In situ testing in low-medium density structured chalk

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ABSTRACT: Chalk, a soft, white, variable, high porosity, rock has been the focus of recent research into pile behaviour following the rapid expansion of offshore windfarms in Northern Europe and the advancement of other major infrastructure projects in areas where foundations are installed in chalk. An overview of recent in-situ testing (cone penetration tests and geophysical tests) at low-medium density chalk sites is presented. Typical cone penetration test profiles are discussed, which illustrate that while cone resistance and friction ratio in chalk lie within the typical ranges for sands and clays, pore pressures are remarkably high and dissipate quickly, leading to partial drainage occurring during cone penetration tests conducted at standard velocities. The CPT cone resistance increases markedly with reducing penetration rate due to increasing degrees of drainage developing around the advancing cone tip. While both cone resistance and friction ratio have been shown to increase with improving chalk grade, a consistent method to classify chalk grade using CPT parameters has not yet been developed. Shear wave velocities measured in the field through geophysical testing fall below the trends interpreted from laboratory tests on intact samples, which may be attributable to the presence of fractures in the chalk mass or differences in applied effective stress levels. However, the cone resistance profiles developed in structured chalk provide sensitive indicators of local variations in key factors that affect mass shear strength and density. This observation has encouraged the authors to propose CPT based design methods for piles driven in chalk.

Keywords: chalk; CPT, piles, partial drainage

1. Introduction

Chalk is a white, pure biomicrite (limestone) comprised almost entirely of calcium carbonate ($CaCO_3$) derived from the remains of plant and animal life. In Northern Europe extensive deposits can be found in Belgium, Denmark, England, France, Germany and Holland and across the Baltic and North Seas [1], 2] where it is typically encountered as a highly variable, soft, porous material. Chalk outcrops over almost 15% of England's surface area [3] and is the UK's main aquifer for potable groundwater [4].

Large engineering projects constructed in chalk include the Channel tunnel and rail link, sections of the M4, M20 and M25 motorways in the UK, the TGV railway network in Northern France and numerous offshore wind energy projects [see for example 5]. Ongoing projects involving chalk include the Dover harbour expansion, the UK High Speed 2 network as well as several hydrocarbon and offshore renewable energy projects.

While piles are driven routinely for such projects, current guidance on their driveability, axial capacity, set-up, lateral resistance and response to cyclic loading is limited. Recent research has focused on improving design methods in these materials through high-quality field testing combined with in-situ tests, laboratory tests and theoretical developments [6-9].This paper provides an overview of cone penetration testing (CPT) and geophysical tests from recent studies at typical low-medium density chalk profiles, where classification testing and geological profiling has been undertaken. Correlations with laboratory measurements are made and comparisons drawn with previously published studies. While CPT testing cannot provide detailed information on the chalk's macro-structure, the cone resistance profiles do provide sensitive indicators of local variations in the key factors that affect mass shear strength and density. This observation has encouraged the authors to propose CPT based design methods for piles driven in chalk, the bases of which are set out at the end of the paper.

2. Classification of chalk

CIRIA PR11/C574 [10-12] identified chalk hardness, discontinuity spacing and aperture as key factors influencing the behaviour of the intact mass. In their classification scheme, the chalk is split into categories of either structured (Grade A/B/C) or structureless (Grade D) material.

Structured chalk is classified as low, medium or high density based on field and/or laboratory determinations of intact dry density (IDD) (see [12]) and subdivided by discontinuity aperture (Grade A to C) and by discontinuity spacing (subscript 1 to 5). Structureless material is subdivided further; into Dm and Dc where the coarse fragments are <65% and >65% respectively.

The CIRIA scheme replaces the previous [13] Mundford classification scheme which was intended to be specific to the Mundford test site. [14] provides a tentative means of converting the broad Mundford grades to the CIRIA grades.

3. Cone penetration testing in chalk

3.1. Typical profiles

An example piezocone (PCPT) profile established in low-medium density chalk at the Imperial College St Nicholas at Wade test site (near Margate NE Kent, UK) as described by [6] is shown on Fig. 1. Cone tip resistance in chalk tends to be higher than is seen in most clays and closer to that developed in medium dense sands. Friction ratios fall between 1 and 5%, within the ranges seen in both sands and clays. CPT q_t profiles frequently include sharp peaks over small (<0.5m) intervals. These are thought to be related to the presence of flints and the manner in which penetration resistance "builds up and is then followed by grain crushing and closure of discontinuities" [15].

