Imperial College London

ALPACA: investigating the axial and lateral, cyclic and static behaviour of piles driven in chalk

Journée Technique CFMS du 6 décembre 2018
« Fondations d'éoliennes offshore »

IFSTTAR, Marne la Vallée

Richard Jardine

Five main topics

I – Background and drivers for research

II – Chalk, Wikinger Baltic Offshore Windfarm & Innovate JIP

III – Field tests at Nicholas at Wade, Kent

IV – Preliminary Chalk ICP-18 design method

V - ALPACA JIP research project

Background and drivers

Renewable offshore windenergy growing in N Europe & worldwide

In 2016 Germany had 29% of worldwide offshore wind capacity, UK had 36%

UK greenhouse gas emissions now 1/2 peak levels

Offshore gas & wind should allow UK coal power generation to end by 2025

Rapidly growing Asia-Pacific interest

Foundations comprise ≈25% total capital outlay

Dramatic cost reductions being made, aided by university-based research

Geotechnical research questions

Axial response: key for jacket, tripod and tension leg platforms

Improved design for sands and clays from instrumented ICP tests in UK and France

1984 to 2018

Database checks and reliability studies verify applicability

Can we make similar improvements for Chalk?

Existing design methods' CoVs far poorer than for sand or clays

Cyclic response?

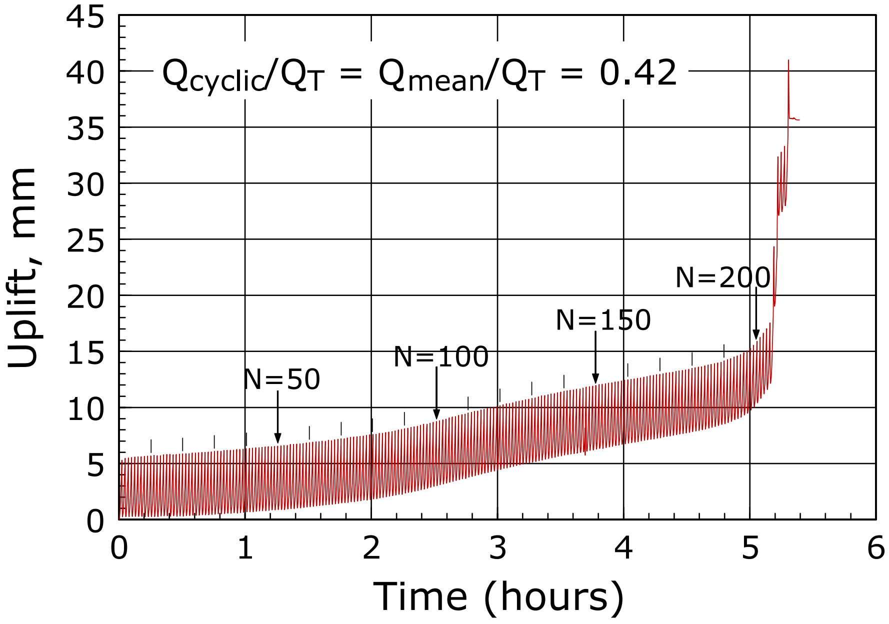
And lateral behaviour? Key for monopile wind-turbines, also ports and bridges

Cyclic loading
Unstable, Stable or Metastable global response?

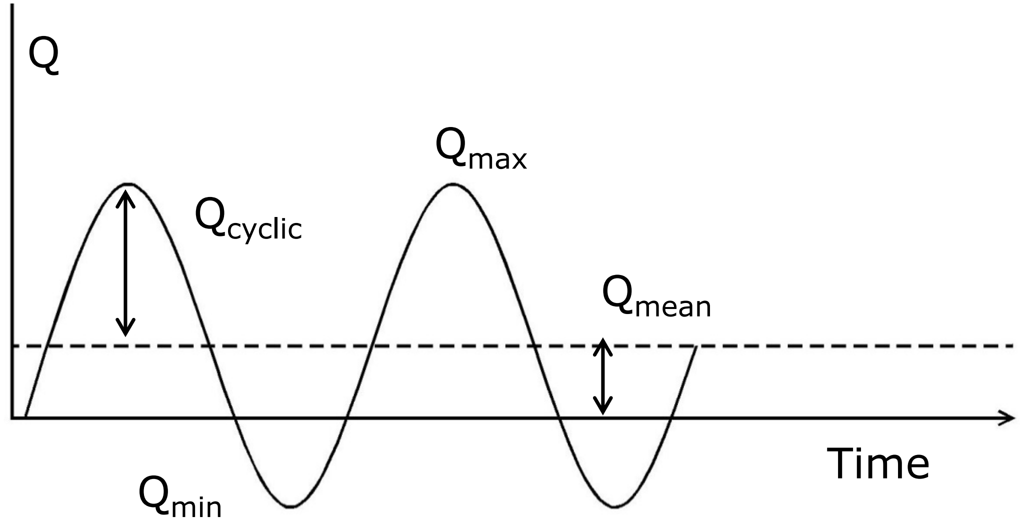
Depends critically on:

N, Q_{cyclic} & Q_{mean}

Related to tension capacity Q_T



Jardine and Standing 2012



14 tests on 19m, 0.5m OD piles - Dunkerque sand

Drained pore pressures

Example of one that failed at N_f = 206

16% capacity loss

But what causes shaft capacity degradation?

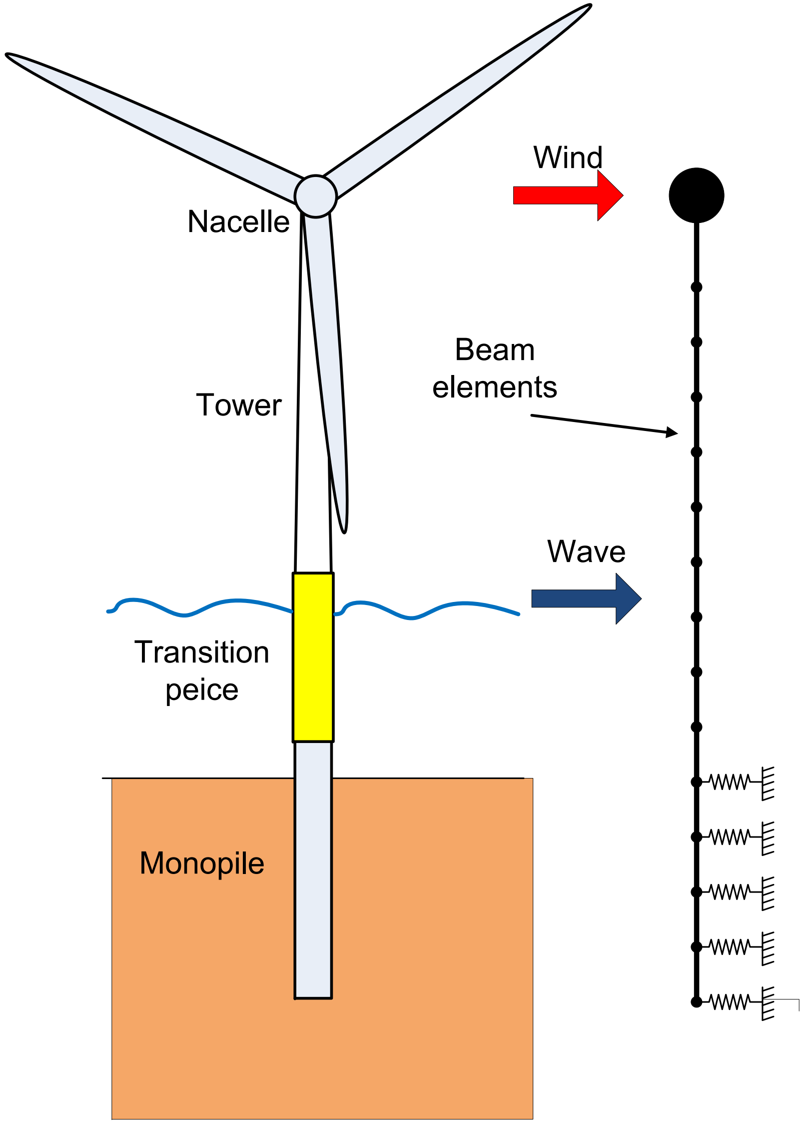
Cyclic shaft mechanisms from mini-ICP tests in Grenoble 3S-R calibration chamber

Local interface stress paths

Stable: 1000s cycles, capacity grows
No drift in σ'_r or displacements

'ICP' design procedures formulated & applied: σ'_r drift rates tracked under storm loads

Tsuha, Foray, Jardine, Yang, Silva, & Rimoy 2012; Jardine 2013



Lateral response: PISA Joint Industry Project

Academic team: Oxford, Imperial, UCD

Industrial group led by Ørsted

Cut costs, enable deeper water use in sands & clays

Analysis, laboratory & large field tests

Replace standard p-y methods

Low L/D: add extra components

Calibrate: FE, stress path tests and 28 instrumented piles tested at Cowden & Dunkirk

Recognise: cyclic response

Byrne, McAdam, Burd, Houlsby, Martin, Zdravković, Taborda, Potts, Jardine, Sideri, Schroeder, Gavin, Doherty, Igoe, Muir Wood, Kallehave & Skov Gretlund 2015

What about Chalk?

