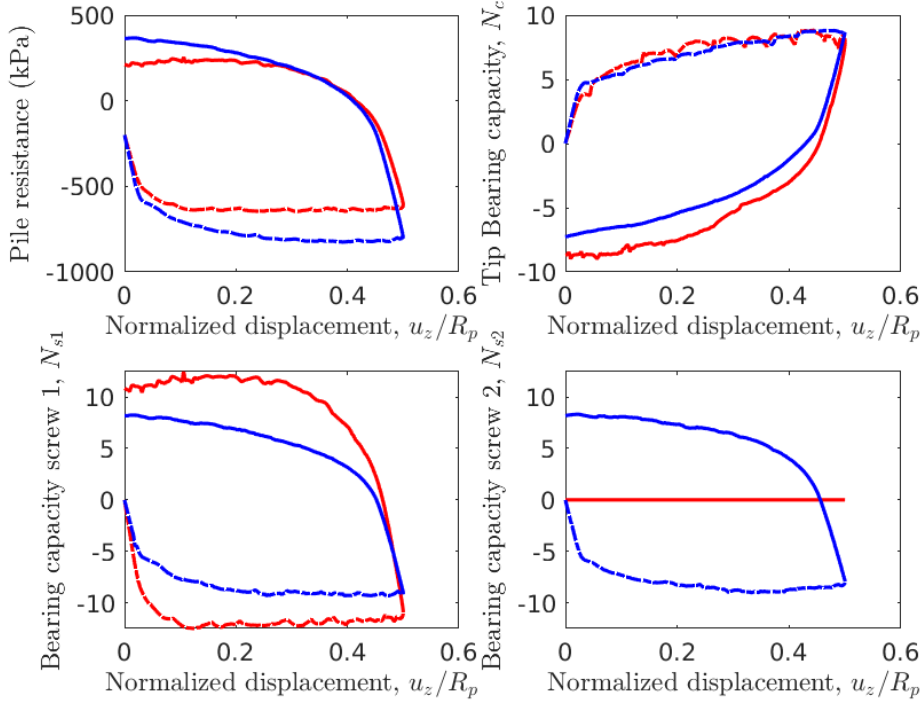


Figure 5: Push-pull sequence. Evolution of the pile resistance, tip bearing capacity and bearing capacity factors. Results for two plates are depicted in blue. Results during the penetration phase are plotted with a discontinuous line.

In both cases (Figure 3) the vertical stress (negative in compression) is reduced below the tip of the pile, whereas it is in high compression above the upper helix. Interestingly, no large variations in the stress field appear in the region between the two helices. Also, due to the moderately high initial stress (200 kPa), all the soil remains in contact with the structure

during pull-out. Figure 3 also reports incremental plastic shear strain, to give an indication of the failure mechanism. With two helices, a cylinder-shape failure mechanism is observed between both helical plates, since they are relatively close to each other ($2 R$). For a single helix, a flow-around mechanism is obtained. Finally, another set of simulations was run in a first approximation to installation effects. This time, first, the pile is penetrated $0.5 R$ and then pulled out by the same amount. Figure 5 presents load-displacement curves, where the penetration phase is depicted with discontinuous lines and the subsequent pulling test with a continuous line. No large discrepancies from the previous result are observed for the pulling phase.

CONCLUSION

This contribution has outlined preliminary results of the numerical simulation of screw pile pull-out by means of the Particle Finite Element method. In particular, the effect of the number of helical plates has been assessed. Details of the total resistance and also the failure mechanism have been shown. The developed numerical scheme appears to be a promising tool for the simulation of tool-soil interaction.

ACKNOWLEDGEMENT

This research was partly funded by the Spanish MEC through grant BIA2017-84752-R

REFERENCES

1. Wang, D., Merifield, R. S: and Gaudin, C. Uplift behavior of helical anchors in clay. *Canadian Geotechnical Journal*, 50: 575-584 (2013).
2. Al-Baghdadi, T. *Screw piles as offshore foundations. Numerical and physical modelling*. PhD Thesis (University of Dundee) (2018)
3. Oñate, E., Idelsohn, S.R., Del Pin, F. & Aubry, R. The Particle Finite Element Method – an overview. *International Journal of Computational Methods* 1(2) 267-307 (2004).
4. Rodriguez, J.M., Carbonell, J.M., Cante, J.C. & Oliver, J. The Particle Finite Element Method (PFEM) in thermo-mechanical problems. *Int. J. for Numerical Methods in Engineering*, 107(9): 733-785 (2016).
5. Monforte, L., Arroyo, M., Carbonell, J.M. & Gens, A. Numerical simulation of undrained insertion problems in geotechnical engineering with the particle finite element method (PFEM). *Computers and Geotechnics*. 82, 144-156 (2017).
6. Monforte, L., Carbonell, J.M., Arroyo, M. & Gens, A. Performance of mixed formulations for the particle finite element method in soil mechanics problems. *Computational Particle Mechanics*. 4(3), 269-284 (2017).
7. Monforte, L., Arroyo, M., Carbonell, J. M., & Gens, A. (2018). Coupled effective stress analysis of insertion problems in geotechnics with the Particle Finite Element Method. *Computers and Geotechnics*, 101, 114-129.
8. Monforte, L., Navas, P., Carbonell, J. M., Arroyo, M., & Gens, A. (2019). Low-order stabilized finite element for the full Biot formulation in soil mechanics at finite strain. *Int. J. for Numerical and Analytical Methods in Geomechanics*, 43(7), 1488-1515.
9. Skempton, A. W. The Bearing capacity of clays. *Building Research Congress*, London, The Institution of Civil Engineering, 180-189 (1951).

NUMERICALLY MODELLING THE INSTALLATION AND LOADING OF SCREW PILES USING DEM

Y U SHARIF, M J BROWN, M O CIANTIA, J A KNAPPETT, C DAVIDSON
B CERFONTAINE, S ROBINSON

Civil Engineering, School of Science and Engineering, University of Dundee, Dundee, DD1
4HN, Scotland, UK
yusharif@dundee.ac.uk

J BALL

Rodger Bullivant Ltd, Burton Upon Trent, Derbyshire DE11 9DU UK

SUMMARY: In this paper a new numerical modelling technique for simulating the installation and loading of screw piles is described. The method uses the discrete element method (DEM) and in a single model is able to assess the installation requirements as well as the ultimate tensile and compressive capacity. Numerical modelling of screw piles has traditionally been conducted using finite element analysis (FEA), in which piles are wished in place into a soil body consisting of a meshed continuum. Although this has provided many insights into the capacity of screw piles and the mechanisms that form when they are loaded, they do not usually consider the effects of installation on the behaviour of the soil. Using 3D DEM calibrated against element tests and geotechnical centrifuge tests, it is now possible to assess the local changes in density and stress caused during the installation process and what effects this has on the capacity of screw piles.

Keywords: DEM installation effects

INTRODUCTION

Screw piles have been proposed as an alternative foundation solution for offshore renewable structures in deeper waters, up to 50m in depth¹. Screw piles are commonly used in onshore applications to resist large tensile forces and to underpin existing foundations. To upscale the foundations for use in the harsh offshore environment, a greater understanding of how the geometric features and installation methods effect the installation requirements and ultimate capacity is needed. Existing literature in which screw piles have been previously studied can be categorised into three categories. These are scaled model tests, either 1g^{2,3} or centrifuge tests^{4,5}, field tests⁶ and numerical models⁷ usually finite element analysis⁸ (FEA). Each of these experimental types has been able to provide valuable information with each of them having their strengths and weaknesses.