Variations in the CPT profile are likely to relate to degree of cementation, jointing and fissuring and changes in density, since the dry density of chalk can vary by as much 0.1 Mg/m^3 over 0.1m depth [10]. The spiky nature of cone penetration profiles in chalk has led previous researchers to recommend averaging the resistance over some interval of penetration to give more representative results.

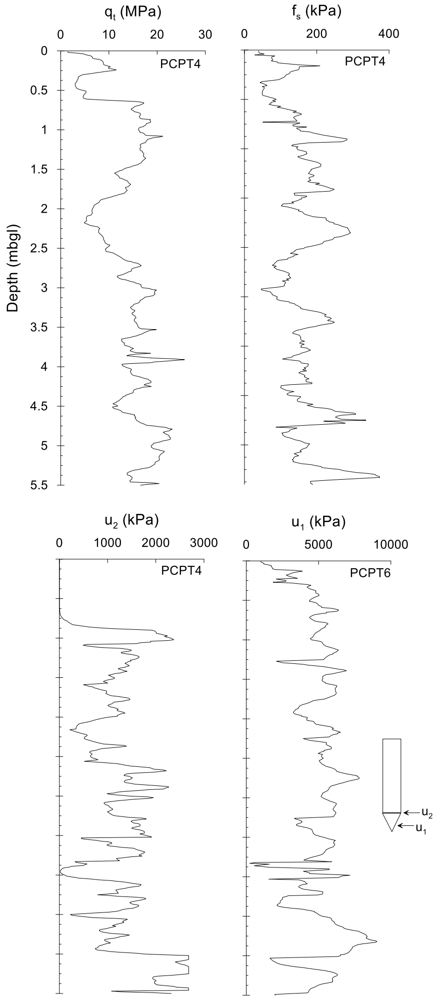


Figure 1. Typical profiles of cone resistance, q_t, sleeve friction, f_s, pore pressure at the sleeve position, u_2 and u_1 measured in PCPT4 at the Imperial College test site: Note u_1 plot is from an adjacent CPT [16]

While [15] recommended averaging over 1m penetrations, [17] concluded that an averaging interval of 0.3m penetration was more reasonable in relation to the dimensions of the cone. Ambiguities in differentiating chalk from other materials in PCPT tests are most conclusively resolved by consideration of the excess pore water pressures (EPWP). While very little EPWP is induced in sands due to the free draining nature of the material, pore pressures are generally remarkably high in low-medium density chalk. Fig. 1 shows values up to ≈3MPa at the shoulder (u_2) position and 10MPa at the tip (u_1) position at the St. Nicholas at Wade site, where the chalk classifies as low-medium density grade B3-A2. While high EPWP may also develop in clays, their dissipation will usually be far slower. Fifty per cent dissipation was shown to occur at the u_2 position after 4 to 13 seconds at the Imperial College test site. Horizontal consolidation coefficients, $c_{h,piezo}$ of $\approx 1 \times 10^{-3}$ m^2/s were assessed after assuming a high rigidity index in the surrounding intact chalk (≈ 3000) and applying the approach of [18]. Similar trends were reported for the same site by [19] and offshore at the Amethyst gas field by [20]. The generation of high pore pressures may be surprising, considering the chalk's silt-size particles and regular discontinuities, which lead to high mass permeabilities. The high penetration pore pressures close to the cone tip may be caused by the collapse of the chalk's structure around the cone. Local grain crushing and the closing of discontinuities is likely as penetration occurs, which is relieved when pushing is halted [20].

3.2. Classification using in situ test results

To date, a consistent method has not been developed that links the CIRIA grades to *in-situ* testing results. The limitations of the standard penetration test (SPT) and the need for various corrections are well documented, see for example [21] for SPT tests in sands. Chalk can completely de-structure under high compressive stresses and SPT N values relate to dynamic bearing capacity failure ahead of the SPT shoe; [11]. The tentative correlation between Mundford grade and N value proposed by [22] was criticised by [23], for attempting to relate blow count to a visual weathering grade. CPTs or PCPTs appear to be a better tool for investigation of chalk strata, providing reliable and repeatable data which can be correlated with site specific descriptions. [24] found cone resistance particularly useful to help identify the extent of cavities and zones of disturbed material at depth within the Upper Chalk at a site near Costessey, Norfolk.

