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Research to Improve the Design of Driven Pile Foundations in Chalk: the ALPACA Project

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

B. W. Byrne, R. M. Buckley & R. A. McAdam
Oxford University, Oxford, UK

Abstract: Large numbers of offshore wind turbines, near-shore bridges and port facilities are supported by driven piles. The design and installation of such piles is often problematic in Chalk, a low-density, porous, weak carbonate rock, which is present under large areas of NW Europe. There is little guidance available to designers on driveability, axial capacity, the lateral pile resistance which dominates offshore wind turbine monopile behaviour, or on how piles can sustain axial or lateral cyclic loading. This paper describes the ALPACA project which involves comprehensive field testing at a low-to-medium density chalk research test site. The project is developing new design guidance through comprehensive field testing and analysis combined with in-situ testing campaigns and advanced static-and-cyclic laboratory testing on high quality block and rotary core samples.

Keywords: chalk, driven piles, foundations, axial capacity, lateral loading, cyclic loading

1 Background to the research

The Chalk of Northern Europe is a soft, white, pure biomicrite limestone comprised almost entirely of calcium carbonate. It extends from Germany and Denmark to the United Kingdom, as shown in Fig. 1, where it outcrops in several countries and at Baltic and North Sea locations as an often low-density, structured very fine-grained porous weak carbonate rock, frequently with silica flint nodules and layers.

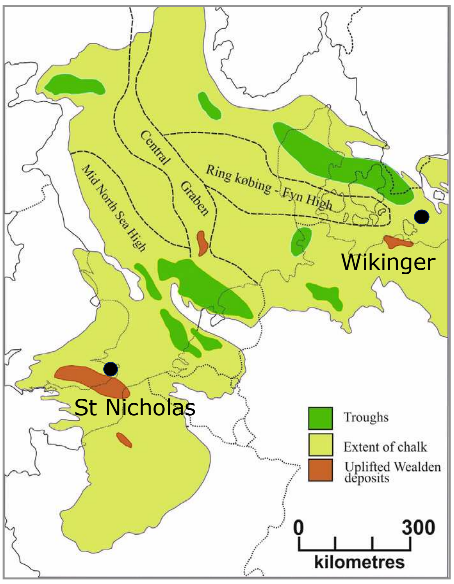

Fig. 1. Chalk of NW Europe, after Mortimore (2012) also showing the Wikinger and St Nicholas at Wade test site locations.

Large diameter open-ended driven tubular pile foundations are employed for most offshore and nearshore developments. Currently, more than two thirds of the global offshore generating capacity is installed in UK and German waters with multiple wind-farms under development in UK, Danish, French and German waters to be founded in chalk. Monopile foundations for offshore wind turbine (OWT) structures (see Fig. 2), which consist of a single large diameter steel tubular pile with a diameter up to 8m, are predominantly loaded by horizontal force and overturning moment providing resistance through a cantilever action. Jacket structures for OWTs, typically used in deeper water, consist of a steel lattice frame founded on multiple piles or suction caissons. In the case of piles, the lateral loads from the structure are transferred through the jacket to the foundations, which develop axial skin friction to resist the applied loads via push-pull action. Large tubular driven piles are also used to support near-shore structures with several port expansions under development in chalk strata in the UK (Buckley, 2018).

Where encountered within the founding stratum, chalk poses difficulties to engineers seeking to design the high capacity, often large diameter, tubular steel piles described above. There is limited data available to inform designers regarding axial and lateral capacity and stiffness. Difficulties may also occur during driving: both free-fall pile ‘runs’ and pile refusals have been reported (Jardine et al., 2018).

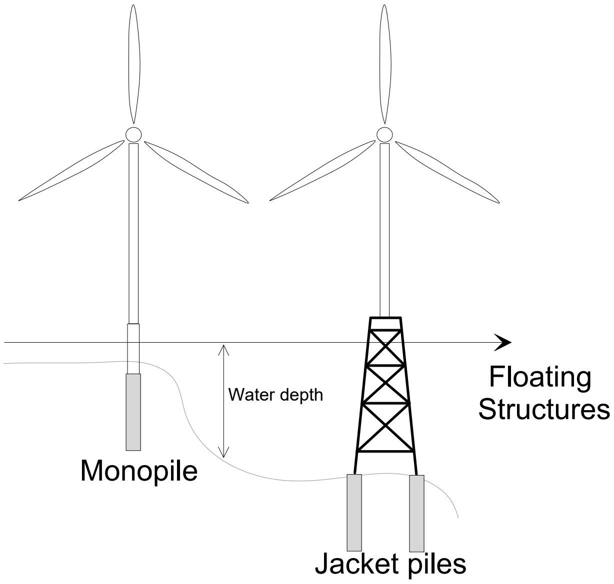

Fig. 2. Schematic of monopile and multi-pile jacket structures used to support offshore wind turbines.