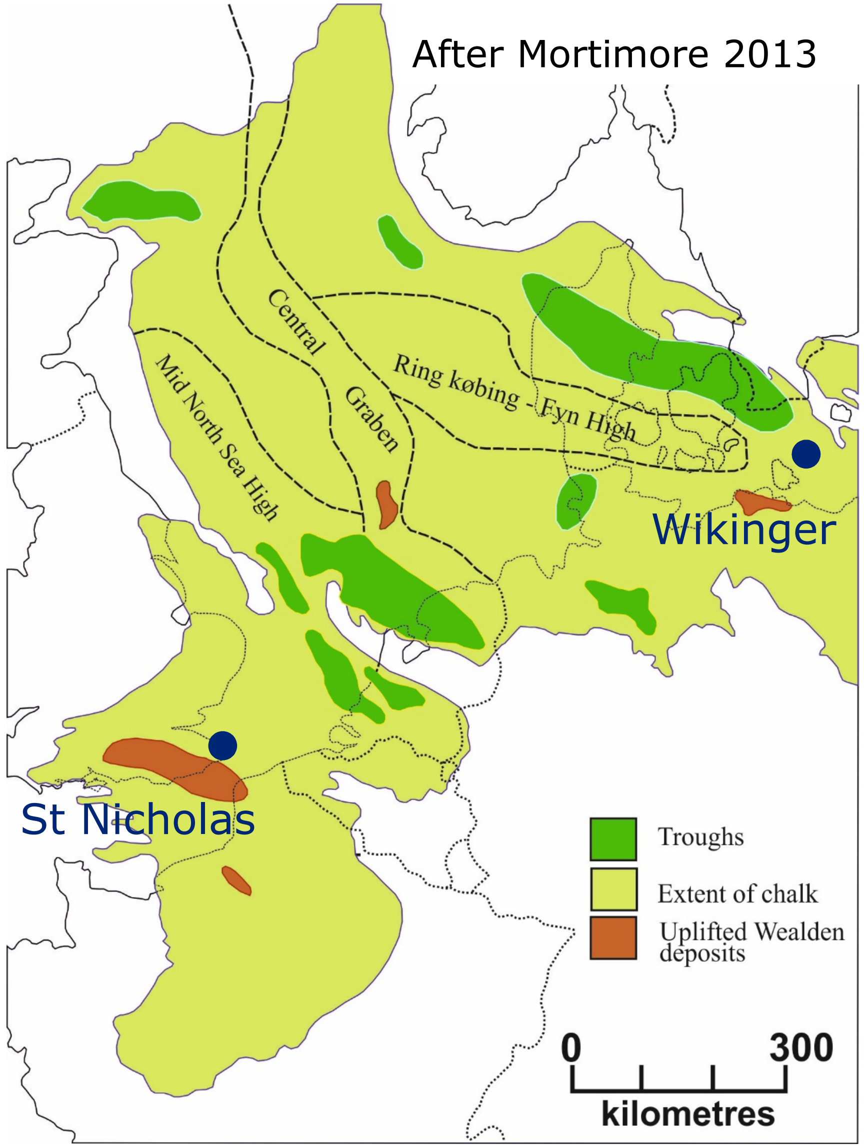
At foundation depth for tens of UK and NW European offshore windfarms

Sensitive to impact & cyclic damage, can give surprises!

Sherringham Shoal Example: Carotenuto et al (2018)

Urgent issue for many projects: such as Wikinger in German Baltic

Innovate UK JIP study focussed on two sites



Guidance available for axial design

CIRIA C574:

Lord et al (2002)

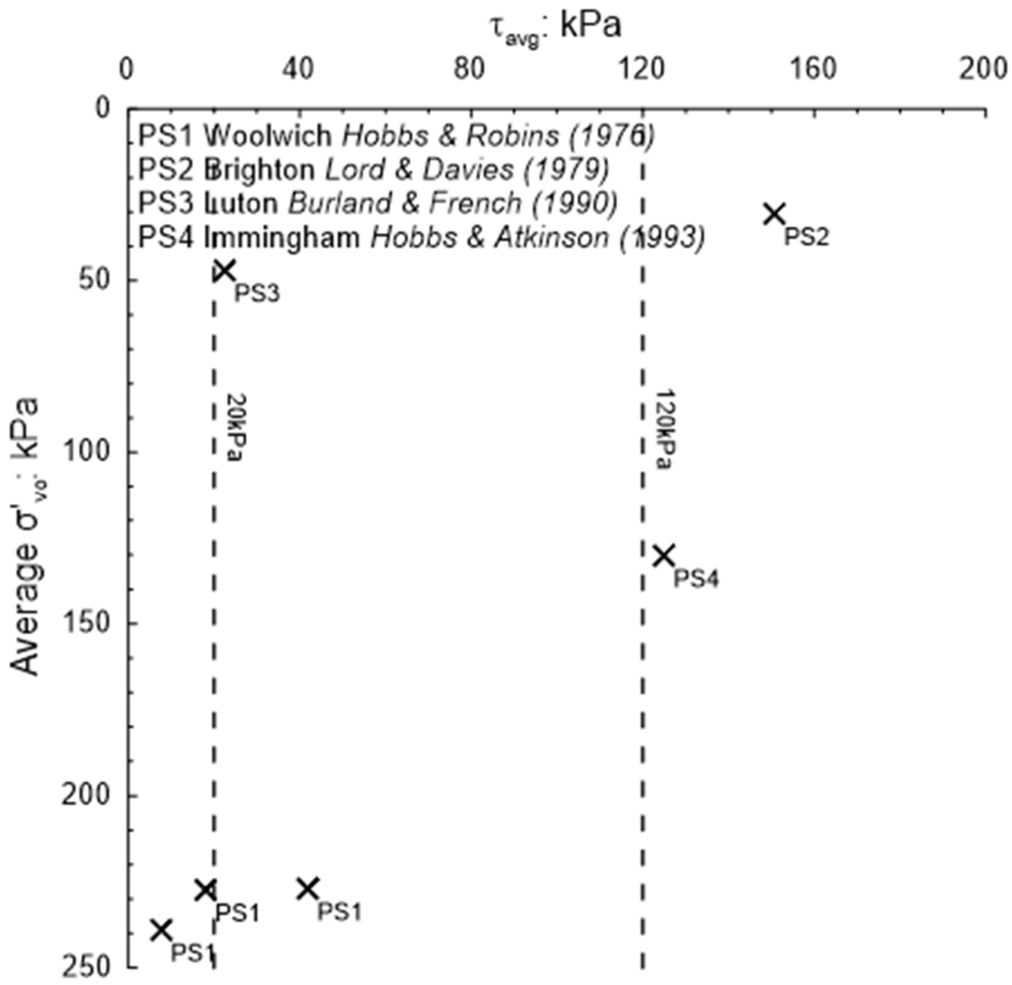
Database of average shaft resistances for open-ended steel piles

Only 4 cases with widely spaced values:

20kPa in low-to-medium &

120kPa in dense chalks

Range of alternative approaches proposed by offshore design consultants, also French design method



Innovate UK Joint Industry Project: 2014-17

Academic Group: Imperial College; Richard Jardine, Stavroula Kontoe, Róisín Buckley

Industrial lead: Scottish Power Renewables (SPR)

SME Partner: Geotechnical Consulting Group LLP

Key aims: better field testing and axial design methods for chalk

Scope: onshore field testing research programme and full engagement in Wikinger field testing and analysis

Outcomes: Barbosa et al (2015) and several other Conference articles

PhD & four Buckley et al (2018/2019) Journal papers; Jardine et al (2018) keynote


German Baltic Wikinger offshore windfarm
Glacial till over low-to-medium density chalk
70 four legged 5MW turbine structures and one OSS
From Wikimedia commons
Nearest exposure: Rugen Island

Wikinger: advance offshore testing campaign

Nine 1.37m OD piles driven 2 years before main construction

	Penetration	% chalk
WK38	16.2m	18
WK43	30.7m	66
WK70	31.0m	78

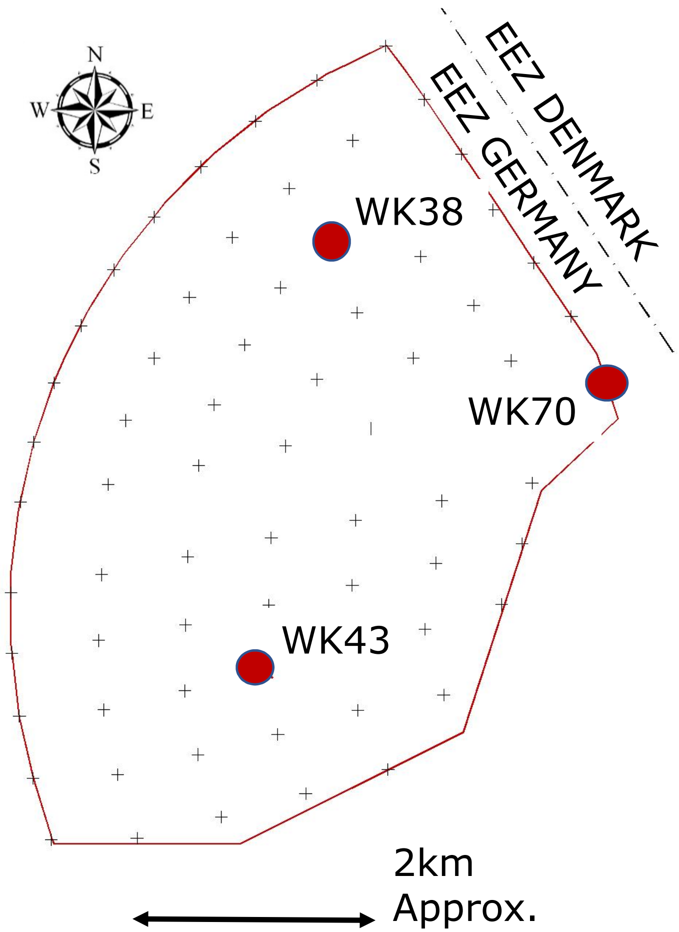
Three piles driven at each location
Dynamic monitoring