Currently the only efficient way to assess the installation requirements of a screw pile is to conduct physical tests, either at prototype or model scale. These methods can be costly if parametric studies are to be conducted, due to the cost of equipment, the manufacturing of piles and the required monitoring equipment. It is also difficult to measure the local changes in stress

and the disturbance in the soil caused by the installation and subsequent loading. Numerical modelling of screw piles usually concerns the ultimate capacity of a pile and the failure mechanism that forms. Most methodologies do not account for the installation process, with the ones that do either use disturbed soil parameters⁹ for the soil surrounding the pile or by applying a series of loads to mimic the installation process¹⁰. These methods are usually based upon assumptions gained from physical tests and may not be truly reflect the soil stress regime or density changes caused by the installation process.

The discrete element method (DEM) is a numerical modelling framework in which discrete particles are used to represent a body of soil. This allows for large displacement and soil structure interaction problems to be conducted numerically. With the addition of an increase in gravitational field a virtual centrifuge can be created. The method has previously been used to model various geotechnical problems including but not limited to slope stability¹¹, pile plugging¹² and cone penetration tests (CPT)¹³. DEM allows the user to inspect the displacement and forces of any particle within the soil body. As a result, it is therefore possible for the level of disturbance and the stresses induced during the installation of the screw pile to be assessed at any given moment. This can be used to further the understanding of what is occurring in physical tests and to inform initial conditions of FEA. As the soil sample can be used multiple times, with geometries very easy to create and modify, it can also be used to conduct parametric studies to aid in prototyping a piles geometry for physical testing. Using Flow Code 3D (PFC3D5.0)¹⁴ this paper will assess the feasibility of using DEM to model the installation and loading of screw piles into granular material.

CALIBRATION OF THE DEM MODEL

To numerically model the installation of the pile two items are required, the first is a body of particles that mimics the response of a soil, in this case the chosen soil is HST95 which is a medium to fine well graded quartzite sand that is commonly used at the University of Dundee. The behaviour and properties of the sand have been well documented for use with physical and numerical modelling. The second item that is required is the pile which is to be installed. The pile in the simulations is modelled as a rigid boundary, commonly called a wall within DEM. The pile has no mass associated with it and is unable to deflect or deform. The pile is controlled by a dual axis servo-control which can be either set to displacement or force control mode.

The contact model that is used for both the particle-particle and particle boundary interactions is a simplified Hertz-Mindilin contact model. The particle-particle contact model was calibrated against laboratory triaxial tests conducted at the University of Dundee¹⁵ and the soil structure interaction (particle-boundary contact properties) was calibrated against geotechnical centrifuge tests of axially jacked (monotonic push) and rotary jacked straight shafted piles¹⁶.

Soil-soil interaction

To calibrate the soil a virtual triaxial was conducted on a representative element volume (REV). A REV is a small cluster of particles, usually in the shape of a disk or a small cube which contains a relatively small number of particles (usually around 5000) which is able to model the response of a soil without requiring large computational resources¹⁷. These REV's are useful for use when calibrating soil as multiple samples can be created and tested in a short period of time.

For the Hertz-Mindilin contact model three parameters are required: shear modulus (G), Poisson's ratio (ν) and an interparticle friction coefficient (μ). Following¹⁸ to mimic particle shape the ability of particles to rotate was restricted. The REV's used in the calibration were cubes with sides of 2.5mm lengths in order to achieve the required 5000 particles. The particle

size distribution of the virtual soil matched that of HST95¹⁹. The REVs were created in two densities, a loose case (relative density $D_r = 30\%$) and dense sample ($D_r=70\%$), to capture the peak and residual responses. The samples were then consolidated and sheared under a confining pressure of 60 kPa. Using the values for the parameters specified in Table 1 it was possible to achieve a response very close to that seen within the laboratory tests (Figure 1). It can be seen that DEM triaxial tests overestimates the critical state strength of the soil by a small amount but is able to match the peak accurately. The volumetric strain also differs from the laboratory tests at large strains. The difference in volumetric strains is unlikely to cause an issue due to the high level of strain required to get to the deviation point. As simulations will be conducted in very dense soils, the response of the calibration is deemed acceptable.

Table 1: HST95 physical properties and DEM parameters.

HST95 silica sand property	Value
Physical properties	
Sand unit weight γ (kN/m ³)	16.75
Minimum dry density γ_{\min} (kN/m ³)	14.59
Maximum dry density γ_{\max} (kN/m ³)	17.58
Critical state friction angle, ϕ (degrees)	32
Interface friction angle, δ (degrees)	18
D_{30} (mm)	0.12
D_{60} (mm)	0.14
DEM Parameters	
Shear modulus, G (GPa)	9
Friction coefficient, μ (-)	0.264
Poisson's ratio, ν (-)	0.2
Interface friction coefficient [pile], μ_{pile} (-)	0.16

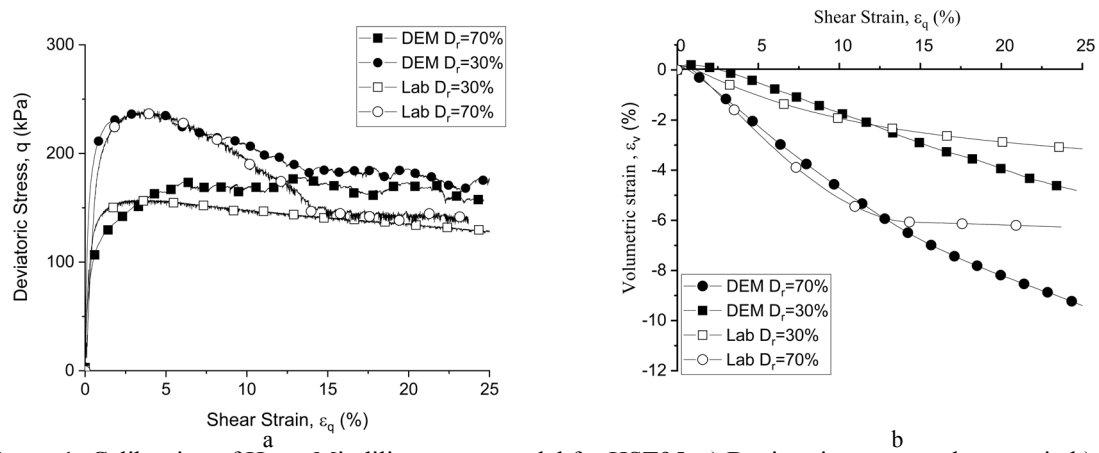


Figure 1: Calibration of Hertz-Mindlin contact model for HST95. a) Deviatoric stress vs shear strain b) Volumetric strain vs Shear strain

Soil chamber generation

To create the soil chamber the particle refinement method (PRM)²⁰ was used in conjunction with the periodic boundary replication method (PBRM)²¹. PRM is a method of creating samples that enables the use of a small particle scaling in the centre of a sample and larger scaling of the particle size distribution (PSD) further away, similar to the way in which mesh refinement is used within FEA. As the properties of each layer of particles is the same, with only the scaling of the PSD increasing, the overall response of the soil body is the same. This reduces the computational time required for a simulation, while not limiting the precision of the results. PBRM is a method used to create large homogeneous soil samples in relatively low periods of time. The method uses a thin slice of the final sample as a REV, with a thickness of three diameters of the largest particle in the sample and periodic boundaries in the vertical direction. As detailed in²¹, this REV

is consolidated under a confining stress found at the base of the sample to the required voids ratio. The REV slice is then replicated to the required height for the simulation and the forces between the particles are scaled to match the correct stress profile in the soil under a given gravitational field. An example of a sample created implementing both PRM and PBRM can be seen in Figure 2.