Very few load tests on piles driven in chalk have been reported. Limited lateral load testing has been described by Ciavaglia et al. (2017) and analysis methods suggested (e.g. Muir Wood et al., 2015); there is currently no widely accepted lateral loading design method for piles in chalk. In the same way, little data from high quality static axial testing have been published or collated. The CIRIA C574 design recommendations axial design (Lord et al., 2002) reflect this uncertainty and recommend taking ultimate shaft resistances of 120kPa for high density chalk and 20kPa in all other densities and grades, reducing to 10kPa, if the pile can “whip”. These recommendations appear surprisingly low given the relatively high Unconfined Compressive Strengths (UCS), (up to 5MPa, (Bowden et al., 2002), and cone tip resistances, q_c (4 to 50MPa (Power, 1982),) of Northern European chalk.

Pile driving can also be difficult in chalk with refusals reported on driving through high-density material. In low to medium density material, piles have penetrated to significant depths under their own self weight, see for example Carotenuto et al. (2018). Compressive stresses caused by impact pile driving are thought to de-structure the high porosity chalk, causing a low strength remoulded putty material to form around the shaft. Low installation resistances can be replicated by high level cyclic loading in laboratory simple shear tests (Carrington et al., 2011, Diambra et al., 2014) or by Proctor laboratory compaction of intact samples at their natural water contents (Doughty et al., 2018). Reports of offshore pile runs developing without any hammering prove that very low shaft stresses can develop without load or displacement cycling. Installation resistance measurements show shaft shear stresses applying at any fixed depth attenuating sharply with increasing relative pile tip depth, h, as the pile penetrates, as observed in clays and sands (see Jardine et al., 2005). The extent to which time affects pile capacity in chalk is not yet well quantified or understood. Similar uncertainty applies regarding the effects of axial or lateral load cycling, which is a significant concern for OWT foundations that sustain large numbers of significant load cycles under the actions of wind, waves and rotating turbine blades.

Designers are therefore faced with limited guidance and stark choices when designing offshore and nearshore structures founded wholly or partly on chalk, which can significantly impact the economics of projects. CIRIA recommend site-specific pile load tests wherever possible, which can generate significant savings in major OWT projects (Barbosa et al., 2017).

A Innovate-UK funded Joint Industry Project (JIP) study (2014-2017) combined industrial and academic research to investigate the axial capacity of piles driven in chalk. Led by Iberdrola with an academic team from Imperial College, the JIP aimed to (i) develop new methods of field pile testing and analysis; (ii) expand the database of high quality field measurements; and (iii) produce new design rules for axially loaded piles. Experiments were conducted at two low-medium density chalk sites, shown on Fig. 1; one onshore at St. Nicholas at Wade, Kent, UK (see Buckley et al., 2018) and one offshore at the Wikinger offshore windfarm in the German Baltic Sea (Buckley et al., 2019b). Multiple dynamic measurements were made during driving along with long term static tension and cyclic loading tests.

The Innovate-UK research gave new insights into the basic mechanisms of behaviour and strong field ageing processes leading to new preliminary effective stress design methods that: (i) offer more reliable predictions for static axial capacity; and (ii) consider cyclic loading. While the programme was fully successful, more comprehensive research was required to cover further cases, including using instrumented piles, two-way cyclic loading and static and cyclic lateral loading.

2 The ALPACA JIP

The ALPACA (Axial lateral pile analysis for chalk applying multi-scale field and laboratory testing) JIP research project is currently underway, funded by the UK's EPSRC (Grant EP/P033091/1) in conjunction with offshore wind developers (Equinor, Iberdrola, Innogy, LEMS, Ørsted, Siemens Gamesa and Parkwind) and consulting organizations (Atkins, Cathie Associates, Fugro and Geotechnical Consulting Group, TATA steel). The research aims to advance the design of tubular piles driven in chalk, particularly for OWTs by investigating a range of axial-and-lateral, static-and-cyclic loading conditions through high quality tests on 36 driven piles, sixteen of which are instrumented with novel fibre bragg grating (FBG) sensors.