↓

11 to 15 weeks set-up

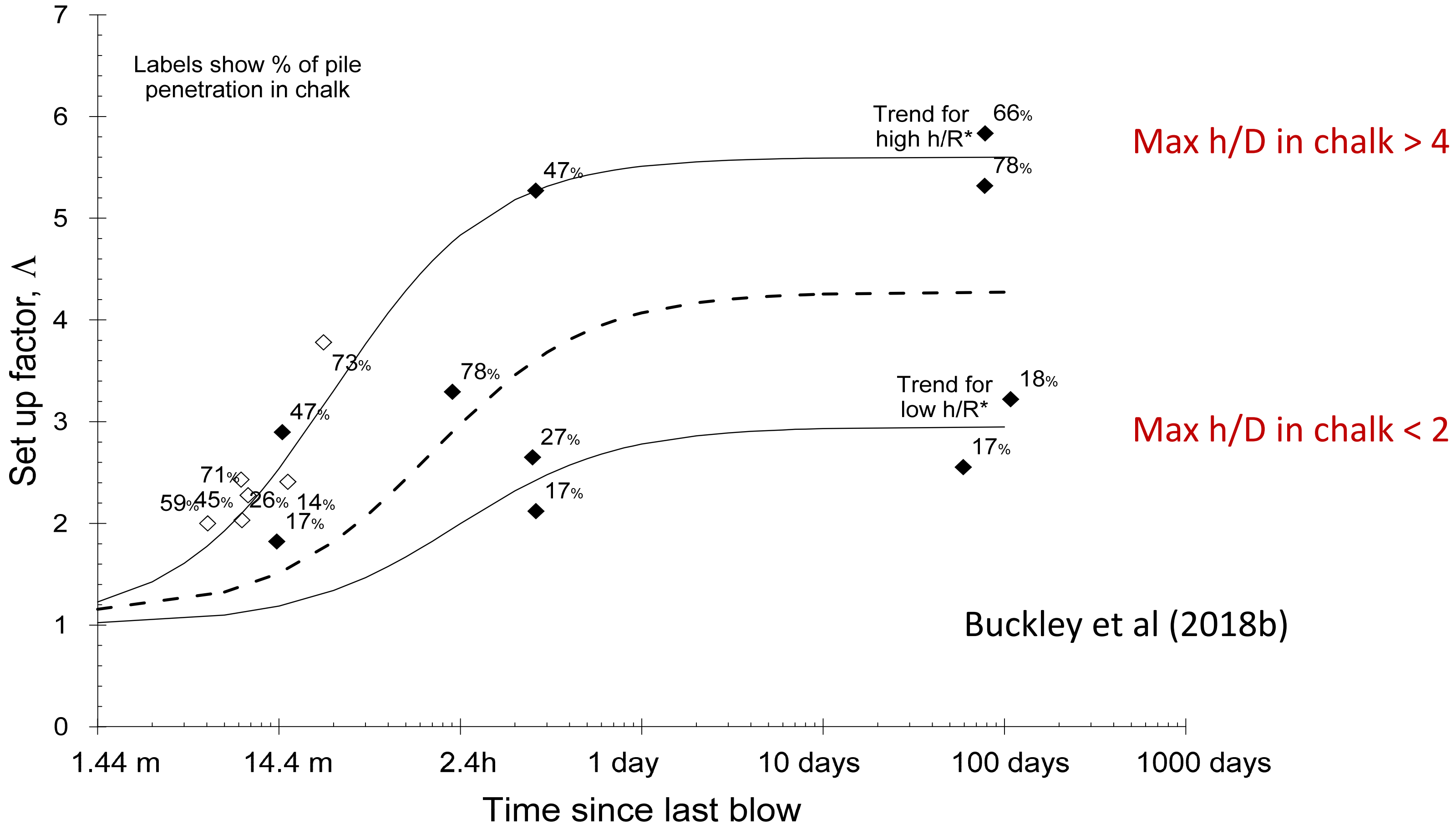
↓

At each location
Static tension to failure
Instrumented restrike
Cyclic test at WK38




Test pile installation
October 2014
Barbosa, Geduhn, Jardine,
Schroeder & Horn 2015

Dynamic re-strike shaft capacity set-up trends in Wikinger chalk

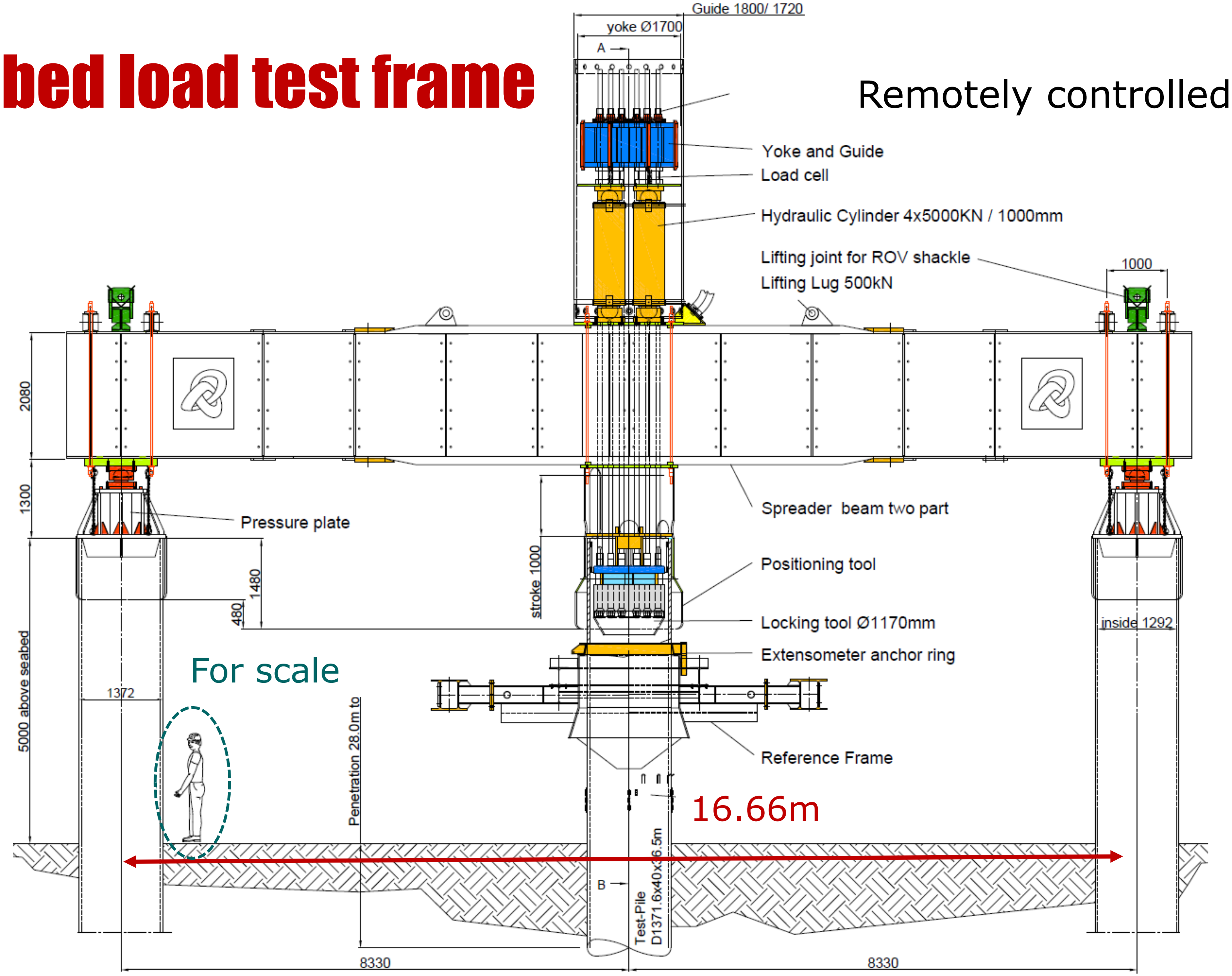


Signal matching analyses: 1.37 to 3.6m OD test & production piles

Interpreted shaft resistances normalised by End of Driving (EoD)

Seabed load test frame

Remotely controlled static tests



40 m water depth

1.37m OD Wikinger static tests: capacities far greater than expected in chalk

	WK38	WK43	WK70
Time after driving (days)	108	78	77
Percentage profile in chalk (%)	18	66	78
Net static tensile failure load (MN)	8.8	20.9	22.4
End of driving shaft load (MN)	5.3	4.8	4.6
Dynamic restrike shaft load (MN) [2]	9.7	18.3	27.7
Global set-up factor, L (static/EOD)	1.65	4.37	4.86

Need for further investigation of ageing & cyclic responses

Innovate UK JIP: Testing scope at St Nichols at Wade, Kent, UK 2015-17

Basic mechanics for displacement piles in chalk

Experiments with highly instrumented ICP piles; closed ended, jacked-in-place

Ageing study: tension tests on driven open-steel tubular piles

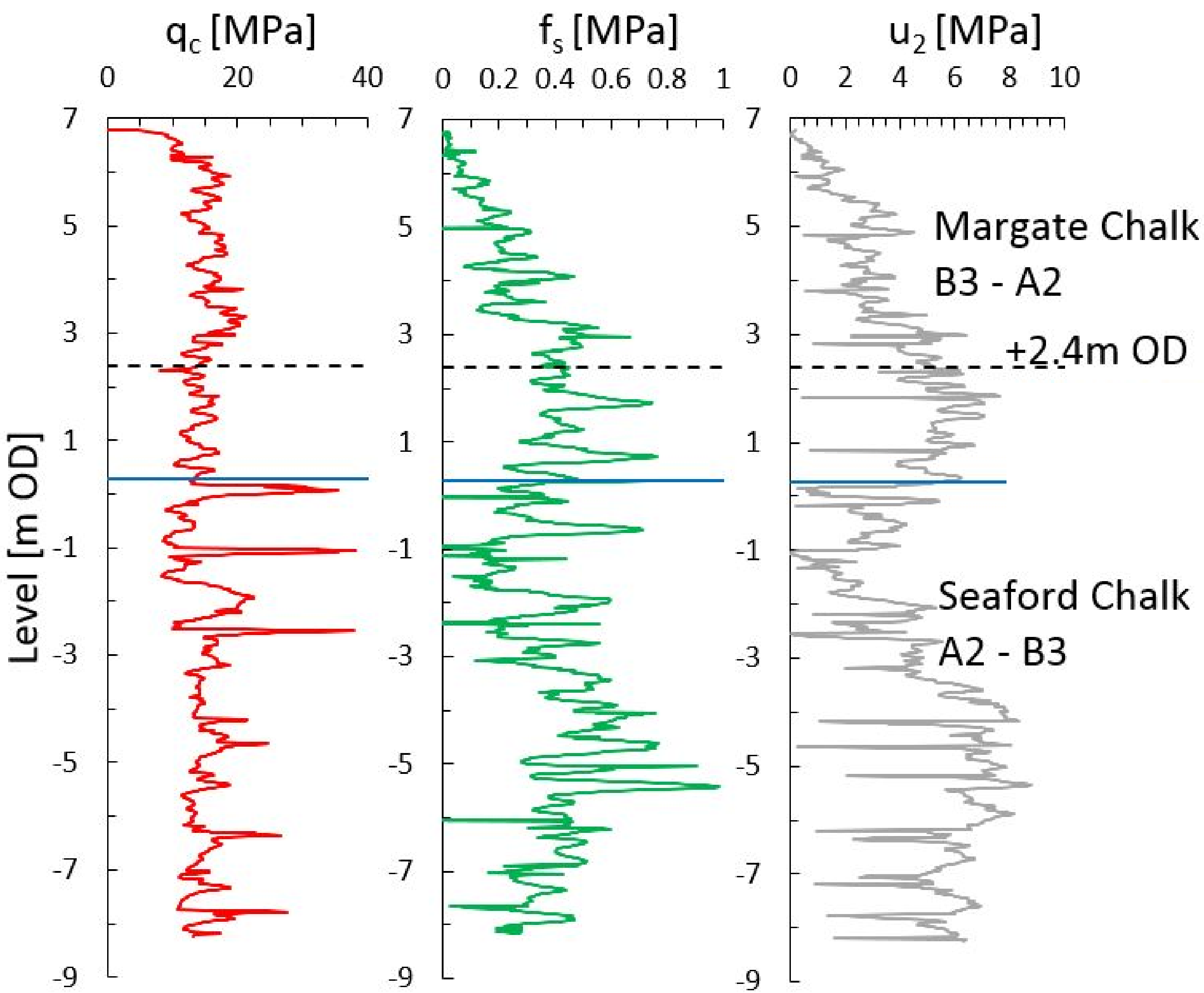
Cyclic study: one-way loading on driven open-steel tubular piles