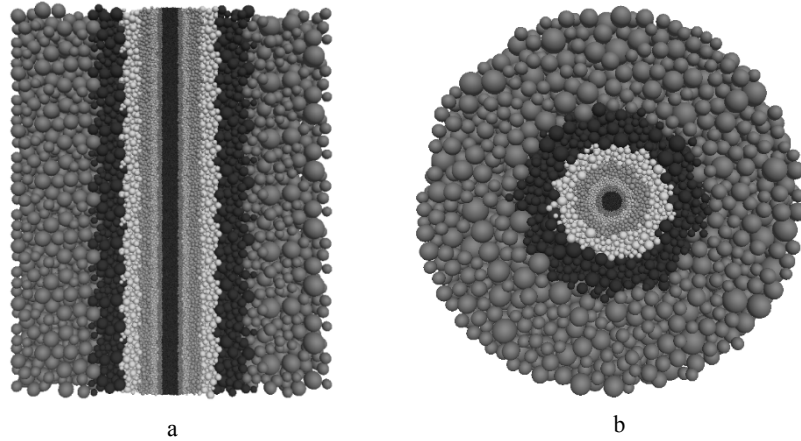


Figure 2: Example sample made using PRM and PBRM method, Colours indicate different particle scaling applied to the PSD. a) Cross sectional view of sample, b) top view of sample.

Soil structure interaction

The modified Mindlin-Hertz contact model was also used for the soil-structure interaction contact model. The same parameters are required to calibrate the contact model. Screw piles are installed under both a vertical and rotational velocity, with the ratio of vertical - rotational velocity (installation pitch) being dependent on the helix pitch and the installation method. The calibration therefore had to be able model the change in response under different installation pitches. To calibrate the contact model, a straight shafted pile with a diameter of 10mm, an installation length of 200mm and a 60° cone apex angle was installed into a dense soil sample ($D_r = 80\%$).

To ensure that the parameters would be applicable to all vertical - rotational velocity rates the installation was conducted under both a monotonic axially jacked installation (push in) and a monotonic rotary jacked installation (rotated in). The results of these tests were compared to the geotechnical centrifuge tests conducted within HST95¹⁶. These tests were completed with a vertical velocity of 21mm/min and 3.33 RPM for the rotational installation.

Using a particle-pile frictional coefficient of 0.16, it was possible to match the results of the centrifuge tests across multiple densities for both the torque and vertical force. This represents a similar ratio that is seen between the interface friction angle and the critical state friction angle of HST95. ($0.16/0.264 \approx \tan\delta/\tan\phi'$) The results of the calibration can be seen in Figure 3.

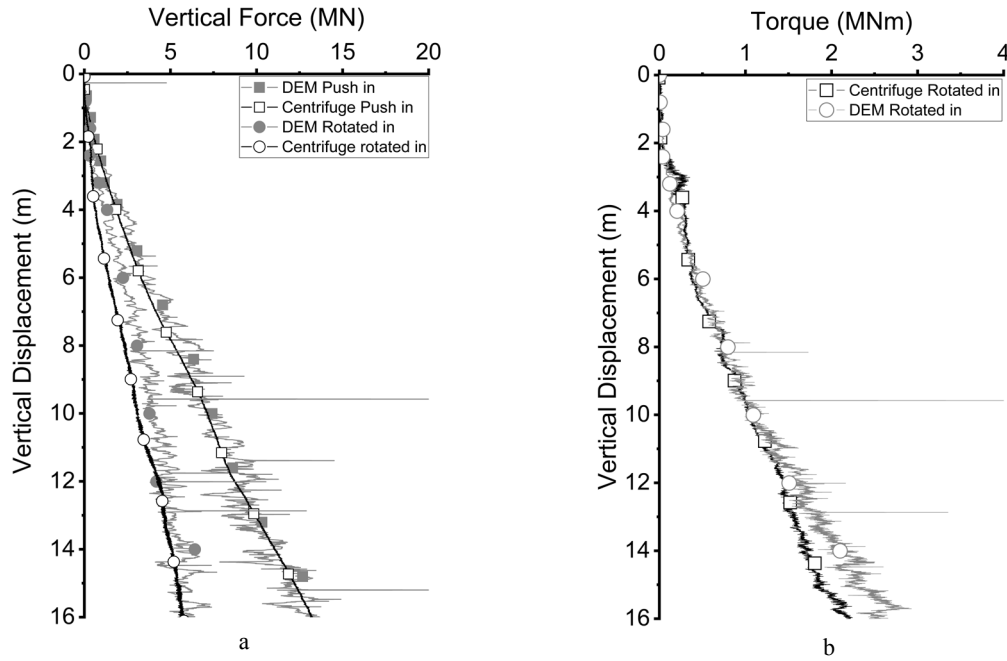


Figure 3: Calibration of soil structure interaction a) Installation force vs Displacement for DEM and centrifuge Experiments, b) Installation torque vs vertical Displacement for DEM and centrifuge

Validation

To test if the calibration had been successful and that it was possible to model the installation of screw piles, a potential screw pile geometry reported by Davidson et al.⁵ was chosen. The geometry of the screw pile can be seen in Figure 4. This geometry represents a potential screw pile design for use offshore and will be able to test whether the calibration can be used to model large variation in geometry. The vertical force and torque required to install the pile under pitched matched conditions (for each rotation the vertical displacement is a helix pitch in magnitude) was monitored throughout. The particle position and the stress state of the soil was exported at regular intervals. This data can be used to monitor the evolution of stress and voids ratio during various stages of the installation.

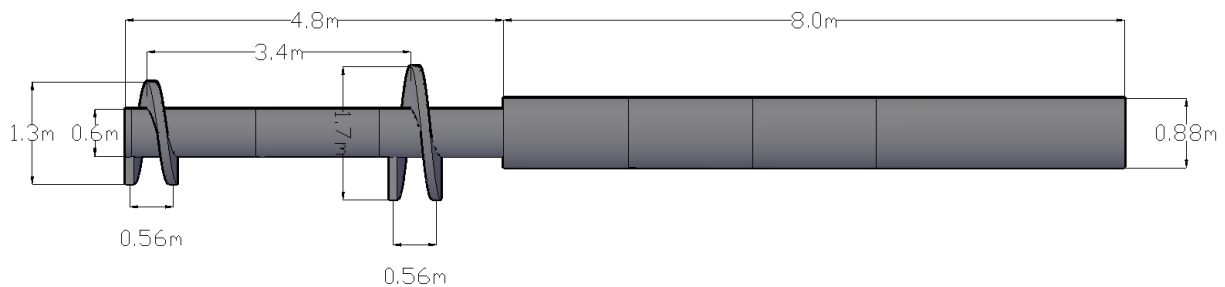


Figure 4: Dimensions of screw pile (prototype scale).

Testing procedure

The screw piles were created as rigid boundaries with the properties listed in Table 1. A displacement controlled virtual servo was then used to install the pile, with the pitch of installation matching the helical pitch of the screw pile in question. Once the helix had reached the required depth, the pile was unloaded to a zero-vertical load. From this point a compression test was conducted. The simulation was then reset to the end state of installation and a tension test was then conducted.

