Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0161

XVII European Conference on Soil Mechanics and Geotechnical Engineering
ECSMGE 2019 Reykjavik

The design of axially loaded driven piles in chalk

La conception de pieux battus chargés axialement dans de la craie

R.M. Buckley

Oxford University, Oxford, UK formerly Imperial College London, London, UK

R.J. Jardine, S. Kontoe
Imperial College London, London, UK

P. Barbosa
Iberdrola Renovables Offshore, Deutschland, Berlin, Germany

F.C. Schroeder
Geotechnical Consulting Group LLP, London, UK

ABSTRACT: The behaviour of driven piles in chalk is poorly understood; their installation resistance, set-up characteristics and response to cyclic and static loading all warrant further investigation. Current axial capacity design methods have poor reliability, particularly in low-medium density chalk. This paper gives an overview of research which combined systematic investigations at an onshore chalk site in Kent, UK, with careful analysis of large scale offshore tests. The onshore studies involved reduced-scale open-ended driven piles and heavily instrumented closed-ended Imperial College Piles. The offshore analyses addressed static and dynamic pile tests conducted on full scale open-ended steel tubular piles driven in glacial till and low-to-medium density chalk. The understanding drawn from both streams of research form the basis for a new Chalk ICP-18 effective stress-based design approach, which centres on the key physical phenomena identified: (i) the close correlation between pile resistances and local variations in CPT cone resistance (ii) the marked effect of the relative depth, h/R*, of the pile tip below any given chalk horizon (iii) the effective stress shaft interface shear failure characteristics and (iv) very significant capacity gains over time. The new method offers better predictions of field behaviour with time than the current industry method.

RÉSUMÉ: Le comportement des pieux battus à la craie est mal compris; leur résistance à l'installation, leurs caractéristiques d'installation et leur réponse aux charges cycliques et statiques justifient toutes des recherches supplémentaires. Les méthodes actuelles de calcul de la capacité axiale ont une fiabilité médiocre, en particulier pour les craies de densité faible à moyenne. Cet article donne un aperçu des recherches combinant des enquêtes systématiques sur un site de craie terrestre dans le Kent, au Royaume-Uni, et une analyse minutieuse d'essais en mer à grande échelle. Les études à terre portaient sur des pieux battus à échelle ouverte et à échelle réduite et sur des pieux à instrument fermé et fortement instrumentés. Les analyses en mer ont porté sur des essais de pieu statiques et dynamiques conduits sur des pieux tubulaires en acier à bouts ouverts et à pleine échelle, enfoncés dans du till glaciaire et des craies de densité faible à moyenne. La compréhension tirée des deux axes de recherche constitue la base d'une nouvelle approche de conception efficace basée sur les contraintes Chalk ICP-18, qui est centrée sur les principaux phénomènes physiques identifiés: (i) la corrélation étroite entre les résistances des pieux et les variations locales de la résistance au cône CPT (ii) l'effet marqué de la profondeur relative, h / R *, de la pointe du pieu au-dessous d'un horizon de craie donné (iii) les caractéristiques de rupture par cisaillement à l'interface contrainte de l'arbre de contrainte et (iv) des gains de capacité très importants dans le temps. La nouvelle méthode offre de bien meilleures prédictions du comportement sur le terrain.

Keywords: Piles; chalk; axial capacity, ageing, cyclic loading,

1 INTRODUCTION & MOTIVATION

Low density, structured, fine grained, porous chalk rocks are encountered over large areas of North West Europe. Low to medium density material is found across the Southern UK and the North and Baltic Seas (Mortimore, 2012). The offshore wind energy sector in Northern Europe has developed rapidly over the last decade. Large, high-capacity, open-ended tubular driven steel piles are typically used to support these offshore developments (as well as near-shore and marine structures). In chalk, engineers frequently encounter difficulties in designing such piles to withstand axial static and cyclic loading in service, relying on potentially uncertain design recommendations.

