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Driven pile behaviour in low-to-medium density chalk: the ALPACA JIP outcomes

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**ABSTRACT:** Offshore pile design presents multiple challenges in low-to-medium density chalks, whose sensitivity and brittleness often leads to very low driving resistances. Also, existing design rules have proved unable to give reliable predictions for axial and lateral resistances under offshore field loading conditions. This paper summarises how the ALPACA and ALPACA Plus Joint Industry Projects (JIPs) addressed the current lack of knowledge through comprehensive field, laboratory and theoretical research. Axial and lateral field tests were conducted, under dynamic, cyclic and monotonic conditions, on 43 piles with diameters between 139mm and 1.8m, made with a range of materials, wall thicknesses and tip conditions, driven to depths between 3 and 18m. Over 100 tests were completed, after ageing for up to 400 days. Most test piles were instrumented with robust fibre-optic strain gauge systems. The experiments were supported by intensive in-situ and laboratory stress-path and cyclic testing. New monotonic and cyclic axial design methods developed for the JIP represent field behaviour far better than existing approaches. Important new observations were also made regarding pile behaviour under cyclic lateral loading, while the monotonic lateral pile tests were interpreted to generate ‘p-y’ load reaction curves and test more advanced 3-D FE approaches, developed through parallel research.

1 Introduction

Northern European offshore developments frequently encounter chalk, which can present in states ranging from a competent limestone through to a high porosity soft lightly cemented carbonate silt with liquidity index close to unity (Clayton, 1990). Both extremes present challenges when designing piles to support offshore oil, gas or wind turbine structures. Driving refusals can occur in high density chalks and piles can fall freely under their self-weight in lower density strata (Buckley et al., 2020a; Carotenuto et al., 2018). Little information exists to guide designers on axial and lateral pile capacity, stiffness or cyclic response. CIRIA C574 (Lord et al., 2002) advise site-specific pile tests wherever possible and recommend default ultimate shaft resistances of 120kPa in high density chalk and 20kPa in all lower densities, reducing to 10kPa if the piles can whip. Lord and Davies (1979) and Ciavaglia et al. (2017a) report just two isolated lateral loading case studies involving chalk and no guidance is available on the effects of axial or lateral cyclic loading, which can be critical in offshore design. A recent joint industry project (JIP) between Imperial College, Iberdrola and GCG (funded by Innovate-UK) provided new insights into (i) installation behaviour (ii) the marked effects of age after driving on axial capacity and (iii) cyclic axial loading. The outcomes described by Barbosa et al. (2017) and Buckley et al. (2018a, b) led to Jardine et al. (2018) and Buckley et al. (2020b) proposing a new design approach in a tentative and preliminary manner that recognised that more extensive research was required to cover a wider range of pile geometries, chalks and lateral loading conditions. The ALPACA and ALPACA Plus JIPs were launched to address the need for further research and more definitive guidance.

2 The ALPACA JIPs

The ALPACA (Axial Lateral Pile Analysis for Chalk Applying multi-scale field and laboratory testing) and ALPACA Plus JIPs ran between October 2017 and April 2022, led by an Academic Work Group from Imperial College and Oxford University. They were funded by the UK’s EPSRC (Grant EP/P033091/1), Royal Society (Grant NA160438), ORE Supergen Hub (EPSRC Grant EP/S000747/1), offshore wind developers (Equinor, Iberdrola, Innogy, LEMS, Ørsted, Parkwind, Siemens-Gamesa, Vattenfall) and consultants Atkins, Cathie Group, Fugro and GCG. The research focused on the St Nicholas-at-Wade (SNW) test site employed previously by Ciavaglia et
al. (2017b) and the Innovate UK JIP, located ≈15km west of Margate, Kent, UK. The JIPs advanced five main streams of research: (i) characterising, through advanced testing, the properties of SNW chalk, (ii) driving 43 piles manufactured to a wide range of scales from various steels and reinforced concrete, (iii) conducting systematic and tightly controlled axial-and-lateral, static-and-cyclic load tests, (iv) analysing the results and (v) developing improved practical design procedures. The research was supported by parallel 3D-FE numerical modelling by Pedone et al (2023). Figure 1 gives a plan of the ALPACA and ALPACA Plus testing layout.

