Imperial College London

SIMSG ISSMGE

Society for Underwater Technology

The 6th ISSMGE McClelland Lecture

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

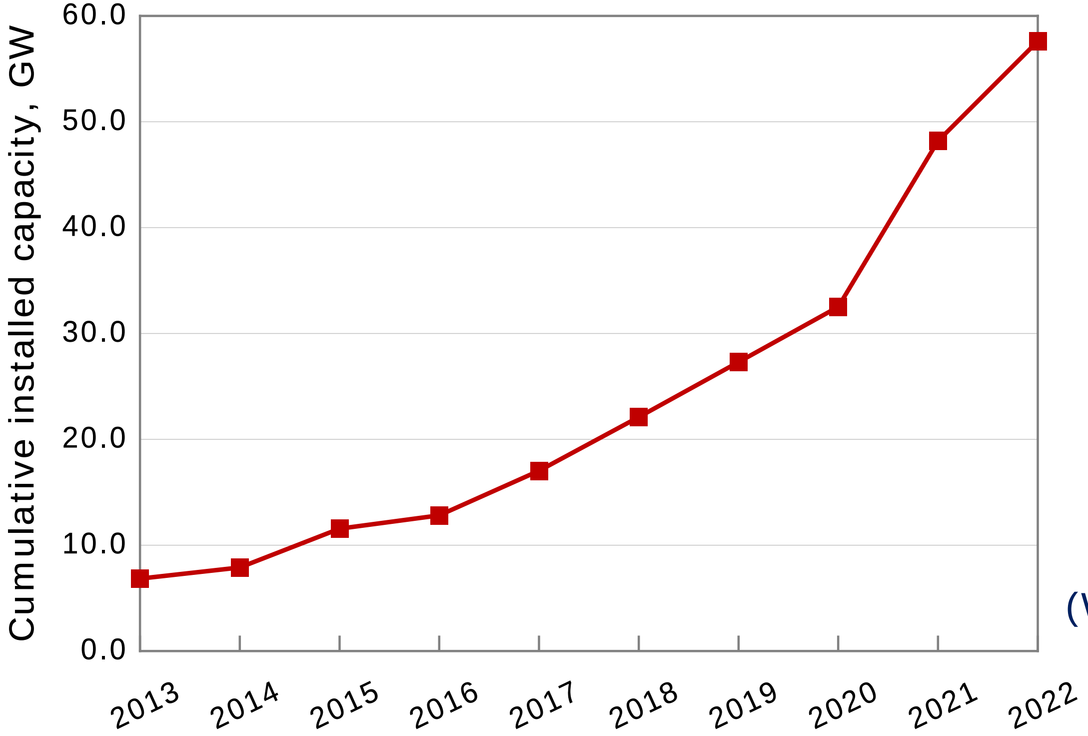
Richard Jardine

12th September 2023

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?



(WFOW 2023)

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

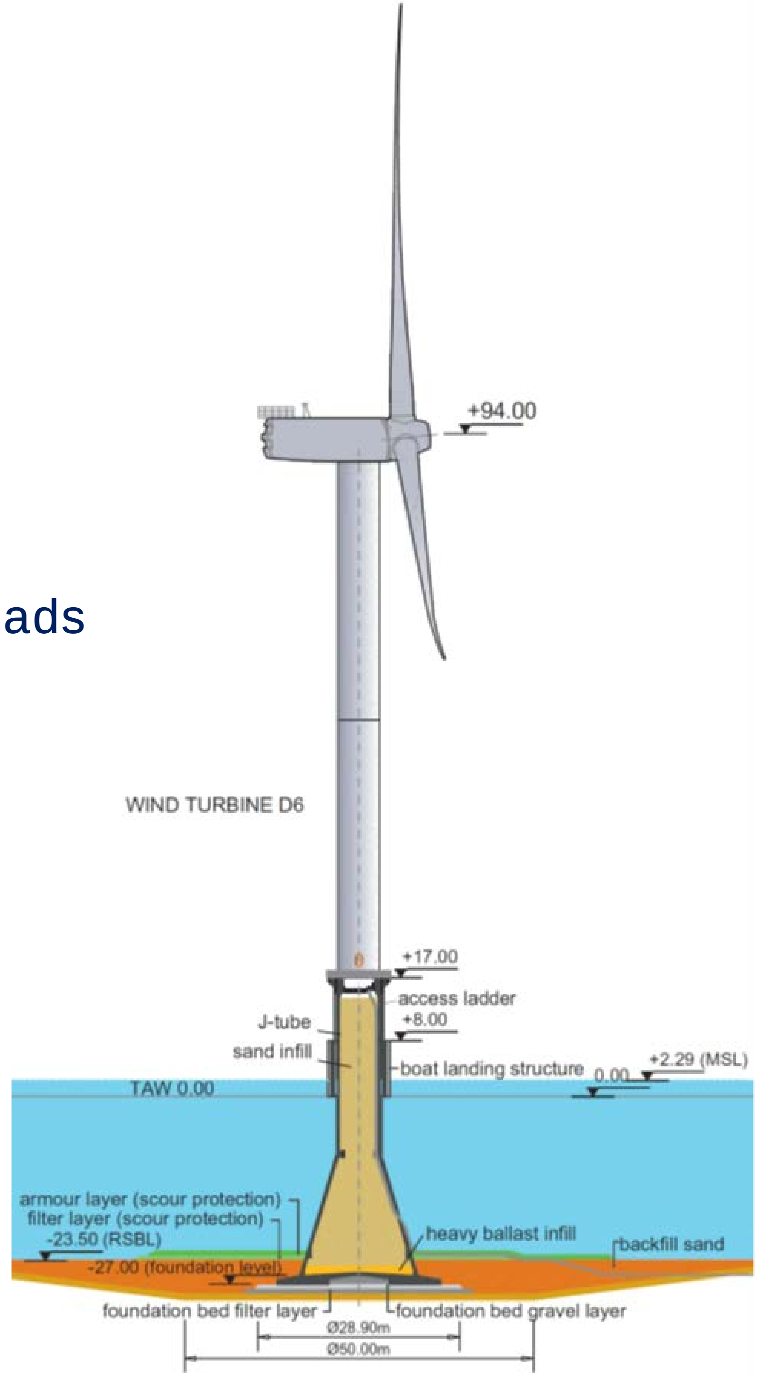
Mats for light structures

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)



Soft clay ageing under load: Jardine et al. (1995), Lehane & Jardine (2003)

Bothkennar, Scotland, 1990 to 2001

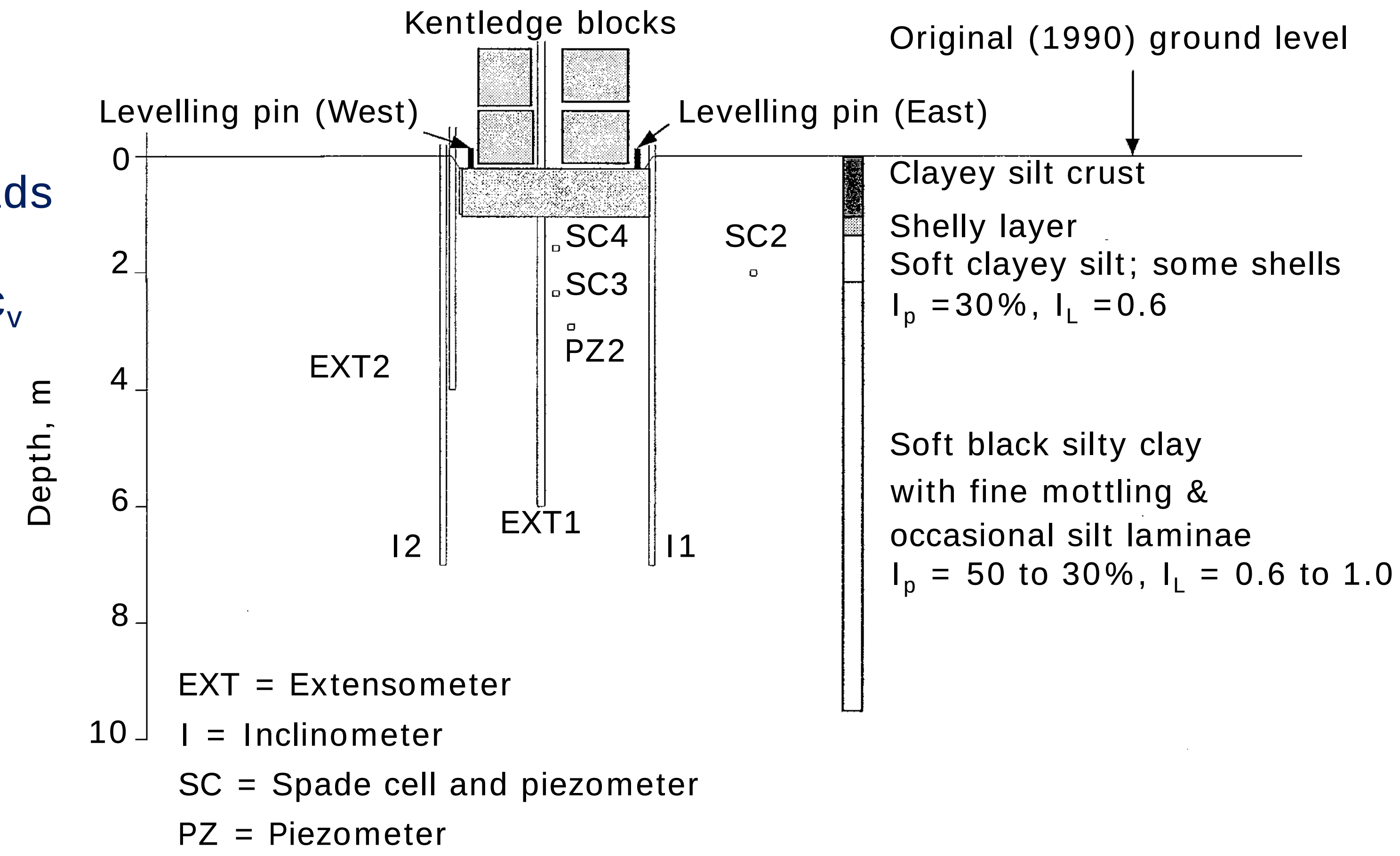
Instrumented, 2.2 & 2.4m (*B*) square pads

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

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

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

I_p = 40 ±10%, 2-7% organic, 0.6 ≤ I_L ≤ 1.0, Sensitivity S_t ≈ 7

S_u depends on testing & sampling methods

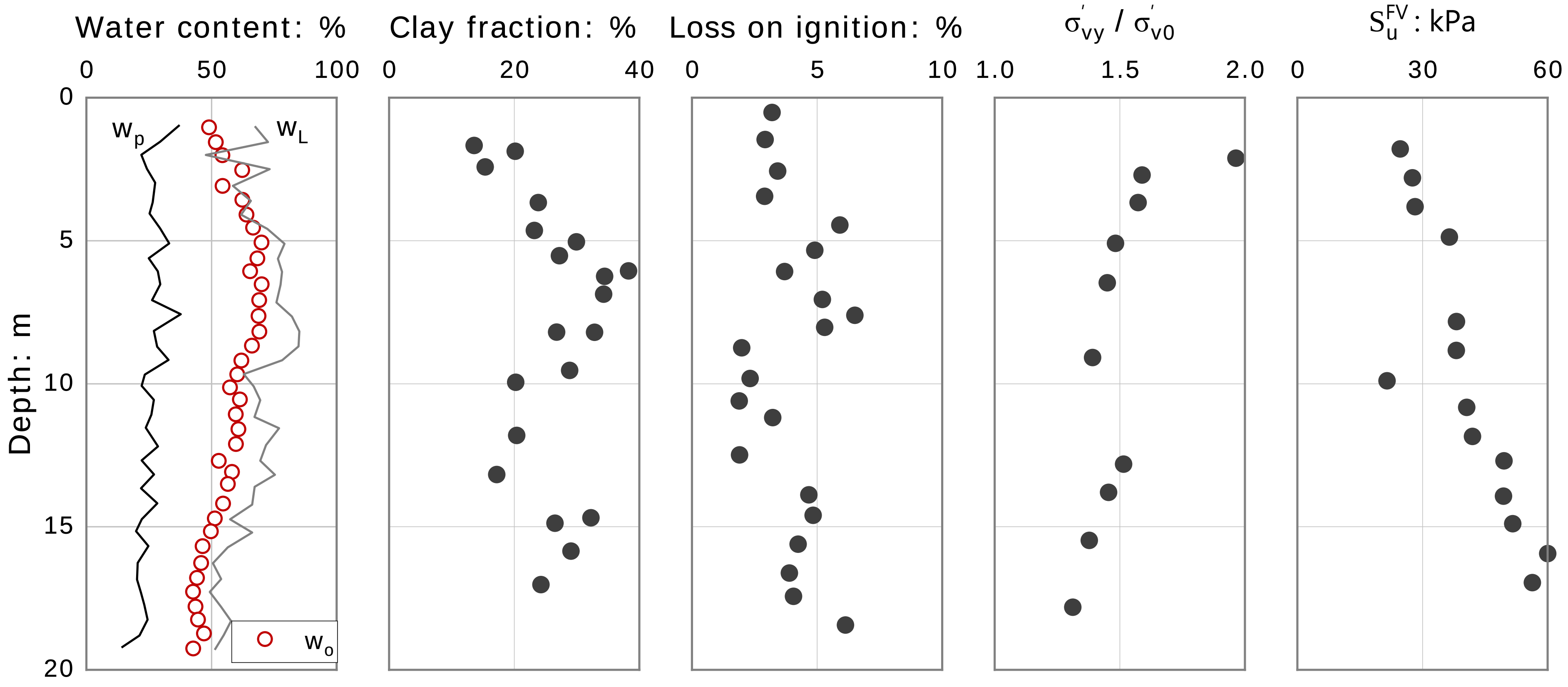
Anisotropic, brittle

S_u^{TC}/S_u^{TE} ≈3.1

High φ'_{cs} and δ'

High C_c & secondary $c_{\alpha e}$

Non-linear $k = f(e)$



Leroueil et al. (1992)

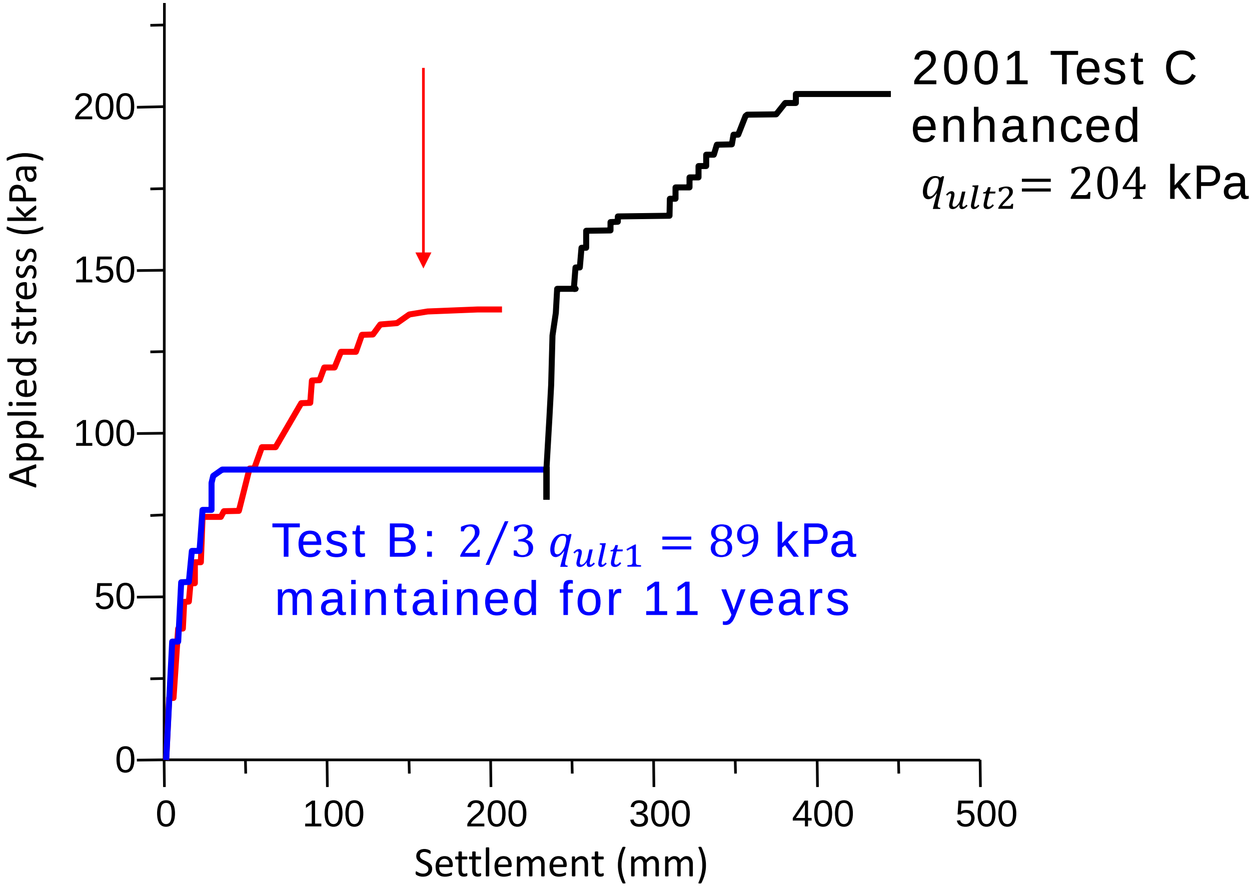
Load-displacement outcomes

Test A back analysis: operational S_u = ¾ peaks from CAU tests on Sherbrooke samples