The limited data set available to Lord *et al.* (2002), when developing the CIRIA C574 guidelines, led them to recommend adopting ultimate shaft resistances in design of 120kPa in high density chalk and 20kPa in all other densities and grades. The latter value is extremely low considering that low-medium density chalk has Unconfined Compressive Strength (UCS) in the range of <3-5MPa and cone tip resistance, q_t of 4-50MPa. The current recommendations can lead to stark choices in design and impact significantly on the economics of OWF (Barbosa *et al.*, 2017).

The behaviour of driven piles in chalk during installation has also proven difficult to predict; both pile refusals, free falls under self weight and very low driving resistances have been reported (Carotenuto *et al.*, 2018, Buckley *et al.*, 2018a). The low installation shaft stresses are linked to the chalk found at any depth z losing its structure due to the high strains developed beneath the pile tips (Hobbs and Atkinson, 1993) and a putty annulus forming as the pile tip advances to achieve greater relative depth, h below the depth in question in an analagous way to that seen in sands and clays (Randolph *et al.*, 1994, Jardine *et al.*, 2005). A simple method is required to predict chalk resistance to driving (CRD) which can capture the influence of the relative tip depth, h.

Set-up or increase in shaft capacity with time has been reported for piles in chalk from static pile re-tests and driving data (Vijayvergiya *et al.*, 1977, Skov and Denver, 1988, Lahrs and Kallias, 2013, Ciavaglia *et al.*, 2017, Dührkop *et al.*, 2017). However, the effect of cyclic loading on axial pile capacity in the short and long-term remains unknown in chalks. The requirement for further research to predict pile driveability and service performance is clear. This paper summarises a programme of joint industry project (JIP) research which aimed to use field investigations to (i) understand the mechanisms behind low installation resistances (ii) investigate the underlying effective stress processes (iii) obtain information on the set-up characteristics of previously unfailed piles and (iv) to assess the effect of axial cyclic loading on set-up capacity. The over-arching aim of the research was to develop more reliable procedures and guidance for axial design of driven steel piles in chalk. (Buckley *et al.* (2018a), Buckley *et al.* (2018b), Jardine *et al.* (2018), Buckley *et al.* (2019a), Buckley *et al.* (2019b)) provide further details.

2 RESEARCH PROGRAMME

2.1 Offshore testing programme

Iberdrola‘s requirement to carry out novel offshore static and dynamic field tests to verify and refine pile design for the Wikinger OWF (Figure 1) in the German Baltic Sea (see Barbosa *et al.*, 2017), prompted a Joint Industry Project (JIP) involving Iberdrola, Imperial College London (ICL) and the Geotechnical Consulting Group (GCG), supported by Innovate-UK. Wikinger includes seventy 5MW wind turbines supported by jackets installed in up to 42m of water. The jackets are supported by 2.7m dia. open ended steel tubes founded in varying profiles of Weichsellian glacial till and low-medium density Maastrichtian chalk. An Offshore Substation (OSS) is supported by similar 3.67m dia. piles. The glacial and fluvioglacial till deposits are well-graded and of low plasticity and are relatively insensitive (Buckley *et al.*, 2019a). Cone resistances in the till range from 5-15MPa, sleeve friction f_s from 100-300kPa and excess pore water pressures, u_2 lie between -200 and -250kPa. The chalk typically classifies as low-medium density Grade A1/A2 material (Bowden *et al.*, 2002) with UCS q_u values of 0.2-0.8MPa, which fall below the published range (Matthews and Clayton, 1993). Cone resistances in the structured chalk range from 10-20MPa, f_s from 200-400kPa while u_2 reaches 10MPa. Where CPT data was not available composite profiles were asssessed by developing a correlation with shear wave velocity (Buckley *et al.*, 2019a). Doughty *et al.* (2018) showed that Proctor compaction applied at natural mositure content to samples of Wikinger chalk caused marked de-structuration into a putty with undrained strength, s_u of ≈4kPa. Interface ring shear tests in the till gave δ'_{ult} angles of 26.5-28° (Buckley, 2018) and 32-34°in the chalk (Fugro, 2013).