Many similarities with static & cyclic responses seen in ICP tests in sands

Pile exhumation and sampling

Laboratory testing

St Nicholas at Wade (SNW): Low-medium density chalk strata; deep water table



Also seismic CPT
Geobor-S holes
Pressuremeter tests
Tensiometers, etc

Jacked ICP piles at SNW

ICP configuration, dual SST clusters

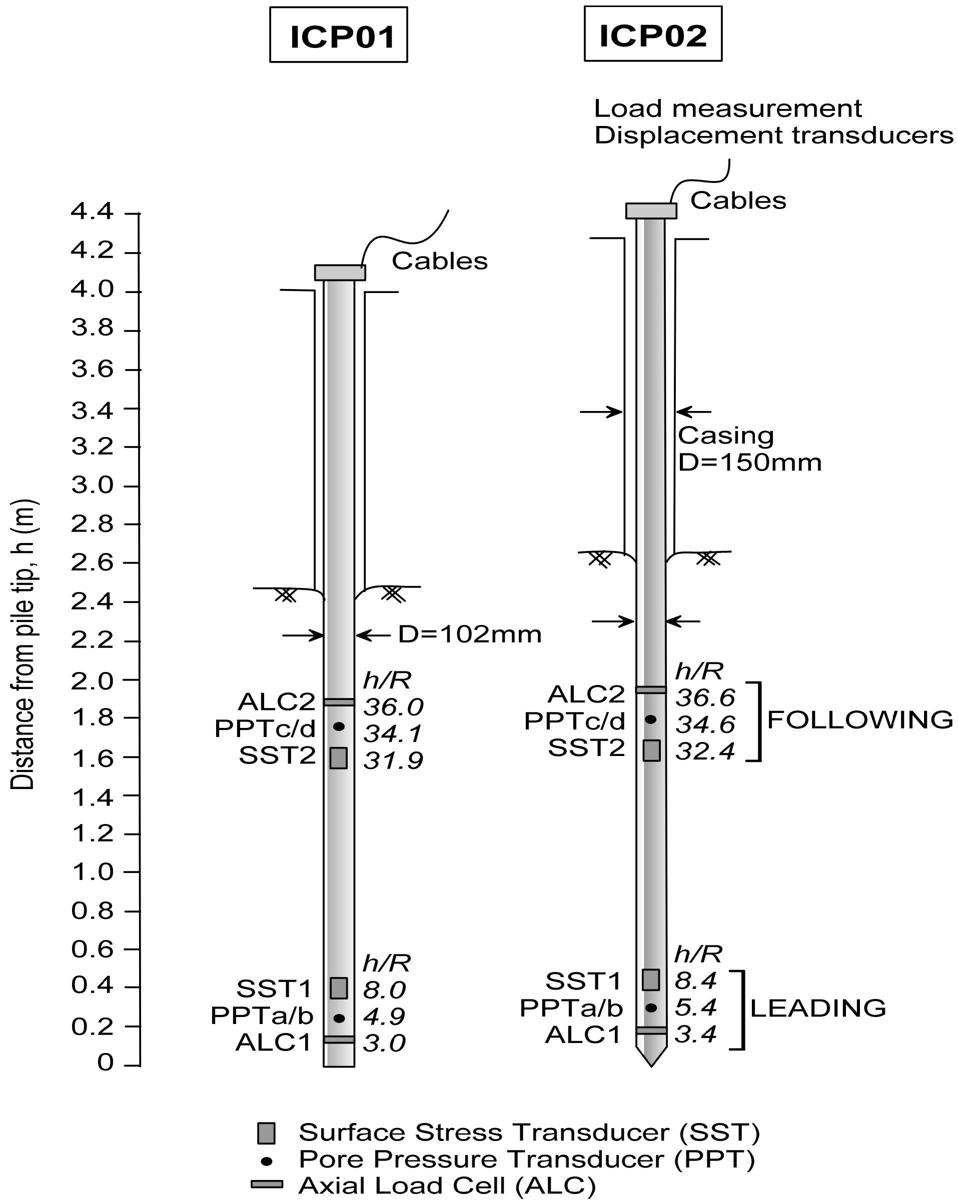
102mm OD, ≈2.5m penetration lengths

Mild steel shafts

Stainless SST clusters that can measure local shear, radial stresses and pore pressures

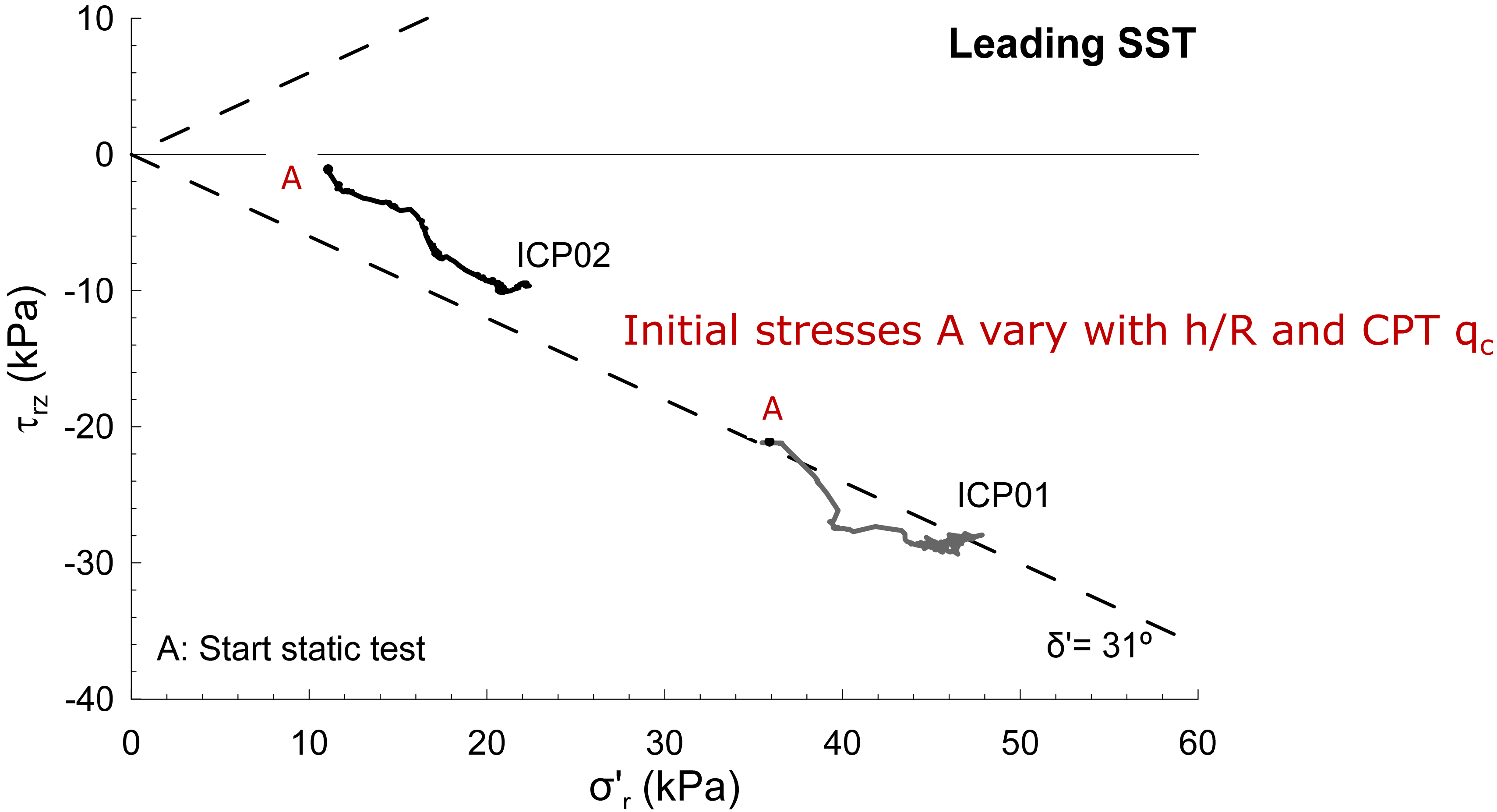
Conducted with Prof Barry Lehane

Buckley et al (2018)c



Local shaft failure criterion on loading in tension:

Effective stress paths show similar dilatant response to sands



Field failure δ angle similar to ring-shear interface lab tests, Buckley et al (2018)c

