Behaviour of piles driven in chalk

R.J. Jardine[*1], R.M. Buckley[1], S. Kontoe[1], P. Barbosa[2] and F.C. Schroeder[3]

[1] *Imperial College London, London, UK*
[2] *Iberdrola Renewables, Berlin, Germany*
[3] *Geotechnical Consulting Group LLP, London, UK*
[*] *Corresponding Author*

ABSTRACT. Driving resistance is difficult to predict in chalk strata, with both pile free-fall self-weight 'runs' and refusals being reported. Axial capacity is also highly uncertain after driving. This paper reviews recent research that has explored these topics. Programmes of onshore tests and novel, high-value offshore, experiments involving static, dynamic and cyclic loading are described. The key findings form the basis of the Chalk ICP-18 approach for estimating the driving resistance and axial capacity of piles driven in low-to medium-density chalk. The new approach is presented and the highly significant impact of set-up after driving is emphasised. It is shown that Chalk ICP-18 overcomes the main limitations of the industry's current design guidelines by addressing the underlying physical mechanisms. While further tests are required to enlarge the available test database, the new approach is able to provide better predictions for tests available from suitably characterised sites. A new Joint Industry Project is outlined that extends the research to cover further axial, lateral, static and cyclic loading cases.

1 INTRODUCTION

This keynote paper summarises recent industrial and academic research advanced by the Authors to aid the design of piles driven in chalk. More detailed reporting on, and analysis of, the collaborative research is given by Barbosa et al (2015 and 2017), Buckley (2018), Buckley et al (2018a, b, c) and Jardine (2018).

The main research objectives were to: (i) develop new methods of field pile testing and analysis; (ii) expand the database of high quality field data and (iii) produce new effective-stress based design rules that capture the key aspects of pile behaviour in a comparable manner to the ICP-05 procedures developed by Jardine et al (2005) for sand and clay strata.

The ICP-05 methods are now applied internationally and can offer considerable benefits over conventional approaches, including cases where cyclic loading must be addressed. Multiple onshore and offshore applications are reported by Williams et al (1997), Overy (2007), Merritt et al (2012), Jardine et al (2015), Argiolas and Jardine (2017), Hampson et al (2017) and Rattley et al (2017).

This paper offers a background review of the need for research into the behaviour of piles driven in chalk, before describing field experiments conducted at two low-to-medium density chalk sites: one (the St Nicholas-at-Wade test facility) developed onshore in Kent (UK), and another (the Wikinger windfarm) located in the German Baltic Sea. Multiple dynamic (compressive) pile tests conducted at various ages after driving were combined with static and cyclic tension loading experiments. Review and interpretation of the pile experiments and site characterisation studies led to the 'Chalk ICP-18' effective stress methods that: (i) offer more reliable predictions for static capacity; and (ii) can be extended to consider the impact of axial cyclic loading. The latter can be a key concern, particularly with offshore oil, gas and wind-turbine foundations.

After setting out approaches for assessing driving resistance and long-term static axial capacity, the new ALPACA research programme is outlined. This Joint

Industry Project (JIP), led by Imperial College and Oxford University offers new opportunities to test and refine design rules for axial lateral and cyclic loading through comprehensive testing on 26 driven piles, most of which are instrumented with novel fibre optic strain gauge systems. It is supported by comprehensive laboratory and in-situ testing research.

This paper emphasises that advancing understanding of how driven piles behave in chalk enables more economic foundation design and also helps to ensure reliable field performance. Potential applications exist in many offshore, nearshore and onshore projects.

2 THE NEED FOR RESEARCH INTO DRIVEN PILE BEHAVIOUR IN CHALK

Chalk is present under large parts of NW Europe as shown in Figure 1, extending from Poland and Sweden to the United Kingdom and Ireland.

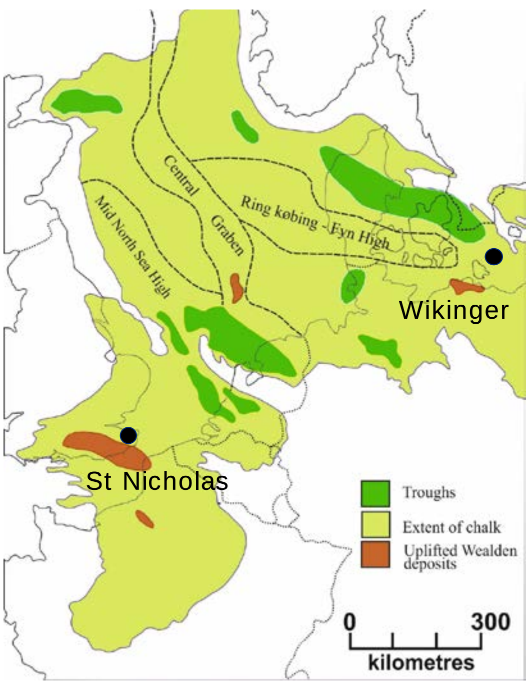

Figure 1 Chalk of NW Europe, after Mortimore (2012) also showing the Wikinger and St Nicholas at Wade test site locations

Chalk deposits are often encountered in geotechnical investigations conducted in these areas to aid design for ports and harbours, roads and railways, commercial and domestic buildings, industrial plants and utilities, as well as offshore oil, gas and wind-energy installations. While bored and CFA piles are selected for many applications, large open-ended driven piles are employed more frequently for large bridge, port and offshore works; see Lord et al (2002), Hamre (2017), Buckley (2018), Jardine (2018).

Offshore wind-energy has developed very rapidly over the last decade in Northern Europe. Over two thirds of the world's installed offshore generating capacity is currently installed in UK and German waters. Multiple major wind-farms have been, or are being, developed at offshore sites in UK, Danish, French or German waters. Potentially thousands of large wind turbines will be sited over the generally white low-density, structured very fine-grained porous weak carbonate Chalk rocks encountered (often with silica flint nodules and layers) frequently in these offshore areas.

Chalk poses difficulties to engineers seeking to design the high capacity, often large diameter, tubular steel piles that are routinely driven to support offshore structures. Designers seeking to ensure satisfactory performance in service can only draw on limited published information regarding axial capacity and stiffness. Once designs have been developed, the pile driving itself can be problematic, with both pile refusals and 'runs' or self-weight free-falls being reported. The most common current design practice is to adopt the CIRIA C574 recommendations (Lord *et al.*, 2002) which is based on the limited database outlined in Figure 2. Only six uncoordinated tests of mixed quality were found from two low-medium density chalk sites (Hobbs and Robins, 1976, Burland and French, 1990) and two high density chalk locations (Lord and Davies, 1979, Hobbs and Atkinson, 1993).

The dataset indicate no systematic relationship between average unit shaft resistances, τ_{avg} and overburden pressures, σ'_{vo}, so CIRIA C574 and earlier the CIRIA PR11 guide (Lord *et al.*, 1994) replaced the CIRIA PG6 effective stress method proposed by Hobbs and Healy (1979) with fixed shaft resistance values that vary only with chalk density.

Even the low-medium density NW European Chalks have relatively high Unconfined Compressive Strengths (UCS), generally from <3-5MPa (Bowden *et al.*, 2002), and cone tip resistances, q_c from 4-

50MPa (Power, 1982). However, the limited dataset of tests suggests that (open-ended) driven piles mobilise:

(i) Very low (8-42kPa) average shaft shear stress (τ_{avg}) values in low-medium density chalks, comparable to those expected in very soft to soft clays. The τ_{avg} values do not appear to increase with depth or vertical effective stress.

(ii) Markedly higher τ_{avg} values of 125-150kPa in medium-high density chalk.

The CIRIA guidelines recommend taking ultimate shaft resistances of 120kPa for high density chalk and 20kPa in all other densities and grades, reducing to 10kPa if it is considered that the pile may experience significant lateral deflections, or "whip" during driving. The recommendations lead to stark choices for designers in variable chalk ground conditions, which can impact very significantly on windfarm and other project economics; see Barbosa *et al.* (2017).