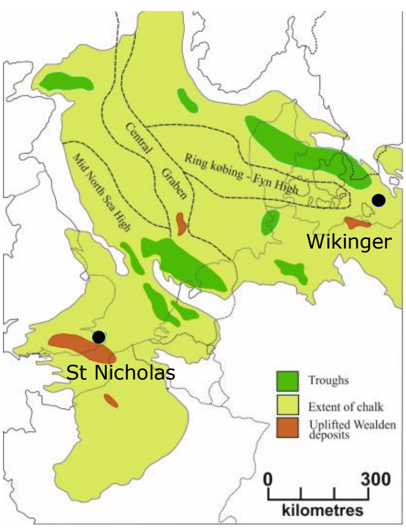

Figure 1 Chalk of NW Europe, after Mortimore (2012) also showing the test site locations

The Wikinger testing campaign comprised six instrumented 1.37m dia. steel open-ended piles, driven with dynamic monitoring at three locations WK38, WK40 and WK70. One pile was tested statically at each location, using a remotely operated sea-bed testing system, after 12-15 weeks of ageing, followed by dynamic re-strikes on an adjacent pile. Further instrumented driving and re-strike monitoring followed on the larger diameter production piles.

2.2 Onshore testing programme

In tandem with the high value offshore tests, the ICL team carried out investigations at an onshore test site close to St. Nicholas-at-Wade (SNW), NE Kent, UK (Figure 1). The onshore experiments were more easily controlled than the offshore tests and allowed systematic field investigation of how ageing and cyclic loading affect steel piles in chalk. The test site's chalk is similar to that encountered at Wikinger. The SNW chalk classifies as low-medium density Grade B2/B3. The fractures are more open (to<3mm) and closely spaced (between 60 and 200mm) than those encountered at Wikinger. CPT tests indicate q_t of 5-35MPa, f_s up to 400kPa and u_1 pore water pressures as high as 8MPa within the depth of interest.

The testing programme employed seven un-instrumented 139mm dia. open steel tube piles driven to depths of 5.5mbgl and two closed-ended 102mm dia. highly instrumented Imperial College Piles (ICP). The ICPs can measure local axial load, pore water pressure, shear stress and radial stresses following the design of Bond *et al.* (1991). Three of the piles were instrumented dynamically during driving and three were used to investigate ageing effects using static tension tests at various ages after installation. The remaining four piles were used to investigate the effects of axial cyclic loading on piles of ≈8months age. All of the tests were conducted using test equipment designed and built at Imperial College (Buckley *et al.*, 2018a). The two ICP tests (one with a flat end condition and one with a conical tip) were conducted in collaboration with Prof. Barry Lehane and colleagues at the University of Western Australia. Two levels of instruments were used in the chalk tests as shown on Figure 2. The ICPs were monitored during installation, equalisation (up to 80 days) and static tension testing to failure (Buckley *et al.*, 2018b).

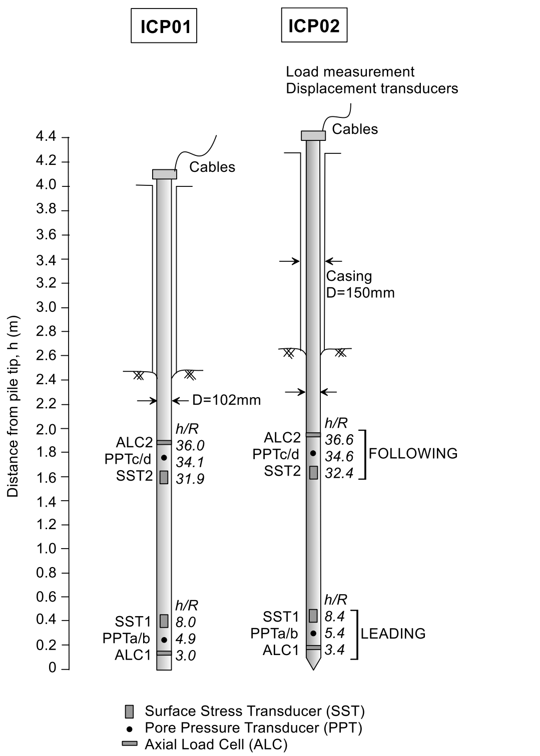

Figure 2 Imperial College Pile configuration used in chalk tests; Buckley et al. (2018b)