RESULTS AND DISCUSSION

The results of the simulation in comparison to the centrifuge tests can be seen in Figure 5. It can be seen that the DEM model is able to match the results of the centrifuge tests for the installation requirements of the screw piles very well. The ultimate capacity of the pile in the DEM at large displacements exceeds the centrifuge tests. This is potentially due the initial calibration (Figure 1b) overestimating the volumetric strains at large shear strain values. The difference could also be attributed to the restriction in rotation of the particles, as this would potentially increase the force required for particles to slide past each other under large displacements. The initial stiffness of the pile after installation shows good correlation with the centrifuge tests at low normalised displacements (displacement over helix diameter). This is the region of the test in which the information is of most importance when considering the serviceability state of the pile. Therefore, the capacity calculated from the DEM is considered acceptable.

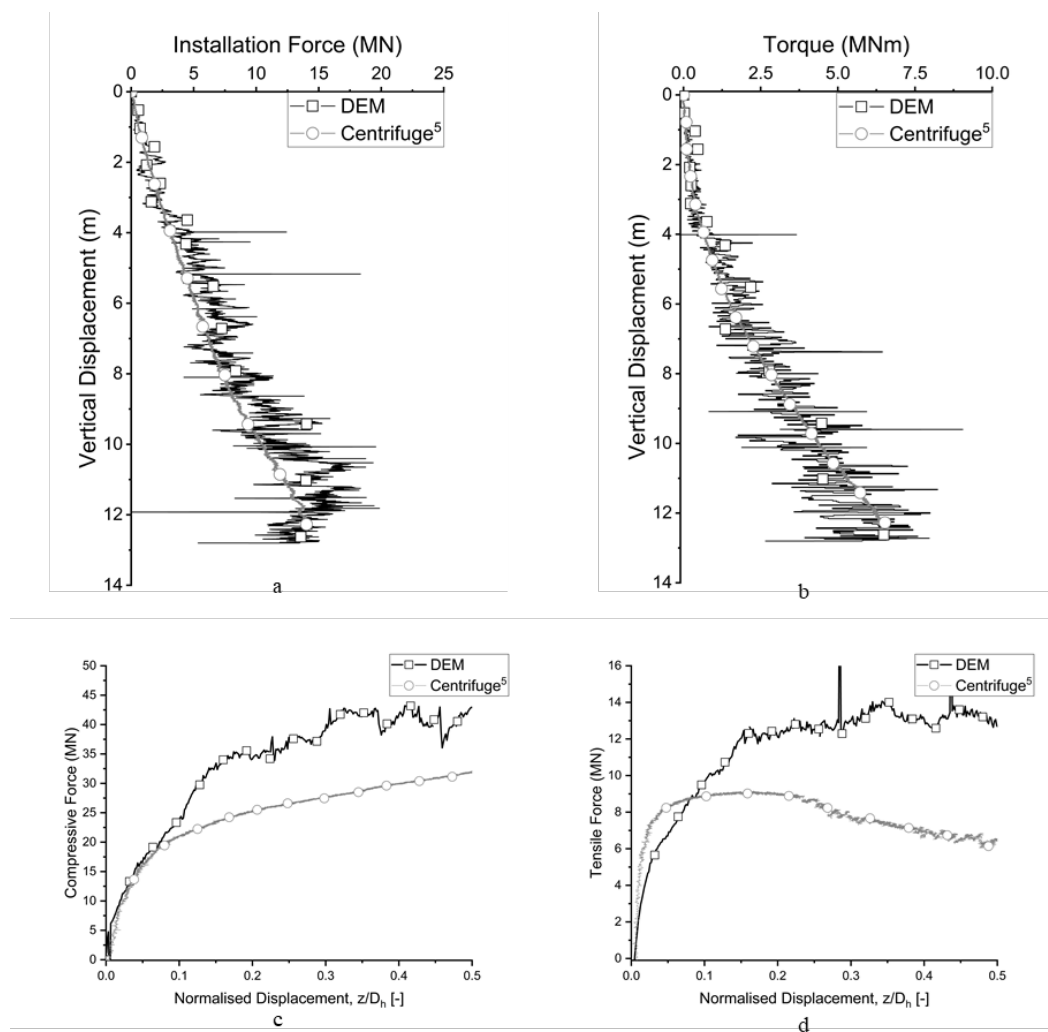


Figure 5: Comparison of DEM and centrifuge (5) results, a) Installation vertical force vs depth, b) Installation torque vs depth, c) Normalised displacement vs compressive force, d) Normalised displacement vs tensile force.

By averaging the particle scale data, the soil stress state and voids ratio was assessed, when under zero load conditions at the end of the installation. It was found that large residual vertical stresses form below the base of the pile as well as below both helices. Between the helices a region of low is present close to the shaft. Above the second helix once again a region

of low stress is present. The radial stress acting on the pile forms around both helices with a localised reduction once being close to the shaft between the helices. Unlike the vertical stress this region of high stress encompasses the helices, being present both above and below. When assessing the change in voids ratio, it was noted that the soil surrounding the pile has increased in voids ratio from its initial very dense condition ($D_r = 80\%$) to medium dense one ($D_r = 55\% - 60\%$). The density change is localised to close to the pile and would most likely only cause a change in stiffness to occur during loading for shallow embedment depths and potentially drop in axial capacity at deep embedment depths.

The change in density and the location of the residual vertical stress being below the helices is the most likely cause for the lower stiffness of the pile in tension with the required displacement to achieve the peak capacity being larger than in compression. This supports the FEM method of applying compressive forces to the soil before conducting tensile tests proposed by Cerfontaine et al.¹⁰. By applying a succession of compressive forces to the soil through which the screw pile has passed, the method is able to apply the change in voids ratio of the installation as well as the difference in residual vertical stress above and below the helix.

CONCLUSION

In this paper a new method of numerically modelling the installation of screw piles into a discrete analogue of HST95 sand is presented. The contact parameters of the DEM model are calibrated against geotechnical centrifuge tests and laboratory element tests. The calibrated model is then used to simulate a centrifuge test of the installation of a screw pile. The good match between the DEM and the experiment demonstrate the applicability of micromechanical approaches to study such a complex soil structure interaction problem. The simulation was able to establish that a localised density change occurs and that large residual stresses form below the tip and around the helices of a screw pile when installed into granular matter.

ACKNOWLEDGEMENTS

This research is funded by Rodger Bullivant Ltd and has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 753156. The authors would also like to acknowledge the support of EPSRC (Grant no. EP/N006054/1: Supergen Wind Hub: Grand Challenges Project: Screw piles for wind energy foundations).

REFERENCES

1. Byrne BW, Houlsby GT. Helical piles: an innovative foundation design option for offshore wind turbines. *Philosophical Transactions of the Royal Society A Math Physics Engineering Science*. 2015;373:1–11.
2. Adams, J I, Hayes, D C. *The Uplift Capacity of shallow foundations*. Ontario Hydro Res Q. 1967;19(1):1–13.
3. Ghaly A, Hanna A. Experimental and theoretical studies on installation torque of screw anchors. *Canadian Geotechnical Journal*. 1991;28(3):353–64.
4. Schiavon JA, Tsuha C, Thorel L, Neel A. Physical modelling of cyclic loading on a single-helix anchor in sand. In: *Proceedings of the 3rd European Conference on Physical Modelling in Geotechnics*. Nantes; 2016. p. 275–9.