The research programme also includes parallel laboratory research, in-situ testing and analysis. The JIP is led by an Academic Work Group from Imperial College London and Oxford University. The field work was conducted between 2017 and 2019 at the onshore site employed by the Innovate UK JIP (see *Fig. 3*), which is located within a previous chalk quarry (UK Grid TR 25419 66879).

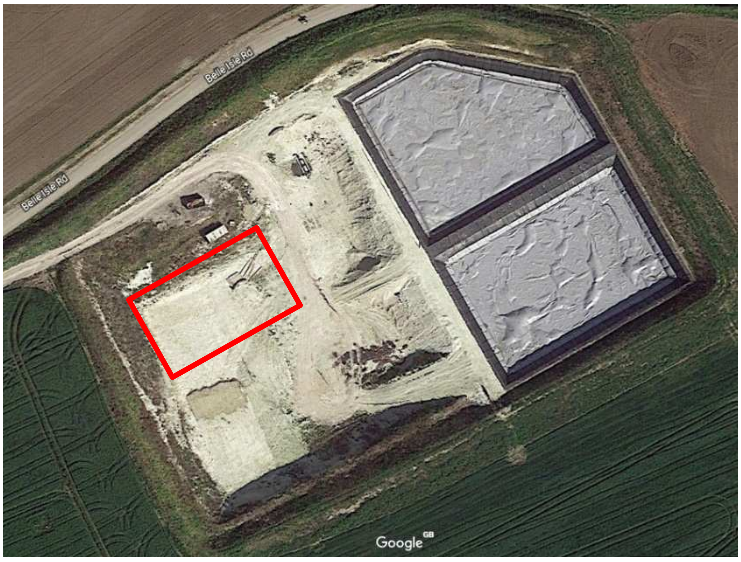

Fig. 3. The St Nicholas at Wade test site showing approximate test area for ALPACA JIP programme (Google Earth).

2.1 The Site

The site comprises structured, low-medium density chalk from surface; all overburden and weathered chalk has been removed, and the chalk is similar to that encountered at greater depth offshore. The site was used previously as part of the Innovate-UK JIP as well as for earlier research (see Ciavaglia et al., 2017). To support the ALPACA interpretation, new piezocone, seismic CPT and full displacement pressuremeter testing has been conducted, while three 15m deep Geobor-S boreholes and block sampling from 4m deep test pits has provided high quality samples for a parallel laboratory element testing programme at Imperial College that aims to characterise the chalk behaviour under static and cyclic conditions through advanced stress path testing. Piezometers and flushable piezometers have been installed to give detailed information on ground water conditions.

The site's chalk classifies as CIRIA Grade B2/B3 (structured low-medium density), with discontinuities open to less than 3mm and a fracture spacing of between 60 and 200mm. The water table lies at around 6m below ground level. The Intact Dry Density (IDD) ranges from 1.38 to 1.54Mg/m^3 over the pile depths, indicative of a low density material (Bowden et al., 2002). The UCS q_u range of 2 to 2.8MPa is within the range expected for material of this porosity (Matthews and Clayton, 1993).

CPT tests indicate a range of $5<q_c<35$ MPa with higher resistances in flint bands (Fig. 4). Very high excess pore pressures are recorded at the u_1 cone face piezocone position. Lower, but still considerable, pressures develop at the u_2 cone shoulder location. Although the high cone tip stresses cause the chalk to de-structure, it retains sufficient shearing resistance to give sleeve frictions up to 400kPa as it flows around the cone.

