The 6th ISSMGE McClelland Lecture

Time-dependent vertical bearing behaviour of shallow foundations and driven piles

Richard Jardine

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Rapid pace of, and urgent need for, energy transition

Main theme of 2023 OSIG Conference

Growth in offshore wind capacity over decade: 2,000 to 3,000 GW (>\$2tn foundations) by 2050?

Foundation ageing behaviour: key factor to consider from design to decommissioning
Vertical bearing behaviour over time

Field observations at clay, chalk (carbonate silt) & sand sites

Supported by characterisation, analytical & model studies

Part 1
Shallow foundations, effects of long-term loading

Part 2
Driven steel piles, ageing after installation

Full exposition: see written paper

Includes pile ageing under maintained load & load-displacement responses
Factors considered

Consolidation
Effective stress & strain changes due to excess pore pressures dissipation

Creep
Variations of strains and/or stresses over time under steady loading, independent of consolidation

Micro-to-macro fabric & structure
Bonding, sensitivity; grain contacts, soil-interface system, residual fabric, fissures & fractures

Chemistry
Particle bonds & corrosion reactions
Shallow foundations on clay

Soft, low YSR clays

Mats for light structures
Deep skirts for higher loads

Stiff, high YSR clays

May carry heavier structures
Thornton Bank wind turbines on Gravity Base (GBS) foundations offshore Belgium; Piere et al. (2009)

Bothkennar, Scotland, 1990 to 2001

Instrumented, 2.2 & 2.4m ($B$) square pads

Simple consolidation theory: $t_{95} \approx 4 \frac{B^2}{c_v}$

Test A: Defined initial $q_{ult1}$

Test B: Loaded to $2/3 q_{ult1}$ for 11 years

Test C: Defined age-enhanced $q_{ult2}$

Later modelling with elastic visco-plastic (EVP), Modified Cam Clay (MCC) Bodas Freitas et al. (2015)

Calibrated to advanced laboratory testing Smith (1992), Smith et al. (1992)
Site Profile  13 Geotechnique papers, June 1992

Holocene silty soft clay, open fabric & light bio-cementing

\[ \text{YSR} = \sigma'_{vy}/\sigma'_{v0} = 2 @ 2\text{m}, \text{falling to } 1.25 @ 20\text{m} \]

\[ I_p = 40 \pm 10\%, \text{2-7\% organic, } 0.6 \leq I_L \leq 1.0, \text{Sensitivity } S_t \approx 7 \]

\( S_u \) depends on testing & sampling methods

Anisotropic, brittle

\( S_u^{TC}/S_u^{TE} \approx 3.1 \)

High \( \phi'_c \) and \( \delta' \)

High \( C_c \) & secondary \( c_{ae} \)

Non-linear \( k = f(e) \)

Wp, WL, Wp, Wo

Leroueil et al. (1992)
Load-displacement outcomes

Test A back analysis: operational $S_u = \frac{3}{4}$ peaks from CAU tests on Sherbrooke samples

35% of long-term settlement developed after all pore pressures dissipated; $t_{95} \approx 1$ year

Test C: $q_{ult2}$ 20% higher than predicted by ‘standard’ MCC modelling: hence EVP analysis

1990 Test A, initial $q_{ult1} = 138$ kPa

2001 Test C enhanced $q_{ult2} = 204$ kPa

Test B: $2/3 q_{ult1} = 89$ kPa maintained for 11 years

Test B long-term settlement Matched well by EVP analysis
Other predictions from rate-dependent (EVP) MCC modelling

Shear strength beneath pads

- Predicted $S_u$ profile after 11 years (before Test C)
- Initial $S_u$ profile (before Tests A & B)

Loading response before, during & after ageing
- Well predicted

- Test A
- Test B
- Test C

- A - field
- A - model
- B - field
- B - model
- C - field
- C - model

Less significant $q_{ult}$ gains for high YSR cases
MCC less applicable if clays form residual shear fabric see paper
Shallow foundations on chalk

Widespread across NW Europe, North & Baltic Seas & elsewhere – even Texas!