3 SNW test site conditions and chalk characterization studies

The SNW test site is a former chalk quarry where weathered layers have been removed, exposing structured Margate and Seaford White Chalk, which are comparable to strata encountered at several offshore low-medium density chalk development sites. Both formations classify as CIRIA Grade B2/B3 with discontinuities open to less than 3mm (Grade B) and fracture spacings between 60-200mm (B3) and 200-600mm (B2). Hydraulic flushable piezometers identified a water table several metres below ground level, marginally above mean sea level. They also tracked the seasonally varying suctions that develop at higher levels. While the overlying chalk has a high degree of saturation, air circulates through the chalk’s open macro fissures (Vinck et al., 2022).

Geophysical studies performed at SNW before ALPACA included downhole and crosshole seismic surveys. Investigations conducted for ALPACA included 41 new CPTs, 48 dissipation tests, 3 seismic CPTs, and pressuremeter profiling. The example CPT traces shown on Figure 2 indicate $5<q_{t}<35$MPa corrected tip resistances, with higher values in flint bands. Very high excess pore pressures were recorded at $u_2$ cone shoulder piezocone positions; even higher pressures develop at $u_1$ face locations. The chalk fails in compression and starts to de-structure under the high CPT tip stresses but retains sufficient strength to give sleeve resistances of up to 1MPa as the chalk flows around the cone shoulder. Fully de-structured SNW chalk presents as a soft $S_0<10$ kPa putty that offers very low CPT (or pile) shaft resistances.

A 7m×10m sampling pit was excavated to 4mbgl to retrieve multiple high-quality block samples and Geobore-S wireline rotary-core boreholes were advanced to a maximum of 16.25mbgl. Intensive laboratory testing was undertaken, principally at Imperial College, on the samples obtained. The chalk’s behaviour was characterized through full logging, index test profiling and monotonic mechanical tests including uniaxial compression (UC), high pressure oedometer, direct simple shear (DSS), Brazilian Tension (BT) and triaxial tests. Ten suites of triaxial compression tests were conducted at depths between ≈0.5m and ≈16m, under both drained (CID) and undrained (CIU) conditions, after consolidation to states that represented (i) the in-situ mean effective stress $p\ell_0$ and (ii) $p\ell_0 + 300$ kPa. All tests deployed high-resolution local strain instruments and checks were run on the influence of sample size with 38mm and 100mm diameter specimens. The triaxial experiments revealed the very stiff and nearly linear pre-failure behaviour illustrated in Figure 3, as well as a notably brittle post-peak response, which involved tensile fracturing and leading to far lower shear strengths after large strains; Vinck et al. (2022). High-pressure triaxial testing identified the SNW chalk’s highly curved failure envelope, shown in Figure 4, as well as its gradual transition under increasing $p\ell$ levels from brittle towards ductile behaviour; Liu et al. (2023a). Both features are critically important to numerical modelling of the piles’ axial and lateral loading responses, as are (i) the impact of fissures in reducing mass stiffness and (ii) the damage imposed around pile shafts during driving; Pedone et al. (2023) and Wen et al. (2023a, b).
Cyclic loading was central to ALPACA. More than 20 locally instrumented cyclic triaxial tests were conducted on intact chalk specimens, which demonstrated a response more like that of crystalline rocks or metals than sedimentary soils (Ahmadi-Naghadeh et al., 2022). Noting that the near shaft, fully de-structured chalk, dominates axial capacity development in chalk, Liu et al. (2022) conducted suites of locally instrumented monotonic and cyclic triaxial tests on chalk, and suggested that chalk, dominates axial capacity development in chalk. Liu et al. (2022) conducted suites of locally instrumented monotonic and cyclic triaxial tests on chalk that had been de-structured by dynamic compaction at natural water content before re-consolidation to the conditions applying adjacent to the pile shafts. Over 20 undrained cyclic tests were undertaken on ‘putty samples’ to cover anticipated pile shaft stress conditions, along with oedometer and DSS tests. Liu et al. (2023b) summarise the laboratory cyclic testing on both intact and de-structured SNW chalk. Jardine et al (2023) and Buckley et al (2023) employed the tests to interpret the monotonic and cyclic axial pile tests. Extensive interface shear testing was also conducted, coupled with metallurgical investigations into the rates of steel-pile corrosion under a range of in-situ conditions (Vinck, 2021).