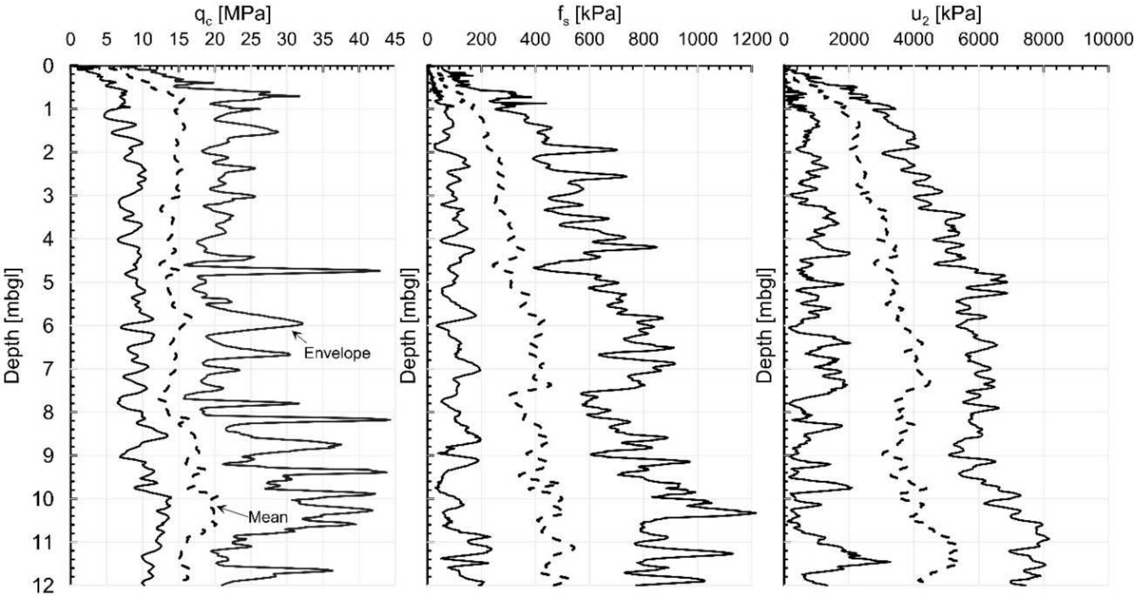

Fig. 4. CPT profiles from the ALPACA test site.

2.2 Pile configuration and installation

Of the 36 piles installed, fourteen had outside diameters (OD) of 508mm and were driven to depths of between 3.05 and 10.16m (L/D = 6 to 20). The 508mm OD piles were fabricated from high yield strain X80 steel that allowed geotechnical failure to be achieved under lateral loading before the steel walls yielded. These large diameter (LD) series piles were instrumented with opposing pairs of FBG sensors (see Doherty et al., 2015, Byrne et al., 2018 or McAdam et al., 2018). In thirteen cases, two diametrically opposite strings of gauges were employed, while one pile had four strings of diametrically opposite gauges. Each string consisted of 12 gauges, which were spaced to capture the distribution of strain down the pile and to accurately capture the bending moment during lateral loading tests. The LD piles were allowed to age for several months before being subjected to a series of static and cyclic, axial and lateral loading tests. The pile driving of the LD series piles is shown in Fig. 5.

Eighteen 139mm diameter tubular (SD series) various material steel piles (L/D≈38-40) were also installed, of which sixteen were open-ended and two closed-ended. Two of the open-ended piles driven from ground level were instrumented with two strings of diametrically opposite FBG gauges. Four of the open-ended piles were driven through a pre-bored hole cased above the water table. In addition, two 200mm square pre-cast concrete piles were driven; one from ground level (L/D≈21) and one through a pre-bored hole cased above the water table (L/D≈19) along with two SM-J sheet piles, with an equivalent diameter of 290mm, (SD series) driven from ground level. These installations explored the extent to which pile set up varies with pile material type and degree of immersion below the water table.

Fig. 5. Driving of FBG instrumented 508mm OD piles at St. Nicholas-at-Wade.

The piles were installed in three phases in November 2017, May 2018 and October 2018 with the timing of the subsequent testing planned systematically to quantify the effects of time on the results. All piles were monitored dynamically at a rate of 40kHz during driving using PDA sensors installed near the pile heads. The FBG sensors were also monitored during driving with a high frequency (5kHz) interrogator, which allowed the passage of hammer induced stress waves along the pile to be observed in detail for the first time (Buckley et al., 2019a). All open-ended piles were fully coring during installation with the internal chalk plug typically reaching above ground level at the end of driving. The LD piles were installed using an additional "driving dolly" which was used to prevent the up-welling chalk plug from coming into contact with the hammer ensuring uninterrupted driving.

The test pile layout and site investigation locations are shown in *Fig. 6*. The pile dimensions and types were selected as giving the best balance between covering a suitably broad scope of experimental variables and project economic viability, which matching appropriate field conditions.

2.3 *Testing phases*

The ALPACA pile testing was carried out in four main phases. The main set of LD pile tests followed in the sequence shown in Fig. 7. The work was conducted with the aid of a subcontractor (SOCOTEC UK Ltd) from June to October 2018, at times between 66 and 307 days after each pile had been driven.