Fractured very weak biomicrite CaCO₃ rock

Dominated by discontinuities, as recognised in GSI & other rock engineering approaches

Often high mass permeability, rapid consolidation

Can support GBS structures

71 (7 MW) turbines at Fécamp, offshore NW France, 2022

Properties: consider first lab tests on high-quality intact cores
St Nicholas at Wade (SNW) cores: low-to-medium density, CIRIA B3/B2 chalk

Locally instrumented triaxial tests  Vinck et al. (2023), Liu et al. (2023)

Multi GPa, near-linear, stiffness: $E'_v > E'_h$

Brittle: peak, post-rupture & ultimate strengths

Prone to creep

Pressure ($p'$) dependent peak resistance
**Field response:** Mundford test, Norfolk UK, with 183kPa loading: Ward et al. (1968)

Lord et al. (2002) macro-fabric grading

Mortimore (2022)

**Stratigraphy**

1: Overlying sands
2: Structureless melange
3: Friable and rubbly chalk
4: Blocky and rubbly, some joints open to 3 mm
5: Tough blocky, joint closed

**CIRIA Grade**

1. Grade D_m
2. Grade D_c
3. Grade B
4. Grade A

**Linear stiffnesses from precise extensometers**

$E'_v$ rises sharply with depth as Grade improves

Maximum, initial, field stiffness dominated by macro-fabric
Broad trends from Mundford, 1.8m plate tests at 3 sites & ALPACA pile tests
Matthews & Clayton (2004), Jardine et al. (2023)

<table>
<thead>
<tr>
<th>Grade</th>
<th>Max Field $E'/Lab E'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≈ 0.7</td>
</tr>
<tr>
<td>B</td>
<td>≈ 0.25</td>
</tr>
<tr>
<td>C</td>
<td>≈ 0.1</td>
</tr>
<tr>
<td>D</td>
<td>≈ 0.025</td>
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</tbody>
</table>

Creep under load
42% extra settlement after 4 months
At Mundford & in plate test at ‘NO’ site

Grade A: no creep & full recovery on unloading

Grades B to D: permanent strains & stiffness gains through gradual fracture closure

Macro-fabric also dominates creep
Behaviour under higher loads

1.8m plate tests on CIRIA Dc to B3 chalk at LE, NO and NE sites       Matthews & Clayton (2004)


• Peak core properties: highly non-conservative
• Crucial to recognise fractures & brittleness
• Divide lab $E'$ by factors of 4 to 40 depending on Grade
• Degrade shear strength with strain: from post-rupture ‘maximum’ to ultimate $\varphi'_c$
• FE predictions then bracket field response at weathered (Dc to B3) plate test sites

Macro fabric also limits capacity
Shallow foundations on silica sand

0.71m square, 0.7m deep, pad tests at Labenne, SW France


Site used for ICP tests
Lehane et al. (1993)

Loose-to-medium dense dune sand
Mean sand $I_D = 55\%$

ICL stress path tests:
Strongly non-linear stiffness
Critical state $\phi'_{cs} = 33^\circ$
Peak $\phi'$ varying with state

Borehole log

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>Notation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
<td>Fine-medium light brown uniform sand</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>Some clay traces</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>12.7% organic content</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
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</table>

CPT $q_{cr}$, MPa

CPT $f_{sr}$, MPa
Load-settlement-time

Marked long-term creep

Impact of densification on bearing capacity?

Simple analysis suggests \( \approx 40\% \) \( q_{ult} \) gain for Test B, enhanced further by micro-fabric effects?

Not checked experimentally

Scale effects? 100 by 50m nuclear power station raft showed similar creep under \( q_{mean} = 320 \) kPa

Summary

Consolidation
Major capacity benefits with low YSR clays
Can capture with critical state models; residual fabric cases need special attention

Creep
Provides additional benefits: accurate EVP modelling demonstrated for soft clay
Similarly important with chalk & sand, rarely addressed in practice

Fabric & Structure
Open void structures, residual fabric, fissures & fractures proven influential in clays & chalk
Micromechanical features likely to affect response in sand

Chemical bonding
Adds to field stiffness, yield stresses, shear strength & brittleness
Part 2 – Steel piles driven in clays, chalks & sands

Focus on ageing trends provoked by driving
Consider >200 ‘micro-to-mega’ piles

Essential
High quality SI, including CPT profiling
Good 1st time tests-to-failure at known ages
Reliable pore water pressure dissipation estimates

Desirable
Installation resistances to define setup \( \Lambda = Q(t)/Q(t=0) \)
Local stresses: shaft shear \( \tau, \sigma_r \) & pore water pressures \( u \)
Interface fabric observations
Supporting numerical & physical modelling
ICP tests: 1984-2015  