3 RESEARCH OUTCOMES

3.1 Wikinger testing campaign

The primary outcomes from the Wikinger pre-construction and production piling testing can be summarised as

1. Analysis of dynamic and static tests showed that shaft resistances apply mainly on piles' outside areas and reduce sharply with increasing relative tip penetration (h/R*) in tills and, still more sharply in chalk, where $R^* = [R^2_{outer} - R^2_{inner}]^{0.5}$ and R_{outer} and R_{inner} are the pile's outer and inner radii;
2. Significant shaft capacity increases applied in chalk, with ultimate set-up factors greater than 5.5 that followed a hyperbolic trend with time and increased with h/R*;
3. Shaft capacity increases, as assessed from analysis of dynamic data, appeared to be extremely rapid in the chalk reaching 50% of the final long-term equilibrium value within an hour of the final driving blow;
4. Shaft set-up greatly exceeded the pre-test predictions made by the designers and as a result the field capacities at the two chalk dominated sites (WK43 and WK70) exceeded the safe limit of the static test rig (Figure 3);
5. Good agreement was found between independent dynamic and static tests that helped the interpretation of reliable estimates for shaft capacity in the chalk layers;
6. Analyses of the chalk layers showed long-term shaft capacities well above the the CIRIA C574 method recommendations which appeared highly conservative;
7. High impact benefits could be taken by recognising the positive effects of pile ageing, updating design procedures and supporting engineering assessments with field testing;
8. Full scale static testing is fully feasible offshore and the results proved cost-effective (see Barbosa *et al.*, 2017).

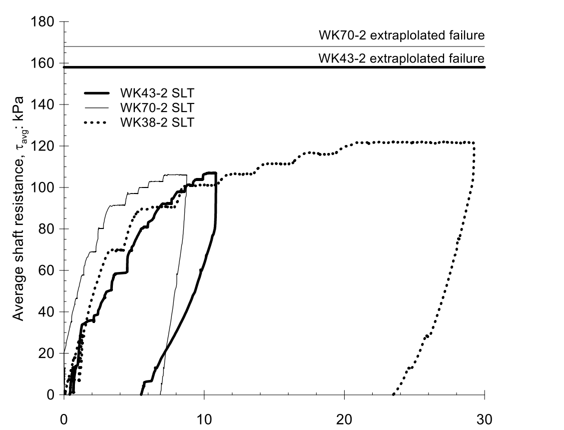

Figure 3 Offshore static load tests at Wikinger including extrapolated failure points

3.2 Onshore testing campaign

The multiple experiments conducted with driven steel open-ended piles and jacked highly instrumented Imperial College (ICP) piles at SNW (Buckley *et al.*, 2018a, Buckley *et al.*, 2018b) demonstrated that:

1. Very high excess pore water pressures develop around the tips of piles in chalk and low strength chalk putty annuli form around their shafts during driving;
2. High in-situ permeabilities allow partial drainage during CPT and pile installation. Marked water content reductions occur as pore-pressures dissipate;
3. Low average shaft resistances, compatible with the CIRIA values, apply during and immediately after driving. Shaft shear stress distributions vary markedly with depth and show far stronger reductions with relative pile tip depth h/R* than in sands or clays;
4. The shaft radial effective stresses developed during installation correlate with the CPT cone resistance, mobilising comparably low σ'_{rf}/q_t ratios to crushable calcareous sands;
5. The shaft capacity of driven open-ended piles' can increase five-fold after driving to give long-term unit shaft resistances far above the CIRIA value.
6. Chalk set-up appeared to develop more slowly at SNW, where discontinuities are closely spaced and open;
7. Set-up rates may also be sensitive to the installation process and physiochemical processes;
8. Shaft failure can be described by an effective stress Coloumb law, with δ' angles that match laboratory interface tests (Figure 4). Shaft radial effective stresses increase during static loading to failure, as is seen in sands;
9. Cyclic loading of the aged driven piles resulted in a range of observed responses from unstable to stable/metastable. Unstable tests failed with N<100 showing marked reductions in stiffness, large accumulation of permanent displacement and significant decreases in tension capacity;
10. Stable and metastable cycling led to broadly stable capacities and cyclic stiffness combined with displacement accumulation trends that did not stabilise fully as cycling continued.