Table 1 ALPACA test piles. Note D values listed for 200mm x 200mm square concrete and SM-J steel sheet piles are nominal equivalent diameters.

<table>
<thead>
<tr>
<th>Numbers, codes, Type and material</th>
<th>D (mm)</th>
<th>Wall thickness t_w, mm</th>
<th>Length in chalk L_p</th>
<th>L_p/D</th>
<th>Shaft ground water conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 ‘LD’ open steel tubes</td>
<td>508</td>
<td>20.6</td>
<td>10.16</td>
<td>20</td>
<td>40% below WT</td>
</tr>
<tr>
<td>2 ‘LD’ open steel tubes</td>
<td>508</td>
<td>20.6</td>
<td>3.05</td>
<td>6</td>
<td>Above WT</td>
</tr>
<tr>
<td>16 ‘SD’ open steel tubes, including 2 stainless steel</td>
<td>139</td>
<td>8.2-10.1</td>
<td>4.9-5.5</td>
<td>38-40</td>
<td>100% above or below WT</td>
</tr>
<tr>
<td>2 ‘SD’ closed steel tubes</td>
<td>139</td>
<td>8</td>
<td>5.5</td>
<td>39</td>
<td>100% above WT</td>
</tr>
<tr>
<td>2 concrete square*</td>
<td>226</td>
<td>NA</td>
<td>4.9-5.4</td>
<td>22-24</td>
<td>100% above or below WT</td>
</tr>
<tr>
<td>2 steel sheet piles**</td>
<td>290</td>
<td>NA</td>
<td>5.4</td>
<td>18.6</td>
<td>100% above WT</td>
</tr>
</tbody>
</table>

Table 2 ALPACA Plus piles

<table>
<thead>
<tr>
<th>Numbers, codes, Type and material</th>
<th>D (mm)</th>
<th>Wall thickness t_w, mm</th>
<th>Length in chalk L_p</th>
<th>L_p/D</th>
<th>Shaft ground water conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP1</td>
<td>1800</td>
<td>25</td>
<td>18</td>
<td>10</td>
<td>≈70% below WT</td>
</tr>
<tr>
<td>TP2 and R1</td>
<td>1200</td>
<td>24.6</td>
<td>7.3</td>
<td>6</td>
<td>≈80% above WT</td>
</tr>
<tr>
<td>R2</td>
<td>1200</td>
<td>24.6</td>
<td>18</td>
<td>14.8</td>
<td>≈70% below WT</td>
</tr>
<tr>
<td>TP3</td>
<td>508</td>
<td>12.5</td>
<td>18</td>
<td>35.4</td>
<td>≈70% below WT</td>
</tr>
</tbody>
</table>
4 Pile details

A total of 43 piles were driven in two distinct phases. The first, conducted under the ALPACA JIP, involved the piles summarized in Table 1 which were driven between November 2017 and October 2018, and tested in stages over 2018 and 2019. The ageing durations had a marked effect on the piles’ behaviour.

The second, ALPACA Plus JIP, programme commenced in October 2020 with driving five larger piles, all of which were open steel tubes. Re-strike and monotonic axial, and both monotonic and cyclic lateral testing took place on these piles in late 2021.

Figure 5 identifies the pile penetrations relative to the principal strata and water table depths, showing how some SD and concrete square piles were installed through cased holes to prevent any contact with chalk above the water table.

The ALPACA LD piles were fabricated from high yield strain X80 steel that aimed to achieve, if possible, geotechnical failure under lateral loading before the pile walls yielded. The smaller diameter SD, sheet piles and concrete piles investigated the impacts of shaft material (including stainless steel), shape and tip conditions. All the ALPACA LD and ALPACA Plus as well as two SD piles were equipped with two to four, diametrically opposite, strings of FBG sensors to monitor the distributed shaft axial strains.