High YSR clay
Canons Park & Cowden

Low YSR clay
Bothkennar & Pentre

Loose to dense sands
Labenne & Dunkirk

Low-to-medium density chalk
St Nicholas at Wade

Parallel studies on open driven piles

Installation; equalisation & loading to failure
102mm $D$

SSTs at 4 $h/R$ levels
measure shear $\tau$, radial stresses $\sigma_r$ & pwps $u$
Installation pore pressures & dissipation at Canons Park  
Bond & Jardine (1991)

ICP tests in high $I_p$, high YSR, London clay
Fissures & laminations

![Diagram showing water content % vs. Triaxial $S_u$ kPa](image)

- Water content %
- Triaxial $S_u$ kPa

- Profile based on unconsolidated undrained triaxial compression tests
- From cone tests ($N_k = 20$)

Concentrated near the tip
Equalised in 2 days

1D Cavity Expansion & 2D Strain Path analyses
Struggled to match ICP observation sets

Benchmarks to test large-displacement FE analyses?
Staubach et al. (2022), Previtali et al (2023)
Field effects of scale & geometry on dissipation: Cowden glacial clay till


CPTu & ICP tests and 2m $D$ by 10.5m open piles PISA (2015)

Predictions from CPTu tests after Carter et al (1979)

$$t_{95}/[t_{95}]_{CPT} = [D^*/D]^2$$

If coring $D^* = [D_{outer}^2 - D_{inner}^2]^{0.5} = 2R^*$

If plugged $D^* = D$

Near-tip $t_{95}$ times, in days

<table>
<thead>
<tr>
<th>Depth</th>
<th>Measured</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>102mm ICP</td>
<td>$\approx 7$</td>
<td>6.4</td>
</tr>
<tr>
<td>2m PISA pile</td>
<td>$\approx 100$</td>
<td>$\approx 114$</td>
</tr>
<tr>
<td>3m diameter, 50mm $t_w$ coring offshore pile</td>
<td></td>
<td>$\approx 256$</td>
</tr>
</tbody>
</table>
Near tip $t_{95}$ projections, in days, for 3m piles from other pile test site records

<table>
<thead>
<tr>
<th>Test</th>
<th>Measured $t_{95}$</th>
<th>3m $t_{95}$ projection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentre, LDP, 762mm</td>
<td>$\approx 0.3$</td>
<td>1</td>
</tr>
<tr>
<td>Low $I_p$, low YSR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laminated clay-silt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarke 1993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WD58A, 762mm</td>
<td>$\approx 180$</td>
<td>1020</td>
</tr>
<tr>
<td>High $I_p$, low YSR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gulf of Mexico clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bogard &amp; Matlock 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Canons Park, 102mm ICP</td>
<td>$\approx 2$</td>
<td>110</td>
</tr>
<tr>
<td>High $I_p$, high YSR</td>
<td></td>
<td>(closed)</td>
</tr>
<tr>
<td>Fissured &amp; laminated clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bond &amp; Jardine 1991</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baltic Femern, 500mm</td>
<td>$\approx 1500$</td>
<td>3500</td>
</tr>
<tr>
<td>High $I_p$, high YSR clay</td>
<td></td>
<td>(plugged)</td>
</tr>
<tr>
<td>Karlsrud et al 2014</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dissipation could take years offshore, much faster if laminae or fissures are present.
Shaft capacity \((Q_s)\) setup \(\Lambda\) ratios due to consolidation
\[ \Lambda = \text{static capacity at} \ t \approx t_{95} / \text{rate-corrected installation resistance} \]

Examples from cases with installation data, all with 30 < \(L/D\) < 55

<table>
<thead>
<tr>
<th>(\Lambda)</th>
<th>(t_{95})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4 Very short</td>
<td>(\Lambda) cut by partial drainage?</td>
</tr>
<tr>
<td>3.6 to 4.1</td>
<td>Reducing with L/D</td>
</tr>
<tr>
<td>1.1</td>
<td>Similar at Cowden</td>
</tr>
<tr>
<td>1.3 Note (t_{95} \approx 300) days</td>
<td>(\Lambda) boosted by corrosion?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>YSR, (k), Properties</th>
<th>Site</th>
<th>Diam.</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low, high (k)</td>
<td>Pentre, LDP, 762mm</td>
<td>Clarke 1993</td>
<td></td>
</tr>
<tr>
<td>Laminated clay-silt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, low (k)</td>
<td>Bothkennar, ICP, 102mm</td>
<td>Lehane &amp; Jardine 1994</td>
<td></td>
</tr>
<tr>
<td>Organic high (I_p)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, high (k)</td>
<td>Canons Park, ICP, 102mm</td>
<td>Bond &amp; Jardine 1994</td>
<td></td>
</tr>
<tr>
<td>Fissured, high (I_p)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, low (k)</td>
<td>Tilbrook Grange, LDP, 762mm</td>
<td>Clarke 1993</td>
<td></td>
</tr>
<tr>
<td>Low (I_p) till over high (I_p) Oxford clay</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