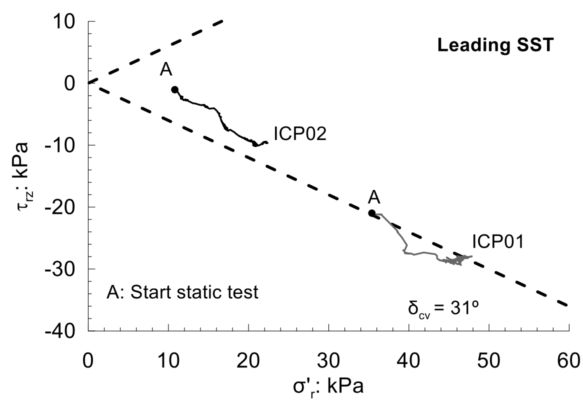

Figure 4 Typical effective stress paths measured during static loading of ICP tests at the SNW site (see also Figure 2)

4 METHODS TO PREDICT SHORT & LONG TERM PILE CAPACITY IN CHALK

The onshore and offshore testing programes were combined with other supporting evidence to develop preliminary rules for predicting short and long term capacity of piles driven in chalk. The development of the method was described in full by Buckley (2018).

4.1 Predicting chalk resistance to driving

Buckley *et al.* (2019b) describe the Chalk ICP-18 approach for predicting CRD which is based on the analysis of dynamic driving data from piles with a wide range of diameters (0.139-3.67m) and diameter-to-wall thickness ratios, D/t_w(≈20-70). The dynamic analyses employed the sofware code IMPACT (Randolph, 2008) which employs the Randolph and Simons (1986) and Deeks and Randolph (1991) soil resistance models. The Chalk ICP-18 equations capture the key findings of the pile test programmes: (i) the ability of CPT cone resistance to characterise local variations in chalk properties (ii) the strong tendency of the local shaft σ'_r and τ_{rz} values to reduce with increasing tip penetration (h/R or h/R*) and (iii) the interface effective stress shear failure characteristics and have similar forms for base and shaft resistance to the ICP-05 sand approach (Jardine *et al.*, 2005). The ultimate interface angles are obtained from ring shear interface tests conducted against remoulded soil consolidated under appropriate normal stresses, employing interfaces that represent the pile shaft material and roughness satisfactorily.

The local degradation rates appear to reduce with D/t_w. The Chalk ICP-18's correlation for short-term chalk shaft resistance, τ_{rzi} to driving takes the form:

$$\tau_{rzi} = \sigma'_{ri} \tan\delta'_{ult} \quad (1)$$

$$\sigma'_{ri} = 0.031 q_t \left(\frac{h}{R^*}\right)^{-0.481\left(\frac{D}{t_w}\right)^{0.145}} \quad (2)$$

Where σ'_{ri} is the radial effective stresses during driving and q_t is the net cone resistance averaged over 300mm (following Power (1982). In both cases, a lower limit of 6 applies to h/R or h/R*. The power law exponent has a larger absolute value for a monopile with D/t_w ratio of 80 than a smaller diameter jacket pile, for which the D/t_w ratio may be less than 40.

As discussed previously, shaft CRD values may increase considerably during any driving pauses, which could reach the long term static value over long pauses. Buckley *et al.* (2019b) showed that the CRD gains degrade as the pile tip advances on re-driving about 1m. The average values of equivalent bearing pressure q_b inferred from the dynamic analyses, varied with the pile penetrations per blow, and amounted to 0.4 to $0.7q_{t,1.5D}$ where q_t is averaged ±1.5D from the base. Buckley *et al.* (2019b) implemented the new method into a driveability analysis program. The traditional Smith (1962) models were used with a modification to account for non-linear dependency of driving resistance on velocity. The proposed CRD method gave better predictions for independent case histories than the currently applied industrial method.