5 Dynamic analyses of pile driving and re-strikes

All pile driving was monitored; Pile Driving Analyzer (PDA) and Fibre Bragg Grating (FBG) sensors were logged at 40kHz and 5kHz respectively. Buckley et al. (2020a) and Jardine et al. (2023) describe the dynamic signal processing and stress-wave matching with IMPACT (Randolph, 2008). The FBG pile driving measurements helped to support the dynamic analysis and led to the development of a framework for data integration in future projects. The installation monitoring provided the End of Driving (EoD) baseline capacity data from which set-up could be gauged in relation to the outcomes of later monotonic testing. Operational pauses required during the ALPACA Plus piles’ driving provided opportunities for eight short-term beginning of re-strike (BoR) tests, which were monitored and analysed, as were two further longer term BoR tests on the 1200mm OD reaction piles R1 and R2 identified in Table 2.

![Figure 6 Profiles of shaft resistances for Pile TP1 at EoD and on monotonic tension loading to failure after 400 days of ageing](image)

Jardine et al. (2023) present the main results from 43 EoD dynamic analyses and show that local shaft driving resistances depend critically on local CPT $q_t$ tip values, pile $D/t_w$ and, very strongly, on the relative depth to the pile tip $h$ normalised by the pile’s effective radius $h/R^*$. Figure 6 shows the profile of local shaft resistance $r_{zi}$ derived by signal matching the EoD data from the largest (1.8m OD) pile, TP1. The driving analyses tracked the degradation of the chalk, showing how the shaft resistances reduced from maxima ≈400 kPa near the tip progressively towards the negligibly low ultimate values offered by the soft chalk putty after the pile tips had advanced to high relative depths, $h/R^*$.

The provisionally proposed Chalk ICP-18 Chalk Resistance to Driving (CRD) formulation was found to give, on average, good overall predictions for the EoD measurements made in SNW chalk. The base resistances $q_b$ were also confirmed to depend principally on CPT $q_t$; Jardine et al. (2023) propose a revised formulation that accounts for $D/t_w$.

6 Axial capacity outcomes

Comprehensive monotonic axial testing was undertaken on 27, mostly FBG instrumented, ALPACA and ALPACA Plus piles covering: diameters between 139mm and 1.8m; lengths giving $6 \leq L_p/D \leq 40$; and $14 \leq D/t_w \leq 72$ wall thicknesses ratios. Varying the
factors systematically identified a remarkable average long-term shaft resistance range from below 11 kPa to more than 200 kPa for piles driven at SNW. The factors that influenced resistance most strongly were: (i) pile end-conditions, (ii) \( L/D \) and flexibility, (iii) shaft material, (iv) age (vi) relative water table depth, and (vii) whether loading was compressive or tensile.

Among the most important observations was proof that setup progresses far more rapidly and effectively above the water table than in fully saturated chalk, due to corrosion progressing more rapidly in the zone where air could flow freely through the chalk’s open fissures. The crucial role corrosion plays in long term setup was demonstrated by the far lower long-term capacities obtained with rough stainless-steel piles.

Another key finding was that compression shaft capacities were around double those available in tension. Closed-ended (steel or concrete) piles also developed notably higher resistances than open piles. While the Chalk ICP-18 short-term formulation driving (CRD) shaft profiles predicted field behaviour well, the provisionally proposed long-term Chalk ICP-18 significantly over-predicted capacity in tension, especially below the water table. As expected CIRIA C574 was over-conservative in most cases.

The piles developed most of their tension capacities from their lower shaft sections which, for the longer piles, were positioned below the water table. The Axial Static Tension (AST) shaft resistance profile from the TP1 test, conducted after 373 days of ageing, is shown in Figure 6, as derived from careful analysis of the pile’s FBG strain gauges. The contrast between the AST and EoD profiles indicates setup, although allowance must be made in making any like-for-like comparison of the tension shaft resistances being \( \approx 50\% \) of the equivalent compression values.