‘Consolidation \(\Lambda\)’ most important in low YSR clays with sensitive fabrics, may reduce with \(L/D\)
Otherwise: use capacity predictions to track shaft capacity-time trends

1) Effective stress ICP-05 method; Jardine et al. (2005)

Coulomb failure \( \sigma'_{rf} = 0.8 \sigma'_{rc} \quad \sigma'_{rc} = K_c \sigma'_{v0} \quad h/R = \text{relative pile tip depth} \quad R = \text{radius} \)

\[
K_c = [2.2 + 0.016\text{YSR} - 0.87 \log_{10} S_t] \quad \text{YSR} \quad (h/R^*)^{-0.2} \quad h/R^* \geq 8
\]

Needs reliable YSR, \( S_t \) and \( \delta' \) from high-quality SI & interpretation
Often unavailable for published case histories

2) ‘Unified’ CPT-approach calibrated to 0.1 to 1.5m OD pile dataset; Lehane et al. (2020)

\[
\tau_{r zf} = 0.07 F_{st} q_t (h/R^*)^{-0.25} \quad h/R^* \geq 1
\]

Much simpler & less ‘operator dependent’, but lacks site-specific \( \delta' \) & \( S_t \) information
Importance of interface shear angles Bond and Jardine (1991), (1994)

Local ICP shaft $\tau_{rz} - \sigma'_{r}$ paths

Plus shear zone fabric studies

Prove Coulomb shaft failure $\tau_{rz} = \sigma'_{r} \tan \delta'$

Near-residual interface fabric: $\delta'_{\text{peak}} = 13^\circ$ falls post peak to $\delta'_{\text{ult}} = 8^\circ$

ICP tests in $I_p = 40\pm10\%$ Bothkennar clay showed $\delta'_{\text{peak}} = 29^\circ = \delta'_{\text{ult}}$ Lehane and Jardine (1994b)

Field $\delta'$ governed by grain shapes & minerals

$\delta'$ correlates poorly with $I_p$ but closely matches ‘ICP-style’ lab ring-shear interface tests
Application to open steel, driven piles: 0.76m ‘LDP’ & 0.5m ‘NGI’ ageing JIP tests
Clarke (1993), Karlsrud et al. (2014)

Normalised by ‘Unified’
Only needs $q_t$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_s(t)$</td>
<td>$Q_{ICP}$</td>
</tr>
</tbody>
</table>

Normalised by ICP-05
Parameter derivation: see paper

Different spreads & method bias

$0.15 \leq Q_s$ gain/log cycle $\leq 0.25$ at $t > t_{95}$ for five sites, but not Stjordal
Stjordal & other outlying sensitive ‘low \( I_p \)’ cases

Low YSR clay-silt: \( 7\% < I_p < 15\% \), high \( \varphi' \)

Very low \( t_{95} \) capacity \( Q_s \) & marked growth over next year

Explanation?

Arching slowly released by creep?

Explains short-term driving setups of large offshore piles in North Sea glacial tills?
See paper & Hampson et al. (2017) Clair cases

Identify ‘outliers’ from CPTu parameters? Ridgway & Jardine (2007), Lehane et al. (2020)

Reduce project risks with: CPT design method & reduction factors, or field tests: Schonberg et al. (2023)

Returning to more ‘typical’ clay sites, what role does corrosion play in post-\( t_{95} \) setup?
Steel corrosion in the ground

Osaki (1982) - 7500 steel loss measurements on 126, 15m long, piles driven in ten profiles

Corrosion product growth $\Delta r$ far exceeds steel $\Delta t_w$ loss: added non-ferrous mass & lower densities

Tends to slow or stabilise with 5 years
Giving < 1mm of corrosion product over 10 years

Rates marginally faster: above the water table; in clays than sands; & in low pH groundwater

Impact on steel driven piles investigated in London Clay at Canons Park

Canons Park: 168mm closed steel pile

Driven to 6.4m, then tested in compression over 3.1 years; Wardle et al. (1992)

Brittle post-peak response on Day 1, reflecting $\delta_{\text{peak}}' = 13^\circ$ reducing towards ductile residual $8^\circ$