5. Davidson C, Al- Baghdadi T, Brown M, Brennan A, Knappett J, Augarde C, et al. Centrifuge modelling of screw piles for offshore wind energy foundations. In: *Proceedings of the International Conference on Physical Modelling in Geotechnics*. London; 2018. p. 255–61.
6. Lutenegeger AJ. Cylindrical shear or plate bearing - Uplift behavior of multi-helix screw anchors in clay. In: *Geotechnical Special Publication*. 2009. p. 456–63.
7. Livneh B, El Naggar MH. Axial testing and numerical modeling of square shaft helical piles under compressive and tensile loading. *Canadian Geotechnical Journal*. 2008;45(8):1142–55.
8. Merifield RS, Sloan SW. The ultimate pullout capacity of anchors in frictional soils. *Canadian Geotechnical Journal*. 2006;43(8):852–68.
9. Wang D, Merifield RS, Gaudin C. Uplift behaviour of helical anchors in clay. *Canadian Geotechnical Journal*. 2013;50(6):575–84.
10. Cerfontaine B, Brown MJ, Knappett JA, Davidson C. Finite Element Modelling of the Uplift Behaviour of Screw Piles in Sand. In: *Proceedings of the 1st International Symposium on Screw Piles for Energy Applications*. 2019.
11. Kim JS, Kim JY, Lee SR. Analysis of soil nailed earth slope by discrete element method. *Comput Geotech*. 1997 Jan 1 [cited 2019 Apr 15];20(1):1–14.
12. Thongmune, T. Matsumoto SK. Experimental and Numerical Studies on Push-Up Load Tests for Sand Plugs in a Steel Pipe Pile. *Soils Found*. 2011;51(5):959–74.
13. Butlanska J, Arroyo M, Gens A, O’Sullivan C. Multiscale analysis of CPT in a virtual calibration chamber. *Canadian Geotechnical Journal*. 2014;26(July):80–6.
14. Itasca Consulting Group I. PFC 5.0. Minneapolis: Itasca Consulting Group, Inc.; 2016.
15. Robinson S. *Internal report for project Seabed Ploughing : Modelling for Infrastructure EP/M000362/1*. Dundee; 2016.
16. Al-Baghdadi T, Davidson C, Brown M, Knappett J, Brennan A, Augarde CE, et al. CPT Based Design Procedure for Installation Torque Prediction for Screw Piles Installed in Sand. *Society for Underwater Technology*; 2017 [cited 2019 Apr 18]. p. 346–53.
17. Ciantia MO, Arroyo M, Zhang N, Emam S. Periodic cells for large-scale problem initialization. In: *EPJ Web of Conferences*. 2017. p. 15012.
18. Ciantia MO, Arroyo M, O’Sullivan C, Gens A, Liu T. Grading evolution and critical state in a discrete numerical model of Fontainebleau sand. *Géotechnique*. 2018;(February):1–15.
19. Lauder K. *The performance of pipeline ploughs* PhD submitted to the University of Dundee; 2010.
20. McDowell GR, Falagush O, Yu H-S. A particle refinement method for simulating DEM of cone penetration testing in granular materials. *Géotechnique Letters*. 2012 Sep 3 [cited 2019 Jan 27];2(3):141–7.
21. Ciantia MO, Boschi K, Shire T, Emam S. Numerical techniques for fast generation of large discrete-element models. *Proc Inst Civ Eng - Eng Comput Mech*. 2018;171(4):147–61.

PHYSICAL MODELLING OF A HELICAL PILE INSTALLED IN SAND UNDER CONSTANT CROWD

A S BRADSHAW

Department of Civil and Environmental Engineering, University of Rhode Island, Kingston,
RI 02881, USA
abrads@uri.edu

R ZUELKE

Technical University Braunschweig, Germany

L HILDEBRANDT

Mittelweser-Tiefbau GmbH & Co., Beverstedt, Germany

T ROBERTSON

Triton Systems, Inc. Chelmsford, MA, USA

R MANDUJANO

Triton Systems, Inc. Chelmsford, MA, USA

SUMMARY: This paper presents 1g physical modelling of a ‘deep’ single-helix pile installed in sand under constant downward ‘crowd’ forces. The objective of the study was to investigate how constant crowd force installation might affect the advancement rate, installation torque, and pull-out capacity of the helical pile. Physical modelling was performed on 1/5-scale piles in both loose and dense sand. Reducing the interface friction of the helix plate surface improved the advancement rate and reduced torque but also reduced pull-out capacity. Over-rotation seemed to improve the torque factor in the loose sand possibly by improving the soil above the helix. Removal of soil from within the shaft to prevent plugging reduced the installation torque but also reduced the pull-out capacity.

Keywords: Crowd Force, Helical Piles, Helical Piles, Installation Torque, Pull-out Capacity

INTRODUCTION

There is continued interest in using helical piles for offshore energy applications as an alternative to conventional piles. The obvious benefits are improved pull-out capacity and avoidance of pile driving noise that can adversely impact some marine animals (e.g., right whales along the Atlantic coast, United States). Typically helical piles are installed by applying a variable downward crowd force as needed to advance the helix at a specified rate. Current onshore

practice, for example, recommends a penetration of at least 80% of the pitch per revolution to minimize soil disturbance¹. However, there are limited data on helical piles in sands under constant crowd installation (i.e. ‘self-installing’ piles) where advancement is difficult to control or predict. The objective of this study was to investigate the behaviour of a single-helix pile under constant crowd in both loose and dense sands. This includes the advancement rate, installation torque, and pull-out capacity. This was accomplished through small-scale 1g physical modelling of a ‘deep’ helical pile in sand where failure of the soil around the helix during pull-out is localized. First, the physical modelling approach is described including scaling considerations. This is followed by a discussion of the results.

PHYSICAL MODELLING APPROACH

The physical modelling was performed at 1g acceleration on 1/5-scale single-helix piles in dry sand as described in². The experimental setup is shown in Figure 1. It is anticipated that the installation and loading of the piles will be a drained process and thus dry sand is a reasonable representation of the saturated field conditions. The dimensions of model pile were based off the largest commercially available onshore helical pile available on the market. The ‘plain’ steel model pile had a plate diameter of 127 mm, pitch of 18 mm, plate thickness of 3.8 mm, and shaft diameter of 45.7 mm with a wall thickness of 3 mm.

The test bed consisted of a cylindrical plastic tank (0.91-m diameter x 1.52-m high) embedded in the ground and filled with dry Westerly sand at two different relative densities. The test sand was used in previous 1g model testing studies and has been well characterized^{3,4}. The D_{50} is 0.3 mm and e_{min} and e_{max} are 0.44 and 0.84 respectively. The sand was placed in the test tank using a portable pluviator that resulted in relative densities of either 28% or 65%.

A commercially available hydraulic driver was used to install the piles vertically at a rate of 8 to 12 rpm to a final embedment of 115 cm. The driver was suspended from a gantry crane and a constant crowd was applied from the weight of the driver and additional deadweight that was fixed to the driver. A torque load cell was fixed between the driver and the helical pile shaft to measure the applied torque during installation. Vertical pile displacements were monitored using a string potentiometer. A winch and gantry crane were used to pull the piles out of the loose sand. A loading frame and pneumatic jack were required to pull the piles out of the dense sand.

Initial tests indicated that plugging occurred quickly at an embedment to shaft diameter of approximately 14. Therefore, steel plugs were inserted at the bottom of the pile tip to force plugging. Some additional modifications were made to the piles to change their behavior. This included making the helix plate ‘rough’ by adhering 60 grit sandpaper to the top and bottom surfaces of the plate, or by making the plate ‘smooth’ by adhering a Teflon film to the plates.



Figure 1: Experimental setup used in this study¹.

Tests were also performed on an ‘unplugged’ pile where the steel plug was removed and the soil entering the shaft was continuously removed with a vacuum near the tip of the pile to prevent a soil plug from forming.