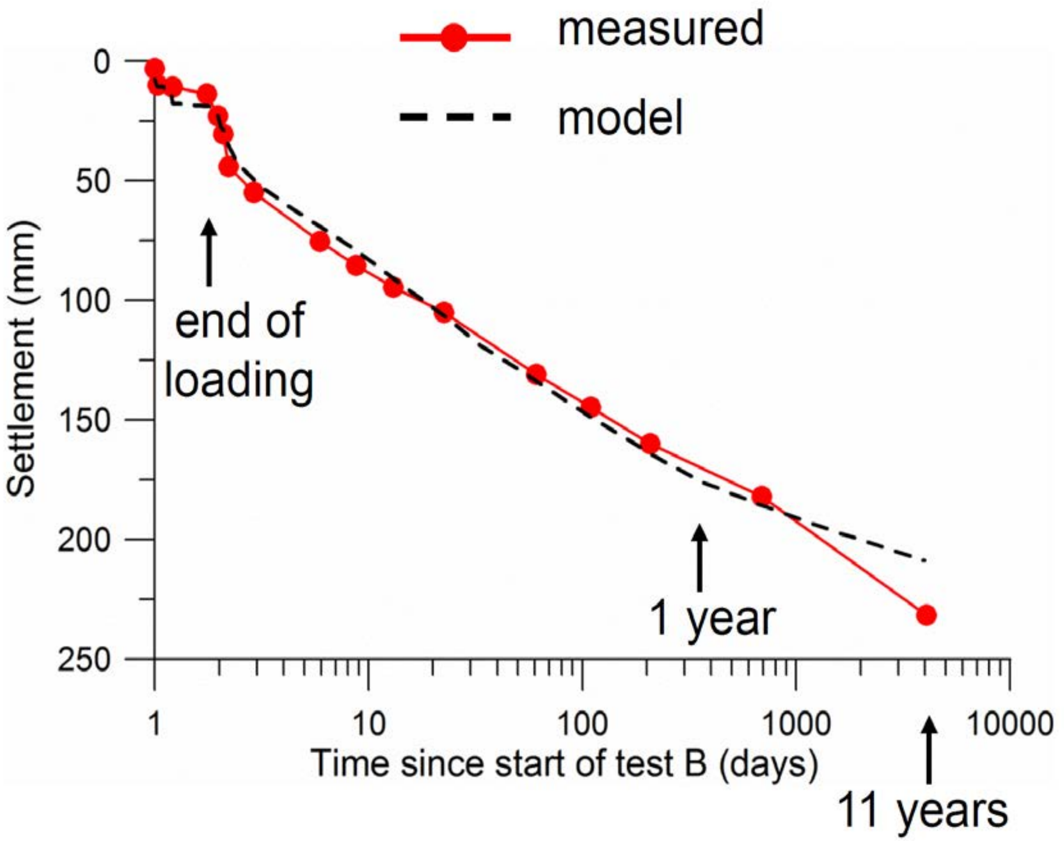
35% of long-term settlement developed after all pore pressures dissipated; $t_{95} \approx$ 1 year

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

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

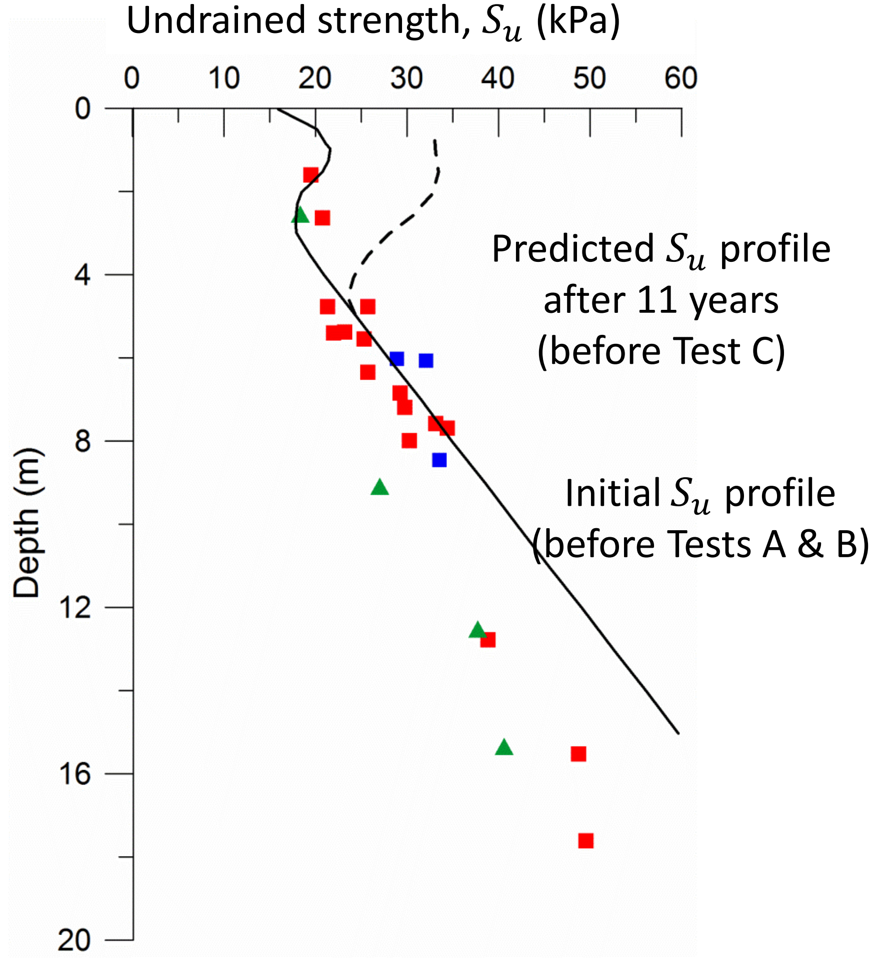


Test B long-term settlement
Matched well by EVP analysis



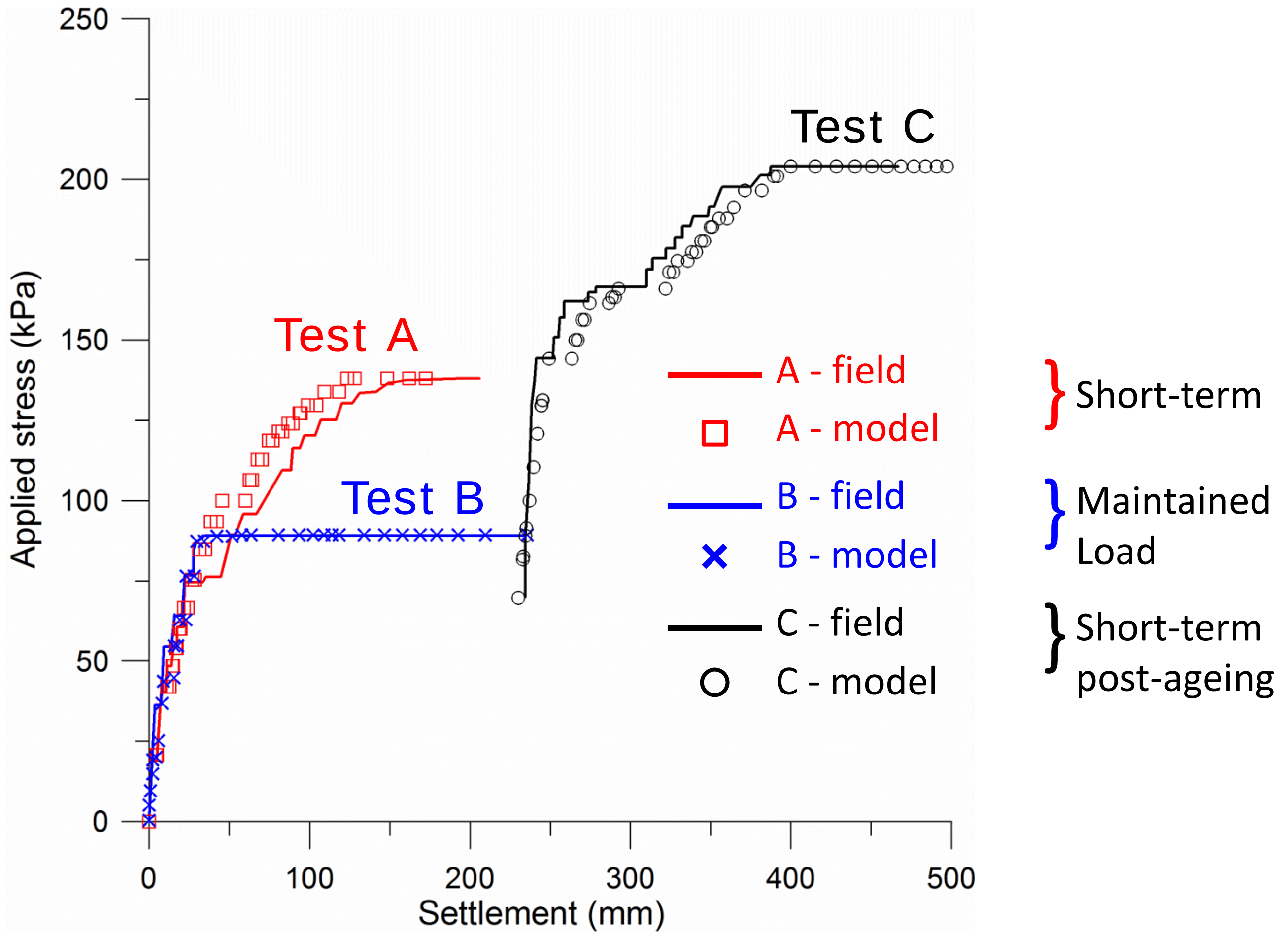
Other predictions from rate-dependent (EVP) MCC modelling

Shear strength beneath pads



Loading response before, during & after ageing

Well predicted



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!


Photo: Heerema Marine Contractors

Fractured very weak biomicrite $CaCO_3$ rock

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

Often high mass permeability, rapid consolidation

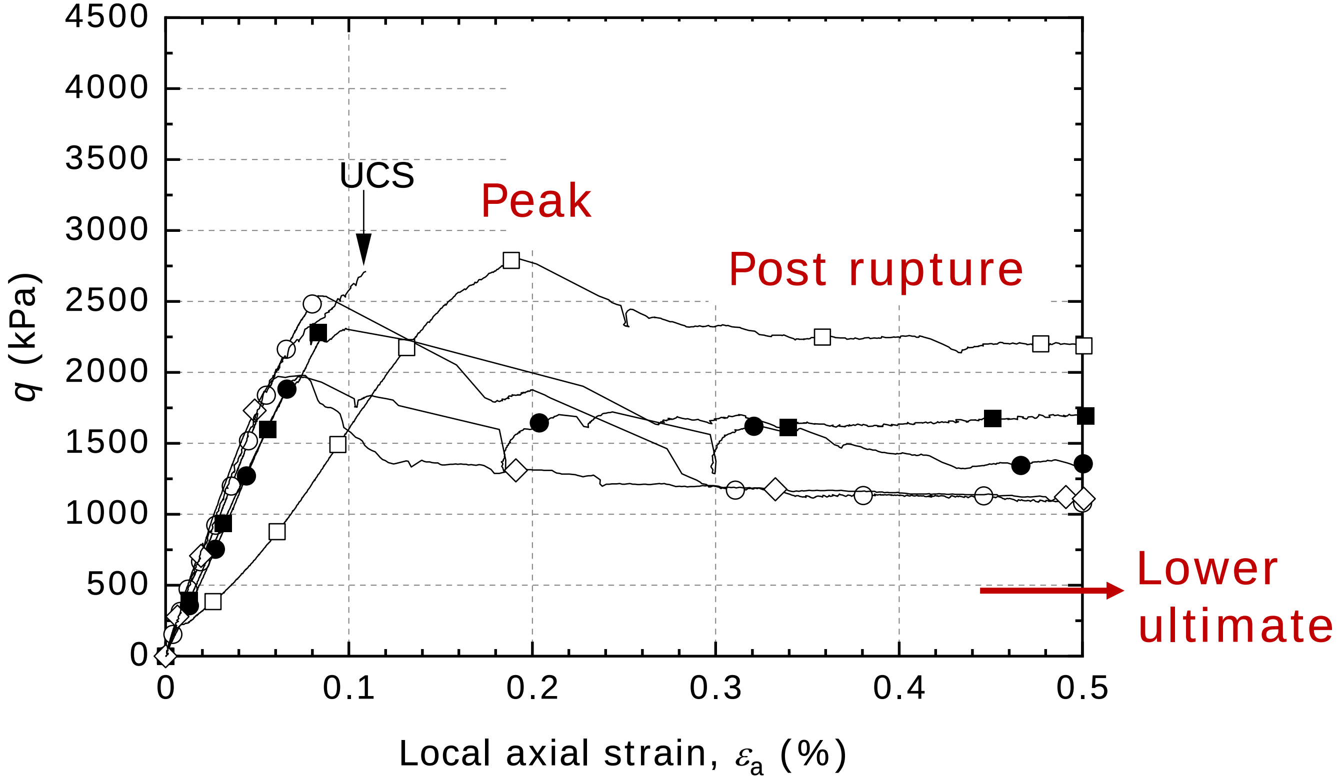
Can support GBS structures

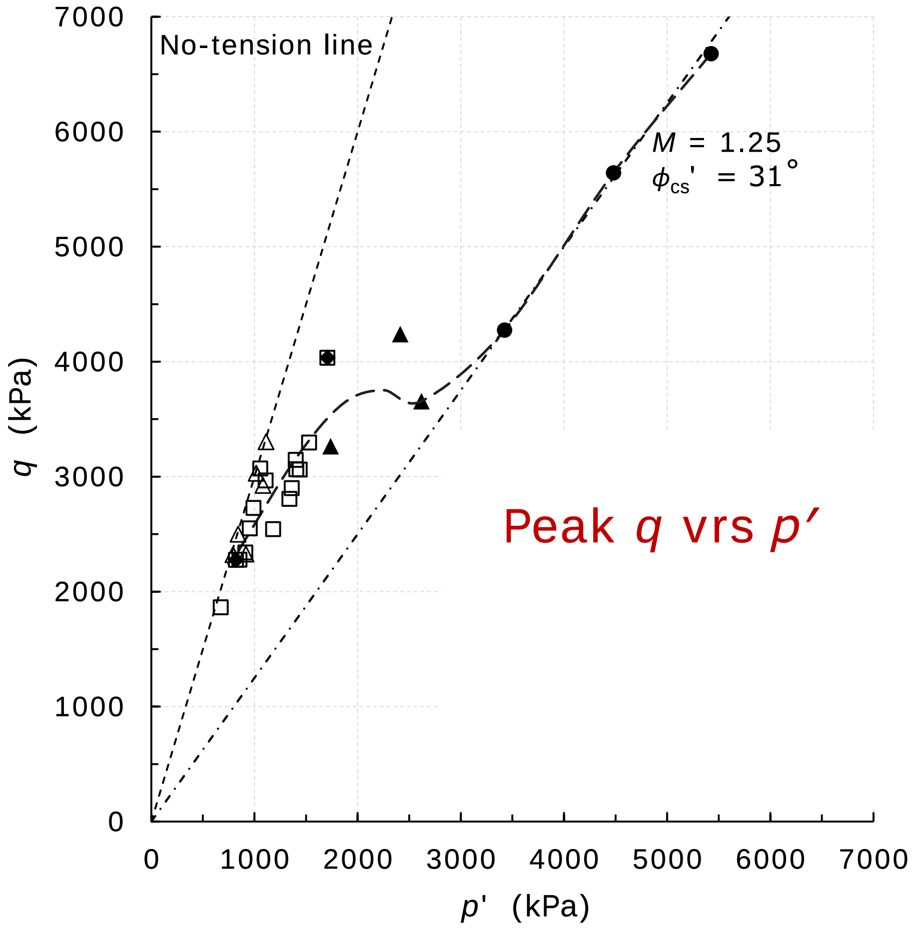
71 (7 MW) turbines at Fécamp, offshore NW France, 2022