4.2 Predicting long term axial capacity for piles driven in chalk

The static axial capacity method in chalk ICP-18 follows a similar approach to the CRD treatment. The long-term radial effective stress response to shaft shear failure (σ'_{rf}) includes a contribution from the constrained interface dilation mechanism, as observed in the ICP tests, which adds to the local shaft resistance. A dilation component, $\Delta\sigma'_{rd}$, is therefore included (3) which offers a significant contribution to small diameter piles, but may become negligible with large offshore piles. A different expression is proposed for the local long term (fully equalized) σ'_{rc} component:

$$\sigma'_{rf} = (\sigma'_{rc} + \Delta\sigma'_{rd}) \quad (3)$$

$$\sigma'_{rc} = 0.081 q_t \left(\frac{h}{R^*}\right)^{-0.52} \quad (4)$$

As with sands, $\Delta\sigma'_{rd}$ can be estimated by elastic cavity expansion:

$$\Delta\sigma'_{rd} = 4G\Delta r/D \quad (5)$$

Where G is the shear modulus and Δr is the average radial movement caused by dilation at the interface. Buckley *et al.* (2018b) ICP tests suggested that $\Delta r \approx 0.5\mu m$ in chalk, which is far smaller than the $\Delta r \approx 2R_{CLA}$ (or peak to trough roughness of the pile surface) radial interface dilation that applies to piles driven in sands (Jardine et al 2005). This reflects the far smaller (mainly silt) size of the chalk grains.

Jardine *et al.* (2018) discuss the performance of the Chalk ICP-18 method at independent test locations. Figure 5 shows measurements and predictions for the shaft shear stresses as applying in dynamic and static tests at (a)a 2.7m dia Wikinger production pile, (b)a strain-gauged static test conducted at 119 days on a 0.762mm dia pile by Ciavaglia *et al.* (2017) and (c) and (d) tests on one closed-ended, strain-gauged, 400mm square pre-cast concrete pile (Pile 1) and another strain-gauged closed-ended 445mm diameter steel tube (Pile 2) driven at Fleury-sur-Andelle, France; Bustamante *et al.* (1980).

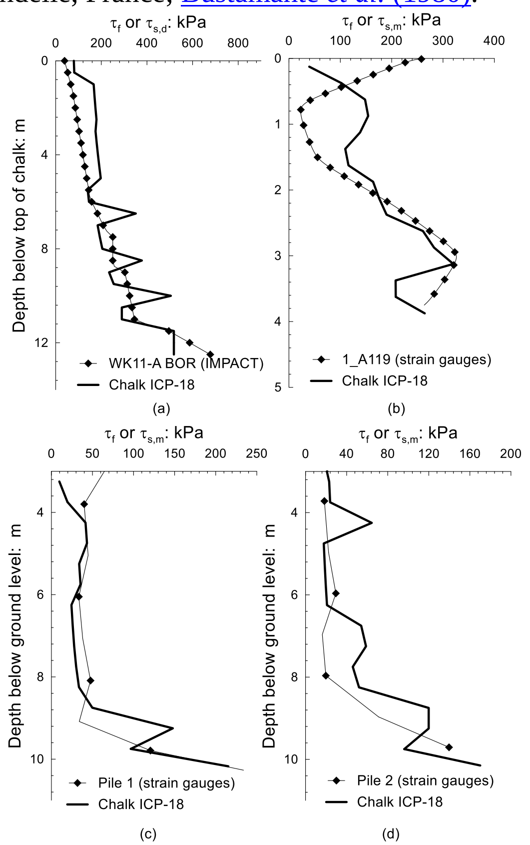

Figure 5 Measured and predicted shaft resistance profiles (a) open-ended piles at Wikinger (b) open-ended piles at SNW (Ciavaglia et al., 2017) (c) closed-ended square concrete pile at Fleury-sur-Andelle (Bustamante et al., 1980) (d) closed-ended steel tubular pile at Fleury-sur-Andelle (Bustamante et al., 1980)

CIRIA C574 approach, which assumes a fixed average 20 kPa shaft resistance, was over-conservative in all the cases considered above and the Chalk ICP-18 captures the local profiles of shear stress far more reliably. Buckley (2018) applied the method to predict four static and eleven dynamic tests on open-ended piles which led to an average calculated to measured (Q_c/Q_m) shaft capacity ratio of 0.97 and a standard deviation of 0.16 for soil resistance to driving measurements. The long-term tests on the same piles led to a Q_c/Q_m mean of 1.0 and a standard deviation of 0.11. While the long-term Q_c/Q_m ratios for Fleury-sur-Andelle are 1.02 and 1.77 for Pile 1 and Pile 2 respectively, indicating that the method over-predicted the long-term shaft shear stresses, both piles had been subjected to several prior tests to failure which may have affected their long-term capacities.