Marked gains in residual capacity after each extended pause

Pellew’s tests, after 14 year pause

$\approx 0.45/\log$ cycle $Q_s$ gain

2-3 rates with larger D NGI & LDP piles

Parallel bored r/c pile: no setup

Sampling around shaft from strutted pit

Index & chemical testing

SEM & thin section image analyses

In-situ $p'$ distributions measured

Pellew & Jardine (2008)
Clay fabric & in-situ stresses

Residual shear surfaces
0.5mm thick, FeS annulus, expanding out to $\Delta r/R = 0.6\%$

Sulphate reducing bacteria assist reactions & modify clay index properties

Tens of suction $p'$ measurements
Around 3.3 m depth

Driven 102 mm OD pile after 1 month

168 mm OD pile after 17 years

Profile around similar pile, one month after driving  Bond & Jardine (1991)

After 17 years:
Near shaft mean $p' \approx 2.5$ times higher
Residual shaft capacity $\approx 2.4$ times higher
Due to corrosion-driven cavity expansion
Corrosion-Cavity Expansion (CE) setup mechanism

Illustrate referring to self-boring pressuremeter test from same depth

\[ \Delta \sigma_r \approx 230 \text{ kPa after } \Delta r/R = 0.6\% \text{ cavity strain while pile } \Delta p' \approx 270 \text{ kPa} \]

Final field \( p' \approx 450 \text{ kPa} \) comparable to cavity expansion limit \( p_{lim} \)?

Cavity strains invoked by given corrosion \( \Delta r \) increment scale with \( 1/D \)

So \( \sigma'_{rc} \) & \( Q_s \) gains will fall with diameter

Analogy is not perfect

Drained non-linear FE analysis presented later, incorporating pile installation stage

Jardine (1985)
Piles in low-to-medium density Chalk

Widespread, fractured, sensitive very soft CaCO$_3$ rock

Heavily damaged by impact driving

Soft putty annuli & fractured zones form around shafts

Captured in PFEM analyses  Previtali et al. (2023)

CIRIA 574: 20 kPa $\tau_{rzf}$ for open driven piles, based on very limited information

Onerous consequences, led to closer investigation

Large-scale offshore testing: Wikinger, German Baltic

Linked research at St Nicholas at Wade

Buckley (2018)
Nine 1.37m piles, driven to 30.7m

Driving, tension & dynamic tests after 93 ±15 days show strong setup

Field $Q_s$ far exceeds CIRIA estimate
Dynamic data from 2.7m & 3.76m D Wikinger production piles

Mean $\Lambda > 4$ at 100 days

Tentative Chalk ICP-18, analogous to sand ICP-05 Buckley (2018), Jardine et al. (2018)

But extensive checking required as:

- Tension $Q_s$ exceeded rig capacity
- Incomplete Wikinger CPT profiles
- Till & chalk $Q_s$ split?
- Compression response?
- Setup mechanisms?
- Lateral loading?

ALPACA & ALPACA Plus JIPs
Forty-three driven piles: 0.14 to 1.8m D, range of geometries & materials

Jardine et al. (2023a, b)

All with PDA sensors, most with FBG strain gauges

Driving data
And 13 re-strikes

Monotonic axial tests on 27 piles

All but one in tension

Local $\tau_{rzf}$ profiles on driving & testing

Parallel cyclic & lateral loading programmes
Low-to-medium density, B2/B3 grade, chalk

Weathered layers removed by earlier quarrying

CPTu profile for each pile, dissipation tests

In-situ pressuremeter & geophysics profiling

Geobore-S & block sampling

Comprehensive lab testing Vinck et al. (2022)

Analysis of fabric damage caused by impact driving
Pile driving damage to chalk fabric

Up to 10MPa pore pressures near tip as chalk ‘de-structures’

Dissipation aided by chalk fractures

Putty annulus $\approx t_w$ thick, reconsolidates & governs axial response

Long-term corrosion at interface, faster above water table

Coccoliths ruptured by driving, release water

Additional fracturing to $\approx 10 \, t_w$ from shaft

Putty chalk under SEM
Livia Cupertino Malheiros
Local shaft shear stresses on 1.8m by 19m TP1 pile

End-of-driving (EoD) signal matches & FBG gauges in tension test after 371 days

\( \tau_{rzf} \) proportional to \( q_t \), falls steeply with \( h/R \)

Chalk ICP-18 works for driving SRD

Compression shaft capacity \( \approx \) double tension

‘Like-for-like’ \( \Lambda = 4.3 \), less with higher \( L/D \) piles

Long-term Chalk ICP-18 non-conservative, especially in tension & below water table
Setup of primarily submerged piles

Consolidation $\Lambda$ most marked for $L/D \leq 15$

Corrosion $\Lambda$ only with mild steel piles, none with stainless steel or concrete

Cavity expansion process, as with clays

Contributes most to low diameter piles above the water table

Arching creep setup active after $t_{95}$ & in advance of long-term corrosion?