The setup factors - defined as either \( \Lambda = \text{AST shaft capacity/tension corrected EoD shaft capacity} \), or \( \Lambda = \text{BoR/EoD when both tests involve compression loading} \) are shown in Figure 7, considering piles that developed most of their resistance below the water table. Setup appears to slow down at \( \approx 120 \) days and the \( \Lambda \) values appear to depend on \( L_p/D \). Also shown are the re-strike trends interpreted from offshore BoR tests on 1.37m to 3.5m OD piles at Wikinger; after Buckley et al (2020b). The latter appear to have setup to similar long-term \( \Lambda \) values, but more rapidly. The salinity of the Baltic Sea groundwater may have accelerated in-situ corrosion reactions at Wikinger.

The data interpreted from the strain gauged axial tests allowed Jardine et al. (2023) to develop an updated long-term axial capacity prediction approach for low-to-medium density SNW chalk. Independent checking against several tests conducted on 1m OD open-steel strain gauged piles driven in comparable chalks (and fresh groundwater conditions) at Sauchay, NW France showed encouraging agreement and confirmed the trend for shaft capacity to build slowly at levels below the water table; see Vinck al. (2023). In parallel work, Wen et al. (2023a, b) developed new t-z, Q-z and FE analysis approaches for modelling the piles’ load-displacement behaviour.

7 Axial cyclic loading

The axial cyclic testing programme involved ALPACA SD and LD piles. As described by Buckley et al. (2023), one-way tension and two-way (compression and tension) tests were conducted on fourteen (125 to 332 day age) SD and LD open-steel piles that had not been loaded previously, supported by monotonic control tests. The outcomes were integrated with earlier cyclic tests ‘SD’ piles by Buckley et al. (2018). Noting that open tubular driven piles develop far higher compressive-than-tensile shaft capacities in chalk, and that cyclic tension cases are the most critical for light-weight offshore wind-turbines (Barbosa et al. 2017), the programme focused on conditions where the loading was more onerous in tension than in compression. All the pile movements induced by cycling were consequently vertically upwards.

The tests identified the conditions under which piles showed axial cyclic responses that were stable, unstable or metastable. Figure 8 summarises the main trends. Contours of \( N \), the number of cycles applied, are plotted in an interactive stability diagram, where \( Q_{\text{cyc}} \) is the cyclic amplitude and \( Q_{\text{mean}} \) the mean applied load, which is always tensile. Both are normalised by \( Q_{\text{ref}} \) the monotonic tension capacity of identical control piles at the same age. Cases that involved failure are shown as red data points and \( N_f < 1000 \) contours are interpreted to show the conditions at which failures occurred. The \( N = 1000 \) contour is the lower boundary to the unstable loading region.

Post-cycling monotonic tests confirmed that stable cycling enhanced pile capacity marginally, while unstable cases suffered potentially large losses of shaft resistance. Metastable conditions led to intermediate outcomes. The patterns by which axial deflections
grew under cyclic loading varied systematically with the normalised loading parameters and could be captured by simple fitting expressions. Cyclic stiffnesses also varied with loading conditions, with the highest operational shear stiffnesses falling far below the in-situ seismic or laboratory test values.

The monotonic and cyclic axial responses of the test piles were controlled by the behaviour of, and conditions within, the reconsolidated, de-structured, chalk putty annuli that formed around pile shafts during driving. The FBG gauges identified a progressive failure from the pile tip upwards. Large factors of safety were required for piles to survive repetitive loading under high-level, two-way, conditions involving low mean loads, while low amplitude one-way cycling had little impact. Buckley et al. (2023) set out a simple ‘global’ prediction procedure employing interface shear tests and undrained cyclic triaxial tests on ‘putty’ chalk which provided broadly representative predictions for the field behaviour.

8 Monotonic lateral loading

McAdam et al. (2022) report on the lateral tests conducted on 12 paired and fully aged ALPACA piles, along with supplementary tests on three similarly aged, larger diameter, ALPACA Plus piles and two bi-axially loaded piles. The FBG gauges allowed the local deflections and lateral loads to be estimated over their full shaft depths under the imposed lateral loads through the approach described by Burd et al. (2020).