Driving open tubular piles at SNW

139mm OD, 8.5mm WT mild-steel, driven to 5.5m

End of Driving EoD shaft resistance profiles

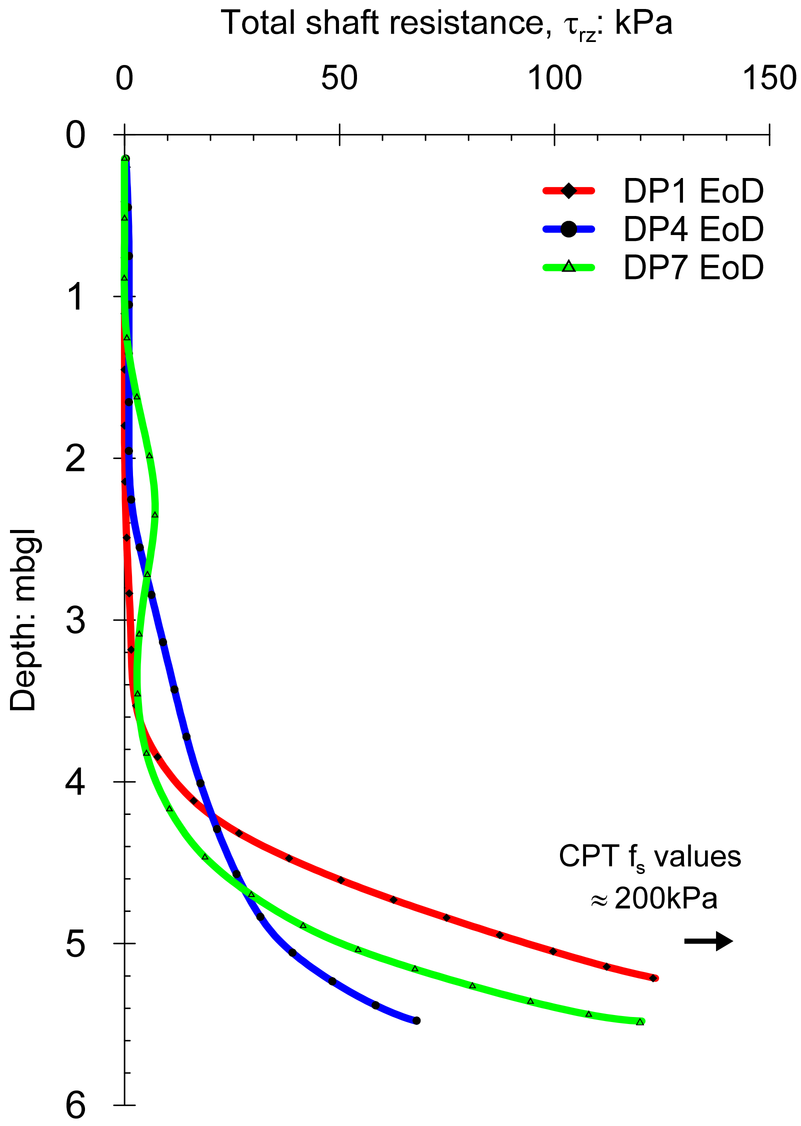
From signal matching of dynamic sensor data

Very low resistances over top 2/3 of shaft

Far greater over lower 1/3, marked relative pile tip (h/R*) effects, even stronger than in sands – also seen at Wikinger

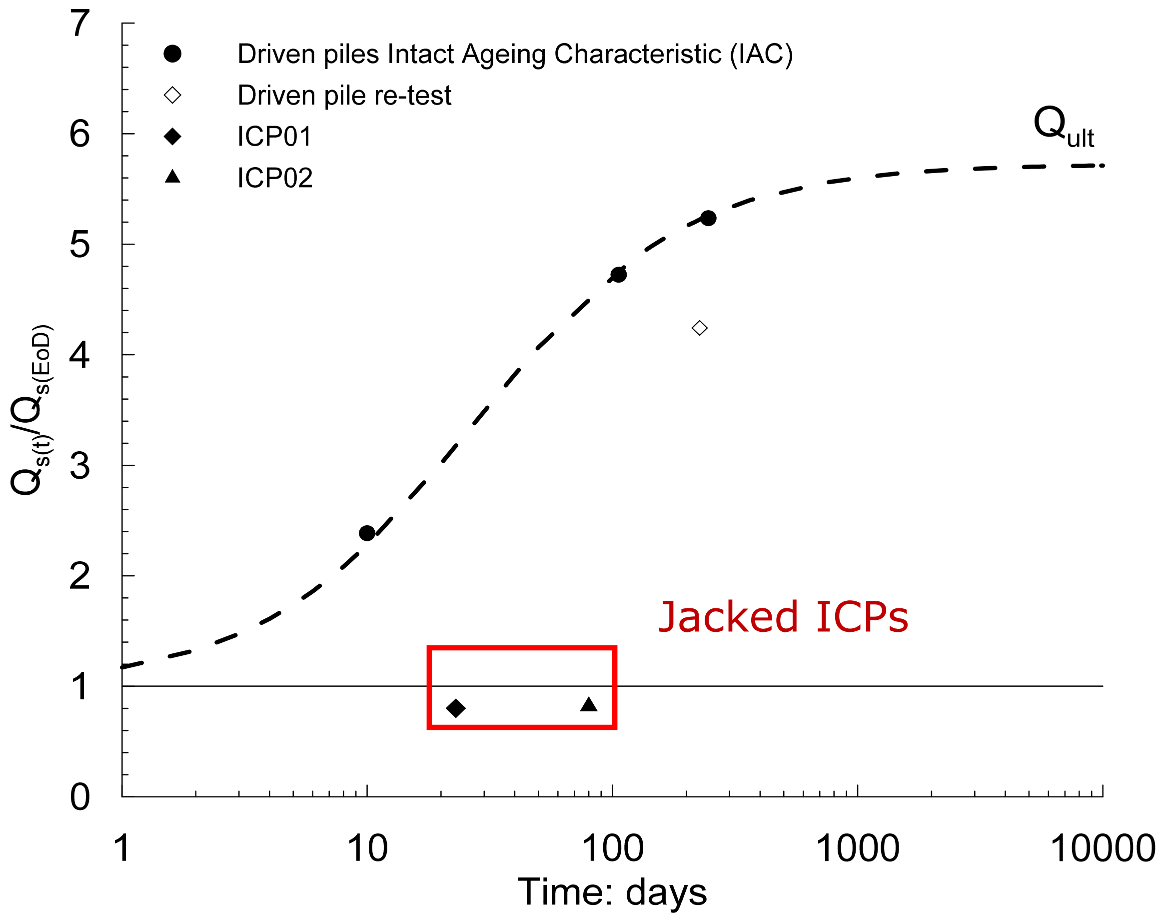
Putty forms around shaft, consolidates over time

Buckley et al (2018)a



Ageing trends at St Nicholas at Wade (SNW)

Driven 139mm OD and jacked ICP piles



Set-up depends on installation process?

And/or pile material?

And/or groundwater chemistry?

Shaft capacities up to 260 days after driving, normalised by EoD; Buckley et al. (2018c)

Key points for low-to-medium density chalk - I

1. Similarly low driving shaft resistances with small onshore and large offshore piles

2. Local resistances reduce markedly with increasing relative tip depth h/R*

3. Driving remoulds the chalk around the shaft creating a putty that consolidates to a lower water content

4. Can lead to long pile 'runs' in the field: see Carotuneto et al (2018)

5. Dynamic laboratory compaction at natural water content gives similar putty: Doughty et al (2018)

6. Putty gains strength in field through consolidation, thixotropy & bonding

Key points for low-to-medium density chalk - II

5. Static capacity after ageing ≈5 times EoD under salty Baltic sea and above the water table onshore in Kent

6. Although no gains for cyclically jacked ICP piles

7. Set-up due to chalk & radial effective stresses changing. Arching system around shaft may playing a role? Or physio-chemical/corrosion processes?

8. Insights gained into basic mechanics through ICP tests, instrumented dynamic monitoring and static testing

9. Basis for preliminary Chalk ICP-18 design method

10. Requires CPT testing, interface-shear tests and in-situ shear stiffness data

Preliminary design method: Chalk ICP-18, SRD

Soil Resistance to Driving SRD in low-to-medium density chalk

Assessed from analysis of driving data from:

Wikinger,

St Nicholas at Wade, and nearby offshore large diameter monopile site

Effective stress, analogous to ICP-05 Chalk

Starts with Coulomb effective stress failure criterion

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

δ'_{ult} measured in lab interface ring-shear tests

Around 31^{o} for St Nicholas at Wade, 32^{o} at Wikinger

Preliminary design method: Chalk ICP-18, SRD

Shaft radial effective stresses on installation σ'_{ri} not related to σ'_{vo} by any constant K factor

Varies with corrected CPT tip resistance, q_t, relative pile tip depth h/R^* and diameter to wall thickness D/t_w ratio

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

Gives highly non-linear variations with depth, most resistance develops over lower shaft; note h/R* limited to minimum of 6

End bearing pressures on pile annulus, $q_b \approx 0.6\ q_t$

Needs checking, we appeal for more high quality data

Preliminary design method: static Chalk ICP-18

Static shaft loading after full equalisation, ageing and set-up

Similar rules for shaft radial effective stress at failure σ'_{rf} to ICP-05 sand: Coulomb failure & dilatant response to loading

$$\tau_{rzf} = \sigma'_{rf} \tan \delta'_{ult}$$

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

Initial σ'_{rc} depends on corrected CPT q_t & relative pile tip depth h/R^*

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

Resistance concentrates over lower shaft, again minimum $h/R^* = 6$

Preliminary design method: static Chalk ICP-18

Change in radial effective stress experienced on loading depends on chalk shear stiffness G, diameter D

And radial dilation Δr required to form shear band:

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

G can be measured by in-situ geophysical tests: P-S logging or seismic CPT, or estimated from CPT q_t

Δr assessed from ICP tests at St Nicholas at Wade as $\approx 0.5\mu m$

End bearing pressures on pile annulus, $q_b \approx 0.6\ q_t$

Needs checking, we appeal for more high quality data

Checking static Chalk ICP-18

Measured & predicted shaft resistance profiles

Instrumented dynamic & strain gauged static tests

Open-ends:

(a) 2.7m OD pile at Wikinger and

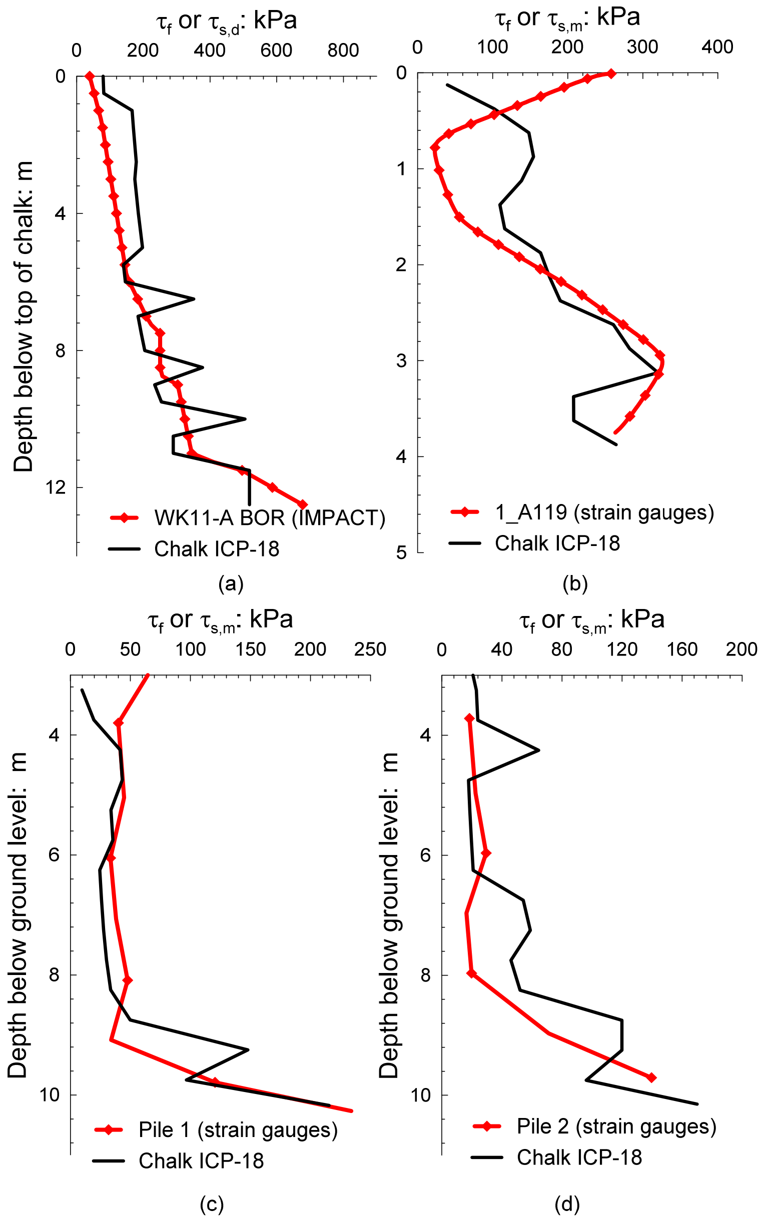
(b) 760mm at SNW, Ciavaglia et al (2017)

Closed-ends: Fleury-sur-Andelle, France

(c) 400mm Concrete square

(d) 442mm OD Steel tubular

Bustamante et al., (1980)



Cyclic behaviour: driven piles at SNW

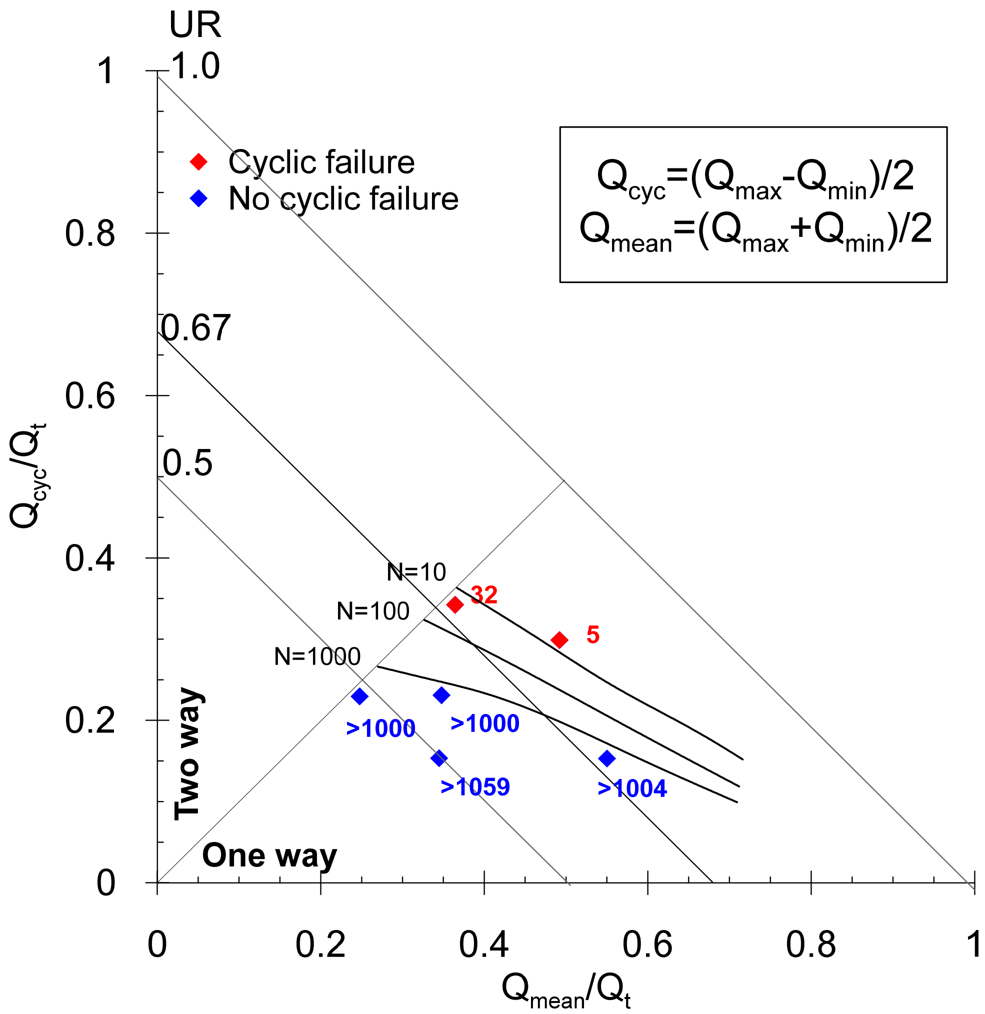
Cyclic stability: six tests on four aged 139mm OD driven piles

One-way tension cycles Utilisation Ratios (UR) 0.5 < UR < 0.8

Contours for cycles to failure N_f significant scope for degradation

Need more tests: larger piles, extension to lower loading levels, and more severe two-way cases?

Buckley et al. (2018a)



New ALPACA Joint Industry Project: 2017-2020

Academic Work Group

Imperial College: Richard Jardine, Stavroula Kontoe, Róisín Buckley

Oxford University: Byron Byrne, Ross MacAdam

Partners: EPSRC, Iberdrola, Innogy, LEMS, Ørsted, Siemens, Statoil

Atkins, Cathie Associates, DNV-GL, Fugro, GCG

Key aims: axial-&-lateral, static-&-cyclic design methods for piles driven in chalk, employing novel instrumentation and testing at SNW

Progress: October 2017 start, field testing on aged 508mm piles now complete; many new findings. Further tests in Q1/Q2 2019

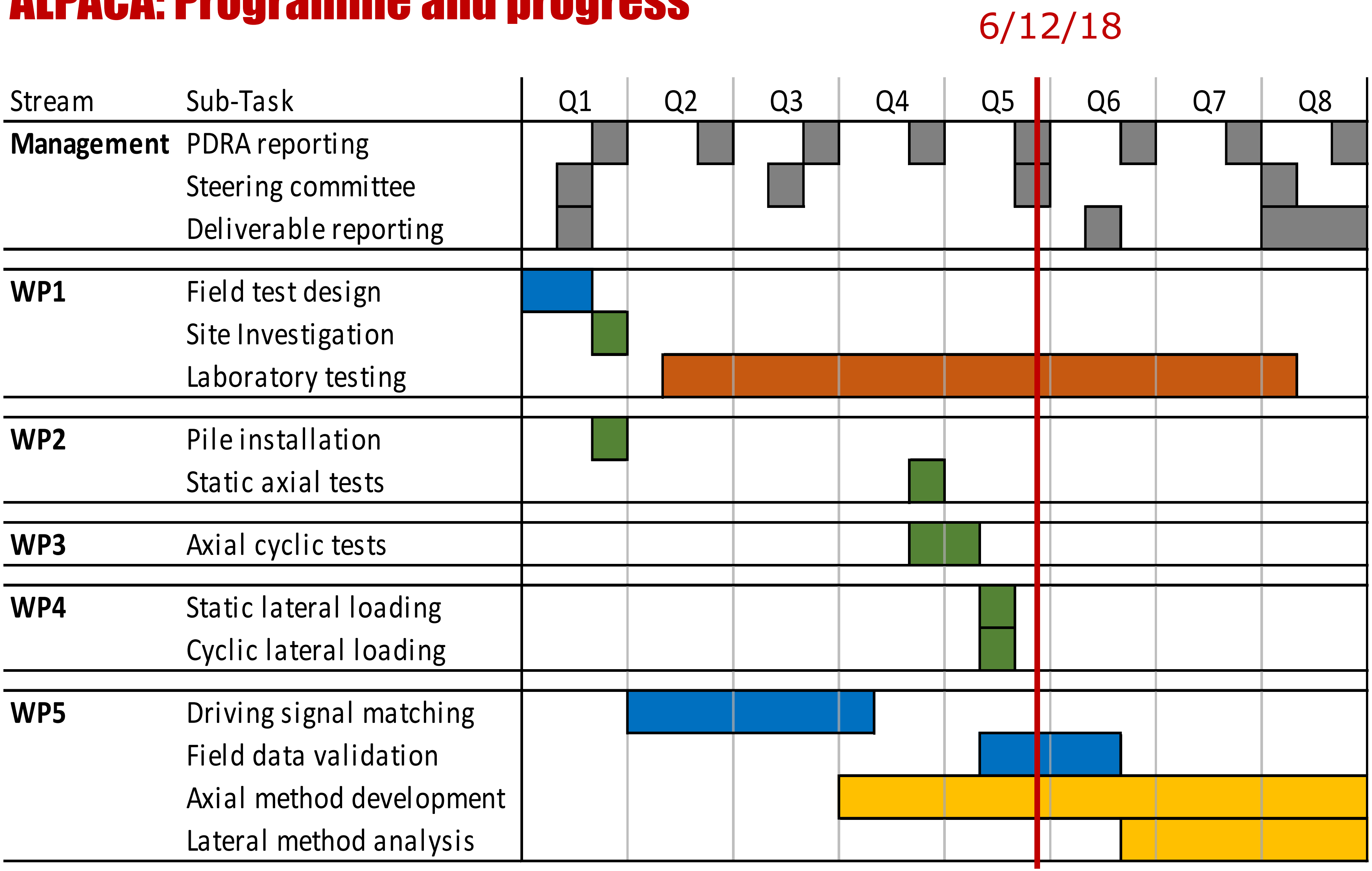
ALPACA JIP at St Nicholas at Wade: 2017-2020

Geobor-S and block sampling, advanced laboratory & in-situ testing

37 piles installed at three scales, integrated with Innovate UK & PISA monopile study