Interface shear tests were also performed on the test sand⁵ to determine the critical state interface friction angle (δ_{cs}) that is representative of the soil-helix interface conditions during installation. The following results were obtained for the three different interface conditions: sand-steel- 23°, sand-Teflon- 16° and sand-sandpaper- 33°.

In small scale 1g physical models, the soil will behave more dilative because of the very low confining pressure levels. However, representative behavior can be achieved to some extent by preparing the model soil looser than it would be in the prototype and presenting the results in non-dimensional form³. Soil strength parameters were interpreted for the test tank conditions using the method proposed by⁴. Peak friction angles were interpreted to be approximately 37° and 43° at relative densities of 28% and 65%, respectively.

The non-dimensional pull-out load for horizontal plates is typically defined by the following relationship:

$$\tilde{Q} = \frac{Q}{\gamma H A} \quad (1)$$

where Q =load on the helix plate, γ = unit weight of soil, H = embedment depth of plate, and A =area of plate. When \tilde{Q} reaches failure it is commonly referred to as a breakout factor (N_γ). Depending on whether the failure mode is ‘shallow’ or ‘deep’ the gross or net helix area may be used, respectively. In a shallow failure the slip surface propagates toward the ground surface, whereas in a deep failure the deformations are localized in the vicinity of the helix plate. Previous work has shown the transition from shallow to deep depends on soil relative density but most data fall within embedment depths of 4 to 9 times the helix diameter. The helical piles in this study were installed to a final embedment ratio of 9 and thus assumed to be deep.

The following non-dimensional torque is proposed which was derived through integration of the moments due to shear and normal stresses on the helix, and is similar in form to the non-dimensional quantity proposed by⁶:

$$\tilde{T} = \frac{T}{\gamma H (R^3 - r^3)} \quad (2)$$

where T = torque resistance from helix, R = radius of the helix, and r = radius of the pile shaft. Note that Equation 2 does not consider the torque resistance provided by the shaft.

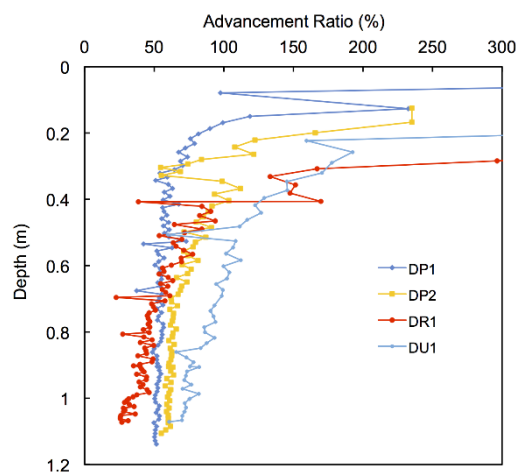
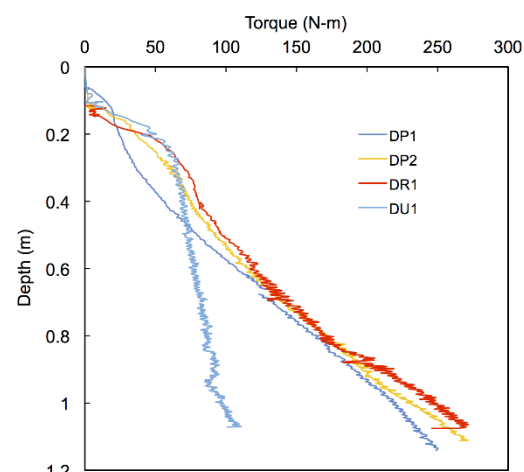
RESULTS AND DISCUSSION

A summary of the test results are presented in Table 1. Each test is given a three character designation: the first letter refers to the sand density (L = loose and D = dense), the second letter refers to the pile modifications (P = plain steel, R = rough, S = smooth, U = unplugged), and the final number indicates the test number. The advancement ratio will be defined herein as the downward movement per revolution divided by the blade pitch. An advancement ratio of 1 (or 100%) means that the pile advanced a distance equal to the pitch in one revolution.

Table 1: Summary of test results.

Test	Crowd (N)	Adv. Ratio	Torque (N-m)	Pull-out Capacity (N)
LP1	680	0.87	28	1800
LR1	680	0.70	32	2000
LS1	680	0.86	23	1450
LS2	680	0.96	19	1450
LU1	680	1.22	19	1250
DP1	680	0.52	204	8700
DP2	2550	0.60	208	7500
DR1	2550	0.35	210	8550
DU1	2550	0.76	84	5800

Typical results are shown in Figures 2 and 3. During initial installation, the crowd was high enough to advance the pile at a ratio in excess of 1 indicating that the pile was causing a bearing capacity failure of the soil below the helix. However, the advancement ratio quickly reduced in most cases below 1 becoming almost constant at embedment depths greater than about 3 to 5 times the helix diameter. The installation torque (Figure 2) generally increased with depth but increased at a faster rate in cases where the advancement ratio was above 1. This suggests that the over advancement from the excess crowd was increasing the friction on the bottom surface of the helix.

**Figure 2:** Advancement ratio during installation in dense sand.**Figure 3:** Torque measured during installation in dense sand.

The final installation torque and advancement ratio were calculated for each pile at the end of installation and summarized in Table 1, along with the ultimate pull-out capacity. The torque and pull-out capacity in Table 1 were analyzed further first by removing the minimal contribution of the pile shaft resistance. The skin friction along the shaft was estimated using the 'beta' method for piles, from which the torque resistance and pull-out resistance of the shaft

were obtained. Then the results were converted to non-dimensional form using Equations 1 and 2.

Figure 4 plots the advancement ratio at the end of installation against the helix interface friction. The results show that for the plugged shaft, as the helix interface friction angle is reduced the pile advances more effectively. Figure 5 indicates that as the interface friction is reduced and advancement ratio increases, it requires less torque to install the pile. The torque resistance is mostly attributed to the interface friction on the top and bottom surfaces of the helix, so a decrease in interface friction angle should reduce torque. However, the torque is also related to the advancement ratio. If the advancement ratio is less than 1 the helix also has to passively push the soil laterally thereby increasing the normal stresses on the plate. Therefore, the data suggest that smooth helix surfaces can reduce torque resistance.

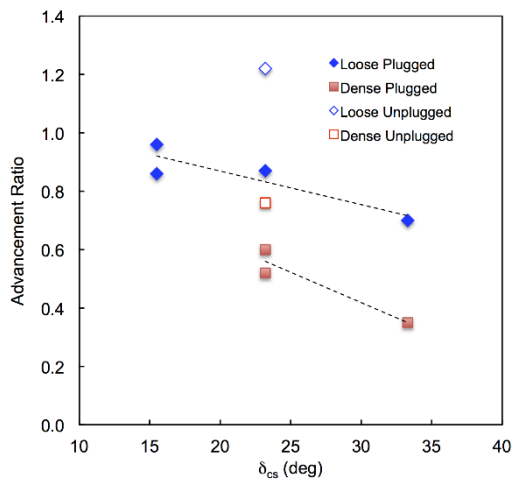


Figure 4: Effect of helix plate interface friction angle on advancement ratio.