Attempts have been made to develop CPT-based classification schemes. [25] proposed relationships between tip resistance, friction ratio and IDD plotting them in a chart which attempted to delineate the results in terms of degree of cementation and the Mundford grades. [15] related CPT parameters to Mundford grade; he found that both cone resistance and friction ratio increased with increasing chalk grade, and gave broad ranges of both parameters for each grade. He noted that penetration may not be possible in high density Grade A chalk. [26] cite an unpublished BRE report by [27] who examined CPTs at five sites including Mundford. While they report that cone resistance and friction ratio increase with improving grade the ranges varied between sites and most of [27] data fell outside the Power classification ranges, even those from the Mundford site (see Fig. 2). [17] observed general trends of increasing cone resistance and friction ratio with improving chalk grade at 11 UK sites, however, there was significant overlap between parameters encountered at different sites.

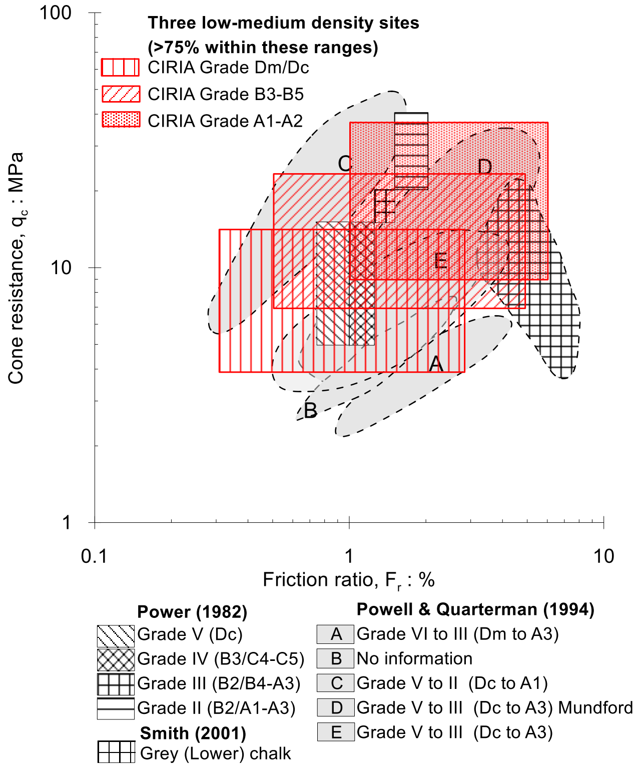


Figure 2. Classification of chalk grade using CPT tests from results available in the literature [data from 15], 27], 17] and three database sites considered in the present study

Fig. 2 shows (in red) the ranges observed by the Authors at three low-medium density chalk sites (i) the onshore test site whose CPT profile is shown in Fig. 1 (ii) an Offshore Wind Farm (OWF) in the Southern North Sea and (iii) an OWF in the German Baltic Sea [9]. While a general trend of increasing cone resistance and friction ratio with improving grade is observed there is significant overlap again between the ranges. Similar conclusions were reached from a review of data at a number of sites by [28]. These studies, when taken together, suggest that identification of the microfabric required to delineate chalk grades may not be possible using only these basic CPT parameters. Additional data is required, in particular from sites with CPT profiles in different grades, densities and at different stress levels, combined with careful borehole logging, to further develop any CPT based classification method.

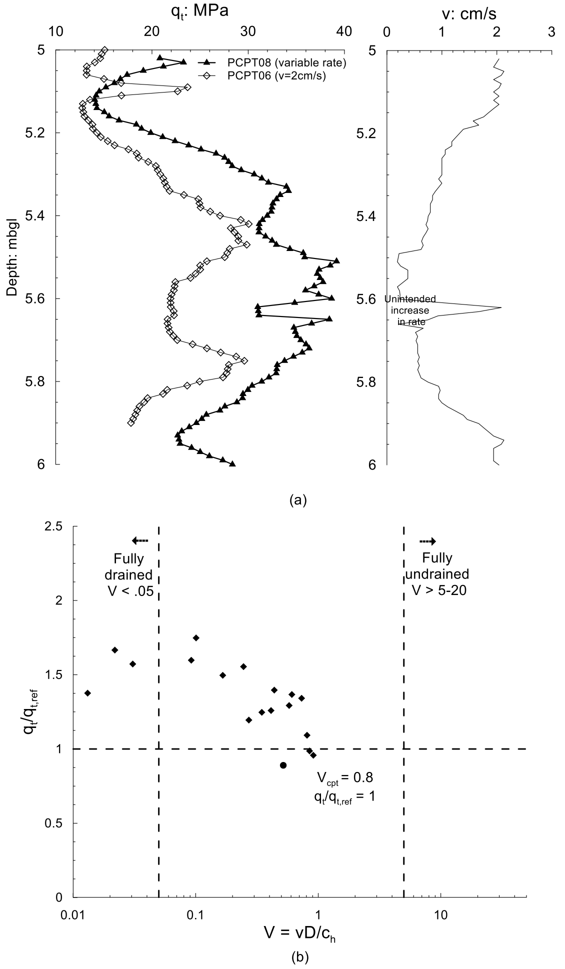
3.3. Drainage during cone penetration

The degree of pore pressure dissipation during a cone penetration test can be assessed using a normalised velocity, V [29] defined as:

$$V = \frac{vD}{c_h} \qquad (1)$$

where D is the diameter of the cone and the standard tip velocity, v is 20mm/s. The critical V ranges where behaviour transitions from drained to undrained, depend on which method is used to define c_h; the normally consolidated values seen in oedometer tests ($c_{h,nc}$) fall well below those measured in a dissipation test ($c_{h,piezo}$) which in turn fall below the maxima applicable in lightly overconsolidated states, $c_{h,oc}$. Centrifuge tests indicate that undrained conditions apply at V values between 10 and 100 when $c_{h,nc}$ is substituted [29-32]. If $c_{h,piezo}$ is considered, approximately equal to five times $c_{h,nc}$ [33] for the chalk tests, the transition range becomes 2 to 20. V is ≈0.8 when evaluated with the CPT $c_{h,piezo}$, found at St Nicholas at Wade indicating that partially drained conditions probably applied in the tests shown in Fig. 1.

The effect of penetration rate on q_t was assessed during PCPT08 at the IC test site. The standard rate of penetration of 20mm/s was reduced manually in steps to a minimum stable value of approximately 5mm/s, or V≈0.022, between 5.02 and 5.9mbgl (Fig. 3).



(a)

(b)

Figure 3. Effect of variable penetration rate on cone resistance at PCPT08. Adjacent PCPT06 also shown where penetration was at a rate of 2cm/s (b) cone resistance during variable penetration versus normalised velocity

The value of q_t, was compared to q_t over the same interval at the adjacent standard rate PCPT06, termed $q_{t,ref}$ (Fig. 3 (a)). Fig. 3 (b) plots q_t/q_{ref} against V for the variable rate test. In this plot q_t/q_{ref} = 1 when V = 0.8 and grows to 1.7 as V falls due to increasing degrees of drainage around the advancing cone tip and fully drained behaviour applying at V < 0.05.

Buckley *et al.*, 2018a applied a similar analysis to show that the chalk's response to the driving of 139mm diameter open-ended piles at the same site was also likley to have been partially drained.

4. Geophysical testing

Elastic shear and compression wave velocities in chalk have been shown to increase with increasing density and reducing porosity [34-36]. [37] showed, from laboratory tests on intact samples from the North Sea (Fig. 4), that ultrasonic compression (P-wave) velocity for low-medium density chalk (porosity = 37% to greater than 43%) ranged from 1.9 to 2.9km/s, and for high to very high density chalk (porosity 28% to 37%) is between 2.9 and 3.7km/s. Shear (S-wave) velocity for low-medium density ranged from approximately 1 to 1.8km/s and for high-very high density lies between 1.8 and 2.2 km/s.

Any correlations between elastic wave velocities (and therefore stiffness) measured in-situ and on intact samples in the lab can be strongly affected by sampling disturbance, ageing effects and sample size. Considering three sites where the chalk ranged from low to high intact dry density, [38] demonstrated that small strain shear stiffness inferred from Rayleigh wave tests fell below those measured with local hall effect strain gauges during labortaory uniaxial compression tests on 38mm diameter samples. For low-medium density chalk, G_{max} measured *in-situ* ranged from ≈300 to 1220MPa and increased with depth and G_{max} measured in the laboratory ranged from ≈1770 to 8100MPa. Apparent increases in G_{max} with IDD were far more marked for the tests conducted on laboratory samples. The difference was attributed to discontinuities, that provide poor contact stiffnesses under in-situ stresses, having a dominant impact on the mass stiffness of the chalk.