The engineers who formulated the design recommendations recognised the implicit uncertainty in predicting axial capacity for piles driven in chalk; Lord *et al.* (2002) suggest that site-specific pile load tests should be undertaken wherever possible.

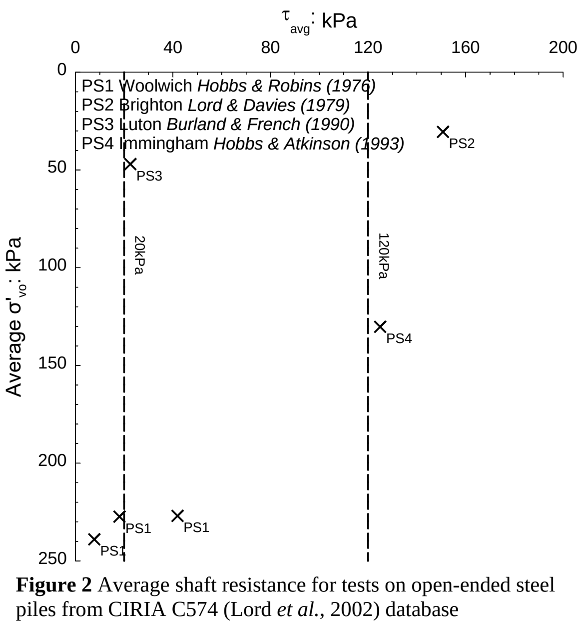

Figure 2 Average shaft resistance for tests on open-ended steel piles from CIRIA C574 (Lord *et al.*, 2002) database

Field behaviour has proven hard to predict from pile installation onwards. Refusals have been reported on driving through hard high-density chalk. However, piles installed at low-medium density offshore windfarm sites have also self-penetrated (or 'run') to considerable depths under their self-weight; see for example Carotenuto *et al.* (2018).

Driving is thought to de-structure the high porosity material, leaving a low strength "putty" around the shaft (Hobbs and Atkinson, 1993) whose low shear resistances can be matched by applying high level cyclic loading in laboratory simple shear tests (Carrington *et al.*, 2011, Diambra *et al.*, 2014) or by simple Proctor laboratory compaction carried out on intact samples at the natural water content (Doughty *et al.*, 2018).

The offshore pile 'runs' prove that very low shaft shear stresses can develop without cycling. Low installation resistances may also be explained by attenuation of stresses with increasing relative distance from the pile tip, h, as the pile penetrates, which is also observed in clays and sands; see Bond and Jardine (1991), Lehane et al (1993), Randolph *et al.*, (1994) or Jardine *et al.*, (2005). A simple method is required to capture the key influence of relative pile tip depth and predict Chalk Resistance to Driving (CRD) reliably on the basis of robust site investigation data.

Dührkop *et al.* (2017) present an approach based on driving back-analyses in which unit shaft resistance and end bearing depend on the intact dry density of the chalk. The effect of relative pile tip depth (h) to reduce the stresses developed at any given horizon was addressed partially by assigning different resistances at the top and bottom of a given layer. However, this introduces inconsistency when the final pile tip penetration does not reach the base of any given layer.

Marked increases in capacity over time, or 'set-up', have also been reported for piles driven in chalk by Vijayvergiya *et al.* (1977), Skov and Denver (1988) and Lahrs and Kallias (2013). Static re-tests by Ciavaglia *et al.* (2017) on piles driven at St Nicholas-at-Wade, Kent (see Figure 1) also showed marked shaft set-up. Dührkop *et al.*'s (2017) field observations led them to recommend, when selecting driving hammers, to allow for the CRD developed on the re-commencement of driving to be temporarily three times higher (after any pause exceeding 1.5 hours) than the driving resistance applying before the pause.

The above paragraphs highlight the need for further research to refine driveability and service performance assessments. The key goal is to develop more reliable, ideally effective-stress based procedures for analysing and designing piles driven in chalk. More information on the set-up characteristics of 'virgin' (previously unfailed piles) is also critically important, as is guidance on the piles' responses to lateral and cyclic loading.

3 COLLABORATIVE INDUSTRIAL AND ACADEMIC RESEARCH INTO PILES DRIVEN IN CHALK

3.1 Background

Scottish Power Renewables' (SPR) decision to develop the Wikinger windfarm project in the German Baltic (see Figure 1) was the key prompt for the research described in this paper. Wikinger involves seventy 5MW turbines installed in 35-42m deep water on four-legged jackets, three of which are depicted in Figure 3. The jackets are founded on open 2.7m outer diameter (OD) steel piles; an accompanying offshore sub-station employs a six-legged jacket and 3.67m OD piles; see Barbosa *et al.* (2015), (2017).

Figure 3 Photograph of three offshore wind turbine jacket structures in transit for installation at Wikinger; courtesy of Scottish Power Renewables

Barbosa et al (2017) summarise how SPR identified a need to conduct field tests to verify and refine their foundation designs for Wikinger. Their decision led to an invitation to Imperial College and Geotechnical Consulting Group (GCG) to work with them and their contractors to develop suitable offshore testing procedures and protocols. This input led in turn to a Joint Industry research project (JIP) involving SPR, Imperial College and GCG, led by SPR, with co-funding from Innovate UK, SPR and GCG.

In addition to the high value offshore testing described later in this paper, the JIP involved the Imperial College research team conducting parallel experiments at an onshore test site is located in a previous chalk quarry, close to St Nicholas-at-Wade on the Isle of Thanet (UK Grid: TR 25419 66879). Ciavaglia *et al.* (2017) had conducted earlier research at the same site. The lower cost onshore experiments could be controlled, varied or repeated more easily than in the highly constrained offshore environment and allowed a systematic field investigation (that extended over 8 months) into how ageing and cyclic loading affect steel piles driven in chalk. Combining and interpreting the onshore and offshore campaigns led to the preliminary Chalk ICP-18 design method set out in this paper. All overburden and weathered chalk has been removed at the quarry site to expose structured chalk from the surface. Earlier site investigations have included five boreholes to a maximum depth of 20.5m and Cone Penetration Tests (CPT and CPTu tests involving pore pressure measurements) to a maximum depth of 17m, as well as laboratory and field seismic testing (Fugro, 2012a, 2012b).

The UK test site was chosen due to the many similarities between the chalk encountered beneath the excavated quarry surface with that found, at greater depth, offshore at Wikinger. The St Nicholas-at-Wade (SNW) chalk classifies as CIRIA Grade B2/B3 (structured low-medium density. The chalk's Intact Dry Density (IDD) ranges from 1.38 to 1.54Mg/m^3 within the depth of interest, indicating low-density. Its discontinuities are open to less than 3mm and have a fracture spacing of between 60 and 200mm.

The average SNW Unconfined Compressive Strength (UCS) values q_u fall around 2.1MPa and within the range expected for low-medium density material. As shown in Figure 4, CPTu tests indicate a

$5<q_t<35$MPa range with higher resistances in flint bands. Very high excess pore pressures are recorded at the u_1 piezocone face position. Lower, but still considerable, pressures develop at the u_2 shoulder location; Buckley (2018). The chalk fails and starts to destructure under the tip in CPT tests, but retains sufficient shearing resistance to give sleeve resistances of up to 400kPa as it flows around the cone.