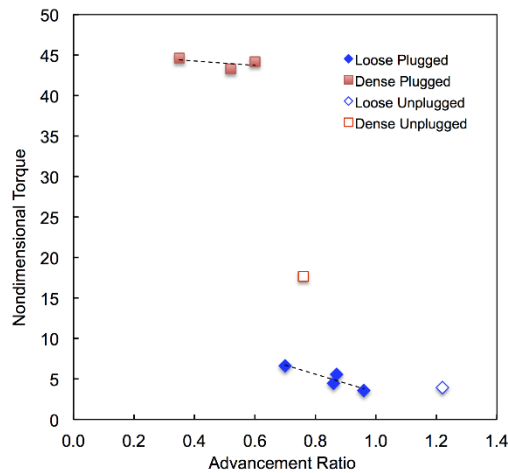


Figure 5: Changes in torque with advancement ratio.

Also, shown in Figure 5, the removal of soil from within the shaft reduced installation torque significantly in the dense sand. When the soil is removed from inside the shaft the advancement increases due to the reduced pile tip resistance. The torque was significantly lower than the plugged case, most likely due to reduced soil displacement and lower lateral stresses in the soil mass.

Figure 6 plots the breakout factor against the advancement ratio at the end of installation. The results for the plugged shaft indicate that under constant crowd the capacity decreases as the advancement ratio increases due to a reduction in helix friction. This suggests two mechanisms. First, the advancement ratios below 1 cause a passive deformation of the soil above the helix, which could be improving the soil in the vicinity of the pile through compaction and/or lateral stress increase. Another reason could be the modification of the deep failure pattern due to interface friction. Previous studies⁷ have suggested that interface friction has little influence on the capacity of shallow plates ($H/B < 8$), but the effect on the capacity of deep plates or helicies is uncertain. The capacities with the soil removed from the shaft (i.e. unplugged) were much lower than the plugged condition, likely due to much lower soil displacement and thus reduced lateral stresses within the soil mass.

The torque factor (K_t) is defined as ratio of the ultimate pull-out capacity to the installation torque. The non-dimensional plot of capacity vs. torque is shown in Figure 6 and thus the slope is a non-dimensional version of the torque factor. Using the theoretical equations for torque factor proposed by⁸, lines representing non-dimensional torque factors are presented in Figure 7 for the three values of critical state friction angle used in this study. As shown in the figure, the data for the plugged shaft in dense sand plot close to the $\delta_{cs} = 23^\circ$ curve (i.e.

steel) making it very consistent with the theory given that two of the three data points are plain steel.

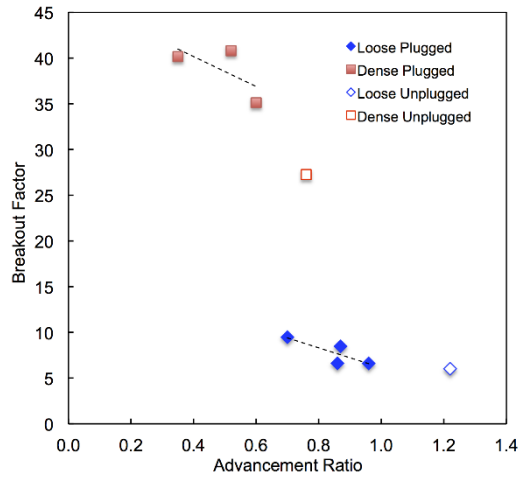


Figure 6: Effect of advancement ratio on the breakout factor.

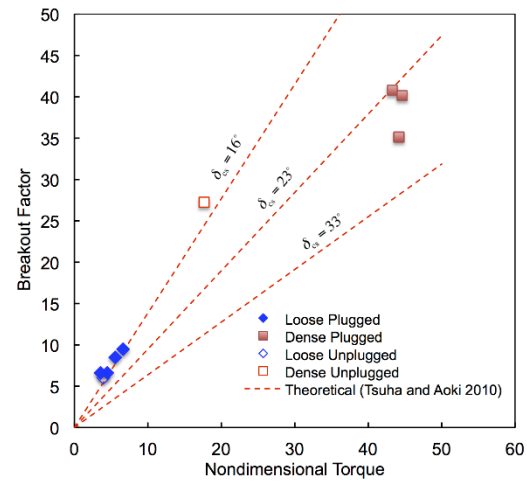


Figure 7: Comparison of non-dimensional pull-out capacity and torque.

The data for the loose sand as well as the unplugged shafts generally follow the curve for $\delta_{cs}=23^\circ$ (i.e. Teflon) independent of the roughness of the helix surface. In these tests, changing the roughness (and advancement ratio) affected both the capacity and the torque in the same way such that K_t did not change. The torque factor for the loose sand is also higher than the dense sand possibly due to improvement of the soil above the helix during installation.

CONCLUSIONS

Physical modelling was performed at 1g to investigate the behaviour of a 1/5-scale single-helix pile in loose and dense sand under constant crowd. Scale effects were accounted for by preparing the soil looser in the model than in the prototype, and by presenting the results in non-dimensional form. Reducing the friction on the helix plate improved advancement of the pile and reduced installation torque, but unfortunately also reduced capacity. The removal of soil from inside the shaft had similar effects but to a greater extent. The decrease in both torque and capacity therefore did not change the torque factor. The torque factor for the constant crowd pile compared favourably with theoretical torque factors that have been validated by centrifuge testing. However, the loose sand had a higher torque factor than the dense sand possibly due to improvement of the soil above the helix.

ACKNOWLEDGEMENTS

This material is based upon work partly supported by the U.S. Department of Energy, Office of Science, under Award Number DE-SC0017969. The second and third Authors were supported through the International Engineering Program (IEP) at the University of Rhode Island in collaboration with the Technical University Braunschweig.

REFERENCES

1. Perko H A. *Helical piles: a practical guide to the design and installation*. John Wiley and Sons, New Jersey, 2009.
2. Zuelke R. *Improving helical pile efficiency: an experimental study*. M. S. Thesis, Civil and Environmental Engineering, University of Rhode Island. 2018.
3. Bradshaw A S, Giampa J R, Gerkus H, Jalilvand S, Fanning J, Nanda S, Gilbert R, Gavin K, and Sivakumar V. Scaling considerations for 1-g model horizontal plate pile tests in sand. *ASTM Geotechnical Testing Journal*, Vol. 39, No. 6, 2016, pp 1006-1014.
4. Giampa J and Bradshaw A S. A simple method for assessing the peak friction angle of sand at very low confining pressures, *ASTM Geotechnical Testing Journal*, Vol. 41, No. 4, 2018, pp 639-647.
5. Hildebrandt L. *Improving helical pile efficiency: analytical modelling*. M. S. Thesis, Civil and Environmental Engineering, University of Rhode Island, 2018.
6. Byrne BW and Houlsby GT. Helical piles: and innovative foundation design option for offshore wind turbines. *Philosophical Transactions of the Royal Society A*, 373, 2015.
7. Rowe R K and Davis E H. The behaviour of pile plates in sand. *Geotechnique*, Vol. 32, No. 1, 1982, pp 25-41.
8. Tsuha, C. H. C., and N. Aoki. Relationship between installation torque and uplift capacity of deep helical piles in sand. *Canadian Geotechnical Journal*, Vol. 47, No. 6, 2010, pp 635–647.

SILENT FOUNDATION CONCEPT: HELICAL PILES FOR SKIRT AND PRE-PILED JACKET FOUNDATIONS

M HUISMAN

Heerema Marine Contractors, the Netherlands

SUMMARY: The offshore installation of monopile and pre-piled jacket foundations for wind turbines and wind farm substations or converter platforms is increasingly challenged by noise restrictions during pile driving. At present such restrictions are mostly in place in countries where offshore renewable projects are dominating. It is however expected that these restrictions will be extended to the offshore oil and gas industry. In addition, the offshore industry is increasingly recognizing the need for sustainable developments and an important factor in this is to reduce the impact of offshore installations on marine life.