Comprehensive dynamic, static & cyclic axial and lateral testing

ALPACA: Programme and progress

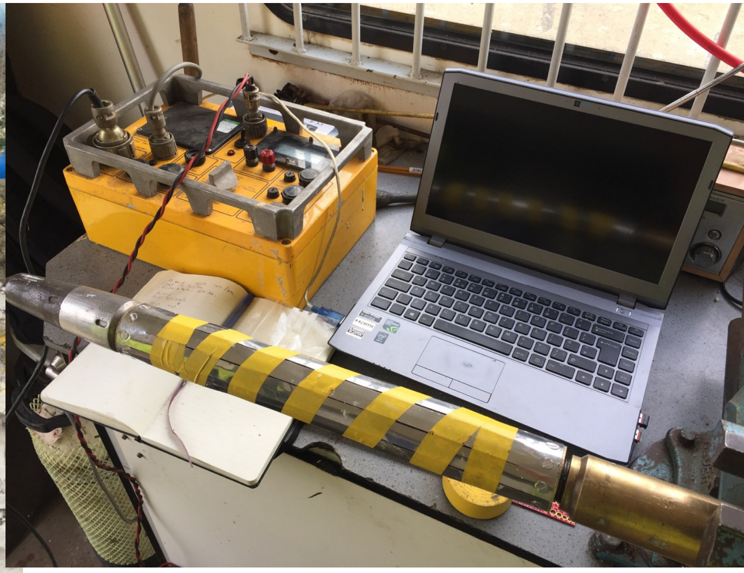


Site characterisation:

Wireline rotary drilling

Block sampling from pits

Pressuremeter, CPTu and SCPT profiling



Plus intensive laboratory stress-path testing

508mm OD instrumented pile testing with Socotec

Example of axial tension & one-way cyclic arrangement

Static and cyclic loading: under load & creep stage control, 10s period cycles

Fibre optic gauges on 16 piles to give shaft shear distribution with depth

Schedule for 508mm piles

Static & cyclic

Two-way axial and bi-axial lateral cycles

Ageing and cyclic responses established

Programme varied as results emerged

Completed by 2/10/2018

Further 139mm piles installed in October 2018
To be tested in March, April 2019

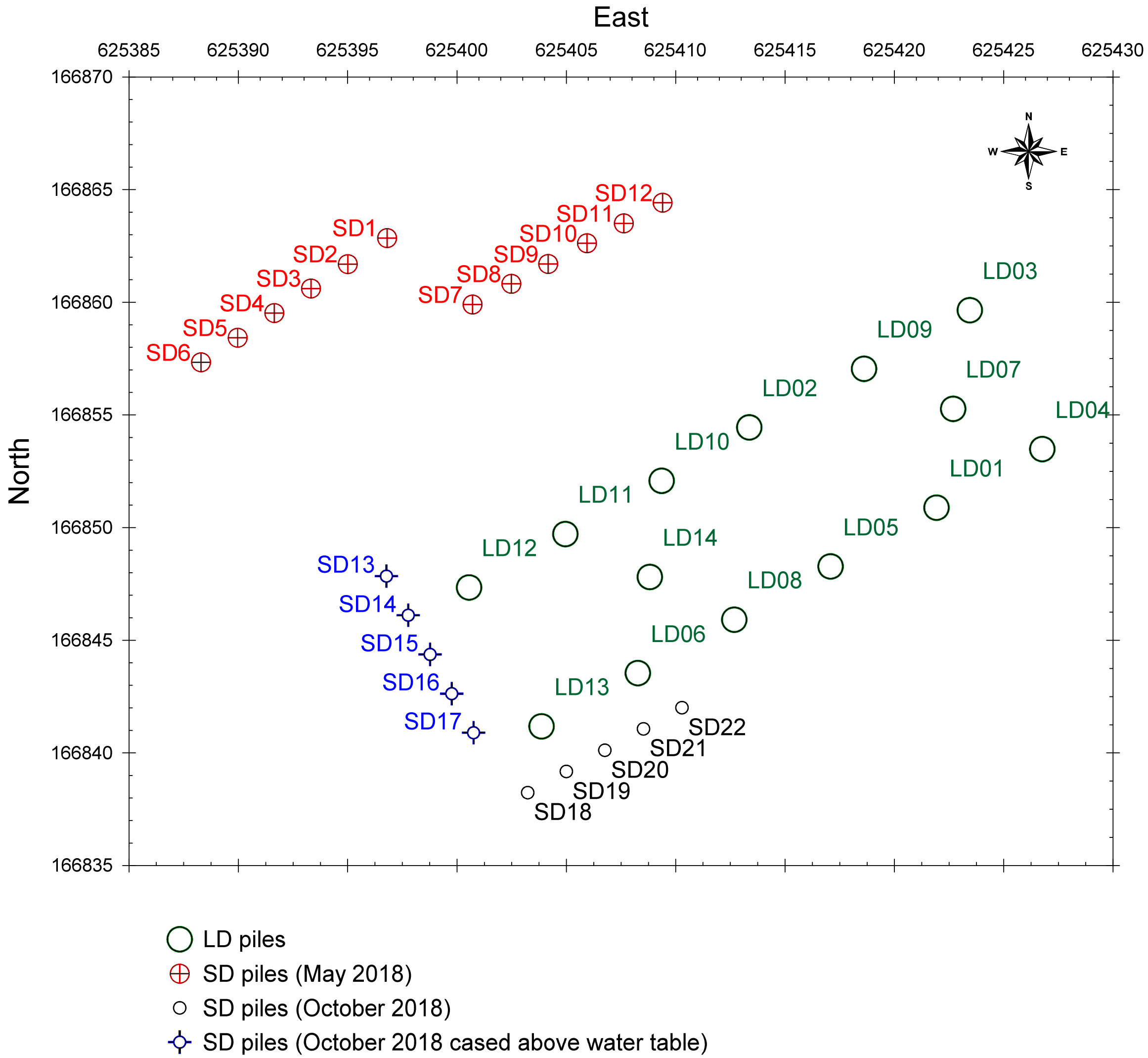
Table 1 – Preliminary schedule of pile test programme

Axial (tests 1–14)

Lateral (tests 15–28)

Test number	Pile Location	Loading type	Load against
1	LD6	AST	Ground mats
2	LD6	AST	Ground mats
3	LD5	AST	Ground mats
4	LD12	AST	Ground mats
5	LD11	A1W	Ground mats
6	LD2	A1W	Ground mats
7	LD10	A2W	LD2 & LD11
8	LD8	A2W	LD5 & LD6
9	LD14	ASC	LD6, LD8, LD10 & LD11
10	LD3	A1W	Ground mats
11	LD4	A1W	Ground mats
12	LD1	A2W	LD4 & LD5
13	LD9	A2W	LD2 & LD3
14	LD7	ASC	LD1, LD3, LD4 & LD9
15	LD6 & LD11	LS	LD6 vs. LD11
16	LD12 & LD13	LS	LD12 vs. LD13
17	LD3 & LD4	L1W	LD3 vs. LD4
18	LD4	AST	Ground mats
19	LD3 & LD4	LS	LD3 vs. LD4
20	LD2 & LD5	L1W	LD2 vs. LD5
21	LD5	AST	Ground mats
22	LD2 & LD5	LS	LD2 vs. LD5
23	LD8 & LD10	L1W	LD8 vs. LD10
24	LD8	AST	Ground mats
25	LD8 & LD10	LS	LD8 vs. LD10
26	LD14	BLC	LD2 & LD5, LD6 & LD8
27	LD14	AST*	Ground Mats
28	LD14	LS*	LD2 & LD5

Plan for 508mm OD, 10m long LD01 to 14 piles and smaller SD1-22 piles



All LD piles tested in 2018

For 2019:

Cyclic and ageing tests on piles SD01 to 12

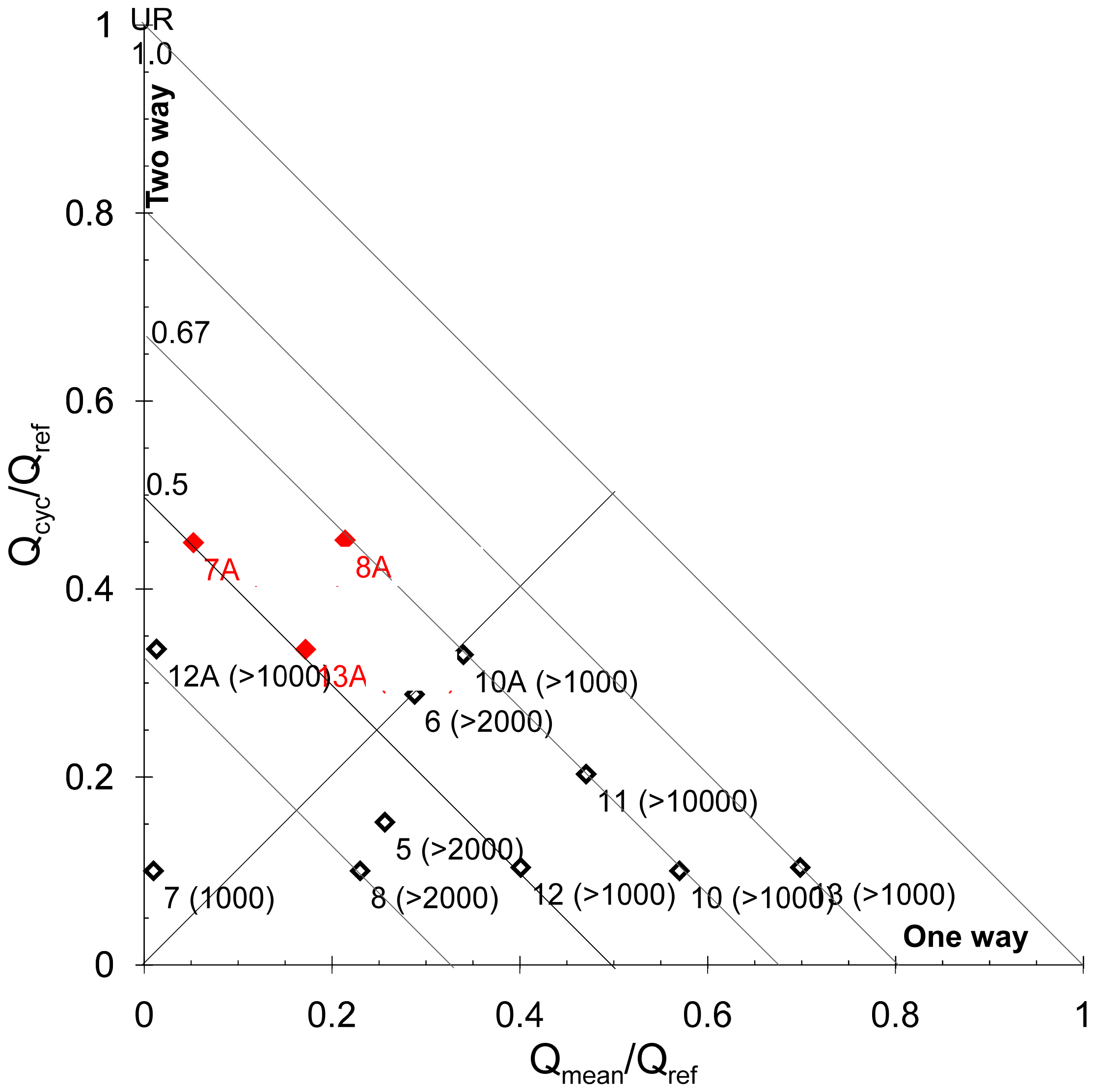
And for piles SD13 to 22

- Cased and uncased
- 4 steel grades
- Also reinforced concrete

Capacities measured at:

- End of driving
- c. 170 days later

Axial cyclic loading tests on 508mm OD steel piles



13 Axial cyclic tests

Eight 1-way cyclic

Five 2-way cyclic

10s period sine waves

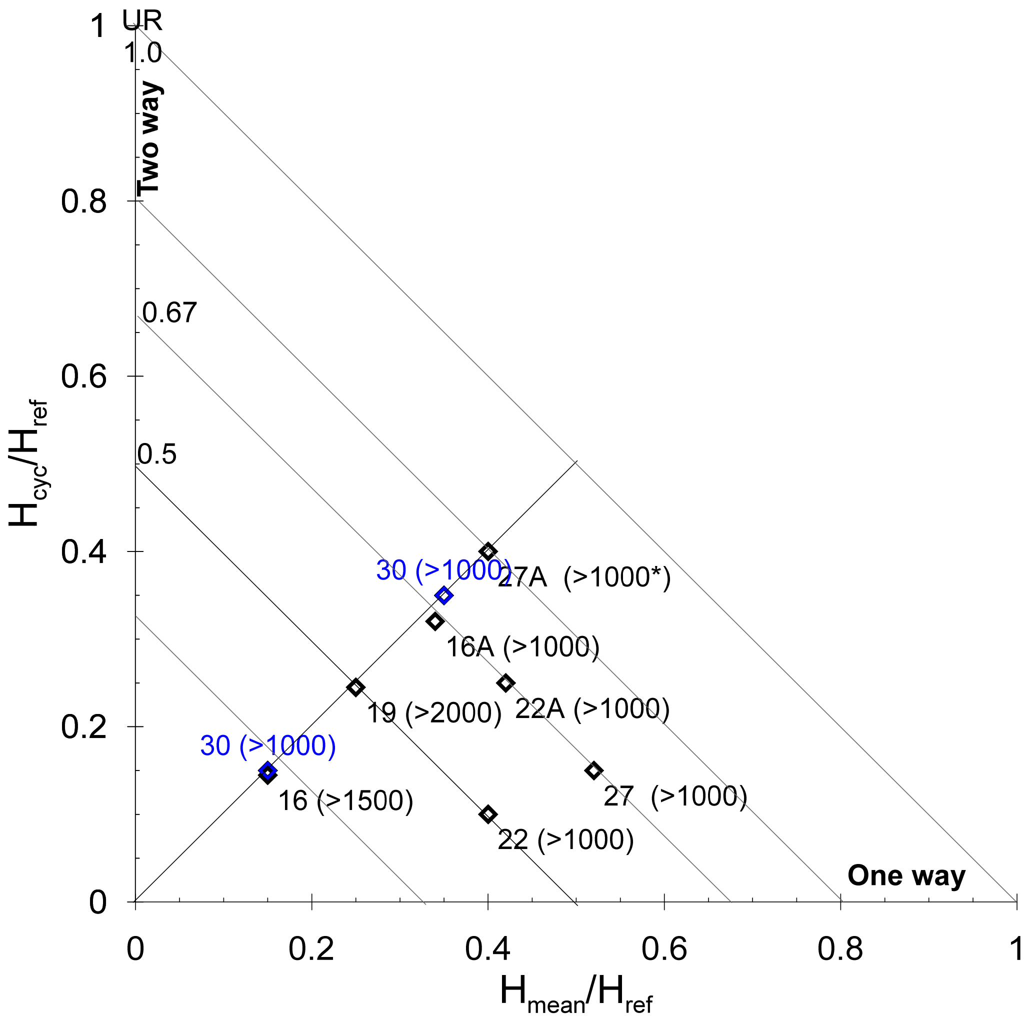
Most taken to 2,000 cycles

Some failed

One taken to 10,000 cycles

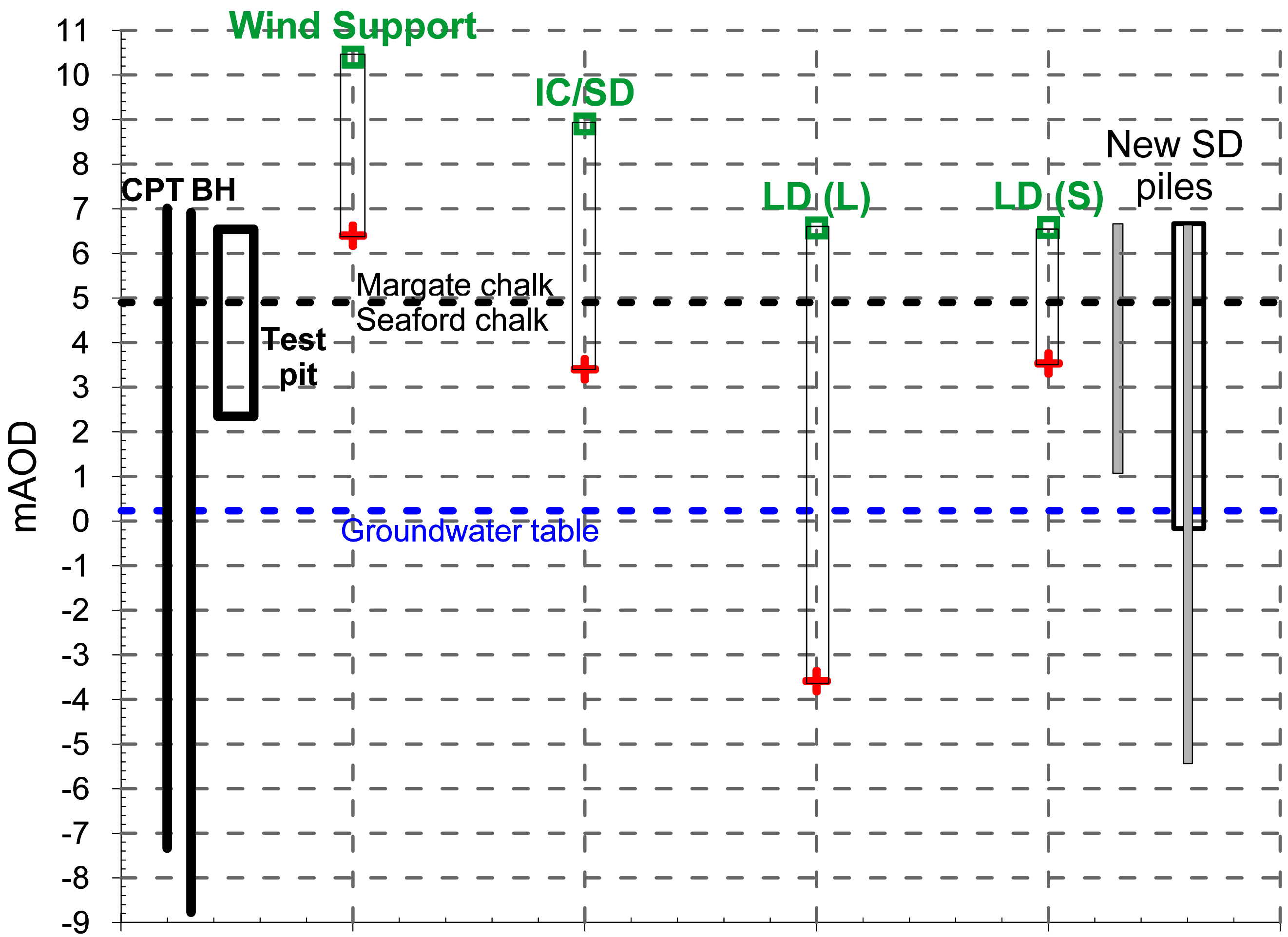
Similar SD programme April 2019

Lateral cyclic loading tests on 508mm LD piles



- Nine cyclic tests
- 10s period sine waves
- Normalised by static failure load
- 8 One-way cyclic tests
- 1 Bi-axial lateral cyclic
- Most followed by static tension test to failure

Ground profiles of SNW piles



Five pairs of new piles with different materials driven October 2018

Cased and uncased

Shafts above & below water table

Static tension tests in March 2019

Roles of groundwater & pile material?

ALPACA results and outcomes?

Main results under analysis at Imperial College & Oxford

Still building team: Post Doctoral position open

Project summary paper for Reykjavik 2019

One early paper to be submitted soon on dynamic analysis of piles equipped with fibre optic gauges under driving

Other data remain confidential to project partners until Q4 2019

Academic Work Group aim to publish in 2020

Summary and main points - I

1. Background outline of research to improve pile design for offshore energy

2. Sand & clay research extending to cover chalk, which is highly problematic for driven piles

3. Novel field tests at German Baltic Wikinger site, supported by onshore programme in Kent, UK

4. New discoveries concerning factors and processes controlling axial behaviour of piles driven in chalk

5. Preliminary axial SRD and aged, set-up, capacity methods developed for low-to-medium density chalk

Main points - II

6. Chalk ICP-18 checked for test cases, papers published

7. ALPACA project extends research to cover different pile materials, piles above and below fresh water tables, wider range of chalks etc

8. Also examines two-way axial cycling, static and cyclic lateral loading in high quality well-instrumented tests

9. ALPACA programme progressing well, around 75% complete, appeal for other contributions to building high-quality test database

10. Aim to publish ALPACA outcomes in 2020

Contact

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