Further research is required and, as summarised by Jardine *et al.* (2019) in these proceedings, the Authors are engaged, in conjunction with other colleagues from Oxford University, in a new EPSRC and Industry funded JIP. The ALPACA (Axial Lateral Pile Analysis for Chalk Applying multi-scale field and laboratory testing) JIP aims to advance understanding of driven piles in chalk, particularly for offshore wind-turbines.

5 CONCLUSIONS

This paper summarises outcomes from a JIP study involving onshore and offshore experiments to advance understanding of driven piles in chalk. The research has led to new rules for predicting installation resistances and long-term axial capacities that offer better predictions for the case studies considered than currently applied procedures. More independent high-quality pile tests are required to evaluate and refine the preliminary Chalk ICP-18. Carefully conducted pile tests at suitable sites supported by site investigations that include high quality in-situ testing, along with interface shear tests, can offer a highly cost-effective means of reducing design uncertainty and optimising design. The ALPACA JIP is further advancing the understanding of how driven piles behave in chalk.

ACKNOWLEDGEMENTS

The JIP was funded by Innovate UK with additional support from Atkins. The offshore tests at Wikinger were carried out by Bilfinger and COWI/IMS. Prof. Mark Randolph is gratefully acknowledged for allowing the use of IMPACT as is Prof. Barry Lehane and colleagues for their support during the ICP work. Lankelma and Cambridge Insitu are also gratefully acknowledged.

REFERENCES

Barbosa P. M., Geduhn, M., Jardine, R. J. & Schroeder, F. C. (2017). Large scale offshore static pile tests-practicality and benefits. *Proc. 8th Int. Conf. on Offshore Site Investigation and Geotechnics*, London, UK: 644-651

Bond A. J., Jardine, R. J. & Dalton, J. C. P. (1991). Design and performance of the Imperial College instrumented pile. *Geotech. Test. J.,* **14**, No. 4: 413-424

Bowden A. J., Spink, T. W. & Mortimore, R. N. (2002). The engineering description of chalk: its strength, hardness and density. *Q. J. Eng. Geol. Hydrogeol.,* **35**, No. 4: 355-361

Buckley R. M., Jardine, R. J., Kontoe, S., Parker, D. & Schroeder, F. C. (2018a). Ageing and cyclic behaviour of axially loaded piles driven in chalk. *Géotechnique,* **68**, No. 2, *https://doi.org/10.1680/jgeot.17.P.012*: 146-161

Buckley R. M., Jardine, R. J., Kontoe, S. & Lehane, B. M. (2018b). Effective stress regime around a jacked steel pile during installation ageing and load testing in chalk. *Can. Geotech. J. doi: 10.1139/cgj-2017-0145,* **doi: 10.1139/cgj-2017-0145**, No.:

Buckley R. M. (2018). *The axial behaviour of displacement piles in chalk.* PhD Thesis, Imperial College London, London, UK

Buckley R. M., Jardine, R. J., Kontoe, S., Barbosa, P. & Schroeder, F. C. (2019a). Full-scale observations of offshore piles driven in chalk and glacial tills: field behaviour under dynamic and static axial loading. Submitted.