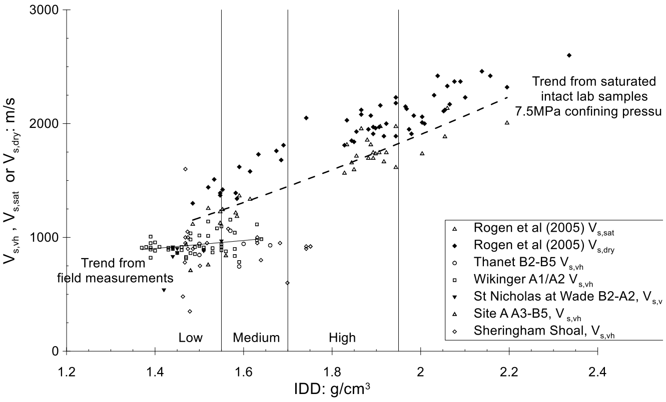


Figure 4. Relationship between laboratory velocity and porosity from [37] and from in situ tests at the IC test site and four offshore sites

Fig. 4 also shows in-situ measurements of shear wave velocity taken at the Imperial College test site and four offshore sites, using a combination of cross-hole seismic, down-hole seismic and P-S suspension logging in boreholes, plotted against IDD at the same depth. [37] chose only samples without fractures or visible inhomogeneities. In all cases, the in-situ results fall below the trend interpreted from laboratory samples, which may be attributable to the presence of fractures in the chalk mass or differences in stress level. Within the field measurements shown on Fig. 5 there is a broad trend of increasing shear velocity with improving chalk grade and decreasing discontinuity spacing. The in-situ stiffness characteristics of the intact chalk mass are likely to be anisotropic due to both depositional features and any systematic system of orientation in the discontinuity sets.

5. In situ tests to inform axial pile design

Recent research into improving the design of axially loaded piles in chalk through field studies with impact driven and highly insturmented jacked model piles is reported by [6-9]. A new effective stress-based approach to predict axial pile capacity has been proposed, which is currently being calibrated and checked through additional testing in the ALPACA Joint Industry Project (see [8] or [39]). The proposed method builds from the key phenomena identified during the field experiments, namely (i) the use of CPT cone resistance to track and allow for local variations in properties (ii) the marked effect of the relative distance, h from the pile tip below any given chalk horizon, normalised by effective pile radius (iii) the interface effective stress shear failure characteristics and (iv) incorporation of dilation-induced changes in radial effective stresses during axial loading.

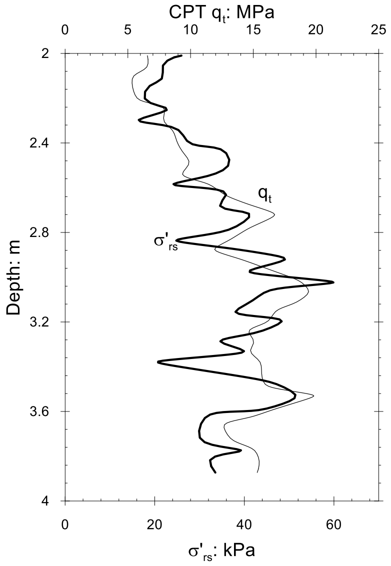


Figure 5. Illustration of variation in CPT cone resistance with radial effective stresses applying on an instrumented model pile

The use of CPT profiling and q_t, measurements is key to allowing for local variations in ground properties. Fig. 5 shows a comparison between CPT cone resistance and stationary radial effective stresses, which control axial shaft resistance, found in the instrumented model pile tests reported by [7]. The stationary radial effective stresses, σ'_{rs} mirror the CPT trace's variations with depth. The σ'_{rs}/q_t ratios observed in these experiments are significantly lower than those seen in silica sands ([40] and [41]) and fall closer to those reported in calcareous sands by [42]. The lower ratios applying in these $CaCO_3$ strata are related to destructuration and crushing beneath the pile tips that lead to severe reductions in radial effective stresses immediately behind the pile tip.