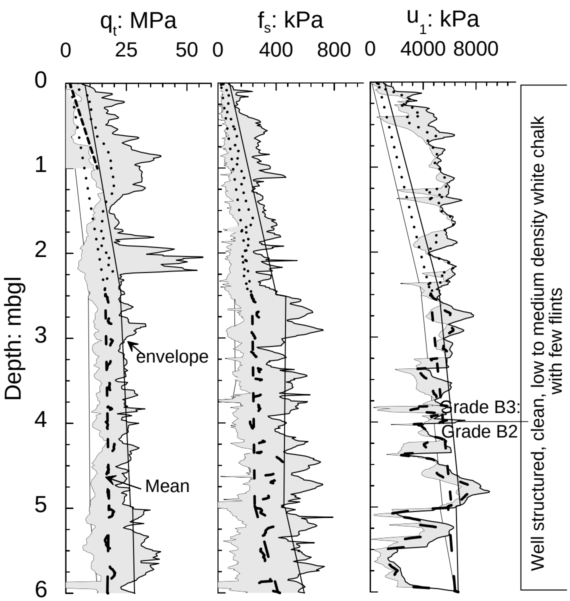

Figure 4 Piezocone profiles at the St Nicholas at Wade site; Buckley et al. (2017a)

3.2 *Pile test campaigns at St Nicholas-at-Wade*

Two pile test programmes were carried out at St Nicholas-at-Wade as part of the Authors' Innovate UK JIP which investigated: i) driving resistance; ii) installation effects; iii) ageing effects; iv) the impact of pre-testing piles; and v) how 'virgin' piles respond to axial cyclic loading 8 months after driving.

The first programme employed seven un-instrumented open 139mm OD steel pipe piles installed by industry-standard driving equipment in October 2015. Three of these piles were dedicated to investigating the effects of ageing on axial loading response, while the remaining four were subjected to series of cyclic loading tests applied after ≈8 months ageing. The second programme involved installation, by slower, cyclic jacking, of closed ended highly instrumented Imperial College Piles (ICP) at the same location. The ICP programme, which ran from October 2015 to February 2016, was planned to supplement the driven pile results with measurements of the effective stresses developed on the pile shaft during installation, equalisation and load testing.

The ICP experiments were conducted by the Imperial College team in conjunction with Professor Lehane and his colleagues from University of Western Australia (UWA), who employed the ICP equipment in recent tests in residual soils and sands. The ICPs, which are illustrated in Figure 5, are closed-ended and have 102mm outside diameters. Their main sections are made of molybdenum steel tubes of ≈9.5mm wall thicknesses. The two ICPs installed at SNW had centre-line average shaft surface roughness, R_a≈5μm.

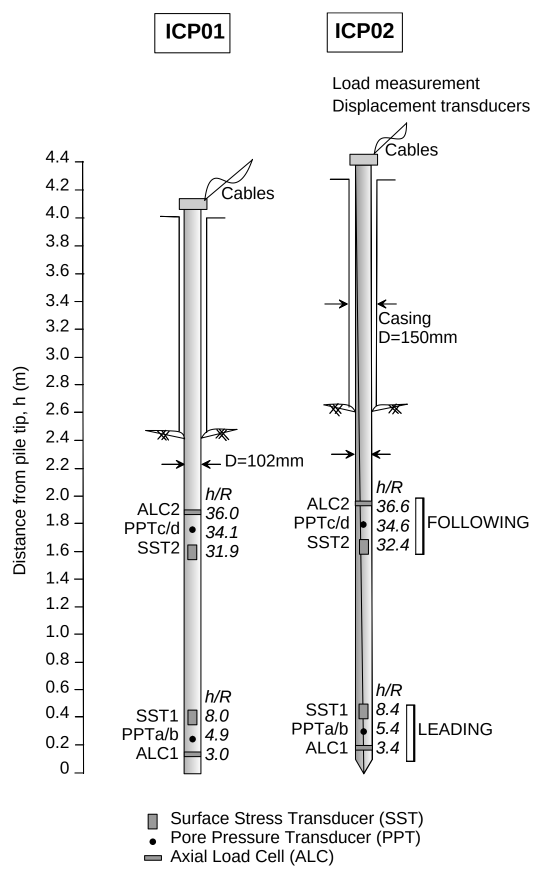

Figure 5 Imperial College Pile configuration used in chalk tests; Buckley et al. (2018c)

The ICPs were developed by Bond et al (1991) to measure the local axial loads, pore pressures, radial effective, σ'_r and shear stresses, τ_{rz} developed on the pile shafts during penetration, equalisation and load testing. Each instrument cluster, which is denoted by its relative position above the pile tip (h, divided by outside pile radius R), consists of an axial load cell (ALC), two pore pressure transducers (PPT) and a surface stress transducer (SST). Although two levels of instrumentation were deployed in the SNW tests, up to four clusters have been employed per pile in previous campaigns at sand and clay test sites.

Buckley *et al.* (2018c) identified trends from ICP installation at SNW that matched those seen in sands by Lehane et al (1993) and Chow (1997). In precis, installation in Chalk led to:

(i) End bearing pressures q_b and local σ'_r stresses that varied systematically with local q_t;
(ii) Local σ'_r stresses that declined with relative pile tip depth h/R;
(iii) Local τ_{rz}-σ'_r effective stress paths that were indicative of constrained interface dilation during static loading to failure, see Figure 6;
(iv) Shaft failure states that followed a Coulomb effective stress interface criterion with $\delta' \approx 31°$, matching ring-shear tests conducted against interfaces that matched the pile shaft's material and surface roughness.

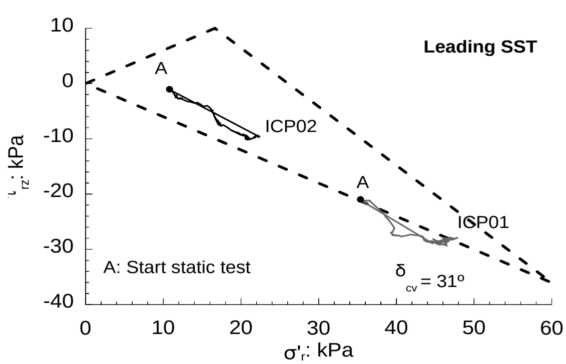

Figure 6 Local shaft effective stress paths for leading Surface Stress Transducer (SST) during ICP tension loading to failure at St Nicholas at Wade test site; Buckley et al. (2018c)

Different phenomena were investigated at the same site through static and cyclic pile test experiments on the 139mm OD open steel piles. The piles were driven to a depth of 5.5m and were equipped with Pile Driving Analysis (PDA) strain gauges and accelerometers. Applying the signal matching code IMPACT (Randolph 2008) to analyse the signals provided key information regarding the base and shaft equivalent static resistances to driving and the distributions of shaft friction over the piles' external and internal surfaces.

IMPACT applies elasto-dynamic soil resistance theory, employing the Randolph and Simons (1986) shaft and the Deeks and Randolph (1995) toe models. In both cases, the input parameters are linked to measurable soil properties including shear modulus, G and soil density, which were assigned as described by Buckley *et al.* (2017b). The local shear stress values, interpreted by matching the driving signals with IMPACT, were lower than those measured during installation of the ICPs, due to the faster rates of installation and the effects of partial drainage. Buckley et al's (2018b) analysis of the dynamic monitoring led to the following primary conclusions:

- Almost all (more than 90%) of the pile's shaft resistance was developed over its outer shaft area. The piles were fully coring with soft chalk emerging from their interiors at EoD;
- The average end of driving exterior shaft shear resistances fell around 15-25% below the Lord et al (2002) static design shaft recommendation (20kPa) for low-to-medium density chalks;
- Local shear stresses declined even more steeply with increasing relative pile tip penetration (h/R*, where h is the distance from the pile tip and R* is the equivalent radius) than has been seen with sands.

The shaft resistance trends are illustrated in Figure 7, where profiles of local shaft shear stresses back-analysed by signal matching with IMPACT are plotted against depth for three 139mm OD piles. The average external End of Driving (EoD) shaft shear stresses of 15–17kPa are comparable to the 11–23kPa range reported for 762mm OD, 4 m long, open steel piles driven at SNW by Ciavaglia et al. (2017b).

These back-analysed values fall only 15–25% below CIRIA's 20kPa recommendation for operational static shaft capacity in low-medium density chalk (Lord et al. 2002).