$t_{95}$ from CPTu dissipation

Consolidation to $t_{95}$

Corrosion setup

$1h < t_{95} < 2h$

ALPACaCA Plus

$3h < t_{95} < 6h$

Wikinger

$\Lambda_{Lp/D}$

Consolidation to $t_{95}$

Corrosion setup

Labels: $Lp/D$
Re-calibrated axial design method  Jardine et al (2023a)

\[ \tau_{rzf} = f_L [ \sigma'_{rc} + \Delta \sigma'_{rd}] \tan \delta' \]

\( f_L = 2/3 \) tension, 4/3 compression, ‘fully rough’ \( \delta' \approx \varphi'_{cs} = 31 \) to 32°

\[ \Delta \sigma'_{rd} = 4 G_{ope} \Delta r / D \]

\( G_{ope} \) varies with fabric  \( \Delta r \approx d_{50} \)  \( \Delta \sigma'_{rd} \) varies with 1/D

\[ \sigma'_{rc} / q_t = f_{tip} \times 0.025 \times (h/R)^{-0.8} \quad h/R \geq 0.5 \]  below water table, different expression above

Mean \( Q_m/Q_c = 1 \), CoV = 0.16 for \( t \geq 120 \) day SNW tests  CIRIA 574 gives mean \( Q_m/Q_c = 3 \)

Independent checking
7 static & 7 dynamic tests: 0.6-1.5m steel piles at five other ‘submerged’ sites
Confirm fitness-for-purpose, CIRIA still more conservative: see paper
Pile ageing in sand

Starting with short-term ICP tests

Local $\tau_{rzf} = f_L[\sigma'_{rc} + \Delta\sigma'_{rd}]\tan\delta'$

Led, with open Dunkirk pile tests, to ICP-05: Jardine et al (2005)

$\sigma'_{rc} = 0.029 q_t [\sigma'_{v0}/P_a]^{0.13} (h/R^*)^{-0.38}$ with $h/R^* \geq 8$

$\Delta\sigma'_{rd} = 2 G\Delta r/R$, base $q_b$ linked to $q_t$

Good predictions for 80 (0.2 to 0.8m) piles, plus 2m Tokyo Bay case, with mean 35 day age, Yang et al. (2017)

‘Unified’ $A_{re}$ expression fitted to agreed database, gives lower CoV

$\sigma'_{rc} = \frac{q_c}{44} A_{re}^{0.3}[Max[1, (h/D)]]^{-0.4}$ Lehane et al. (2020)

Effects of prolonged ageing?
Ageing of open steel piles tension tests normalised by ICP-05

1st tests on 457mm x 19m piles, dense Dunkirk sand
Re-tests show different, staggered, trends
Jardine et al. (2006)

Similar 340 & 500mm piles
Loose silty Larvik & dense Blessington sands

EoD resistance ≈ 2/3 ICP, long-term ≈ 5/2 ICP
Mechanics? Why the plateau? Effects of scale?
Potential setup mechanisms

Consolidation – discounted

Creep-arching: Seen with $\sigma_{\text{lateral}}$ sensors on medium scale piles

Mixed evidence: direct measurement challenging, scaling uncertain


Interface dilation in lab tests & field $\sigma_{\text{lateral}}$ data boosted by ageing: Chow (1997), Gavin et al. (2015)

Impact of dilation reduces with $D$ as $\Delta\sigma'_{rd} = 2G \Delta r/R$

Corrosion cavity expansion: as with clay & chalk, impact likely to reduce with $D$

Concrete driven piles also show setup
‘Micro-to-mega’ pile investigations

Heavily instrumented model tests in Fontainebleu sand

Stainless, 36mm D, mini-ICPs jacked into $I_D = 75\%$ pre-pressurised fine sand, Jardine et al. (2013 a,b)