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

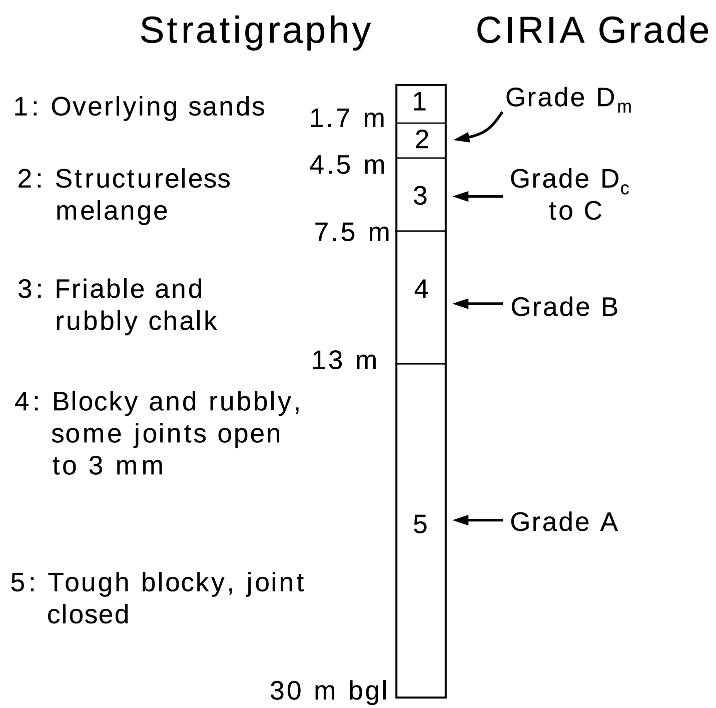
Prone to creep

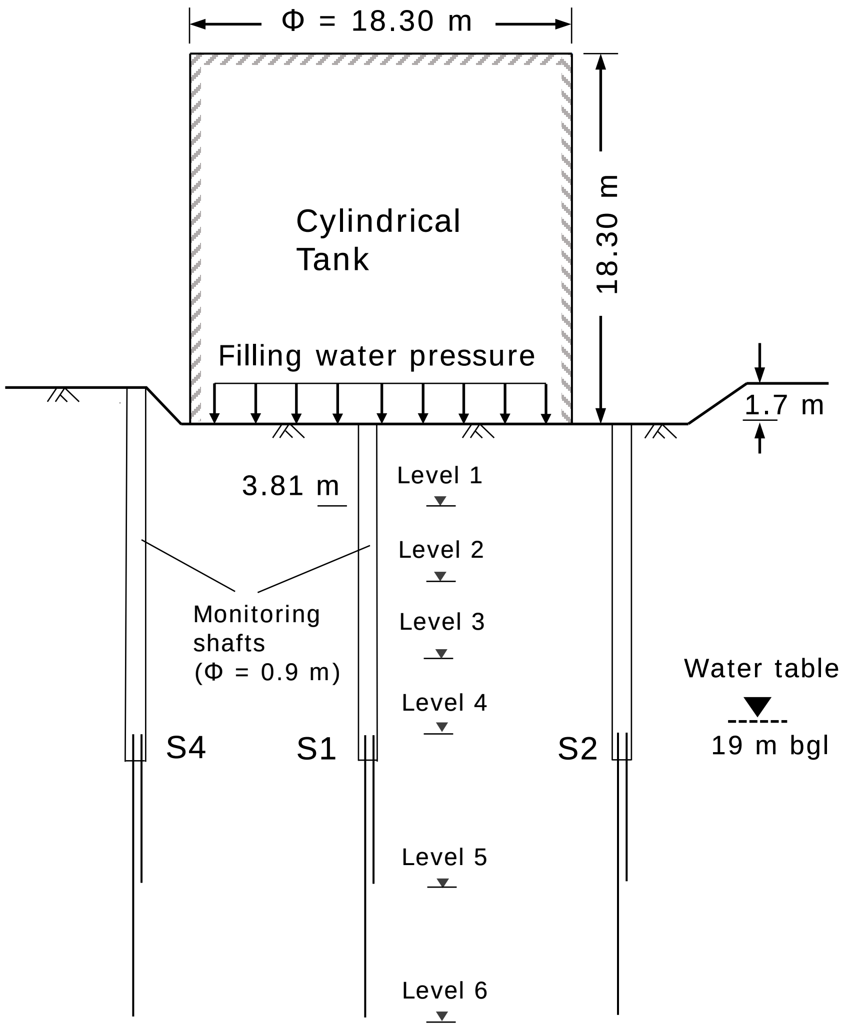
Pressure (p') dependent peak resistance

Field response: Mundford test, Norfolk UK, with 183kPa loading: Ward et al. (1968)

Lord et al. (2002) macro-fabric grading

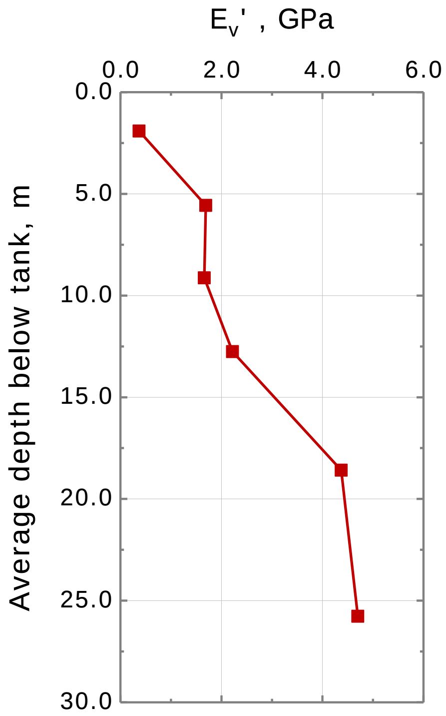
Mortimore (2022)





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)

Grade	Max Field *E´* /*Lab E´*
A	≈ 0.7
B	≈ 0.25
C	≈ 0.1
D	≈ 0.025

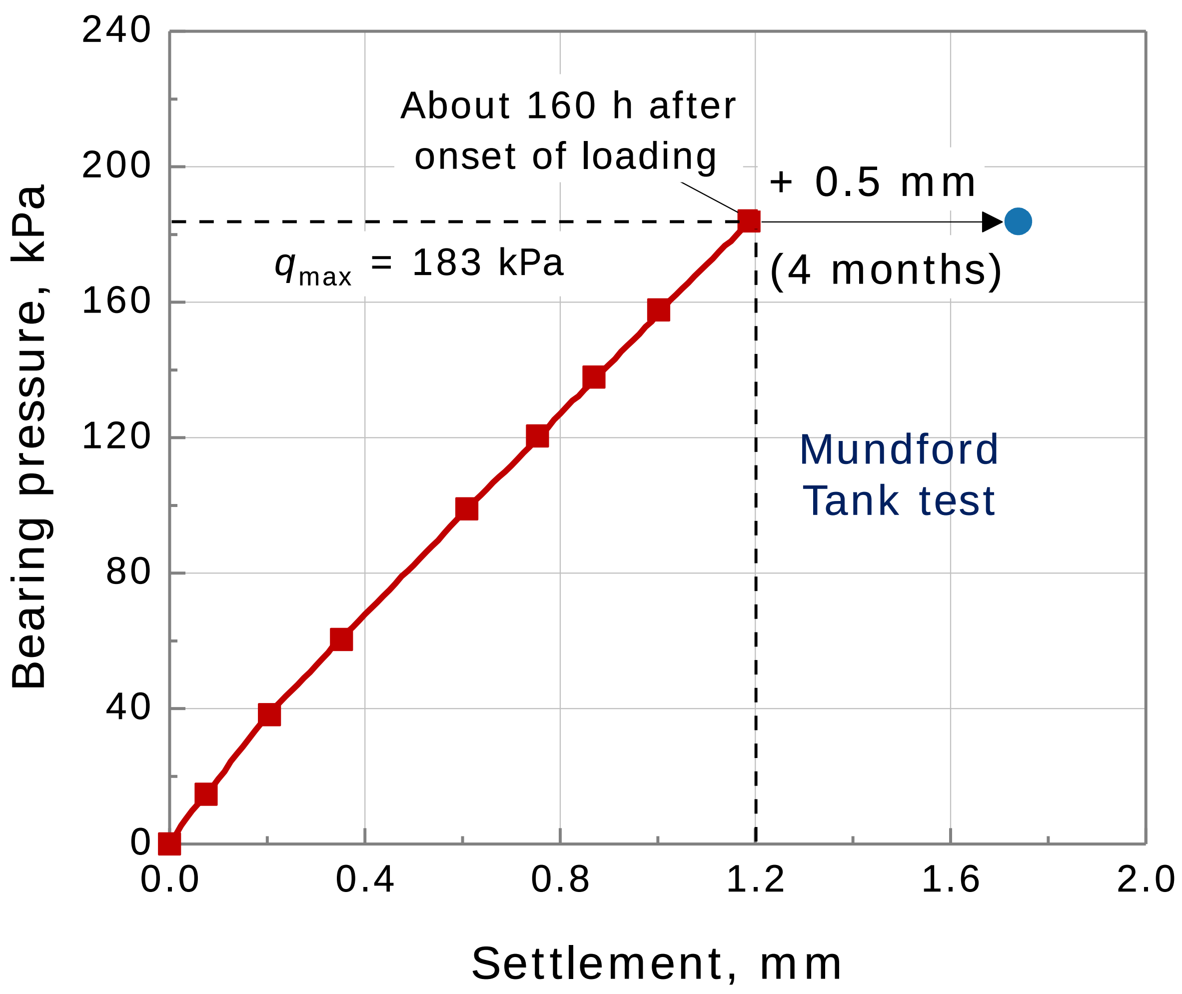
Creep under load

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

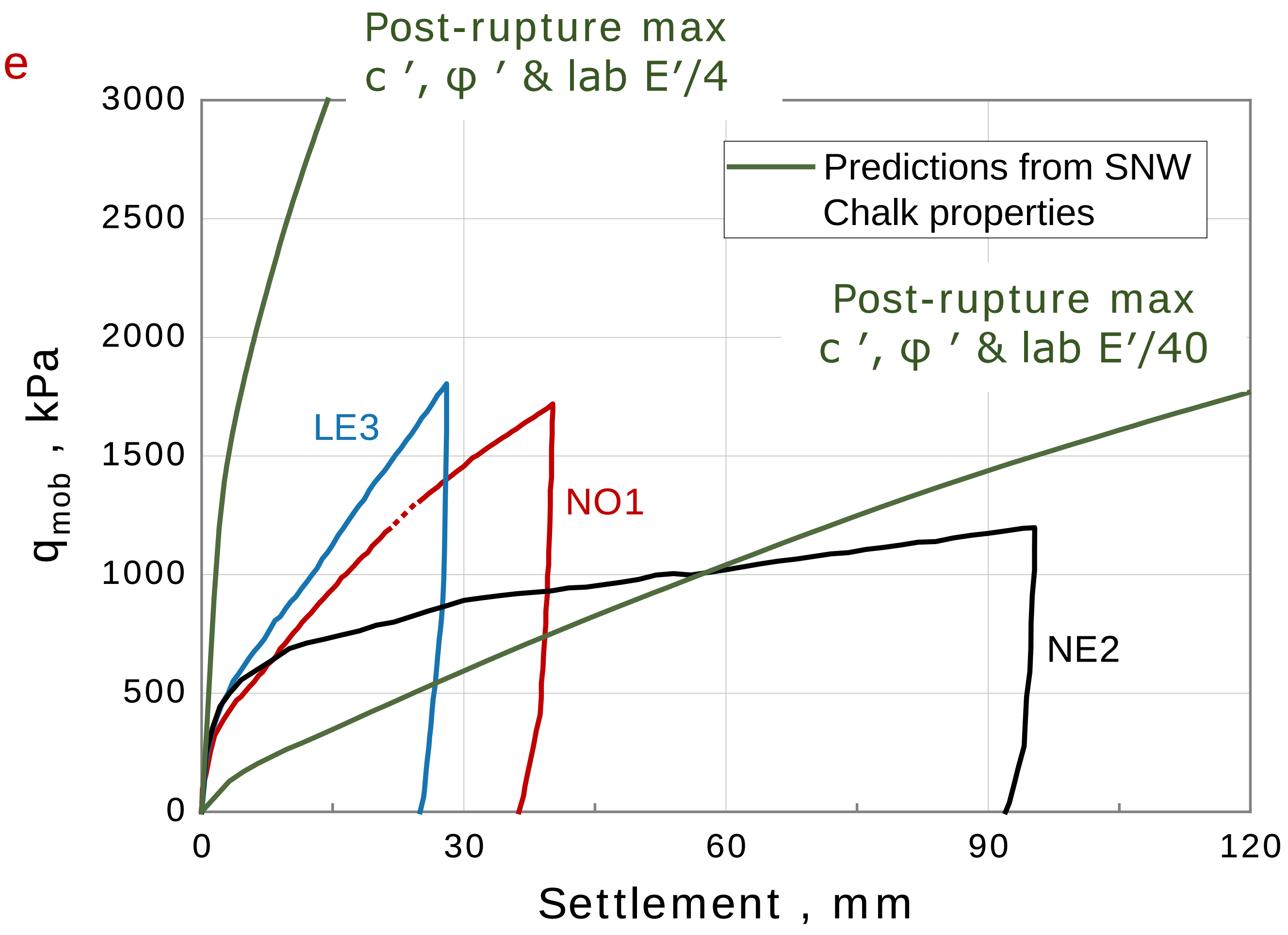
Behaviour under higher loads

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

FE analyses: Pedone et al (2023) model based on B2 SNW chalk lab tests   Kontoe & Jardine (2023)

- 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 φ'_{cs}
- FE predictions then bracket field response at weathered (Dc to B3) plate test sites

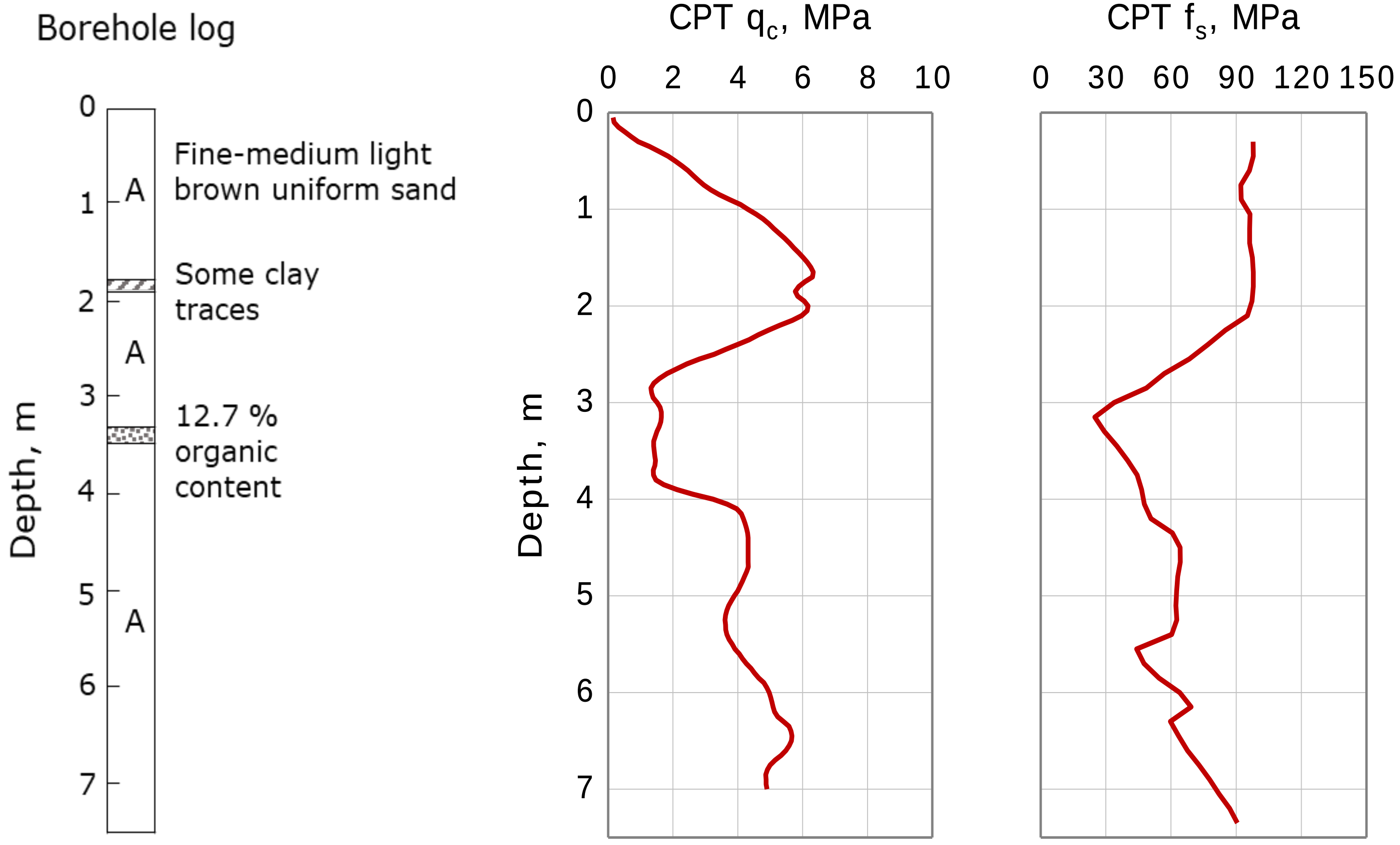
Macro fabric also limits capacity



Shallow foundations on silica sand

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

Laboratoires des Ponts et Chaussées (LPC): Amar et al. (1985), (1994), Canépa & Garnier (2003)