However, markedly higher local τ_{rz} resistances were found over the lowest 1 to 1.5m of the shaft, which tend towards the CPT sleeve frictions near the tip and decay sharply in any given layer as the tip advances to a greater relative depth h, below that that later. Buckley et al (2018b) show that the local shaft resistance profiles primarily reflect the strong influence of 'h/R*' on installation shaft resistance.

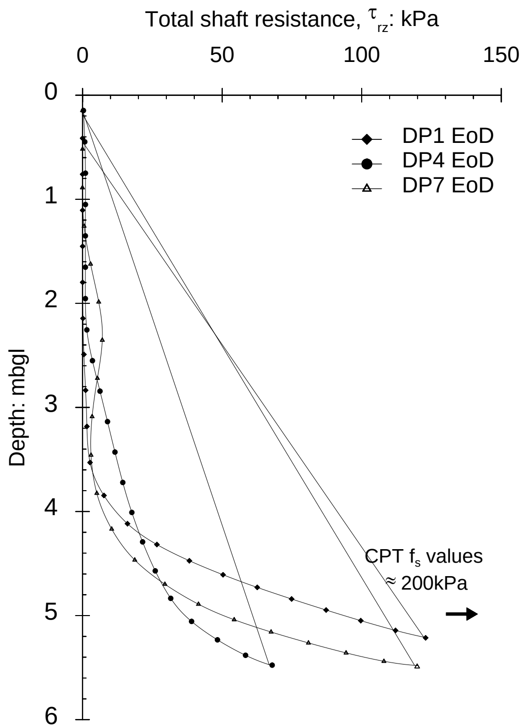

Figure 7: Profile of total EoD shaft resistance obtained by back analysis of the dynamic test results for the 139mm piles at SNW.

Pile exhumation inspections, carried out 274 days after installation (and after all testing) showed that driving the open-ended piles remoulded the chalk close to their shafts, creating a puttified zone and probably generated very high excess pore pressures near to the pile tips during driving. Rapid excess pore water pressure dissipation during and after driving led to markedly lower water contents close to the shafts.

Staged tension testing of identical 'virgin' piles at 10, 106 and 246 day ages provided the shaft capacity-time trend given in Figure 8, with overall shaft resistances increasing five-fold over the End of driving (EoD) capacities. The driven piles' final set-up factors exceed those for sands (Jardine et al., 2006) and the shaft capacity-time trend could be fitted with a hyperbolic relationship with time suggested by Tan et al. (2004). In contrast, the cyclically jacked ICPs did not show any such gains. Set-up appears sensitive in chalk to pile tip conditions (closed-versus-open) and/or installation method (cyclic jacking versus driving). A check test on one previously failed pile showed that it could not recover, on re-testing, the same age trend as the 'virgin' piles; see the open symbol on Figure 8.

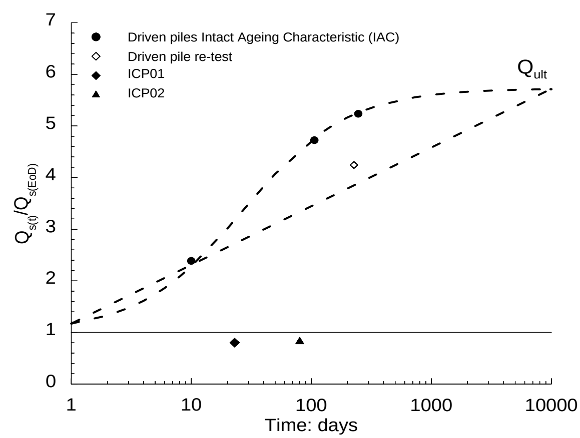

Figure 8 Ageing trends for driven open (139mm OD) and cyclically jacked (102mm OD) closed ICP piles from tension load tests to failure at St Nicholas at Wade; Buckley et al. (2018c)

Parallel laboratory testing at Imperial College by Chan *et al.* (2019) investigated the potential for changes over time in the effective-stress residual interface shear strengths of chalk. Samples from SNW were remoulded and subjected to interface ring shear testing after ageing under appropriate normal stress loading. Various interface steels and ranges of surface roughness were considered. The tests showed that interface corrosion could shearing increase resistance by approximately 10% under constant normal effective stress conditions. Further gains might accrue in-situ through radial stress gains linked to corrosion.

Research on Wikinger samples by Doughty *et al.* (2018) showed that thixotropy can provide modest gains in the undrained shear strength (s_u) of chalk putty samples when aged at constant natural water content. Far greater shear strength gains were obtained in triaxial tests on chalk putty through consolidation to higher effective stresses, with well-correlated reductions in void ratio and increases in s_u. It appears that the 'set-up' illustrated in Figure 8 reflects marked increases over time in the local radial stresses developed around the shaft of the open-end piles.

Buckley *et al.* (2018b) propose a hypothesis to explain the set-up seen at St Nicholas-at-Wade. The remoulded annuli formed around piles during driving are likely to undergo short term reductions in volume through consolidation after puttification, leading to low radial stresses and shaft stresses as pore pressures dissipate. However, higher total stresses are likely to apply at greater radial distances from the shaft, carried by an arching system developed outside the annulus. Creep processes could allow the arching to relax and the radial effective stresses to increase, so increasing shaft capacity gradually over time. Relaxation of the arching is likely to be more rapid for chalk masses with widely spaced and tight fractures than those with more open and closely-spaced fractures.

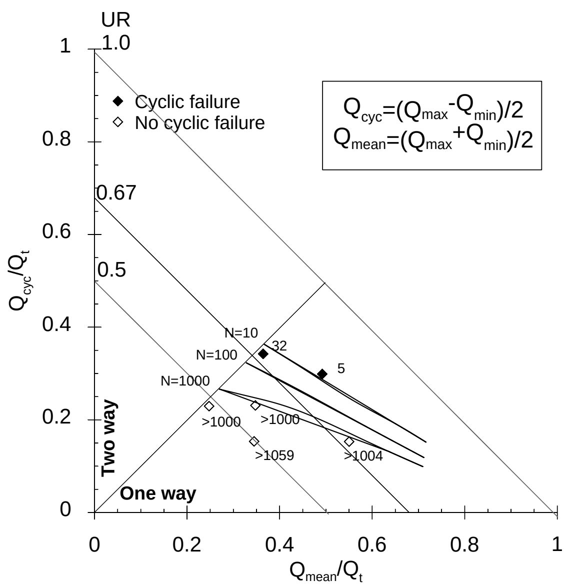

Figure 9 Stability diagram showing one way axial cyclic test results on piles at St Nicholas-at-Wade; Buckley et al. (2018b)

The above mechanism could operate in combination with other chemical and mechanical processes, as suggested for sands by Jardine *et al.* (2006) and Jardine *et al.* (2013).

The effects of one-way axial cyclic loading were also investigated with the 139mm OD piles. One-way axial cycling applied after 250 days led to responses ranging from fully unstable to essentially stable over 1000 cycles, depending on the combination of loading parameters. The normalised interaction diagram presented in Figure 9 shows contours interpreted for conditions under which failure could be expected after 10, 100 or 1000 cycles. Lines indicating the equivalent mobilised levels of Utilisation Ratio (UR), or inverse Factor of Safety (FOS) are also shown.

Figure 9 shares several common features with the equivalent plots for sands; see for example Jardine and Standing (2012). The piles driven in chalk did not appear to be especially sensitive to one-way axial cyclic loading, when applied 250 days after driving. As described later, further tests are in hand to examine the potentially more severe impact of high-level, two-way, axial cyclic loading on piles of greater length.

3.3 Ground conditions at Wikinger offshore test site

The Authors' research also encompassed very high value tests offshore at Wikinger Baltic Sea windfarm site, for which comprehensive site investigations and associated laboratory testing was conducted for SPR by Gardline Geoservices, GEO and Fugro.