The programme commenced with monotonic lateral tests on LD piles driven to $L_p/D$ ratios of 20 and progressed later to the $L_p/D = 6$ cases. The shorter piles developed unambiguous geotechnical failures, but the longer piles developed steel yielding slightly earlier, despite their thick walls and high strength steel. Significant gaps opened between the piles and chalk during loading and unloading, reflecting local yielding in the brittle chalk, which leads to a significantly softer response on unloading, reloading and cycling, as well as marked axial capacity losses.
from the field measurements for application in a 1D numerical model, which performs well in reproducing the ALPACA and ALPACA Plus tests results and other tests reported in the literature. A normalisation framework is proposed that covers the 508mm-to-1200mm diameter cases investigated and may guide design at other sites. Naturally, checking at further sites is recommended.

A key feature observed under monotonic loading was the relatively low limiting lateral resistances developed under monotonic loading in comparison with the SNW chalk’s UCS and undrained shear strengths. Pedone et al. (2023) show that this feature reflects (i) the damage caused to the chalk by pile driving and (ii) the brittle and pressure-dependent chalk behaviour observed in the ALPACA laboratory tests. The monotonic lateral tests also allow 3D-FE analyses to be developed and tested that can feed into the ‘PISA’ design methodology described by Byrne et al. (2020). Pedone et al. (2023) discuss the steps required to obtain representative load-displacement, bending moment and lateral capacity predictions from effective-stress based 3D-FE analyses.

9 Cyclic lateral loading

Cyclic lateral loading tests were conducted on paired FBG gauged piles; McAdam et al. (2022). An example from an ALPACA LD pile (driven with $L_p/D = 20$) is shown on Figure 9(b), while Figure 10 summarises in a cyclic stability diagram the outcomes of cyclic tests on several similar piles driven on the north side of the LD test area identified in Figure 1; the same general outcomes applied to the corresponding ‘south side test piles.

![Figure 10 Cyclic stability diagrams from lateral tests on north-side LD piles, showing maximum ground-line displacements $v_{G,max}$ (% of diameter) and accumulated ground-line displacement $v_{G,acc}$ (% of diameter) at $N = 1000$. $H_D/D_{10}$ is lateral capacity mobilized at a deflection of $D/10$ in monotonic control tests.](image)

One-way cyclic loading led to permanent displacements accumulating and marked stiffness changes. Dual axis lateral loading was applied to one LD pile equipped with four strain gauges on two orthogonal axes, showing that displacements and stiffness losses increased significantly under bi-axial conditions. Tension tests followed most lateral tests to identify their impact on axial capacity, which were followed by static lateral tests to failure. McAdam et al. (2022) describe also the monotonic and cyclic tests performed on the larger ALPACA Plus piles.

10 Dissemination of results

The ALPACA and ALPACA JIP results are being disseminated through a coordinated series of open access journal papers by Ahmadi-Naghadeh et al. (2022), Buckley et al. (2020a), (2023), Jardine et al. (2023), Liu et al. (2022, 2023) and Vinck et al. (2023) and articles in international conferences, including OSIG-2023. Parallel studies at another chalk site are reported by Vinck et al. (2023); Pedone et al. (2023) and Wen et al. (2023a, b) report on related advances in numerical analysis. A half-day open symposium, on 15th March 2023, at Imperial College presented the main results to industry and academia. Additional articles are in preparation, including a summary document that guides practical application of the research.

11 Conclusions

1. Piles are driven routinely in chalk to support offshore wind turbines, as well as oil and gas platforms and many onshore and nearshore structures. Current guidance on their axial capacity, driveability, set-up or lateral resistance is limited, as is knowledge of how such piles respond to axial or lateral cyclic loading.

2. The ALPACA and ALPACA Plus JIPs addressed this shortcoming through tests on 43 piles driven at multiple scales at a well-characterised low-to-medium density research site.

3. Comprehensive site and material characterisation has included in-situ testing, rotary core and block sampling, while the laboratory element program has covered static and cyclic stress path experiments, as well as high-pressure tri-axial, interface shear, chemical and other advanced testing.

4. The research has led to multiple new findings concerning the axial and lateral behaviour of piles driven in chalk under dynamic, static and cyclic loading conditions.

5. New design methods and guidance have been developed that are being checked, wherever possible, against data recorded at other sites.

6. The key findings are being disseminated widely through journal and conference articles as well as through open symposia and other means.
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