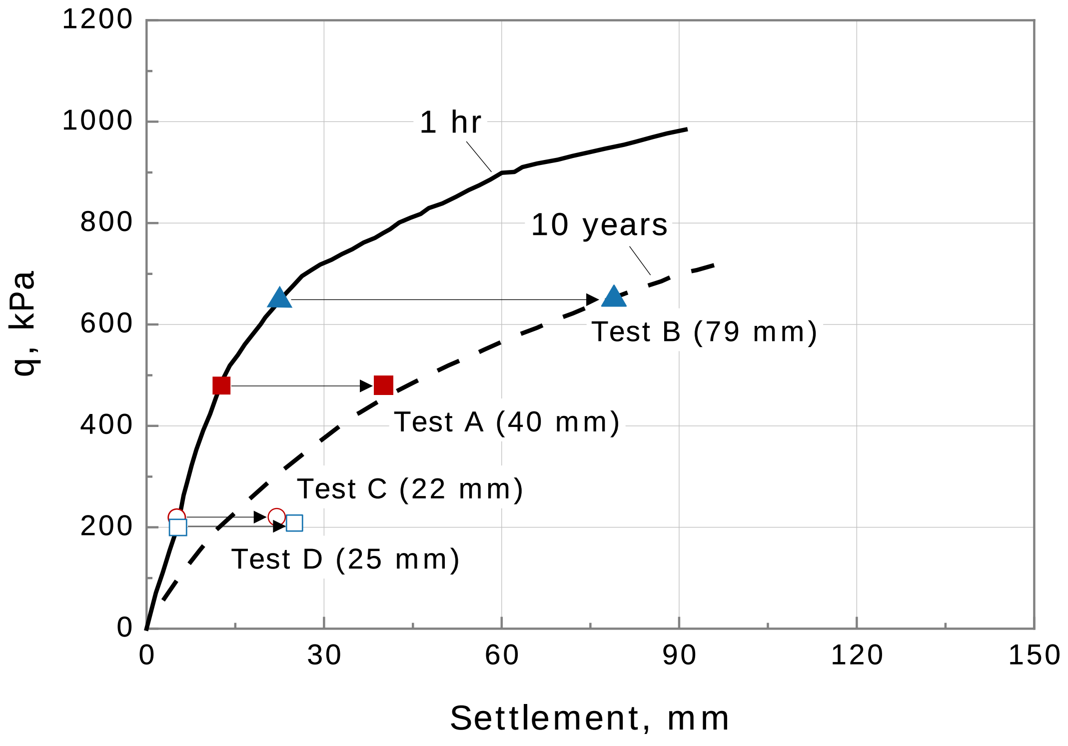


Site used for ICP tests
Lehane et al. (1993)

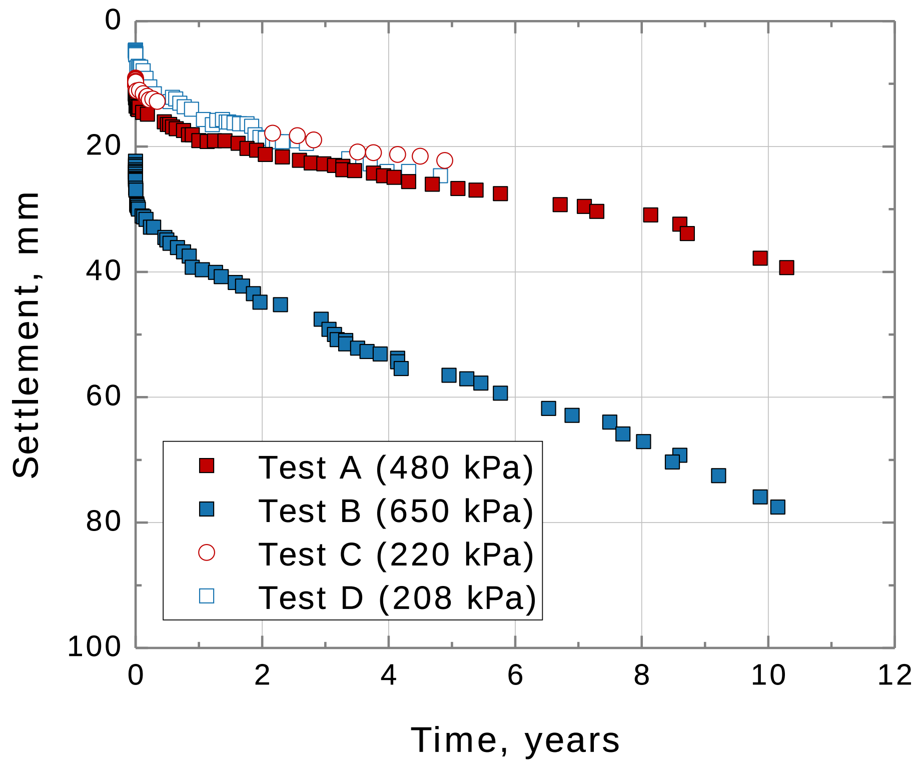
Loose-to-medium dense dune sand
Mean sand I_D = 55%

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

Load-settlement-time



Marked long-term creep



Impact of densification on bearing capacity?

Simple analysis suggests ≈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

See paper & Jardine et al (2005)

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 τ, σ_r & pore water pressures u

Interface fabric observations

Supporting numerical & physical modelling

ICP tests: 1984-2015

Bond 1989, Lehane 1992, Chow 1997, Pellew 2002, Buckley 2018

High YSR clay

Canons Park & Cowden

Low YSR clay

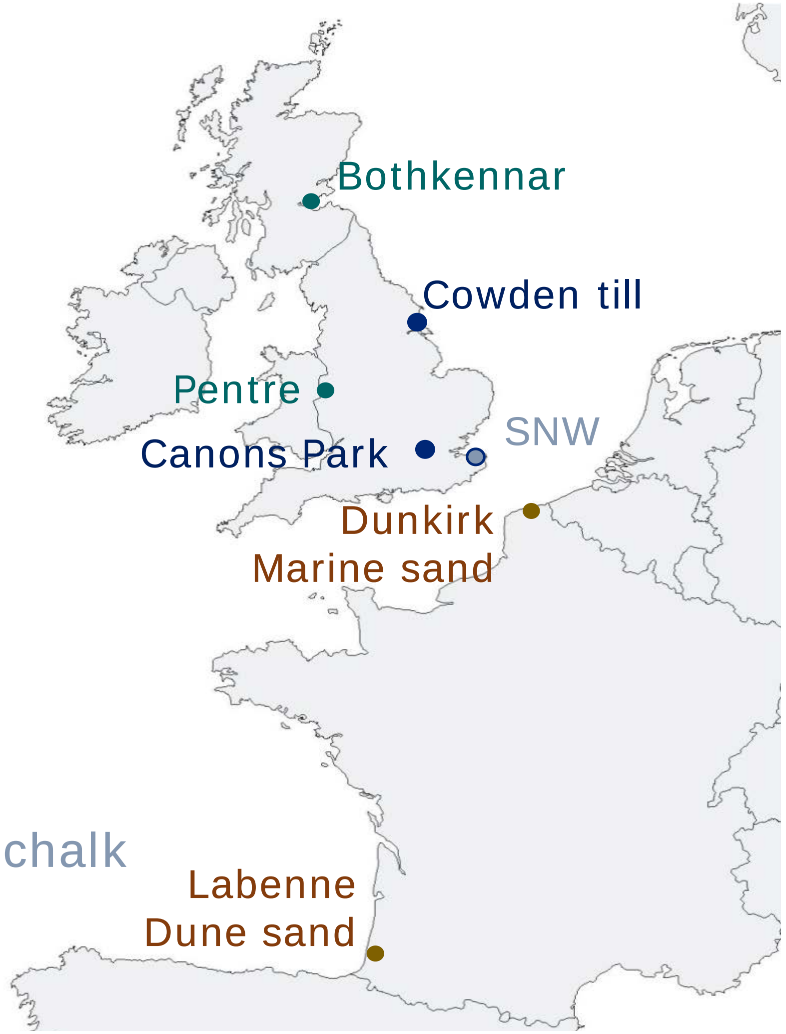
Bothkennar & Pentre

Loose to dense sands

Labenne & Dunkirk

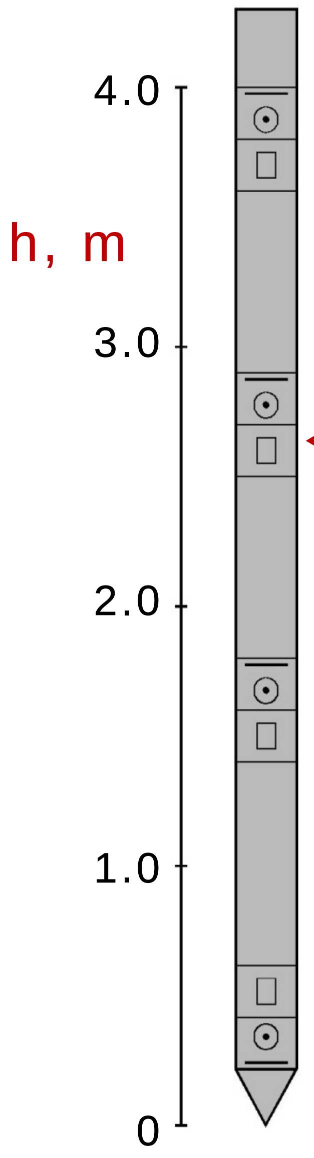
Low-to-medium density chalk

St Nicholas at Wade



Parallel studies on open driven piles

Installation; equalisation & loading to failure 102mm D

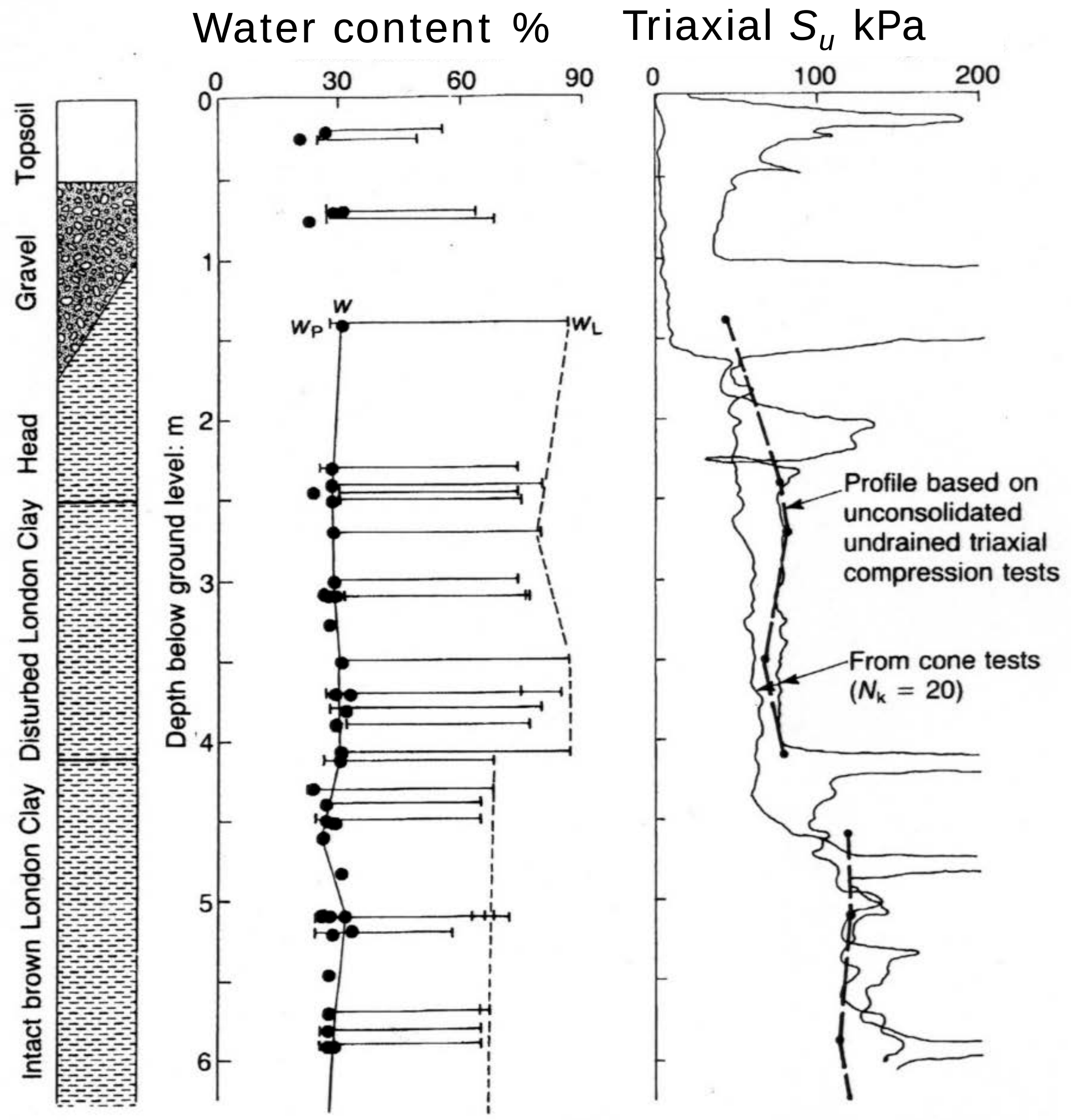


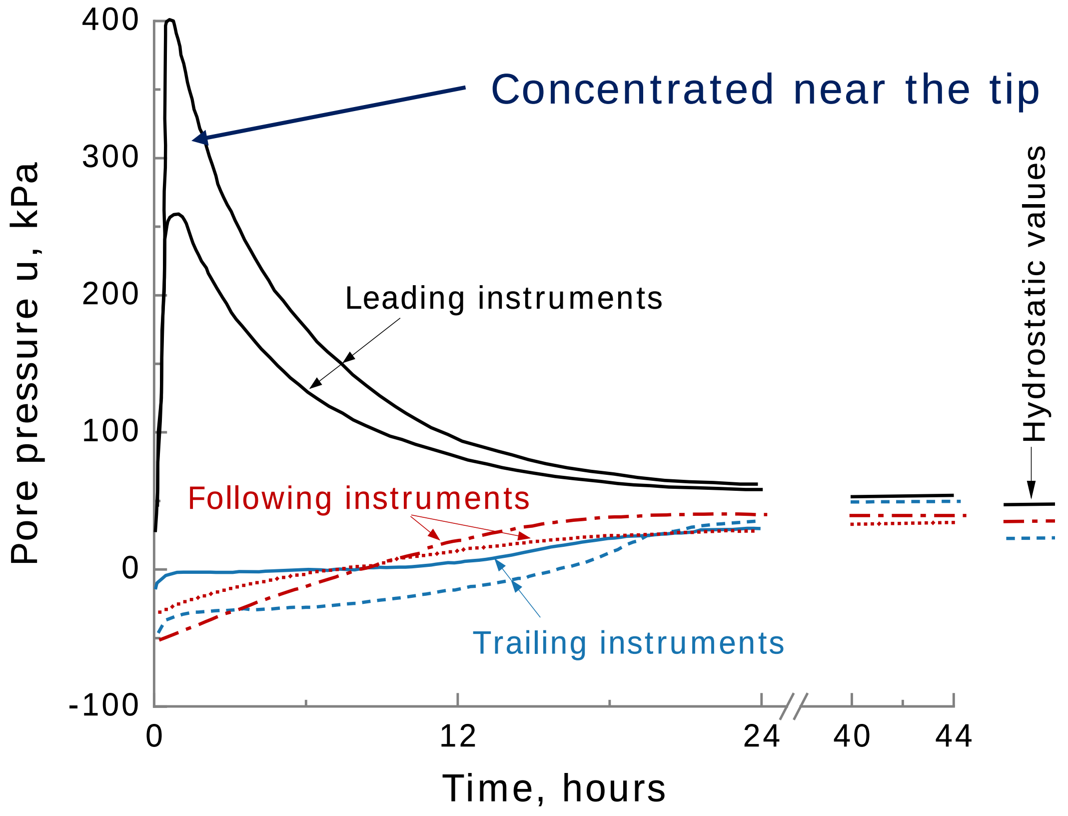
SSTs at 4 h/R levels measure shear τ, radial stresses σ_r & pwps u