Sister companies Heerema Marine Contractors (HMC) and the Heerema Fabrication Group (HFG) have therefore launched a joint internal development project on "silent foundations", in which alternative pile foundations are designed that could be installed without producing underwater noise. One of the concepts being developed is a helical pile foundation, which is suited for post- as well as pre-piled jacket foundations and is characterized by a high uplift and bearing capacity for a relatively shallow penetration.

The project's current status is that concept pile- and equipment designs have been completed as well as the basic installation procedures and simulations of the tool-vessel interaction in HMC's vessel simulation centre. The design for jacket foundations makes use of a double helix, dual diameter tubular pile. The smaller diameter lower pile section, with a single helix near its tip, is joined to the larger diameter upper pile section by a second helix (with same pitch and diameter as the one at the tip). The large diameter upper section is required in order to cope with bending moments induced into the pile by the jacket. The smaller diameter lower section, which will be located at a depth where no significant bending stresses occur anymore, is used to reduce friction during installation as well as overall pile weight and material cost. An additional benefit is that the piles can be installed through traditional skirt sleeves, minimizing changes to the jacket design.

For the tooling, several equipment options were considered: a torque tool at a fixed elevation, with the pile moving through it during installation, or a tool that is connected to the top of the pile and follows it down as the pile penetrates into the soil. The latter concept was selected as it is expected to allow for a more simple tool design that is more flexible for different situations, and the tool is designed as a large "ratchet" that is connected by a long, hinged moment arm to the installation vessel. The main issue with this concept is the reaction force required to counteract the torque on the pile. Simulations showed that the tool can be connected to HMC's semi-submersible installation vessels such as the Thialf, and that the vessel's Dynamic Positioning (DP) station keeping system is capable of keeping the vessel in position as well as generating sufficient thrust to work against the reaction force in the connecting arm.

The basic pile and equipment design is now being followed up by numerical modelling and validation testing in a geocentrifuge, with the aim of proceeding into a technical qualification end 2019 and further, large-scale testing in 2020.

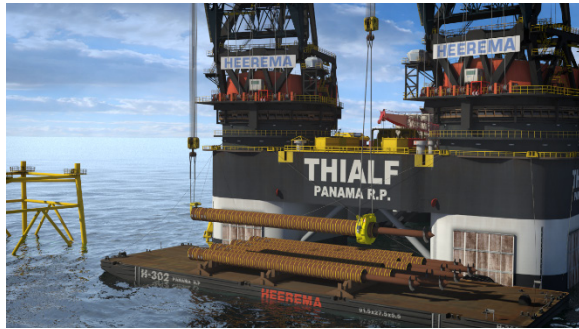


Figure 1 - Double-helix, dual diameter piles for use in jacket foundations.

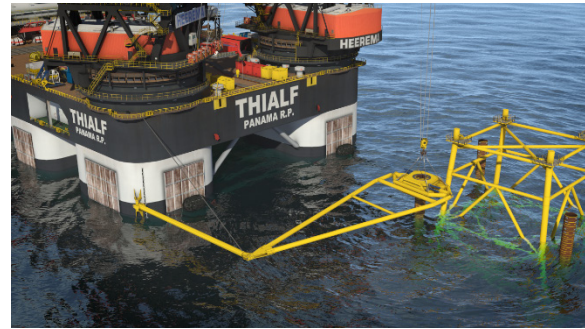


Figure 2 - Torque tool placed on pile top, with hinged moment arm to vessel.

SCREW ANCHOR MOORING OF A TIDAL ENERGY PLATFORM – AN INDUSTRIAL APPROACH TO R&D

A HUNT

Sustainable Marine Energy, Edinburgh, UK

SUMMARY: Screw Anchors were used to secure SME's PLAT-O#1 tidal energy platform which was deployed off the Isle of Wight in 2015 helping solve one of the key problems faced by the tidal energy, the one of low cost foundations and mooring applied by the taut moored system. The presentation will take you through the whole development journey experienced by SME focussing on key challenges encountered on the way and how these were overcome.

Screw Anchor Piles are not a new invention. They have been around for over 150 years. Up until recently their use in the maritime sector has been limited despite their relative simplicity.

Today there have been a few deployments, mainly servicing the shellfish aquaculture market where mooring loads are low.

Other applications have been explored and are being explored in the wave and tidal sector. SME's anchoring business division has installed screw anchors to secure its turbine system PLAT-O and for a new shell fish farm.

Some of the issues encountered on the journey to commercial delivery have not generally been about the design of a screw anchor itself but rather wider project constraints that tend to direct design in a particular direction.

In particular, the scale of these deployments is interesting: too large to deploy from a very small vessel to deploy but too small to the size of traditional oil and gas support vessels. They have started to open up role for multicat size vessels that offer considerable cost savings but demand a fresh technical approach to the whole anchoring solution.

Load requirements from clients are increasing. This can lead to issues regarding anchor installation with extremely high installation load and torque being predicted.

The challenge is to get on the right side of the anchor solution design iteration spiral and not allow installation infrastructure and costs to escalate.

SCREW PILES FOR FLOATING WIND AND OFFSHORE AQUACULTURE

S POWELL

Marine South East Ltd, 2 Venture Road, University of Southampton Science Park, Southampton, SO16 7NP, UK

SUMMARY: Marine South East (MSE) has been working with international partners to explore how screw pile anchoring solutions could enable a major expansion in floating offshore facilities.

There is a growing need for floating structures to expand wind power capacity into deeper waters and offshore aquaculture platforms to increase sustainable seafood production.

Conventional anchoring solutions such as drag-embedment anchors, impose a high installed cost and can represent a significant component of the facility's capital cost. Impact piled anchors emit marine noise and require large specialist vessels for installation.

Screw pile technology is extensively used in terrestrial applications but has very limited small-scale underwater use for anchoring of lightweight moorings.

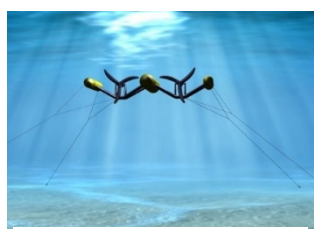


Figure 1: 'PLATO' Tidal Platform

Marine South East Ltd believes anchor designs based around screw pile technology could potentially offer quiet and cost-effective anchoring in a wide range of seabed types. In partnership with Sustainable Marine Energy Ltd, MSE led the 'SAMED' project to develop a screw pile system for tethering marine energy devices to the seabed. An array of 4 screw piles was successfully used to anchor the 'PLATO' tidal energy device in 16m water depth off the Isle of Wight. SAMED received £300K of grant funding from the Energy Entrepreneurs Fund.

To further develop and demonstrate this capability, MSE is leading a consortium focused on the needs of Principle Power Inc (a leading global floating wind platform developer), and involving Lloyds Register and Sustainable Marine Energy Ltd. Case studies have been prepared about the market requirements.

Existing moorings cost €1m x 3 for each platform. The predicted 300GW of floating wind capacity projected by 2030 represents a total anchoring cost of €5B, there is a clear need to reduce this.

The consortium will specify and build a new full-scale rig to achieve 30-50% cost savings. The new system would reduce installation times and dispense with the need for expensive specialist anchor handling vessels.

The consortium is seeking £1m investment to finance a full-scale commercial rig and is keen to collaborate with the screw pile research community, to advance this technology and its expanding application around the world.



Figure 2: 'SAMED' Screw Pile and Installation Rig



Figure 3: Principle Power WindFloat'