The Wikinger ground conditions comprise variable profiles of stiff-to-hard glacial till over chalk. Pile axial capacity is developed predominantly within the Chalk at most of the windfarm's 70 turbine locations, although a harder limestone was encountered at six sites and glacial till governed design for around 20 turbine locations. The till comprises glacial and fluvio-glacial units, both of which are well-graded and have very low plasticity indices (8 to 9%) and water contents close to their plastic limits (around 13%). The till's Yield Stress Ratio YSR (or apparent Overconsolidation Ratio, OCR) generally decreases with depth. Its sensitivity, S_t is thought to be close to 1 (Buckley *et al.*, 2018a).

As at St Nicholas-at-Wade, the Wikinger chalk generally classifies as being structured, low-medium density (with intact dry density, IDD generally <1.5Mg/m^3) Grade A1/A2 material (Bowden *et al.*, 2002). Unconfined Compressive Strength (UCS), q_u

values range between 0.2 and 0.8MPa, falling below the 1.1 to 5MPa range proposed for low-medium density chalk by Matthews and Clayton (1993) and below that seen at SNW. However, the Wikinger fracture systems are generally more closed and widely spaced than at St Nicholas-at-Wade.

Laboratory tests by Doughty *et al.* (2018) on Wikinger samples showed that compaction at natural moisture content causes marked de-structuration to a "putty" material with undrained strength $s_u \approx 4$kPa. As noted earlier, consolidation can lead to significant increases in shear strength and stiffness, while thixotropic s_u gains are relatively modest. Interface shear tests gave δ'_{ult}, of 26.5-28° in the glacial till (Buckley, 2018) and 32-34° in the chalk (Fugro, 2013).

Shear wave velocities were measured in the chalk through P-S probes suspended in boreholes. Cone penetration tests with pore pressure measurement showed net cone resistance, q_t values in the till of 5-15MPa, sleeve friction, f_s of 100-300kPa and pore water pressures at the shoulder position, u_2 for the most part of -200 to -250kPa. In the structured chalk, q_t is 10-20MPa, f_s ranges from 200-400kPa and u_2 is as high as 10MPa. In some cases the CPTs terminated above the pile penetration depth, and composite profiles were developed using correlations with the V_s measurements (Buckley *et al.*, 2018a).

3.4 Full-scale offshore load tests

The Wikinger project and associated Innovate UK JIP provided the opportunity for the first remotely-controlled, full-scale, seabed offshore pile load tests of which the Authors are aware.

Nine 1.37m OD, 40mm wall thickness, piles were driven to penetrations of 16.8m to 31m at three representative locations comprising: (i) a glacial till dominated position (WK38), where 70% of the piles' shaft length was in glacial till, and (ii) the chalk dominated WK43 and WK70 locations where 66% and 78% of the shaft lengths (respectively) were in chalk. Two piles were monitored continuously during driving at each location with strain gauges and accelerometers. Parallel static tension tests and instrumented dynamic re-strikes were conducted on identical pairs of 'virgin' piles at each location around 11 to 15 weeks after driving. The latter period was the minimum expected to apply between production pile driving and turbine installation.

The Innovate UK JIP project team worked to optimise robust and novel field testing arrangements. Dynamic measurements from both the test piling and later production piling campaigns were analysed through signal matching with IMPACT, making use of SPR's site characterisation data, supplemented by testing at Imperial College. Planned long-term dynamic re-strike tests are rarely deemed feasible and static load tests on full-scale piles are usually considered impractical in offshore engineering. The only static offshore pile tests of which the Authors are aware were conducted from existing fixed structures and involved piles with outside diameters no greater than 0.76m (e.g. Angemeer *et al.*, 1973).

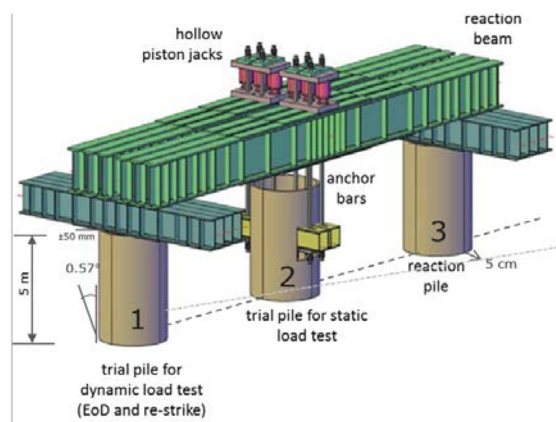

Figure 10 Schematic of loading frame and reaction pile arrangement for subsea static load tests at Wikinger; after Barbosa *et al.* (2015)

The Wikinger field tests showed how remotely operated static testing can be performed in parallel with long-term re-strikes made with fully recoverable driving instrumentation. An 18.46m long beam was placed with its centre over Pile 2, as shown schematically in Figure 10, and connected to the test pile via a locking tool which fitted into a steel ring welded inside each test pile. Pressure plates were connected to the two reaction piles. Four hydraulic actuators were placed on top of the beam that were capable of applying a total tensile load of 15MN and were controlled by programmable hydraulic systems located on a vessel positioned above the test piles. Loads were applied to Pile

2 by reacting against the other two piles and were measured by four load cells connected to the actuators.

Pile head displacements were measured using the Norwegian Geotechnical Institute (NGI) subsea cylindrical extensometer system and an independent reference frame. The self-installing system was placed onto a custom-made sleeve on the top of each test pile to prevent the sleeve landing on the pile. Three extensometers, spaced circumferentially around the pile, were fixed between the sleeve and the ring by three latches. The extensometers employed magnetostrictive linear position transducers, which measure absolute distance between a position magnet and the end of a sensing rod. The system was rigidly connected to the independent displacement monitoring reference frame, supported by four 8m x 8m mudmats spaced at a distance of ≈13m (9.5D) from the centre of Pile 1.

3.5 Dynamic test outcomes

Instrumented dynamic re-strike tests were carried out on the piles installed at all three testing sites (WK38-1, WK43-1 and WK70-1). These were performed after each static test by first retrieving the cables from the seafloor and checking their functionality, followed applying three full energy hammer blows to Pile 1, using the same hammer as employed during driving. An underwater camera connected to the displacement reference frame monitored the displacement of the pile per blow, using a pointer system and pre-made pile markings. The primary technical risks associated with undertaking the novel offshore tests were mitigated and eliminated by including redundancy in the measurement and loading system.

As in the St Nicholas-at-Wade test programme, Buckley (2018) employed IMPACT to carry out signal matching analyses of the dynamic data obtained at Wikinger, which demonstrated broadly similar features to those noted at SNW, with: (i) very marked reductions in local shaft resistance with relative pile tip depth (h/R*) in both the glacial till and chalk, (ii) low EoD resistances in the chalk.

As discussed in detail by Buckley et al (2018a), dynamic analyses of multiple re-strikes on 17 (test and production) piles identified from driving pauses and planned restrikes a gradual trend for shaft capacity to increase over time in the glacial till. The rates of shaft capacity change were consistent with the relatively slow rates at which driving excess pore pressures were assessed as having dissipated around the pile shafts.

Far more rapid and marked set-up was observed in the chalk during driving pauses. Shaft capacities appear to have often increased to reach around 50% of their final long-term equilibrium values within an hour of the last driving blow, growing far more rapidly than had been seen with smaller piles in the chalk at St Nicholas-at-Wade, which had a more open system of fractures that was encountered generally at Wikinger.

3.6 Static test outcomes

Static tension testing was conducted on three Wikinger piles after ageing periods of between 11 and 15 weeks. Slow excess pore pressure dissipation in the glacial tills and ageing in the more permeable chalk strata led to shaft capacity gains in both formations. Shaft set-up in the chalk far exceeded the pre-test predictions made by the foundation designers. As a result, the field capacities at the two chalk-dominated sites exceeded the safe limit of the test frame, although full static failure was achieved at the glacial till dominated WK 38 site.