Installation pore pressures & dissipation at Canons Park

Bond & Jardine (1991)

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





Equalised in 2 days

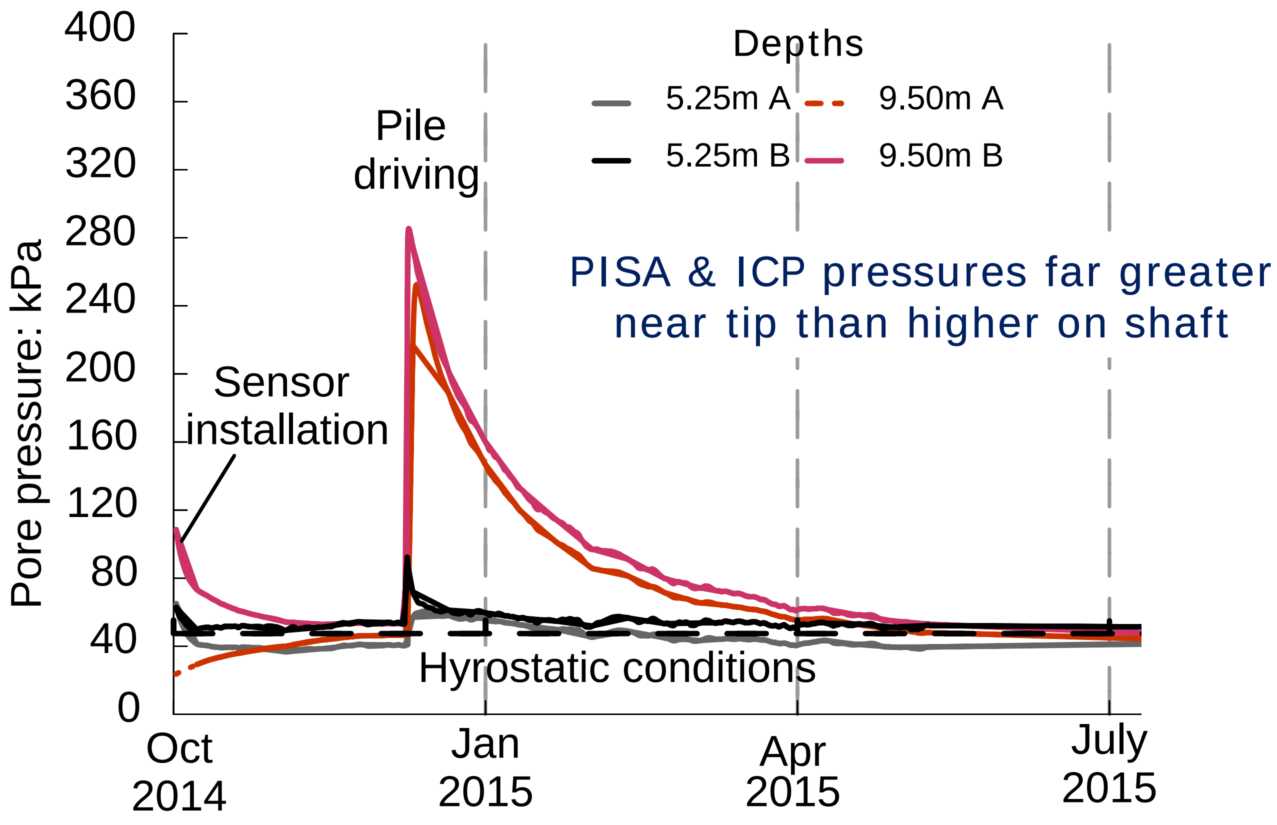
1D Cavity Expansion & 2D Strain Path analyses
Struggled to match ICP observation sets

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

Low I_p, high YSR: Lehane & Jardine (1994a), Zdravkovic et al. (2020), Ushev & Jardine (2022)

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 $D* = [D^2{}_{outer} - D^2{}_{inner}]^{0.5} = 2R*$

If plugged $D* = D$

Near-tip t_{95} times, in days

	Measured	Predicted
102mm ICP	≈7	6.4
2m PISA pile	≈100	≈114
3m diameter, 50mm t_w coring offshore pile		≈256

Near tip t_{95} projections, in days, for 3m piles from other pile test site records

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

Dissipation could take years offshore, much faster if laminae or fissures are present

Shaft capacity (Q_s) setup Λ ratios due to consolidation

Λ = static capacity at $t \approx t_{95}$ / rate-corrected installation resistance

Examples from cases with installation data, all with $30 < L/D < 55$

		Λ	
Low YSR, high k Laminated clay-silt	Pentre, LDP, 762mm Clarke 1993	2.4	Very short t_{95} Λ cut by partial drainage?
Low YSR, low k Organic high I_p	Bothkennar, ICP, 102mm Lehane & Jardine 1994	3.6 to 4.1	Reducing with L/D
High YSR, high k Fissured, high I_p	Canons Park, ICP, 102mm Bond & Jardine 1994	1.1	Similar at Cowden
High YSR, low k Low I_p till over high I_p Oxford clay	Tilbrook Grange, LDP, 762mm Clarke 1993	1.3	Note $t_{95} \approx 300$ days Λ boosted by corrosion? Short-term Λ up to 1.5 at offshore scale: see paper

‘Consolidation Λ’ 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 $\sigma'_{rf} = 0.8\ \sigma'_{rc}$ $\sigma'_{rc} = K_c\ \sigma'_{v0}$ h/R = relative pile tip depth R = radius

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

Needs reliable YSR, S_t and δ' 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)

$$\tau_{rzf} = 0.07\ F_{st}\ q_t\ (h/R^*)^{-0.25} \quad h/R^* \geq 1$$

Much simpler & less 'operator dependent', but lacks site-specific δ' & S_t information

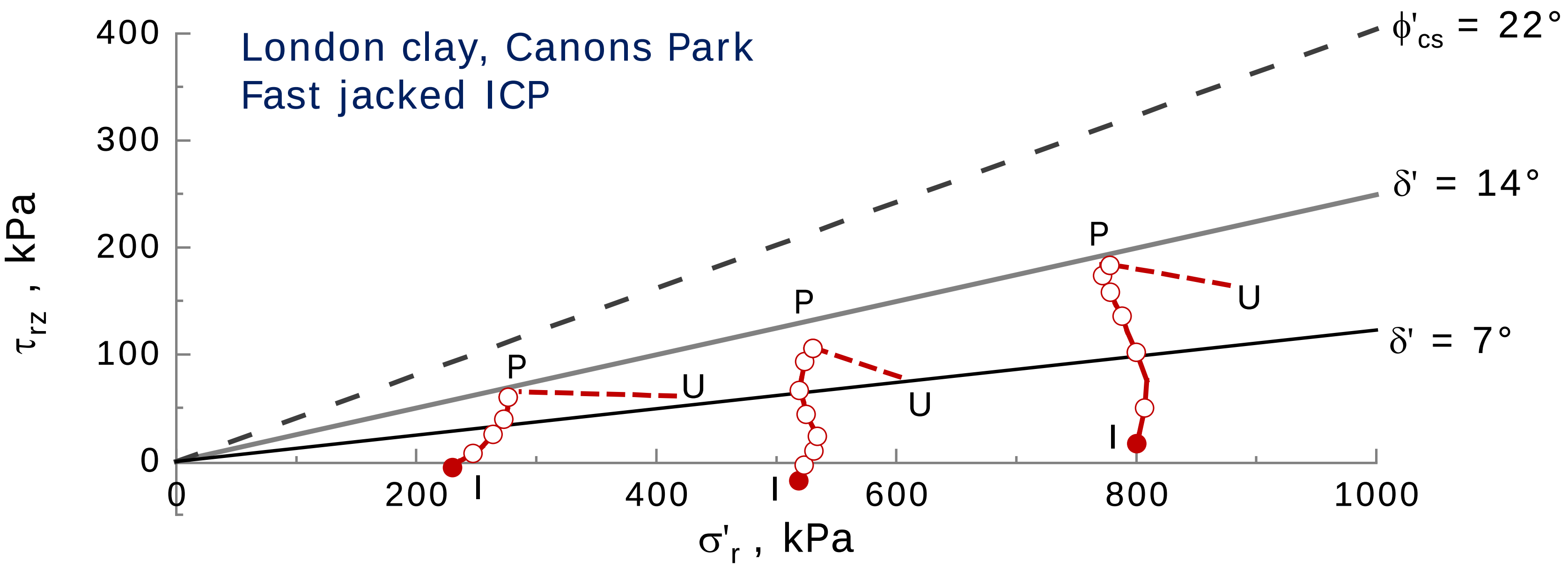
Importance of interface shear angles Bond and Jardine (1991), (1994)

Local ICP shaft τ_{rz} - σ'_r paths

Plus shear zone fabric studies

Prove Coulomb shaft failure

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



Near-residual interface fabric: δ'_{peak} = 13º falls post peak to δ'_{ult} = 8º

ICP tests in I_p = 40±10% Bothkennar clay showed δ'_{peak} = 29º = δ'_{ult} Lehane and Jardine (1994b)

Field δ' governed by grain shapes & minerals

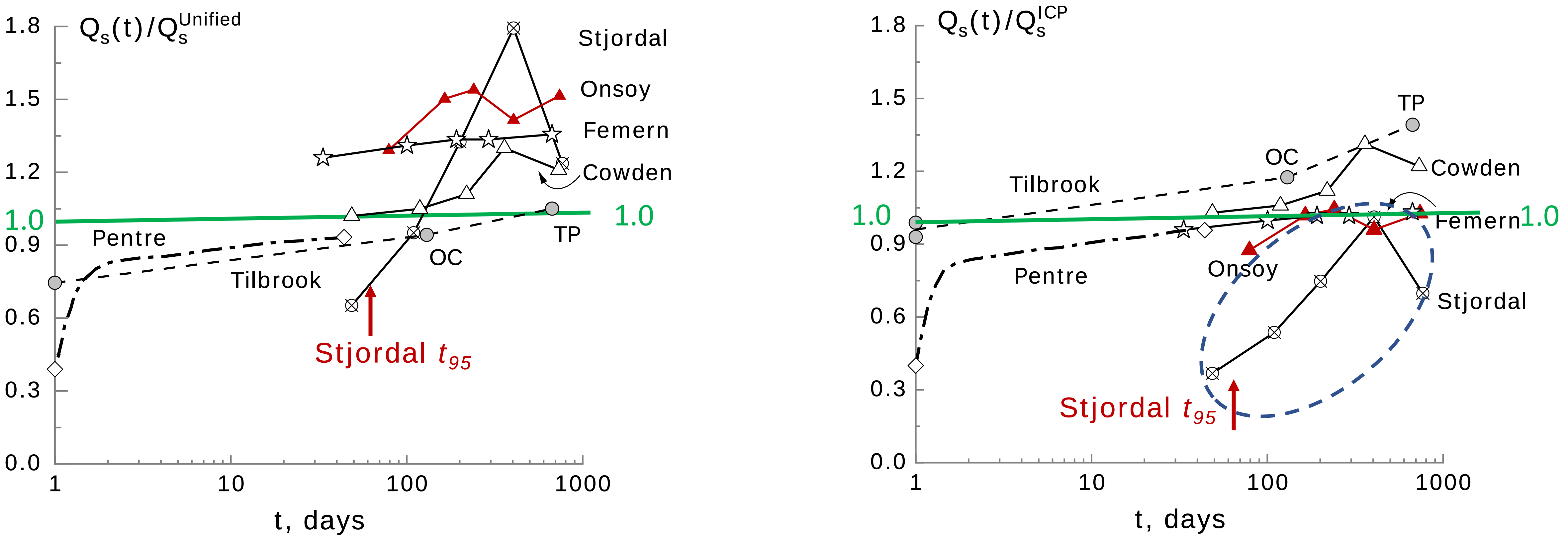
δ' correlates poorly with I_p but closely matches 'ICP-style' lab ring-shear interface tests

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

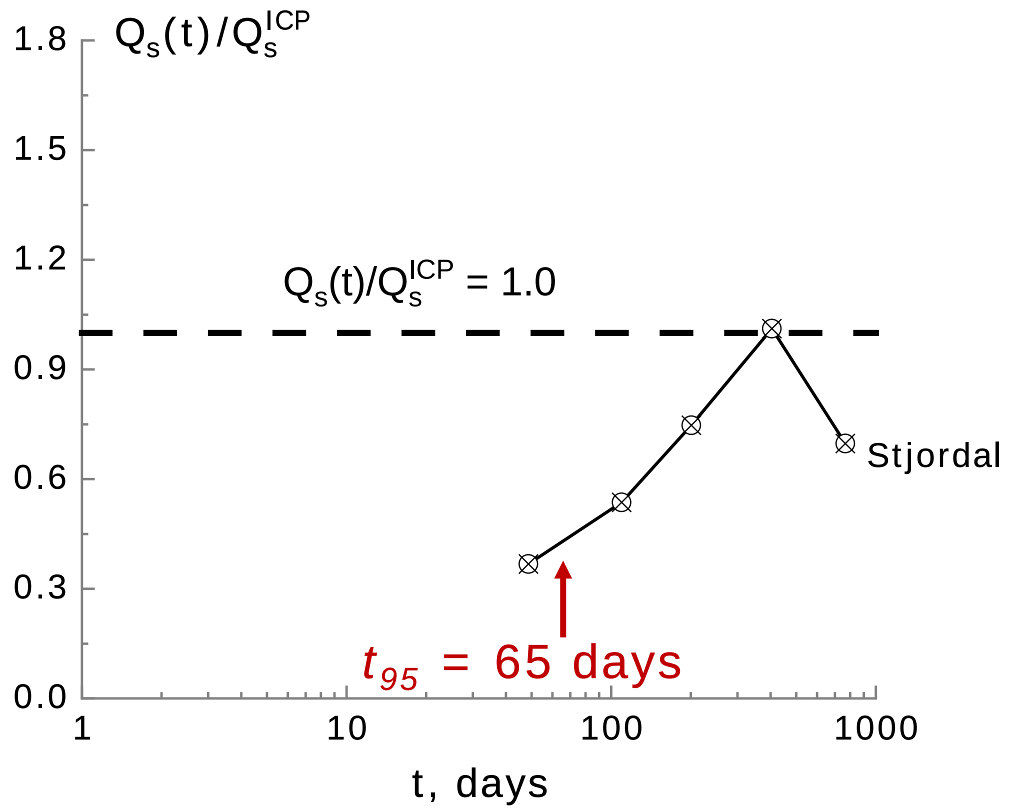
Normalised by ICP-05
Parameter derivation: see paper



Different spreads & method bias

$0.15 \leq Q_s$ gain/log cycle ≤ 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 φ'

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

Explanation?

Arching slowly released by creep?