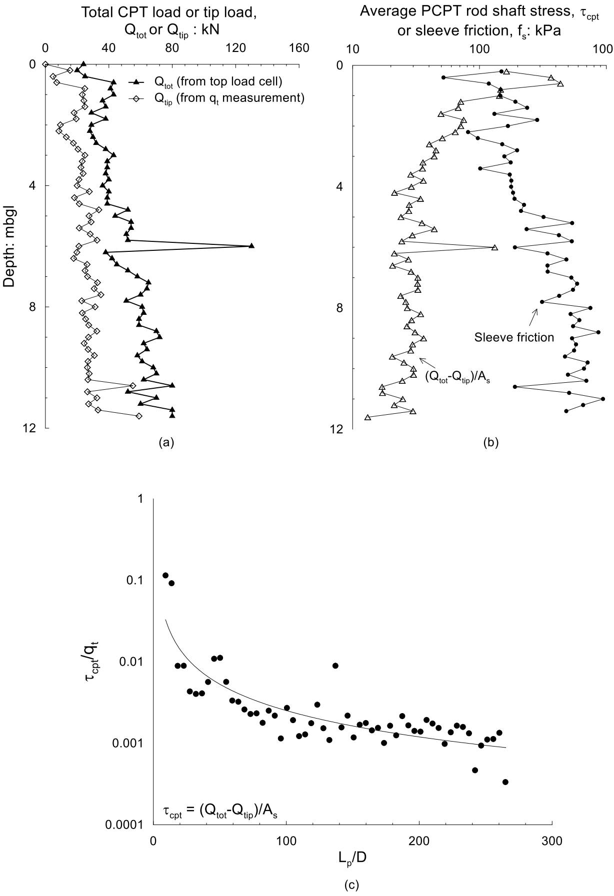


Figure 6. Measurement of PCPT load during installation (a) total load measured in the CPT truck compared with load on the tip (b) average shaft stress during penetration on CPT rods, τ_{cpt} compared with sleeve friction measurements, f_s (c) τ_{cpt}/q_t versus length of penetration/D

The second phenomenon on which the proposed new design rules are based is the marked effect of the relative distance from the pile tip below any given chalk horizon on the local shaft stresses, the h/R* (or h/R for closed ended piles) or 'friction fatigue' effect. Buckley *et al.* [17] [9] showed, using back analysis of pile driving records at several sites, that the effect of penetration on local stresses is far more marked in chalk than in most sands or clays. The same effect can be demonstrated in CPT testing by measuring the load applied (in the truck) i.e. the total axial force required to advance the cone and the rods, Q_{tot} and comparing it to the load measured by the cone tip, Q_{tip}; an example is shown on Fig. 6 (a). This allows the overall average shaft stress along the advancing cone and connecting steel rods, τ_{cpt} to be determined:

$$\tau_{cpt}=(Q_{tot} - Q_{tip})/A_s \qquad (7)$$

where A_s is the area of the shaft. Fig. 5 (b) compares τ_{cpt} with the sleeve friction, f_s measured approximately 120mm from the cone tip. The marked reduction of τ_{cpt}/f_s with increasing relative penetration (L_p/D) is clear. While sleeve friction generally falls between 100 and 400kPa, the average shaft stresses developed along the rods fall to very small fractions of these near tip shear resistances. The influence of length effects on reducing the ratio of τ_{cpt} normalised by q_t is explored further on Fig. 5 (c), which illustrates that τ_{cpt}/q_t follows an approximate power law relationship with L_p/D, where L_p is the penetration of the CPT. Fig. 5 (c) mirrors the effect of length or continued penetration on the local shaft stresses that apply on piles.

The new design approach also considers the chalk's interface effective stress shear failure characteristics which are determined through ring shear tests on samples from the site to determining δ'_{ult} using the procedures outlined by Jardine et al. [43]. Finally, dilation induced changes in radial effective stresses during loading are considered (see equation 4 and 6) utilising the in-situ small strain shear modulus, G, which may be more representative than that measured in the laboratory.

6. The ALPACA JIP

The 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 seven offshore windfarm developers (Iberdrola, Innogy, LEMS, Ørsted, Parkwind, Siemens and Equinor) and four consulting organisations (Atkins, Cathie Associates, Fugro and the geotechnical consulting group). The project is led by an Academic Work Group from Imperial College London (Jardine and Kontoe) and Oxford University (Byrne, McAdam and Buckley). 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 at the St Nicholas-at-Wade site on a range of pile scales. The tests are being combined with additional in situ tests, advanced laboratory testing and comprehensive test analysis.

7. Conclusions

An overview of cone penetration and elastic wave velocity measurements in chalk has been presented, using examples from recent field testing studies to improve the design of axially loaded piles in chalk.

- Typical cone penetration test profiles have been presented which show that while q_t and F_r in chalk lie within the typical ranges for sands and clays, pore pressures are remarkably high and dissipate quickly, leading to cone penetration at standard velocities being under partially drained conditions;
- While both q_t and F_r tend to increase with improving chalk grade, a consistent method to classify chalk grade using CPT parameters has not been developed to date. It may not be possible to identify the microfabric associated with chalk grades using cone parameters alone;
- The CPT cone resistance was shown to increase with reducing penetration rate associated with increasing degrees of consolidation around the cone tip;
- Shear wave velocities measured in-situ fall below the published trend interpreted from laboratory samples. This may be attributable to differences in stress level or to the presence of fractures in the chalk mass;
- The shapes of the cone resistance profiles developed in structured chalk likely reflect local variations in the key factors that affect mass shear strength and density including; intact dry density, degree of cementation, fracture frequency, fracture infill and fissuring;

- The link between cone resistance in chalk and local variations in key factors has been exploited in recently developed axial pile design methods for chalk [43].
- The ALPACA project aims to develop understanding of dtiven piles in chalk and further develop and calibrate the preliminary new proposed axial design methods for chalk.