Buckley *et al.* (2018a) outline how static test failure capacities were extrapolated for the chalk dominated WK40 and 70 cases and combined with closely correlated dynamic measurements obtained in parallel restrike tests on adjacent, nominally identical, piles. The static results, plotted on Figure 11 and dynamic results listed in Table 1, show relatively good agreement (±15%) between the shaft capacities assessed from parallel tests conducted on paired pile at the same age. The IMPACT analyses also allowed estimates of the contribution each layer made to the overall shaft set-up behaviour. Buckley et al (2018a) report that set-up in the glacial till led to shaft capacities growing after driving and reaching, after 15 weeks, values that were, on average, 2.4 times those available at EoD. Significant scatter was seen in the till set-up trends that reflected both the relatively short till sections present at most turbine locations and their probably slow rates of pore pressure dissipation. Dissipation may well have remained incomplete 15 weeks after driving.

However, Buckley et al (2018a) argue that shaft set-up was fully complete in the chalk after ≈ 77 days, by which time it had climbed to reach 5.5 times the EoD shaft resistances at chalk dominated locations. A tendency was observed for lower set-up factors to apply at the sites with thicker overlying glacial till sections, indicating that capacity increase trends depend on relative pile tip penetration, h/R*. Buckley et al (2018) did not find any evidence for significant set up in base resistance in the chalk.

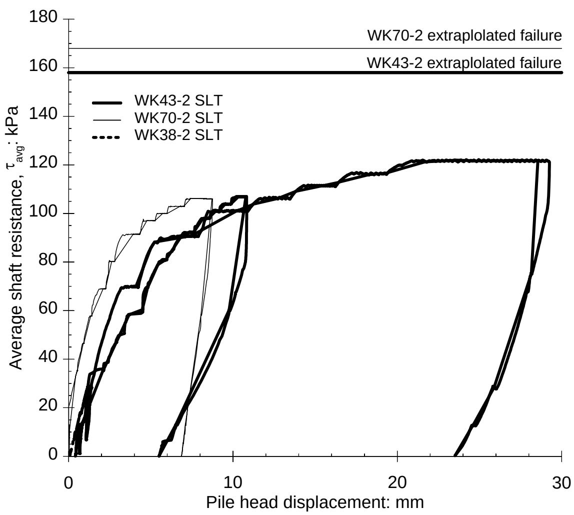

Figure 11 Offshore static load tests at Wikinger including extrapolated failure points for chalk-dominated locations

Table 1 Static tension failure loads and pile capacity predictions for offshore pile tests at Wikinger

	WK38	WK43	WK70
Time after driving (days)	108	78	77
Percentage profile in chalk (%)	18	66	78
Net static tensile failure load (MN)	8.80	20.90[1]	22.44[1]
End of driving shaft load (MN)	5.34	4.78	4.61
Dynamic restrike shaft load (MN)[2]	9.72	18.30	27.69
Global set-up factor, Λ (static/EOD)	1.65	4.37	4.86

1. *Based on extrapolation of creep rates to k_c = 3mm/log cycle*
2. *Restrike test on an adjacent pile at the same age*

Barbosa et al (2017) report on the benefits to the Wikinger project of resolving design foundation uncertainties, through their advance offshore testing, before undertaking their final pile design. Although expensive, the offshore testing allowed pile lengths to be reduced considerably in advance of their manufacture and proved to be highly cost-effective. The testing techniques developed can now be applied in other offshore projects to help assure service performance and optimise final foundation design.

4 THE CHALK ICP-18 METHOD

One of the key aims of the collaborative academic and industrial research was to develop new, more reliable approaches for assessing driveability and long-term static capacity in low-medium density chalk. Buckley (2018) summarises how the offshore and onshore test programmes were combined with other evidence to develop the preliminary ‘Chalk ICP-18’ method.

4.1 Predicting chalk resistance to driving

The Chalk ICP-18 approach for predicting Chalk Resistance to Driving (CRD) relies on Buckley’s interpretation of dynamic driving data from piles with a wide range of diameters (139mm to 3.67m) and diameter-to-wall thickness ratios, D/t (≈20 to 70).

The new rules apply to continuous penetration only and capture the key phenomena identified in the earlier sections of the paper, namely: (i) the ability of CPT cone resistance to characterise variations in properties with depth, (ii) the marked tendency of the local shaft σ'_r and τ_{rz} values to reduce with increasing tip penetration (h/R or h/R*), (iii) the interface effective stress shear failure characteristics and (iv) the significant shaft capacity gains which occur with time. The new method employs similar forms for base and shaft resistance to the ICP-05 sand approach (Jardine *et al.*, 2005) and calls for full CPT profiling and site-specific interface shear testing.

During driving, the local degradation rates appear to reduce with pile diameter-to-wall thickness ratio, indicating that the geometrical system applying in the field and the size of the puttified zone formed around the pile is not fully captured by the simple characterization involving the equivalent radius R*, which is the equivalent radius of a cylinder with the same area of steel as the pile, where $R^* = [R^2_{outer} - R^2_{inner}]^{0.5}$ and R_{outer} and R_{inner} are the pipe pile’s outer and inner radii. The Chalk ICP-18’s correlation for short-term chalk shaft resistance, τ_{rzi} to driving takes the form:

$$\tau_{rzi} = \sigma'_{ri} \tan\delta'_{ult} \tag{1}$$

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

Where σ'_{ri} is the radial effective stresses applying during driving and q_t is the net cone resistance averaged over 300mm (following Power 1982) and t_w is the pile wall thickness. In both cases, a lower limit of 6 applies to h/R or h/R*. Equation (2) leads to radial effective stresses, and therefore shaft stresses, reducing with h/R*. The negative power law exponent applied to h/R has a larger absolute value for a monopile with D/t ratio of 80 than a smaller diameter jacket pile, for which the D/t ratio may be less than 40.

It is important to note that CRD values may increase considerably during any driving pauses. The upper bound values that may apply after long pauses could rise to match the long term static resistances, as outlined below. These temporary CRD gains degrade as the pile tip advances on re-driving. Field experience at Wikinger indicates that the degradation process is complete with a further metre of penetration, after which CRDs return to the steady penetration trends.

The base resistances inferred from IMPACT analyses undertaken at both test sites varied with the pile penetrations per blow. However, the overall average values of equivalent bearing pressure q_b developed over the pile tips' annular area during continuous driving amounted to $0.6q_t$. As noted earlier, internal shaft resistance may be negligibly small and fully coring penetration modes are expected in the field.

4.2 *Predicting long term axial capacity for piles driven in chalk*

The Chalk ICP-18 static axial capacity method is closely related to the CRD approach. The only long-term base resistance assessments available consist of values inferred from dynamic IMPACT analyses of long-term re-strikes conducted at Wikinger. Static testing is required to confirm the preliminary indications that the equivalent bearing pressures q_b developed over the pile tips' annular areas are similar to those observed during continuous driving with $q_b \approx 0.6q_t$. As during driving, internal shaft resistance is considered to be negligibly small for jacket piles and the outer shaft resistance is assumed to follow the Coulomb effective stress Equation (1), matching δ'_{ult} values 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 soft putty formed during driving is assumed to try to contract during shear. However, the dual porosity and generally high hydraulic conductivity of chalk leads to a different response to shear after full consolidation and ageing. Field measurements made at St Nicholas at Wade show that denser than critical state final conditions apply close to the shaft; see Buckley (2018). Under axial loading the long-term radial effective stress response to shaft shear failure therefore 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 in the long-term shaft resistance through Equation (3). This term offers a significant contribution to small diameter piles, but may be negligible with large offshore piles.

A related but different expression is proposed between the local long term (fully equalized) σ'_{rc} component and the net local CPT resistance q_t and relative pile tip depth h/R* in Equation 4.