Karlsrud et al. (1993), Ridgway & Jardine (2007)

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)

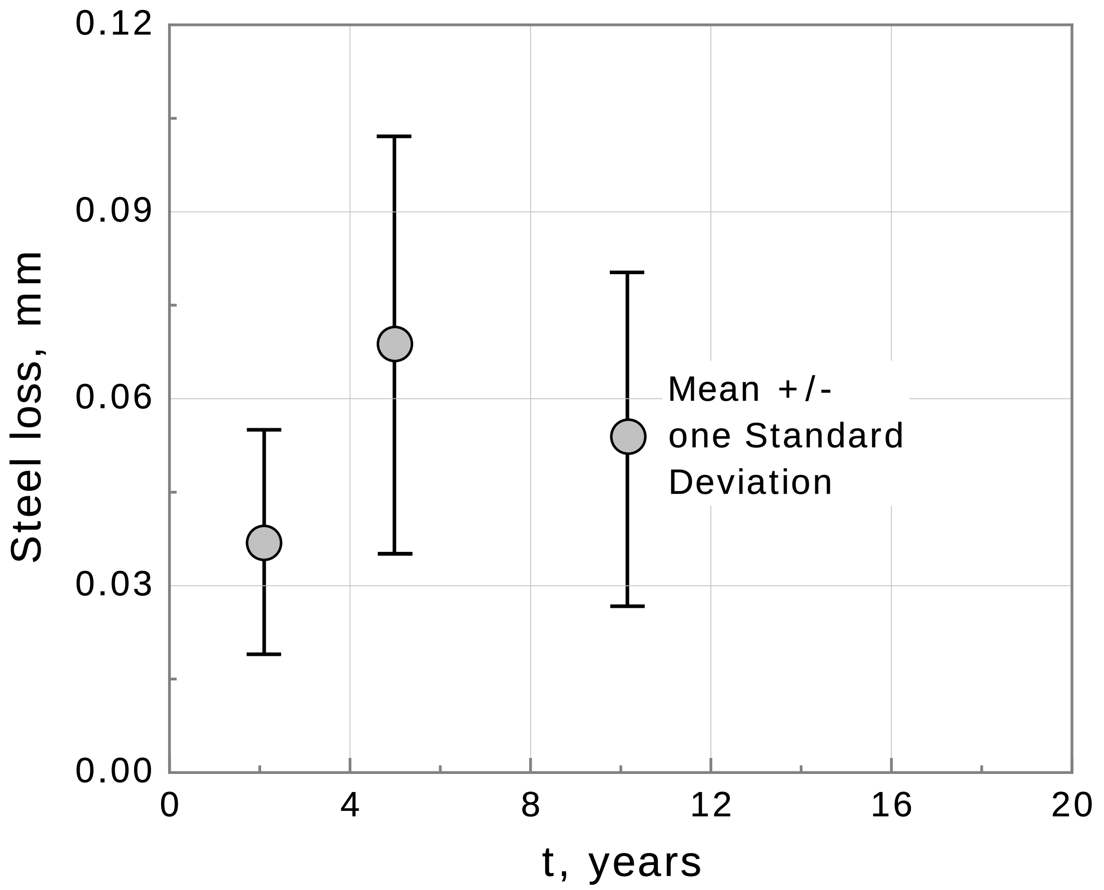
Reduce project risks with: CPT design method & reduction factors, or field tests: Schonberg et al. (2023)

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 Δr far exceeds steel Δt_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

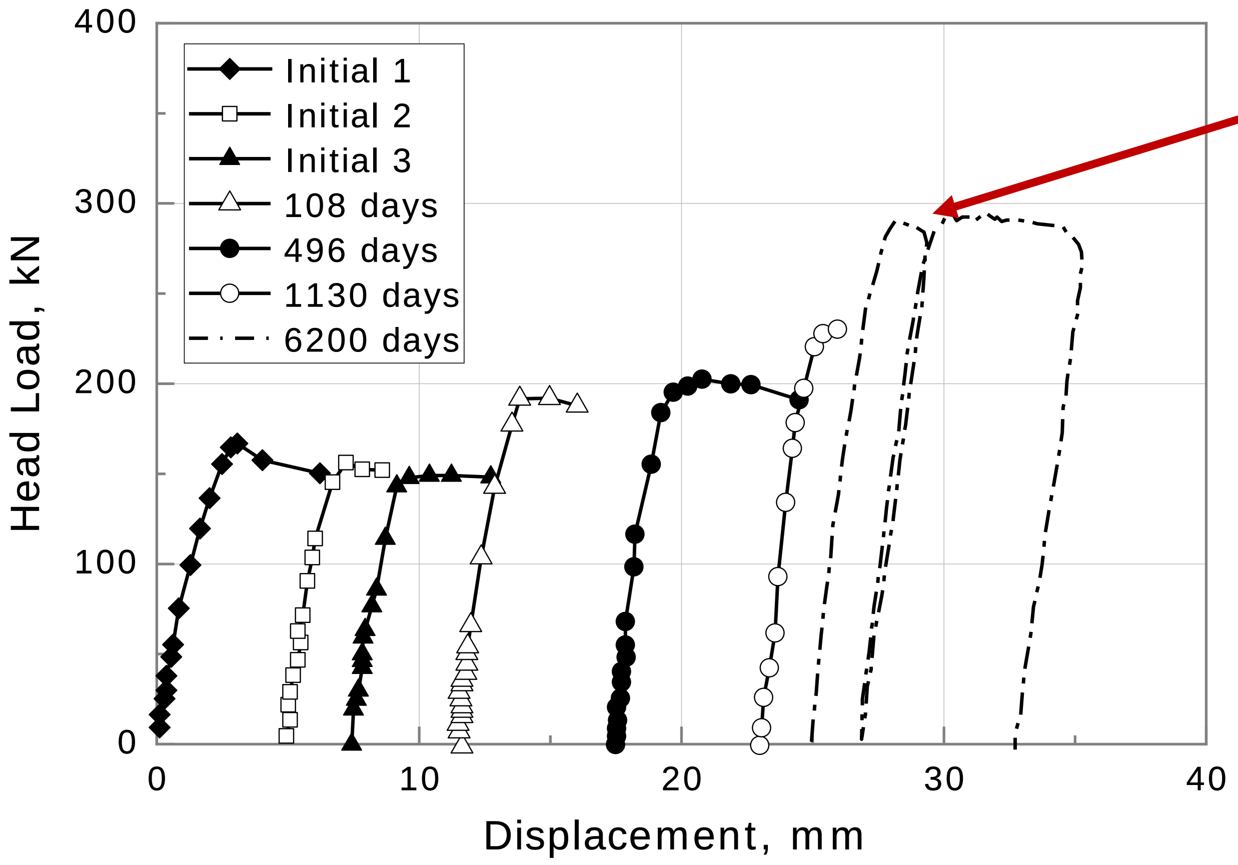
Pellew (2002), Pellew & Jardine (2008)

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 δ'_{peak} = 13º reducing towards ductile residual 8º

Marked gains in residual capacity after each extended pause



Pellew's tests, after 14 year pause

≈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

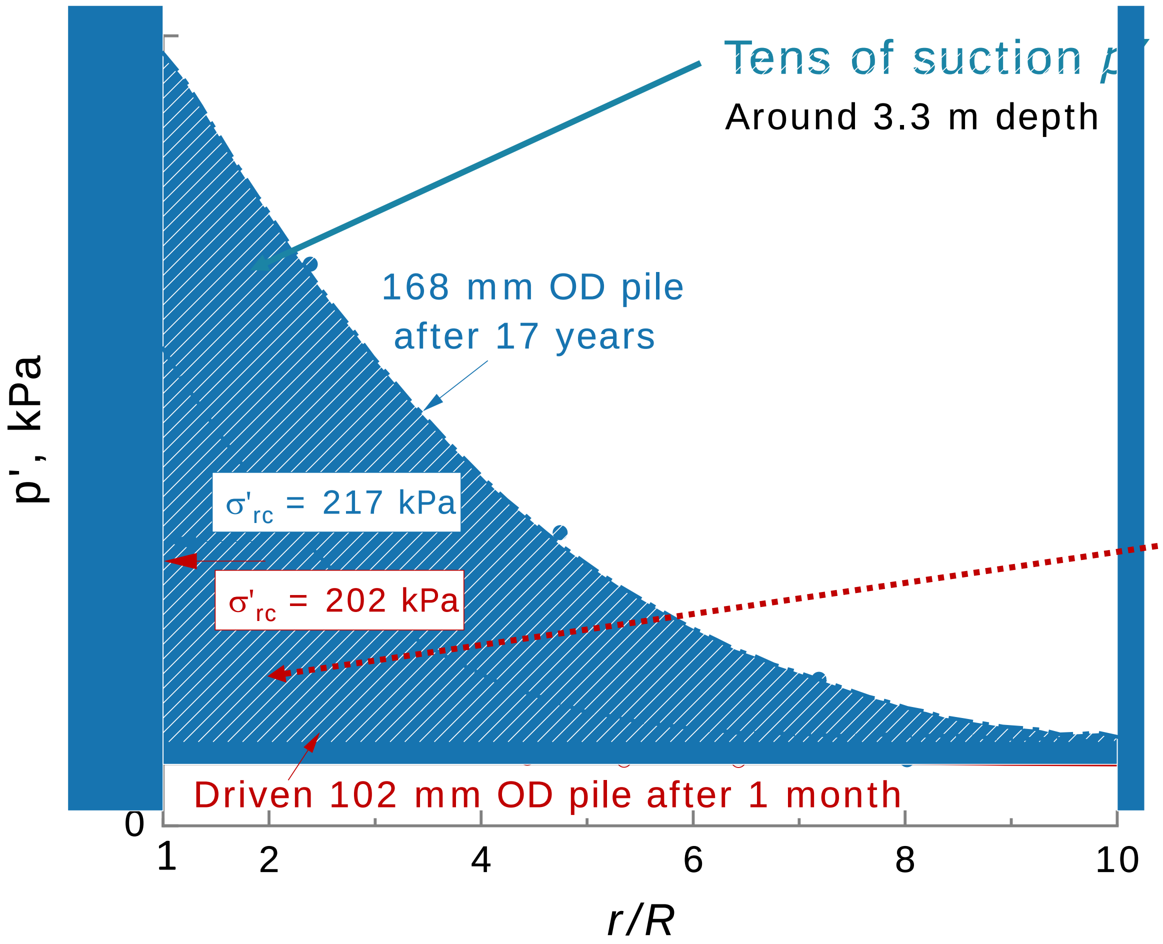
In-situ p' distributions measured

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



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

After 17 years:
Near shaft mean p' ≈2.5 times higher
Residual shaft capacity ≈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

$\Delta\sigma_r \approx 230$ kPa after $\Delta r/R = 0.6\%$ cavity strain while pile $\Delta p' \approx 270$ kPa

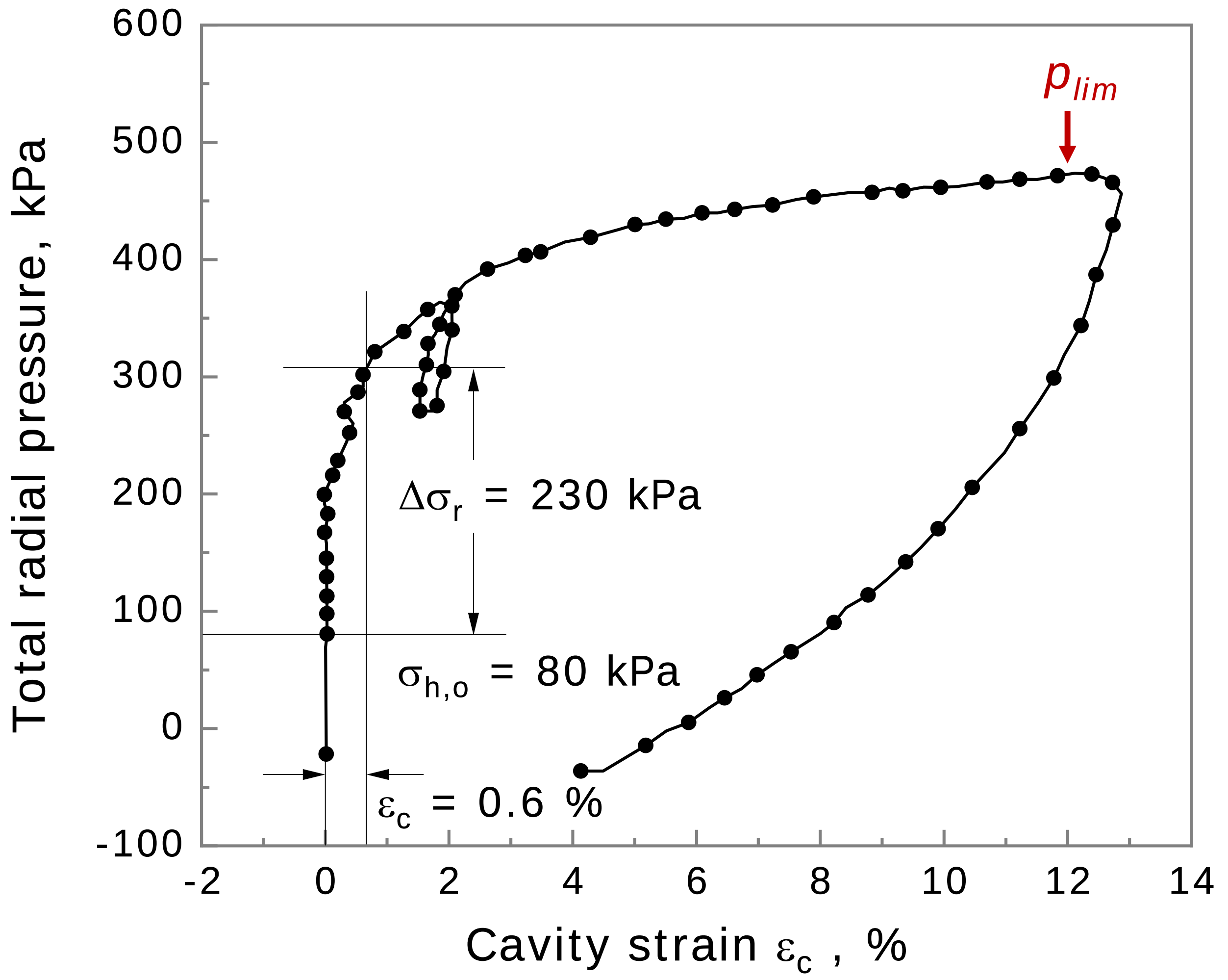
Final field p´ ≈ 450 kPa comparable to cavity expansion limit p_{lim}?

Cavity strains invoked by given corrosion Δr increment scale with $1/D$

So σ'_{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)

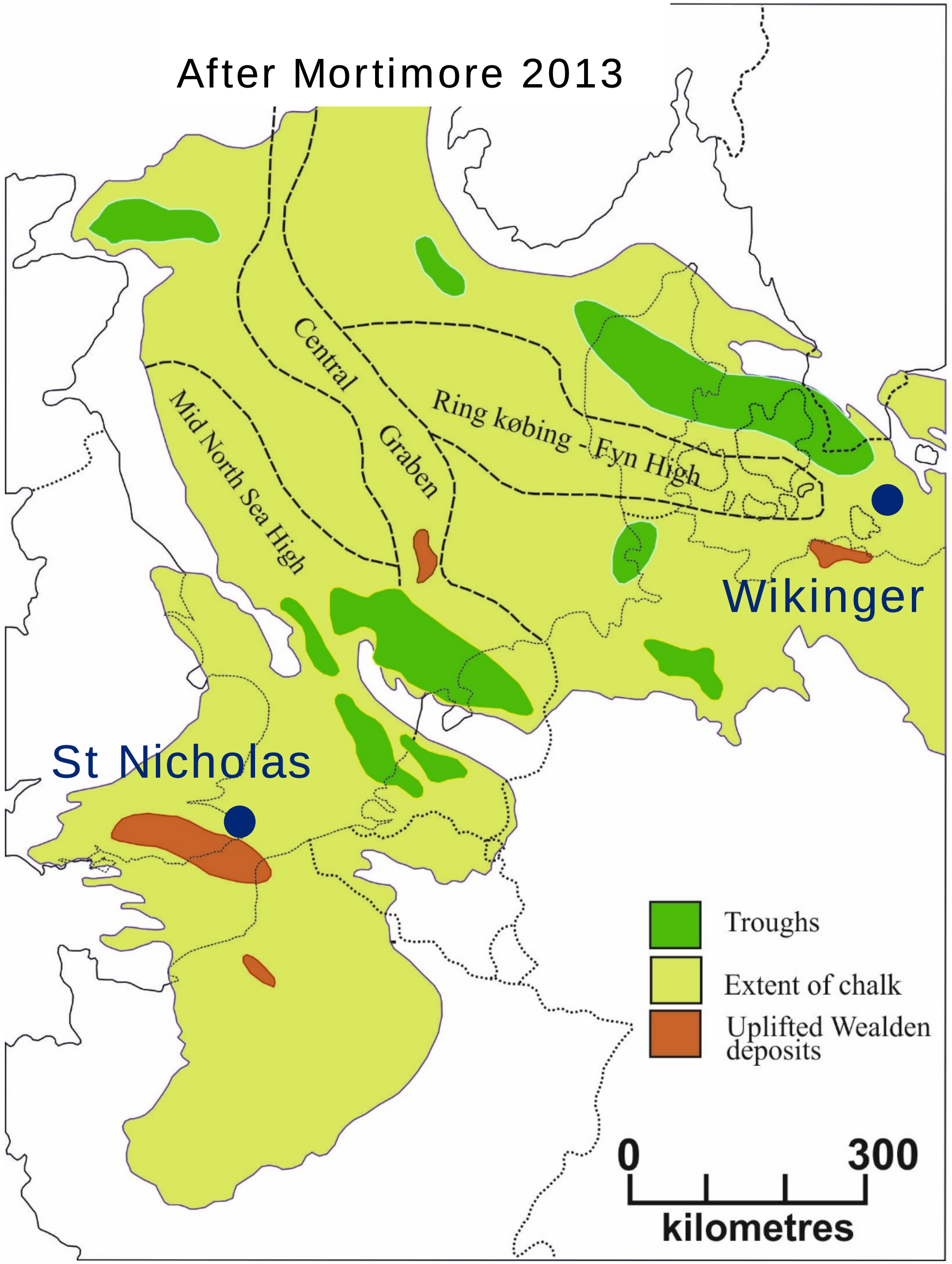
CIRIA 574: 20 kPa τ_{rzf} for open driven piles, based on very limited information