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References

[1] Bell F. G., Culshaw, M. G. & Cripps, J. C. (1999). A review of selected engineering geological characteristics of English Chalk. *Engineering Geology,* **54**, No. 3: 237-269

[2] Clayton C. R. l., Matthews, M. C. & Heymann, G. (2002). The Chalk. *Proc. 1st Intl. Workshop on Characterisation and Engineering Properties of Natural Soils,* Singapore: 1403-1434

[3] Razoaki R. N. (2000). *Effect of ageing on mechanics of chalk slurries.* PhD Thesis, University of Portsmouth, Portsmouth, UK

[4] Mortimore R. N., Wood, C. J. & Gallois, R. W. (2001). The Upper Cretaceous rocks of the British Isles. *British upper Cretaceous stratigraphy, Geological Conservation Review Series, No. 23*. Joint Nature Conservation Committee: 1-26

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

[6] Buckley R. M., Jardine, R. J., Kontoe, S., Parker, D. & Schroeder, F. C. (2018). Ageing and cyclic behaviour of axially loaded piles driven in chalk. *Géotechnique,* **68**, No. 2: 146-161

[7] Buckley R. M., Jardine, R. J., Kontoe, S. & Lehane, B. M. (2018). Effective stress regime around a jacked steel pile during installation ageing and load testing in chalk. *Can. Geotech. J. ,* **55**, No. 11: 1577-1591

[8] Jardine R. J., Buckley, R. M., Byrne, B., Kontoe, S., Macadam, R. & Vinck, K. (2019). The ALPACA research project to improve driven pile design in Chalk. *Proc. 17th European Conference on Soil Mechanics and Geotechnical Engineering*, Reykjavik, Iceland: 1-8

[9] Buckley R. M., Jardine, R. J., Kontoe, S., Barbosa, P. & Schroeder, F. C. (2020). Full-scale observations of dynamic and static axial responses of offshore piles driven in chalk and tills, *Géotechnique,* online ahead of print. https://doi.org/10.1680/jgeot.19.TI.001.

[10] Lord J. A., Twine, D. & Yeow, H. (1994). *Foundations in chalk Report,* CIRIA, PR11

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

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

[13] Ward W. H., Burland, J. B. & Gallois, R. W. (1968). Geotechnical assessment of a site at Mundford, Norfolk, for a large proton accelerator. *Géotechnique,* **18**, No. 4: 399-431

[14] Spink T. W. (2002). The CIRIA Chalk description and classification scheme. *Q. J. Eng. Geol. Hydrogeol.,* **35**, No. 4: 363-369

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

[16] Buckley R. M., Kontoe, S., Jardine, R. J., Schroeder, F. C. & Barbosa, P. (2020). Pile driveability in low to medium density chalk. *Under review.*

[17] Smith A. K. C. (2001). Interpretation of cone penetration tests in chalk. *Ground Engineering,* **34**, No. 9: 30-35

[18] Teh C. I. & Houlsby, G. T. (1991). An analytical study of the cone penetration test in clay. *Géotechnique,* **41**, No. 1: 17-34

[19] Diambra A., Ciavaglia, F., Dimelow, C., Carey, J. & Nash, D. F. T. (2014). Performance of cyclic cone penetration tests in chalk. *Géotechnique Letters,* **4**, No. July–September: 230-237

[20] Power P. T., Gillespie, A. C. & Thomas, S. (1990). Geotechnical investigation in the chalk at the Amethyst gas field, North Sea. *Proc. Intl. Chalk Symposium*, Brighton, UK: 403-412

[21] Skempton A. (1986). Standard penetration test procedures and the effects in sands of overburden pressure, relative density, particle size, ageing and overconsolidation. *Géotechnique,* **36**, No. 3: 425-447

[22] Wakeling T. (1970). A comparison of the results of standard site investigations methods against the results of a detailed geotechnical investigationin middle chalk at Mundford, Norfolk *Proc. Conf. In situ Investigations in Soils and Rocks*, London, UK: 17-22