Shaft roughnesses ($R_{CLA}$), grain breakage & density studied

Clear evidence of $\sigma'_r$ arching around pile shaft

Capacity: ICP $Q_s$ available at end of installation
No growth over months of ageing under pressure
Rimoy et al. (2016)

Tests explored by advanced numerical modelling
Zhang et al. (2014), Yang et al (2014), Ciantia et al. (2020)

ALE, MPM, PFEM & DEM large displacement analyses
Calibrated to high-quality lab tests on NE34 sand
PFEM analysis example Ye et al (2023)
Grain crushing, cyclic loading, open-ended geometry analyses; see paper

End of installation $\sigma'_r c$ profiles, normalised by (computed & measured) CPT $q_c$

![Graphs showing numerical and experimental results of $\sigma'_r / q_c$ vs $r/R$ for different $h/R$ values.]

Captures most features of model tests well; quantifies & explains arching

But over-predicts $\sigma'_r c$ & does not capture dilative interface shearing response

Return to field to investigate ageing
Open micro-piles driven at Dunkirk, Blessington & Larvik 50-60mm by 2m; Carroll et al. (2020)

Dunkirk tension tests
Exhumed after 2 years above water table
Bonded sand grains, anoxic shaft conditions

Plugging, $Q_s \approx 1.5 Q_{ICP}$ achieved 2hrs after driving

- Stainless piles show no further setup, like lab
- Mild steel piles setup markedly to similar final $Q_s/Q_{ICP}$ as 457mm piles, but lower $\Lambda$

Micro-fabric? Impact on interface dilation?
Micro-fabric near shaft of corroding Dunkirk piles

Sketch of 1mm shaft length

SEM from dense ‘crust zone’  
Livia Cupertino Malheiros

Corroding steel pile shaft  
Corrosion products cementing grains

1mm

Larger sand grains

Crushed fine sand filling voids

0.5mm

Shaft failure mechanism pushed out into surrounding sand

Interface shear tests show dilation displacement steps up from $\approx 2R_{CLA}$ to exceed $d_{50}$ see paper
Full-scale offshore ageing behaviour

Track shaft resistance with Stress wave matches of EoD & re-strikes after ageing periods

Borkum Riffgrund I, German North Sea
2.13m OD, 38.5m piles in very dense sand

Six-day re-strike: shaft $\Lambda = 1.45$
Jardine et al. (2015)

Followed by PAGE JIP
25 unpublished, well-characterized, offshore cases
76% \leq I_D \leq 100\% (mean 85\%). Mainly silica sands provide \geq 75\% Q_s \text{ & all } Q_{\text{base}}

Piles
1.37 to 3.35m diameter: 2.8m mean \approx 80 \text{ times mini-ICP}
8 \leq L/D \leq 53 (16 \text{ mean})
18 \text{ to } 67 \ D/t_w \text{ (mean 50)}

High-quality driving & restrike PDA data pairs, known hammers, dates
Signal matching with rigorous QA & independent checking

Plus 22 supplementary dynamic & static tests on other piles, mostly with D < 0.8m
New analyses of published EURIPIDES, Horstwalde, Tokyo Bay, Los Angeles port & other cases

Base resistances: dynamic far lower than static
Static & dynamic shaft resistances: broadly consistent at equivalent ages
Shaft ageing, offshore, cases normalised by ICP-05

Mean EoD shaft resistance ≈0.5*ICP-05 – then double to ‘recover’ ICP-05 over 1st month

Little change after 20 days

Qs/QICP Long-term resistances ‘flat-line’ at ICP Qs values

EoD mean = 0.5 ICP

Mean D = 2.8m
Shaft ageing offshore normalised by Unified method

Mean EoD resistance $\approx 0.7 \times \text{Unified}$, long-term close to $1.35 \times \text{Unified}$

Surprising 35% difference with ICP explored by Scarfone et al. (2023)
Plotting supplementary PAGE case points over offshore trend curves

17 piles with $D<0.8\text{m}$ match offshore trend at 20 days, but show higher long-term $Q_m/Q_c$

Two larger diameter Trans Tokyo Bay piles plot closer to offshore long-term PAGE trend

All $D<0.8\text{m}$

EoD/ICP reductions with $D$

Imply greater arching?

Leading to greater initial setup of large $D$ piles by Arching creep?

Marked longer-term $\Lambda$ of $<0.8\text{m}$ piles, not seen at offshore scale

Because impact of corrosion & enhanced dilation scales with $1/D$?