Onerous consequences, led to closer investigation

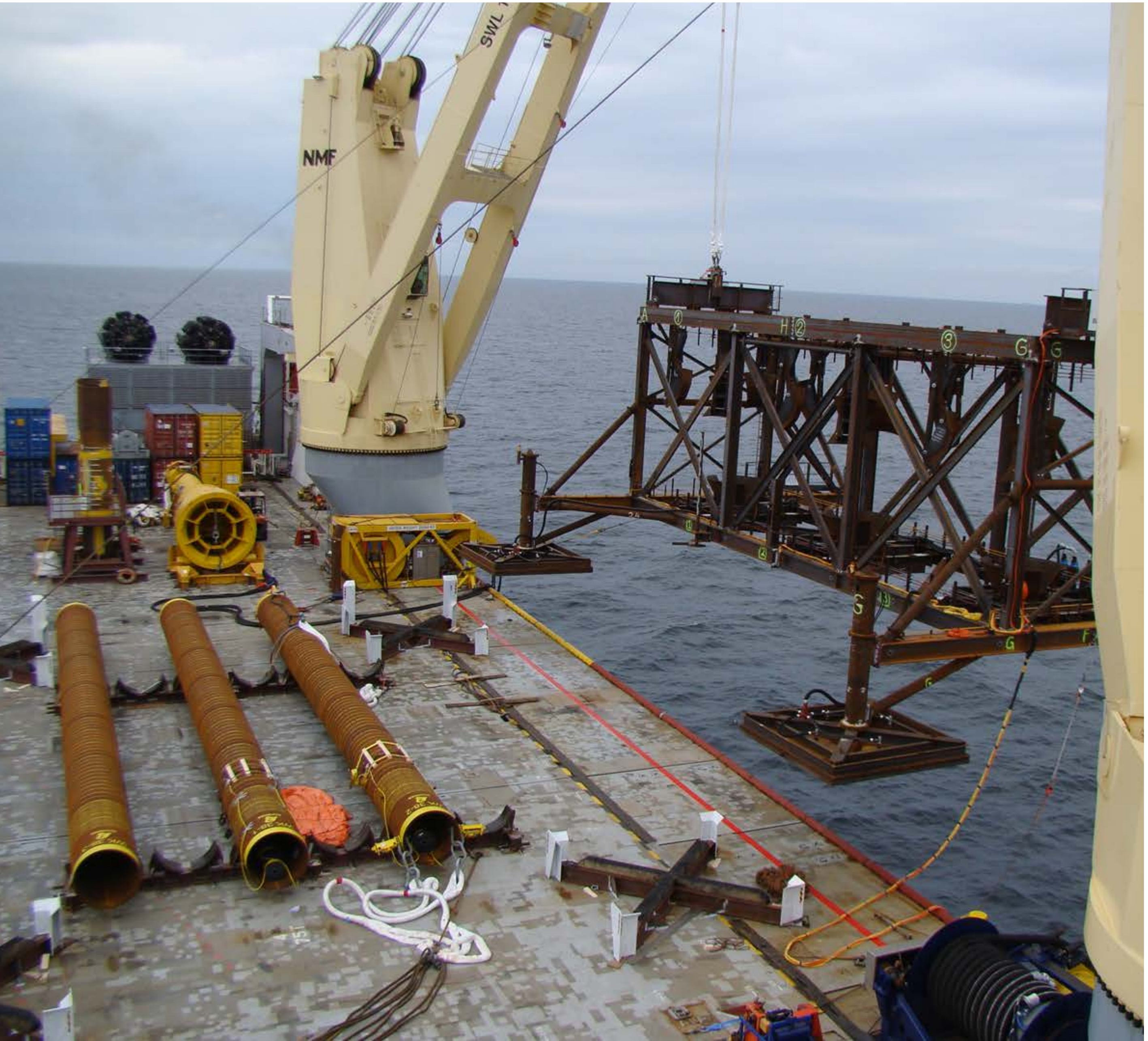
Large-scale offshore testing: Wikinger, German Baltic

Linked research at St Nicholas at Wade

Buckley (2018)



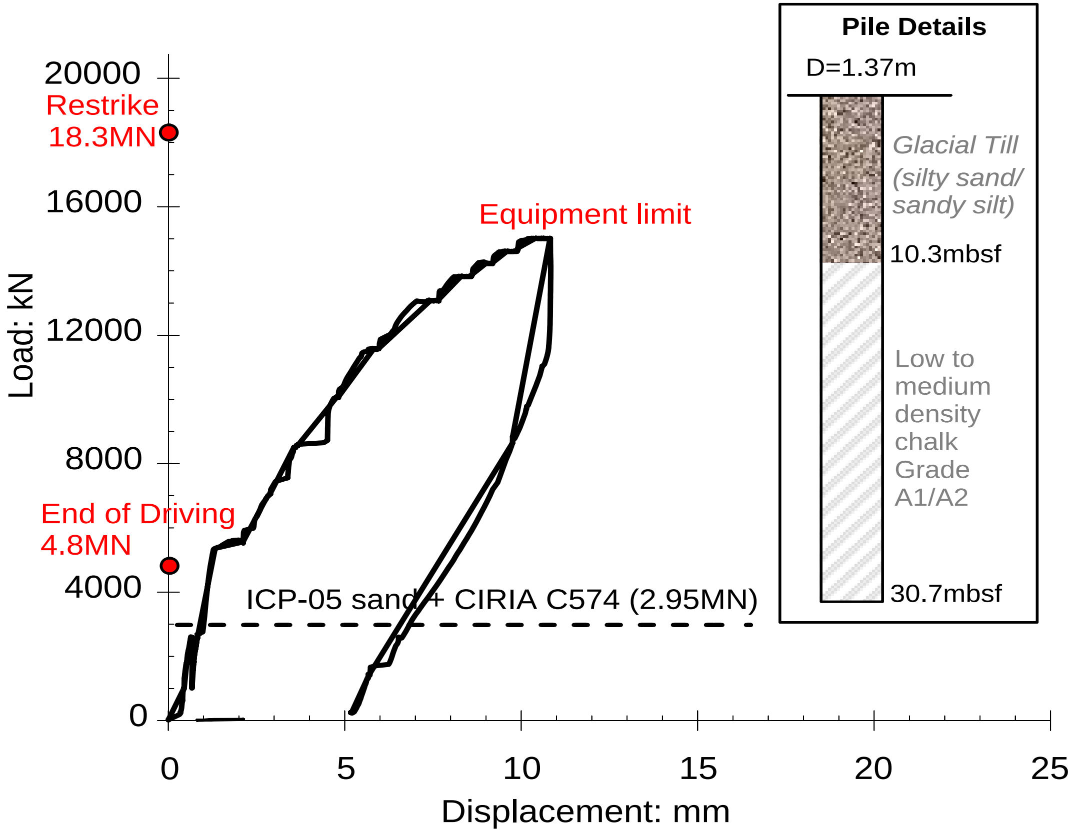
Wikinger: trial pile tests in 40m water Barbosa et al. (2015), Buckley et al. (2020)



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 Λ > 4 at 100 days

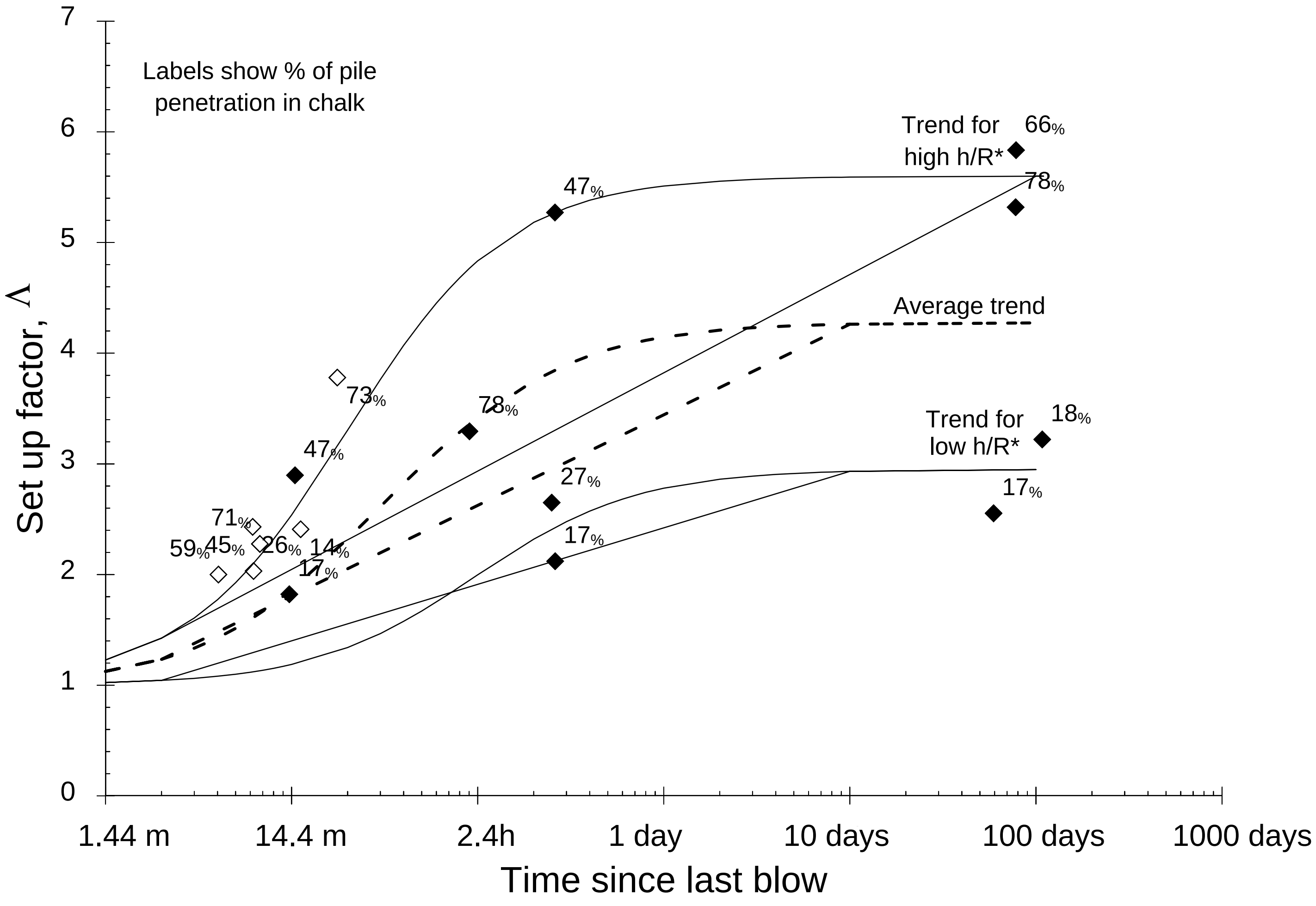
Tentative Chalk ICP-18, analogous to sand ICP-05 Buckley (2018), Jardine et al. (2018)

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



ALPACA & ALPACA Plus JIPs at SNW with Oxford 2017-2022

Forty-three driven piles: 0.14 to 1.8m D, range of geometries & materials Jardine et al. (2023a, b)

Driving 508mm piles, Nov 2017

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 τ_{rzf} profiles on driving & testing

1.22m & 1.8m piles, Oct 2020

Parallel cyclic & lateral loading programmes

Low-to-medium density, B2/B3 grade, chalk

Weathered layers removed by earlier quarrying

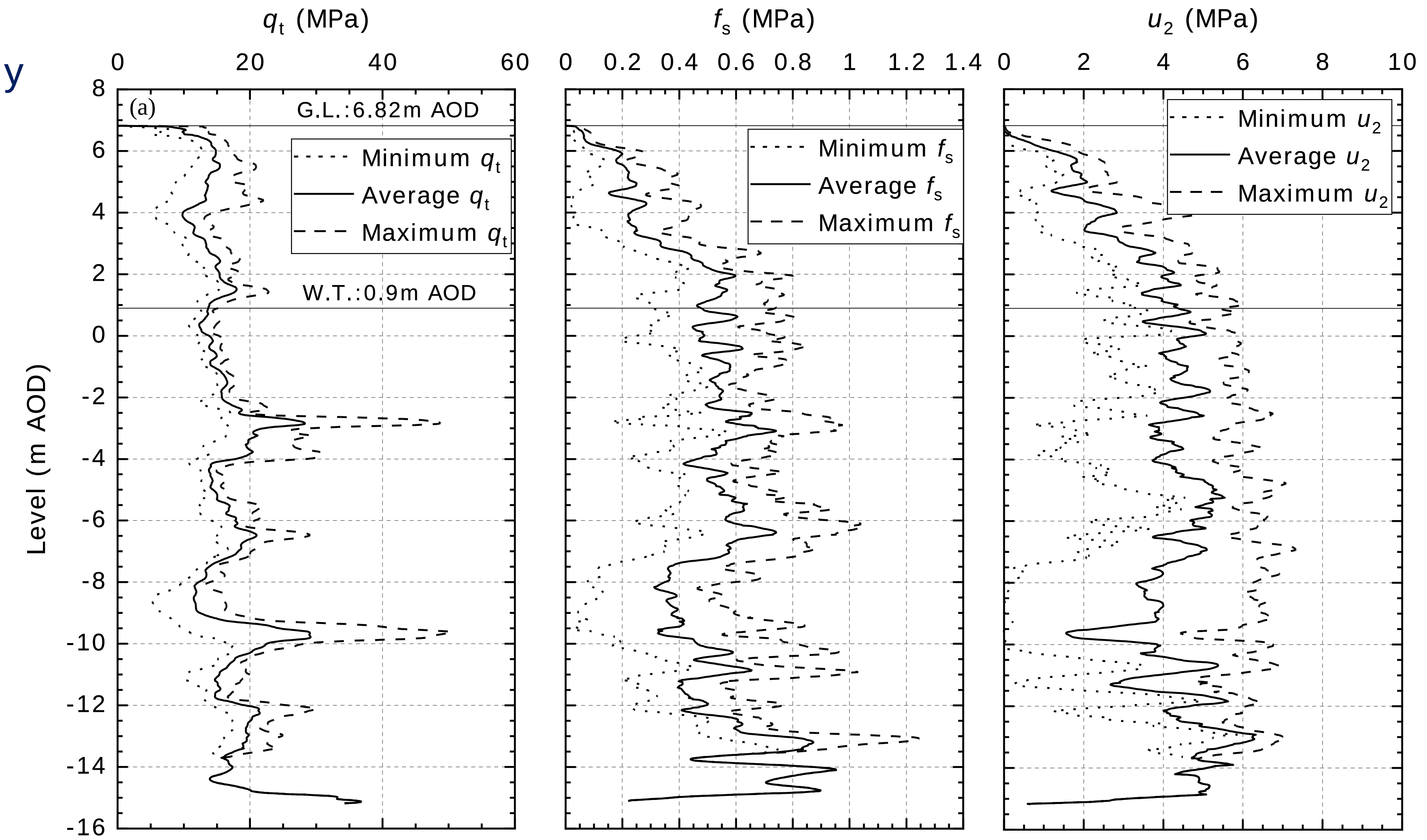
CPTu profile for each pile, dissipation tests

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 ≈t_w thick, reconsolidates & governs axial response

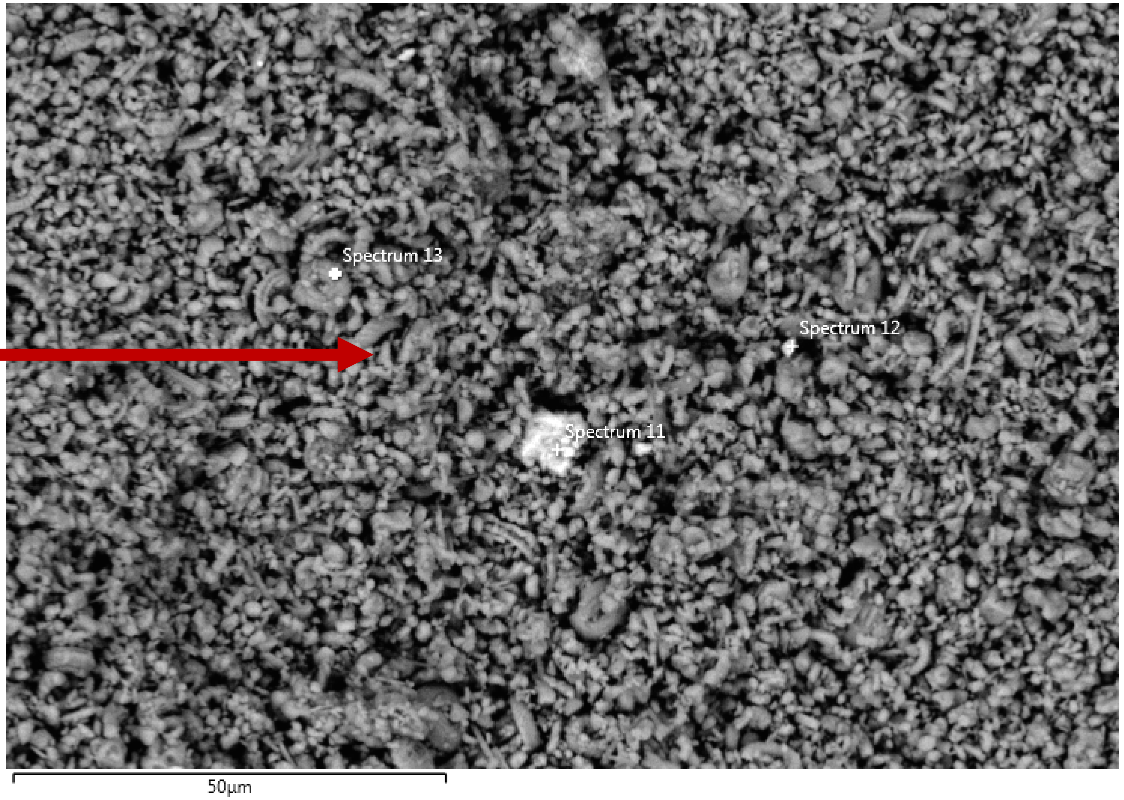
Long-term corrosion at interface, faster above water table