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

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

Unlike the CRD Equation (2), the long-term radial effective stress expression (4) does not depend on the diameter-to-wall thickness ratio. As with sands, $\Delta\sigma'_{rd}$ can be estimated by elastic cavity expansion, with $\Delta\sigma'_{rd}$ is proportional to the shear modulus and inversely proportional to pile diameter, giving:

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

Where Δr is the average radial movement caused by dilation at the interface. The shear modulus, G should ideally be measured in the G_{hh} direction and may need to account for strain level and non-linearity. The friction coefficients and relative roughness values for industrial driven steel piles in sands tend to fall through grains unlocking from the interface in a manner that leads to the Δr term being approximately equal to the average peak-to-trough interface roughness, or double the average interface roughness amplitude, $\Delta r \approx 2R_a$ (Chow, 1997, Jardine *et al.*, 2005). However, the far finer grain sizes of chalk lead to a different mechanism involving a shear band forming in the chalk with far smaller values of Δr. A radial dilation of just 0.5μm was interpreted from the ICP test results by Buckley et al (2018c), suggesting that the degree of radial expansion experienced is far smaller than $2R_a$, reflecting the higher relative roughness of the pile shaft in comparison to the chalk's mainly silt-sized particles.

The Chalk ICP-18 shaft capacity method offers an effective stress approach that can be extended to model or predict the impact of axial cyclic loading. Laboratory element, model pile or field testing approaches can be applied to generate rules that relate pile cyclic loading variables (amplitudes and mean loads as well as numbers of cycles) to shaft radial effective stress and hence shaft capacity reductions, as outlined for example by Jardine et al (2005), Jardine and Standing (2012) or Jardine (2018) and applied in practical offshore design storm loading assessments by Hampson et al (2017) or Rattley et al (2017).

4.3 Testing the Chalk ICP-18 axial capacity method predictions

The Chalk ICP-18 approach was developed primarily from analysis of the (October 2014 to January 2015) programme of advance tests at the WK38, 40 and 70 Wikinger locations, combined with the Authors' tests at St Nicholas-at-Wade. Buckley (2018) shows that Equations 1 to 5 above provide good fits to these pile tests. However, it is important to assess whether the expressions calibrated from these specific tests can predict other fully independent cases, ideally covering a range of scales and chalk grades. It will also be important to check whether shaft capacities are equal under compression and tension loading, as has been assumed in developing the preliminary Chalk ICP-18 approach.

Figure 12 presents assessments made for four independent cases. The profiles shown in Figure 12a) represent ICP-18 predictions for the distributions of shaft shear stresses τ_{rzf} at failure applying to a re-strike test conducted on a large (2.7m OD) open-ended steel 'production' pile at the independent (chalk dominated) WK11 Wikinger location. This 'production pile' was driven long after the advance testing on 1.37m OD piles at WK38, 40 and 70 was completed.

Buckley (2018) interpreted the equalization process as being more than 90% complete at the time the re-strike was conducted. It is encouraging that the shaft resistance 'measurements' interpreted by Buckley's IMPACT signal matching back analysis for the WK11 production pile match the Chalk ICP-18 predictions relatively well.

Profile 12b) presents a similar comparison between shear stresses interpreted from a fully independently static test reported by Ciavaglia *et al.*, (2017) conducted on a 0.76m OD open steel pipe pile 119 days after driving at the St Nicholas-at-Wade. The shaft capacity was estimated from electrical resistance strain gauges attached to the pile's shaft. These field measurements also indicate encouraging agreement with the Chalk ICP-18 predictions.

Profiles 12c) and 12d) present similarly encouraging comparisons from tests on one closed-ended, strain-gauged, 400 x 400mm square section pre-cast concrete pile (Pile 1) and another strain-gauged closed-ended 445mm diameter steel tube (Pile 2) driven at Fleury-sur-Andelle, France.

Ground conditions comprised clay and gravel over structureless chalk encountered at depths between 2.9 and 9m (assumed Grade Dm/Dc) underlain by low density structured chalk of unknown grade. CPT cone resistances in the structureless chalk were significantly lower at Fleury-sur-Andelle than at Wikinger or St Nicholas at Wade, ranging between 2 and 6 MPa, and reaching 10 MPa in the structured material below approximately 9m depth. Both piles at this site were driven to approximately 10.3m penetrations, with a total length of 7.5m in chalk. Compressive loading tests were conducted 118 and 693 days (respectively) after driving.

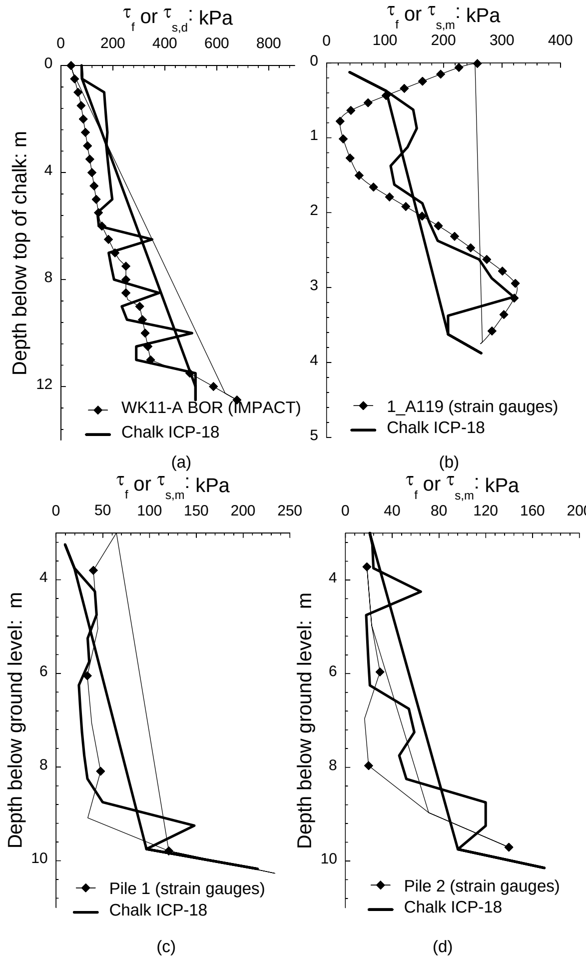

Figure 12 Measured and predicted shaft resistance profiles (a) open-ended piles at Wikinger (b) open-ended piles at SNW (Ciavaglia *et al.*, 2017) (c) closed-ended square concrete pile at Fleury-sur-Andelle (Bustamante *et al.*, 1980) (d) closed-ended steel tubular pile at Fleury-sur-Andelle (Bustamante *et al.*, 1980)

Ideally, piezocone tests should be undertaken to derive net q_t values, along with seismic CPTs to gauge shear stiffness. The Chalk ICP-calculations for the Fleury-sur-Andelle site employed the historical CPT profiles and substituted R* parameters based on: (i) equivalent solid area for the square pile and (ii) outer radius for the cylindrical closed ended pile, as recommended by Jardine et al (2005) for sands and clays. The interface shear angle was taken as 28^o on the basis of test data reported by Bustamante et al (1980). The latter angle falls below the range measured in the Authors' interface shear tests on samples from SNW and Wikinger. Adopting instead the angles from SNW would raise the predictions by around 13%. No site specific shear modulus data were available for Fleury-sur-Andelle, so values measured at St Nicholas-at-Wade were input into Equation (5).

All four cases summarized in Figure 12 indicate that Chalk ICP-18 captures the local profiles of shear stress far more reliably than the CIRIA C574 approach, which assumes a fixed average 20 kPa shaft resistance, that is over-conservative and unrepresentative in all cases. Considering the total of four static and eleven dynamic tests on open-ended piles, applying Chalk ICP-18 leads to a mean calculated-to-measured (Q_c/Q_m) shaft capacity ratio of 0.97 and a standard deviation of 0.16 for measurements taken during driving. The long-term tests on the same piles led to Q_c/Q_m shaft mean of 1.0 and a standard deviation of 0.11.

The long-term Q_c/Q_m ratios found for Fleury-sur-Andelle are 1.02 and 1.77 for Pile 1 and Pile 2 respectively, indicating that the Chalk ICP-18 method over-predicted significantly the long-term shaft shear stresses available to the closed-ended tubular steel pile. However, both of the Fleury-sur-Andelle piles had been subjected to several prior tests to failure and their testing history may well have affected the piles' long-term capacities, as seen in the re-test conducted by the Authors at SNW (see Figure 8).