The LD pile loading tests were performed in a carefully programmed sequence that allowed for significant pile ageing processes to progress over specified periods before any loading commenced. Following an initial set of static tension and compression axial load tests, a total of 13 axial cyclic tests have been performed on previously unfailed piles. Most tests involved up to 1000 cycles of loading, applied with 10s periods. Some tests failed at earlier stages and one was continued to 10,000 cycles. Six of the cyclic tests involved purely tension (one way) loading, while a further 7 tests considered both compression and tension cycling. The fibre optic strain gauges provided key information on the monotonic and cyclic load transfer mechanisms. The impact of earlier axial cyclic loading on axial monotonic capacity were checked through final load tension tests to failure.

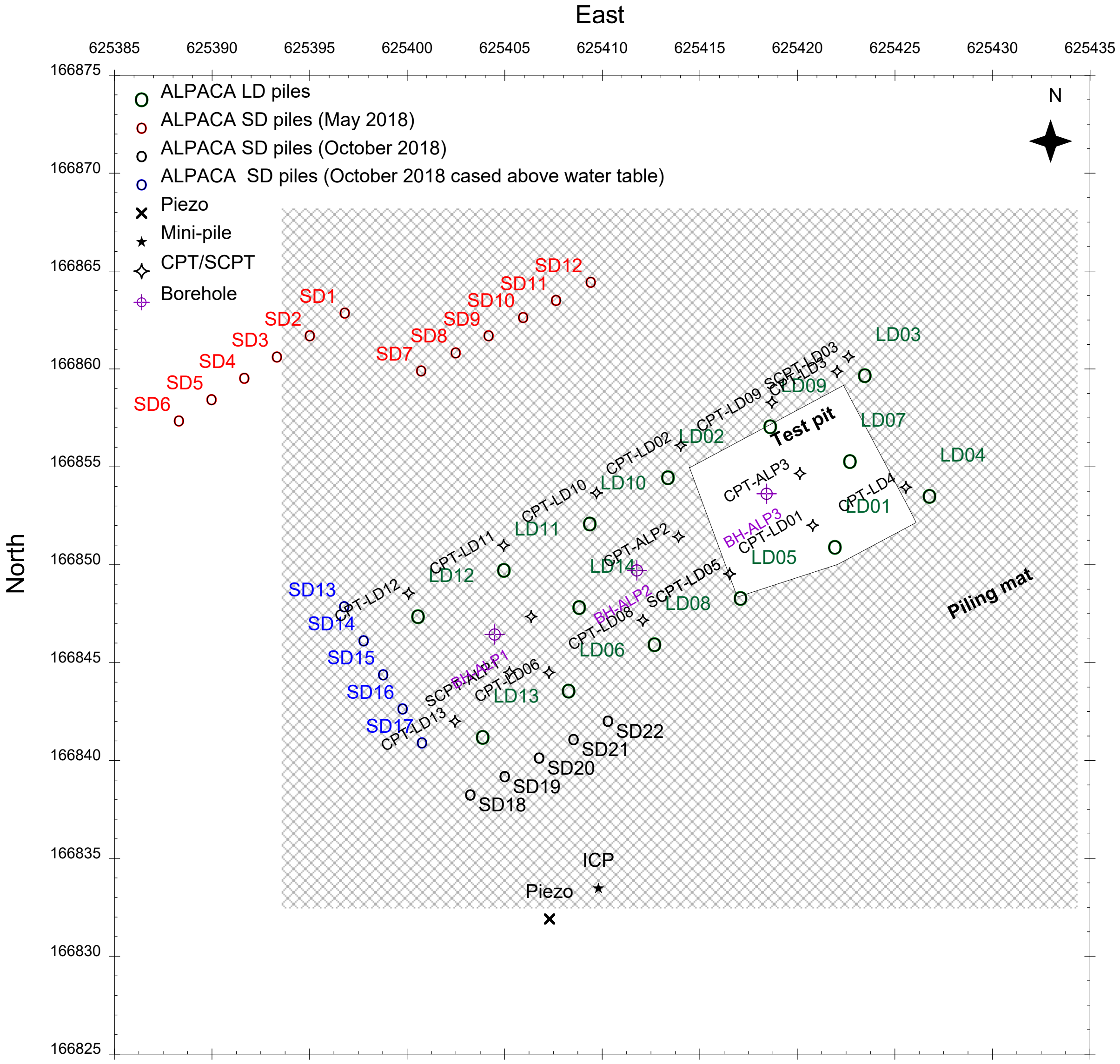

Fig. 6. ALPACA site layout plan.