[23] Burland J. B. (1990). Preface. *Proc. Intl. Chalk Symposium*, Brighton, UK: 1-4

[24] Bracegirdle A., Mair, R. J. & Daynes, R. J. (1990). Construction problems associated with an excavation in chalk at Costessey, Norfolk. *Proc. Intl. Chalk Symposium*, Brighton, UK: 385-391

[25] Searle I. W. (1979). The interpretation of Begemann friction jacket cone results to give soil types and design parameters. *Proc. 7th Eur. Conf. Soil Mech. Found. Eng.,* Brighton, UK: 265-270

[26] Lunne T., Robertson, P. K. & Powell, J. J. M. (1997). *Cone penetration testing in Geotechnical Practice,* E & FN Spon.

[27] Powell J. & Quarterman, R. (1994). *A reappraisal of CPT testing in chalk,* Building Research Establishment, G/GP/9412

[28] Geear J. (2015). *Developing the CPT 'soil behaviour type' descriptor for chalk with respect to current CIRIA guidance.* MSc MSc Thesis, Imperial College London,

[29] Finnie I. M. S. & Randolph, M. F. (1994). Punch-through and liquefaction induced failure of shallow foundations on calcareous sediments. *Proc. Int. Conf. Behavior of Offshore Structures*, Boston, Massachusetts: 217-230

[30] Randolph M. F. (2004). Characterisation of soft sediments for offshore applications. *Proc. 2nd Intl. Conf. on Site Characterisation*, Porto, Portugal: 209-232

[31] Cassidy M. J. (2012). Experimental observations of the penetration of spudcan footings in silt. *Géotechnique,* **62**, No. 8: 727-732

[32] Suzuki Y. (2014). *Investigation and interpretation of cone penetration rate effects.* PhD Thesis, The University of Western Australia, Crawley, Australia

[33] Fahey M. & Lee Goh, A. (1995). A comparison of pressuremeter and piezocone methods of determining the coefficient of consolidation. *Proc. 4th Intl. Symp. on the Pressuremeter and Its New Avenues*, Quebec, Canada: 153-60

[34] Urmos J. & Wilkens, R. H. (1993). In situ velocities in pelagic carbonates: New insights from ocean drilling program leg 130, Ontong Java Plateau. *Journal of Geophysical Research: Solid Earth,* **98**, No. B5: 7903-7920

[35] Pedersen S. H. & Rhett, D. W. (1998). A Parametric Study of Compressional and Shear Wave Velocities in Ekofisk Reservoir Chalk. *Proc. SPE/ISRM Rock Mechanics in Petroleum Engineering: EUROCK '98*, Trondheim, Norway: 1-8

[36] Gommesen L. & Fabricius, I. L. (2001). Dynamic and static elastic moduli of North Sea and deep sea chalk. *Phys. Chem. Earth (A),* **26**, No. 1-2: 63-68

[37] Røgen B., Fabricius, I. L., Japsen, P., Høier, C., Mavko, G. & Pedersen, J. M. (2005). Ultrasonic velocities of North Sea chalk samples: influence of porosity, fluid content and texture. *Geophysical Prospecting,* **53**, No. 4: 481-496

[38] Clayton C. R. I., Gordon, M. A. & Matthews, M. C. (1994). Measurements of stiffness of soils and weak rocks using small strain laboratory tests and field geophysics. *Proc. Intl. Symp. on Pre-Failure Deformation Characteristics of Geomaterials*, Sapporo, Japan: 229-234

[39] Buckley R. M., McAdam, R. A., Byrne, B. W., Doherty, J. P., Jardine, R. J., Kontoe, S. & Randolph, M. F. (2020). Optimisation of impact pile driving using optical fibre Bragg grating measurements, *Under review.*

[40] Lehane B. M., Jardine, R. J., Bond, A. J. & Frank, R. (1993). Mechanisms of shaft friction in sand from instrumented pile tests. *J. Geotech. Eng - ASCE,* **119**, No. 1: 19-35

[41] Chow F. C. (1997). *Investigations into Displacement Pile Behaviour for Offshore Foundations.* PhD Thesis, Imperial College London, London, UK

[42] Lehane B. M., Schneider, J. A., Lim, J. K. & Mortara, G. (2012). Shaft friction from instrumented displacement piles in an uncemented calcareous sand. *J. Geotech. Geoenviron. Eng. - ASCE,* **138**, No. 11: 1357-1368

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