However, it is clear that more independent high-quality pile tests are required to assess, and potentially refine, the preliminary Chalk ICP-18 design approach. Building a far larger open database will benefit all involved in developing chalk sites. As outlined below, the Authors are engaged, in conjunction with colleagues from Oxford University, in a new EPSRC and Industry funded JIP which will expand the database of high quality tests significantly. The Authors also appeal to UK and international colleagues from both practice and academia to share any high-quality tests, accompanied by appropriate site investigations, to which they may have access. Conducting new, carefully planned and stages, tests at suitable sites supported by site investigations that include high quality CPTu and seismic CPT testing, along with interface shear tests, can offer a highly cost-effective means of reducing design uncertainty and optimizing design.

5 THE ALPACA JIP PROGRAMME

The two year long ALPACA (Axial Lateral Pile Analysis for Chalk Applying multi-scale field and laboratory testing) JIP commenced in October 2017 to advance the design of piles driven in Chalk.

ALPACA is funded by the UK's EPSRC (Grant EP/P033091/1) in conjunction with six offshore wind-farm developers (Iberdrola, Innogy, LEMS, Orsted, Siemens and Statoil) and four consulting organizations (Atkins, Cathie Associates, Fugro and GCG). The project is led by an Academic Work Group from Imperial College London (Jardine, Kontoe and Buckley) and Oxford University (Byrne and McAdam). The new JIP aims to advance understanding of how to design tubular piles driven in chalk, particularly for offshore wind-turbines.

Instrumented axial and lateral, static and cyclic, field experiments are being conducted, again at the St Nicholas-at-Wade site, combined with advanced laboratory testing and comprehensive test analysis. Tension and compression capacities and the effects of pile end conditions are also being assessed.

Figure 13 Aerial view from Google Earth of St Nicholas at Wade test site showing in red test area for ALPACA JIP programme.

Figure 13 shows an aerial view of the ALPACA test site, while Figure 14 shows the piling operations undertaken in November 2017. Fourteen 508mm OD instrumented piles have been driven and allowed to age before being subjected to carefully programmed static and cyclic, axial and lateral loading tests.

Thirteen of the piles have been instrumented with opposing pairs of fibre-optic strain gauge strings, of the type described by Doherty *et al.* (2015). The latter all performed well during driving, giving valuable stress wave data and are now being employed for the static and cyclic tests. One extra 508mm OD pile has been instrumented with four axes of gauges, so that dual axis lateral cycling tests can be conducted with full monitoring over each of several thousand cycles.

A further ten 139mm OD largely un-instrumented piles have been driven, which will be subjected to static and cyclic axial loading tests after ageing. Open and closed ends have been employed and pairs of fibre-optic strings have been installed on two piles. Additional sheet-pile experiments are being conducted to assess pile installation effects. Pile Driving Analysis instrumentation was applied in all pile installations and the signals analysed carefully prior to conducting axial and lateral static and cyclic loading tests.

The strain gauge data gathered from the lateral loading tests is being analysed following the procedures developed for the PISA JIP reported by Byrne et al (2017). Laboratory research is also underway to characterise the chalk's behaviour under static and cyclic conditions through advanced stress-path testing on samples from three 15m deep Geobor-S boreholes.

Figure 14 Piling operations underway at St Nicholas at Wade for ALPACA JIP programme; November 2017.

The programme is also supported by piezocone, seismic CPT and pressuremeter profiling and a future block sampling campaign.

6 SUMMARY & CONCLUSIONS

There is a pressing need to improve design guidelines for piles driven in chalk. The collaborative industrial and academic research reported in this keynote addressed the effective stress processes that control displacement pile behaviour in low-medium density chalks, including the variations in chalk properties with depth, the marked changes in shaft capacity with time and the aged piles' behaviour under axial cycling. Twelve main conclusions emerge from the results:

1. Similarly low average shaft resistances apply during driving to small diameter onshore and large diameter offshore piles;
2. Local shaft resistances show a marked tendency to reduce with increasing relative tip depth in the chalk. The reductions are far steeper than observed previously with in sands or clays;
3. Driving remoulds the chalk around the shaft creating a puttified zone that consolidates over time and results in a lower water content;
4. Dynamic compaction of intact samples in the laboratory at natural water content causes a similarly marked de-structuration of low-medium density chalk to putty. Subsequent strength increases can be obtained through consolidation and, to a far lesser extent, thixotropic aspects of the chalk's behaviour;
5. Static testing of piles after ageing at an offshore (saltwater) site and at an analogous (freshwater) onshore test site showed similar shaft set-up over time, with shaft capacities growing to ultimate resistances around 500% those at end of driving;
6. The increases in capacity with time are interpreted as following reductions in void ratio and relaxation of the surrounding radial effective stresses during driving. An arching system created around the shaft may relax over time and allowing radial stress increases to occur. Changes in interface effective stress shear strengths and the formation of expanding corrosion products may also contribute to set-up;
7. One-way axial cyclic loading of aged piles driven in low-medium density chalk led to a range of responses. The chalk does not appear to be particularly strongly affected by one-way cyclic loading, although the effects of two-way axial cyclic loading and pile compressibility remain to be checked through ongoing research;
8. Heavily instrumented ICPs, capable of measuring shaft radial effective and shear stresses, showed further details of the strong radial effective stress reductions that occur behind the pile tip as the pile penetrates;
9. As with piles driven in sands, local shaft and base resistances reflect the trend with depth of net CPT cone resistance. Static loading to failure involves dilation at the interface, interpreted as kinematically constrained interface dilation, in an analogous way to that observed around piles driven in sands;
10. The understanding drawn from the onshore and offshore tests, as well as supplementary data sources, have opened a route towards better rules for predicting the axial capacity of open-ended and closed-ended displacement piles in chalk;
11. The preliminary Chalk ICP-18 equations set out in this paper offer better ways than existing, often highly conservative, approaches for predicting shaft and base resistance during both driving and in long-term tests conducted after full equalisation of driving induced changes, where the piles have reached the asymptotes of their shaft capacity-time ageing trends;
12. The preliminary Chalk ICP-18 relationships, which link radial effective stresses to CPT cone resistance and h/R*, provide good matches for the dynamic and static tests conducted on piles installed at the Wikinger and St Nicholas-at-Wade sites on which they were based. The method shows good predictive reliability when compared to the independent tests conducted at two UK and French onshore sites and the production piling conducted offshore at Wikinger.

The research described provides new insights into the behaviour of displacement piles in chalk. Further work is underway through the ALPACA JIP to expand the database against which new methods may be tested and developed, covering a wider range of conditions.

The JIP, which is supported by EPSRC and ten industrial sponsors, is now extending the research to experiments on 26 new driven piles, supported by ground characterisation and rigorous test analysis. The programme includes experiments that assess static behaviour in compression, the potentially more severe effects of high-level two-way cycling on larger piles, as well as the piles' responses to static and cyclic loading under lateral loading.

However, the database of high-quality tests remains relatively sparse. The Authors appeal for colleagues to share data and conduct, whenever possible, well-planned, supported and executed pile load tests to cover a wider spread of chalk types and pile sizes.

ACKNOWLEDGEMENTS

The Authors' JIP project was funded by Innovate UK, with additional support from Atkins that is acknowledged gratefully. Bilfinger Construction Gmbh and COWI/IMS' contributions in carrying out offshore pile testing is also acknowledged, as is the laboratory and field testing by Gardline, GEO and Fugro. Professor Mark Randolph is thanked for allowing and supporting the use of IMPACT. The contributions of Professor Barry Lehane and his co-workers from UWA as well and of colleagues from Imperial College to supporting the St Nicholas-at-Wade tests are also acknowledged gratefully.

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