The LD piles were also employed for lateral loading tests, which engaged a far larger volume of chalk. In addition to monotonic load tests to lateral failure, seven combinations of uniaxial lateral cyclic loading were applied to the piles. Bi-axial lateral cyclic (BLC) tests were also conducted in which a one-way lateral cyclic load was applied in one direction with a steady state perpendicular lateral load. As outlined in Fig. 7, static lateral tests to failure were conducted after most lateral cyclic tests, followed by axial tension tests to failure that identified how lateral failure affects axial capacity.

Three additional pile testing phases for ALPACA involved:

- Short-term axial static tests conducted by the AWG on the SD piles in May 2018, between 2 and 3 days after driving the test piles;
- Long-term axial static tests conducted by the AWG on the cased and uncased SD piles of various materials between February and March 2019, between 127 and 156 days after driving;
- Additional long-term axial static and cyclic tests conducted by SOCOTEC on the SD piles in April 2019, at pile 'ages' between 317 and 332 days.

The ALPACA field experiments are now complete, and analysis of the data and development of design rules is underway. A parallel study, into steel corrosion effects in fresh and saline water, which will complement the field pile testing results is also underway in conjunction with TATA steel.

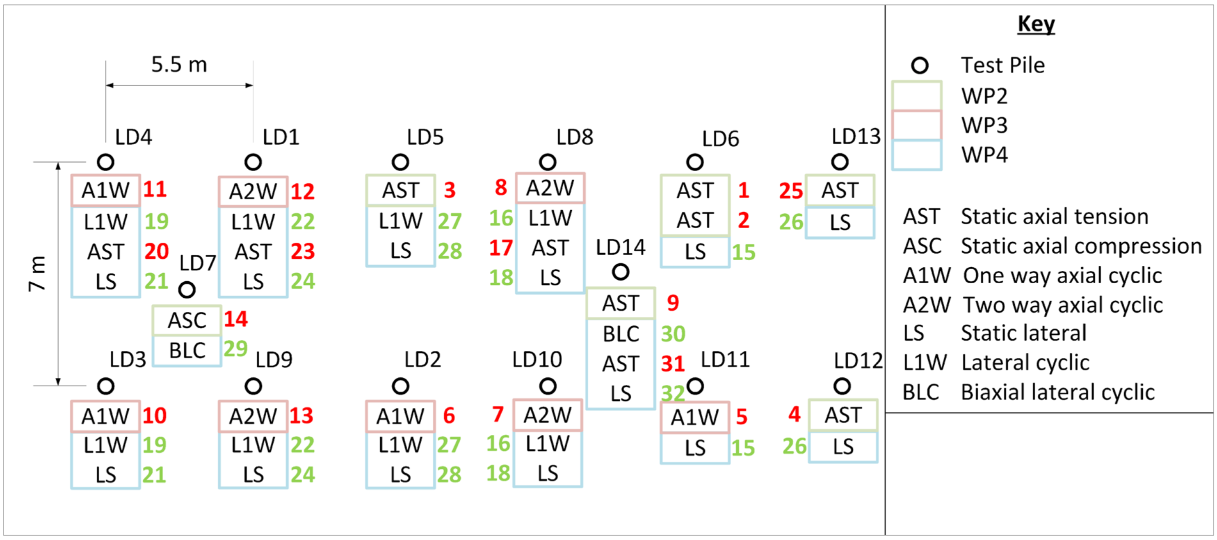

Fig. 7. Location and method of LD pile testing with axial pile test number shown in red and lateral pile test number shown in green.

3 Conclusions

1. Large tubular driven pile foundations are used routinely in chalk to support offshore wind turbines and near shore developments such as ports. However, 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 project addresses this gap in knowledge through comprehensive field testing at a well-characterised low-to-medium density site;
3. The field experiments were enhanced through the use of high-resolution fibre-optic strain gauges and supported by advanced laboratory and in-situ testing, as well as theoretical analysis;
4. The field programme is now complete, and analysis of the data is underway, along with parallel laboratory testing and corrosion studies. The research aims to develop new rules to improve the design of driven pile foundations for application in offshore, coastal or onshore projects.

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