Buckley R. M., Kontoe, S., Jardine, R. J., Schroeder, F. C. & Barbosa, P. (2019b). Pile driveability in low to medium density chalk *In preparation.*

Bustamante M., Combarieu, O. & Gianeselli, L. (1980). Portance des pieux dans la craie altérée. *Annales de L'institut technique du Batiment et des Travaux Publics,* **388**, No. SOL FOND 174: 26-56

Carotenuto P., Meyer, V., Strøm, P. J., Cabarkapa, Z., St. John, H. & Jardine, R. J. (2018). Installation and axial capacity of the Sheringham Shoal offshore wind farm monopiles – a case history. *Engineering in Chalk*, London, UK: 117-122

Ciavaglia F., Carey, J. & Diambra, A. (2017). Time-dependent uplift capacity of driven piles in low to medium density chalk. *Géotechnique Letters,* **7**, No. March: 1-7

Deeks A. J. & Randolph, M. F. (1991). Evaluation of the inelastic response of an axisymmetric foundation to impact loading. *Proc. 7th Intl. Conf. on Computer Methods and Advances in Geomechanics*, Cairns, Australia: 735-740

Doughty L. J., Buckley, R. M. & Jardine, R. J. (2018). Investigating the effect of ageing on the behaviour of chalk putty. *Engineering in Chalk*, London, UK: 695-701

Dührkop J., Maretzki, S. & Rieser, J. (2017). Re-evaluation of pile driveability in chalk. *Proc. 8th Intl. Conf. Offshore Site Investigation and Geotechnics* London, UK: 666-673

Fugro (2013). *Wikinger Offshore Windfarm: Advanced Laboratory and Drivability Assessment,* Fugro Geoconsulting Ltd., J22026-1

Hobbs N. B. & Atkinson, M. S. (1993). Compression and tension tests on an open-ended tube pile in chalk. *Ground Engineering,* **26**, No. 3: 31-34

Jardine R. J., Chow, F. C., Overy, R. & Standing, J. R. (2005). *ICP design methods for driven piles in sands and clays,* London: Thomas Telford.

Jardine R. J., Buckley, R. M., Kontoe, S., Barbosa, P. & Schroeder, F. C. (2018). Behaviour of piles driven in chalk. *Engineering in Chalk*. ICE Publishing: 33-51

Jardine R. J., Buckley, R. M., Byrne, B., Kontoe, S., Macadam, R. & Vinck, K. (2019). The ALPACA research project to improve driven pile design in Chalk. *Proc. 17th European Conference on Soil Mechanics and Geotechnical Engineering, in preparation*, Reykjavik, Iceland:

Lahrs T. & Kallias, A. (2013). Probebelastungen von Stahlrohren in Kreide für den Offshore-Windpark Baltic 2. *Proc. Pfahl Symposium*, Braunschweig, Germany: 451-466

Lord J. A., Clayton, C. R. l. & Mortimore, R. N. (2002). *Engineering in chalk,* CIRIA, C574

Matthews M. C. & Clayton, C. R. I. (1993). Influence of intact porosity on the engineering properties of a weak rock. *Intl. Symp. Geotechnical Engineering of Hard Soils and Soft Rocks*, Rotterdam, the Netherlands: 693-702

Mortimore R. N. (2012). The 11th Glossop Lecture: Making sense of Chalk: a total-rock approach to its Engineering Geology. *Q. J. Eng. Geol. Hydrogeol.,* **45**, No.: 252-334

Power P. (1982). The use of the electric static cone penetrometer in the determination of the engineering properties of chalk. *Proc. 2nd Eur. Symp. on Penetration Testing*, Amsterdam, The Netherlands: 769-774

Randolph M. F. & Simons, H. A. (1986). An improved soil model for one-dimensional pile driving analysis. *Proc. 3rd Intl. Conf. Numerical Methods in Offshore Piling*, Nantes, France: 3-17

Randolph M. F., Dolwin, J. & Beck, R. (1994). Design of driven piles in sand. *Géotechnique,* **44**, No. 3: 427-48

Randolph M. F. (2008). *IMPACT - Dynamic analysis of pile driving,* Manual

Skov R. & Denver, H. (1988). Time-dependence of bearing capacity of piles. *Proc. 3rd Int. Conf. on the Application of Stress-Wave Theory to Piles,* Ottowa, Canada: 879-888

Vijayvergiya V. N., Cheng, A. P. & Kolk, H. J. (1977). Design and installation of piles in chalk. *Offshore Technology Conference*, Houston, Texas: 459-464