Also limited by $p_{\text{lim}}$?
Reconciling multi-scale outcomes see paper for details

Interpretation of dozens of micro-pile tests at 3 sites identified upper limit to mean $\sigma'_{rf}$

Maximum mean $\sigma'_{rf} = [3.2 \pm 0.4] \sigma'_{rc}^{ICP}$

Cavity expansion $p_{lim}$ caps $\Delta \sigma'_r$ gains from corrosion growth & enhanced dilation

Illustrate by drained PFEM analysis based on Grenoble model case  Yang et al. (2023)

First, model 36mm D mini-ICP installation

Then expand ‘pile’ radially outwards

Steep $\sigma'_r/q_c$ gains develop initially

Low gradients after 0.5mm

Final $p_{lim} = 4.6 (\pm 0.7)\% \ q_c \approx 3 \ \sigma'_{rc}$

Analytical result broadly compatible with limit interpreted from micro-pile tests
Next: look for diameter dependency in PAGE data

\( \frac{Q_s}{Q_{ICP}} - D \) trend for all 30+ day age piles with \( D \geq 0.45 \)m

1. Apply \( \sigma'_{rf} \leq 3.2 \sigma'_{rc} \) limit for Dunkirk

Impact on \( \frac{Q_s}{Q_{ICP}} \) illustrated for Dunkirk piles

Less significant when \( D > 0.5 \)m

2. Assume ICP predicts 1 month capacities taking \( \Delta r = 0.02 \)mm, as indicated in database studies

3. Predict subsequent ageing by raising \( \Delta r \) input in \( \Delta \sigma' = 2 G \Delta r/R \) ICP term
Adjusting ICP calculations to capture ageing up to 2 years after driving

$Q_s$ predictions made raising ICP $\Delta r$ term from 0.02 to 0.4mm

Keeping mean PAGE $I_D = 85\%$, $L/D = 16$, $D/t_w = 50$

Plotted over 25 offshore & 19 supplementary PAGE cases

$\Delta r = 0.4$mm curve is upper bound to 43 of 44 field tests

Compatible with fully rough shearing after credible corrosion product growth

Gains reduce with D, but still potentially significant

For site-specific predictions: undertake kinetic modelling of corrosion & interface tests

See paper for details
Taiwan Strait tests  looser silty sands, silts & clays; higher $L/D$  Shonberg et al. (2023)

Re-strikes after $\approx 60$ days on 1.5m, $L/D = 53$, piles with $>60\%$ of $Q_s$ from ‘sands’

Normalisation: ICP-05 in ‘sand’, UWA-13 in ‘clay’ units

Outcomes compatible with $\Delta r \approx 0.3\text{mm}$
Static tests also undertaken, led to large steel savings
Summary for piles

Dissipation & consolidation after driving
Key to setup in low YSR clays & low-to-medium density chalk
  May reduce with $L/D$
Scale-dependent $t_{95}$ times

ALE, CEL, MPM, PFEM & DEM installation analyses becoming feasible

  Need to capture fully:
  Conditions around open tips
  Fabric, sensitivity & anisotropy
Impact of 1000s of driving blow cycles
  Rate dependency & creep

Creep-arching mechanism
  Appears important in high $\phi'$ soils
  Not seen with micro-piles, more influential with larger piles

Arching captured in mini-ICP sand model tests & ALE, DEM, MPM & PFEM analyses
Can future analyses address arching & its relaxation over time?
Open driven piles, cont’d

**Fabric & Structure**

Sensitivity: reduces $Q_s$ in clays & chalks

Fabric: strong influence on $\delta'$ angles in clays, fracturing important in chalk

Grain crushing: putty formation in chalk & shear zones in sand; both affect arching

Interface dilation: $\Delta r$ affected markedly by corrosion in sand; impact scales with $\Delta r \, G/D$

Potential extensions to simplified ‘design methods’ considered
Future incorporation in ‘complete’ numerical analyses?

**Chemistry**

Sub-millimetre corrosion growth contributes to long-term setup

Impact strongly scale dependent
Reaction rates likely to vary with site conditions

Non-conservative to apply smaller tests in design without adjusting for scale
Ageing affects “Whole-life” behaviour, including decommissioning

Studies reported identify key mechanisms, suggest simplified predictive approaches & give benchmark datasets to test modelling advances

Full modelling is feasible for shallow foundations on clay; extension needed to other geomaterials

Full modelling installation, consolidation & ageing of driven piles remains challenging, although evolving rapidly

Field testing can be cost-effective in de-risking & optimising design when foundation performance is uncertain for high-value projects
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