Additional fracturing to ≈10 t_w from shaft

Putty chalk under SEM

Livia Cupertino Malheiros

Coccoliths ruptured by driving, release water



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

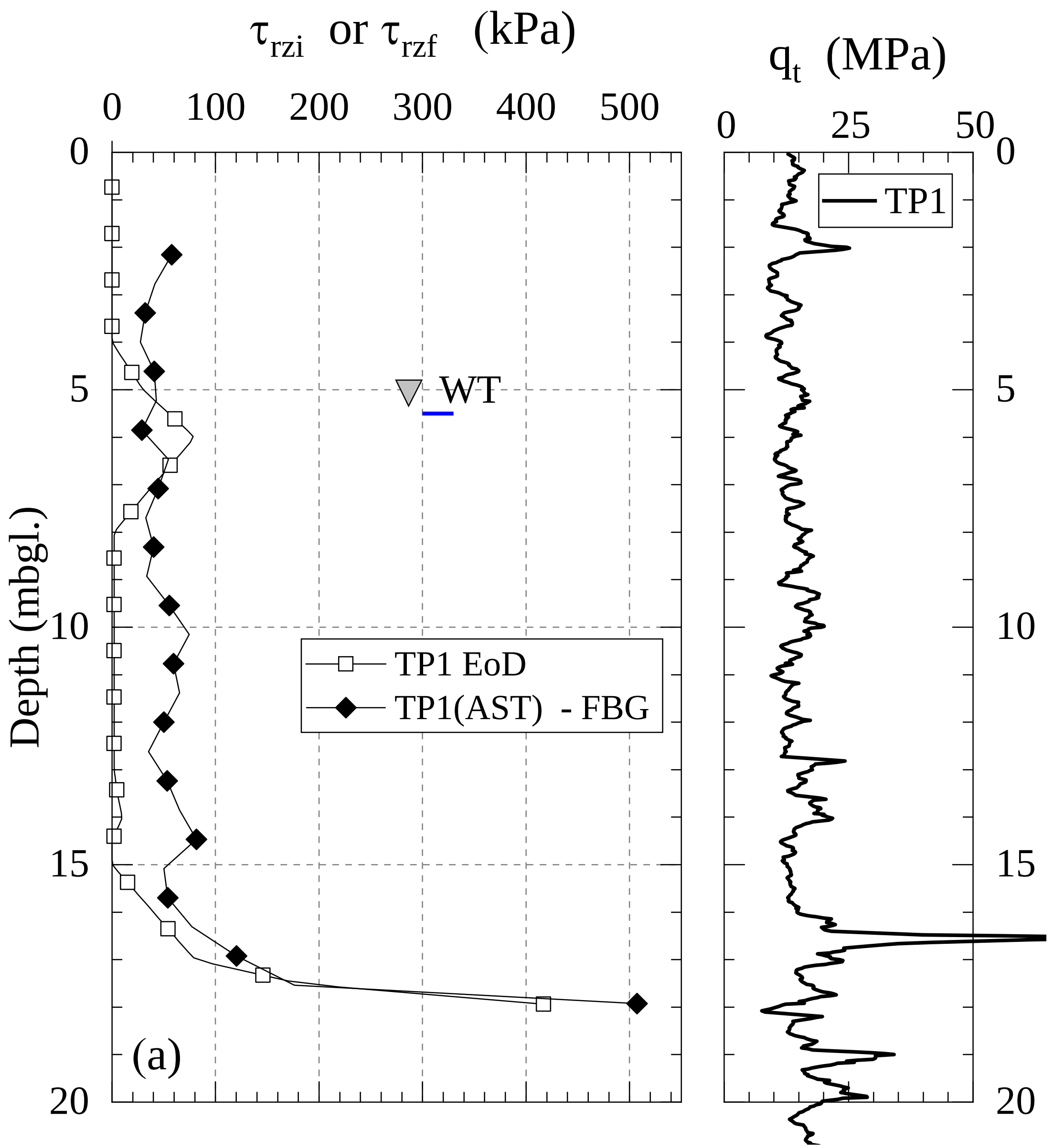
τ_{rzf} proportional to q_t, falls steeply with h/R

Chalk ICP-18 works for driving SRD

Compression shaft capacity ≈ double tension

'Like-for-like' Λ = 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 Λ most marked for $L/D \leq 15$

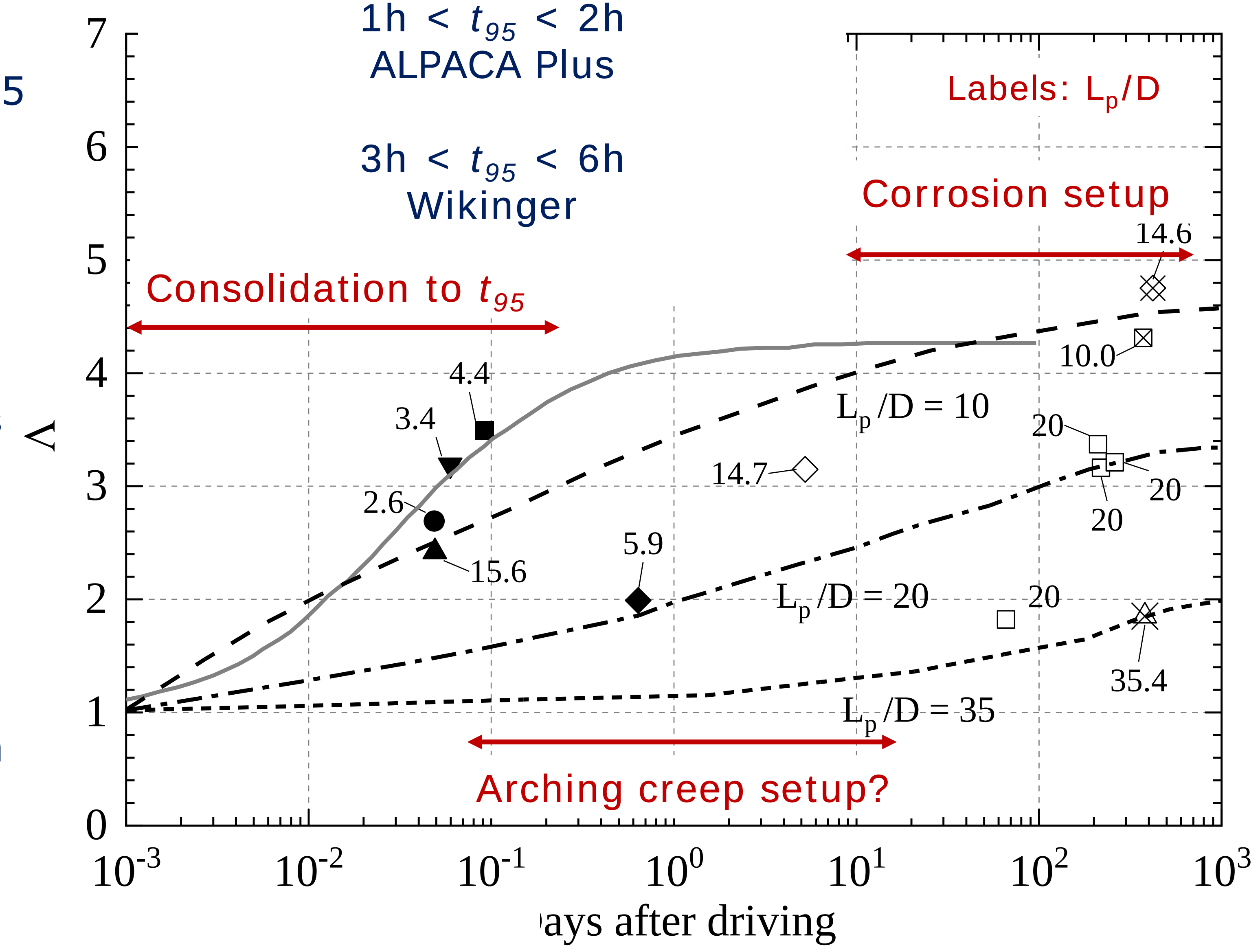
Corrosion Λ only with mild steel piles, none with stainless steel or concrete

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



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°

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

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

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

Mean Q_m/Q_c = 1, CoV = 0.16 for t ≥ 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

Lehane (1992), Lehane et al. (1993)
Chow (1997)

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* ≥ 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)

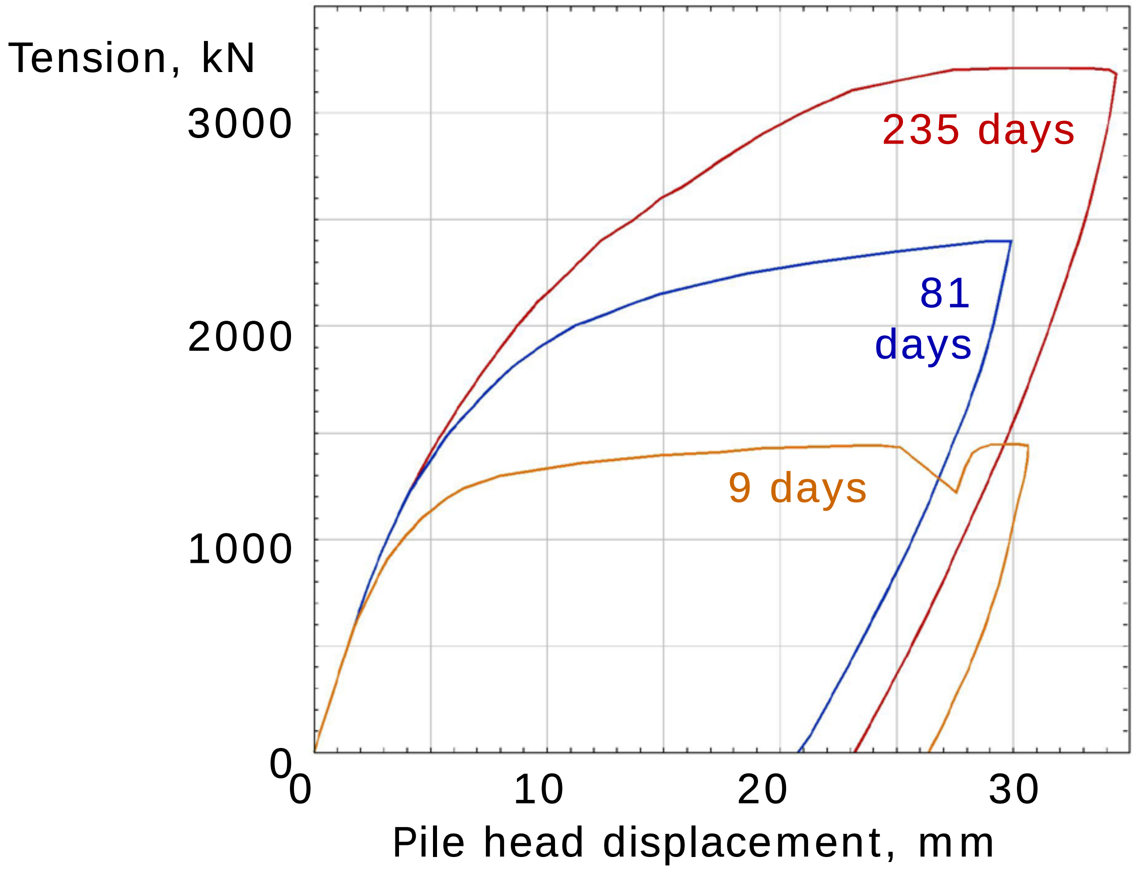
'Unified' A_{re} expression fitted to agreed database, gives lower CoV

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

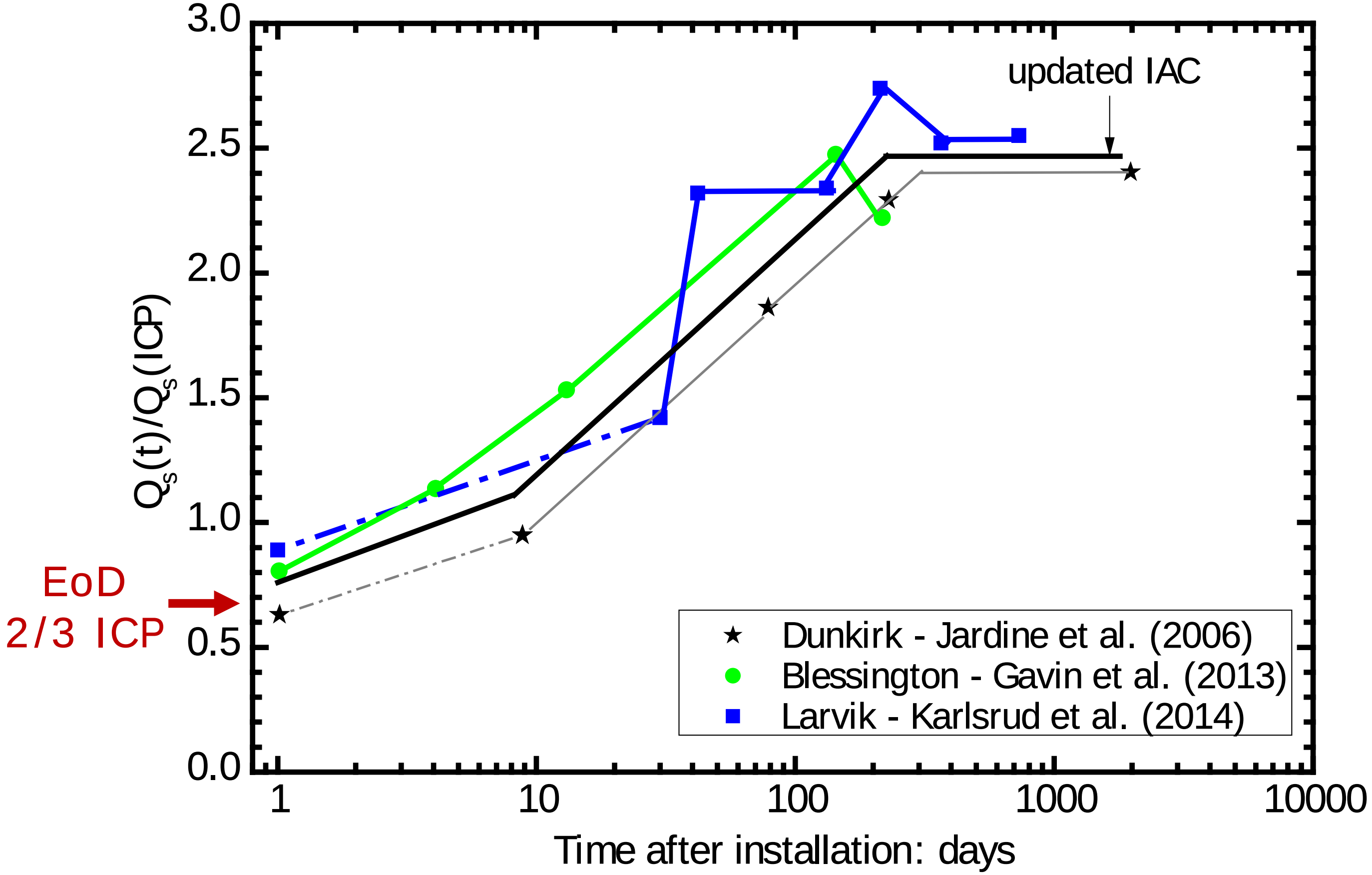
Effects of prolonged ageing?

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
Karlsrud et al (2014), Gavin et al. (2015)



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 $\sigma_{lateral}$ sensors on medium scale piles
Ng et al (1988), Axelsson (2000), Gavin et al. (2015)

Mixed evidence: direct measurement challenging, scaling uncertain

Fabric: Dense 'crust' with crushed grains around shafts: Kolk et al (2005), Yang et al (2010)

Interface dilation in lab tests & field $\sigma_{lateral}$ 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
Tavenas and Audy (1972), Axelsson (2000), Rimoy et al. (2015)

‘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

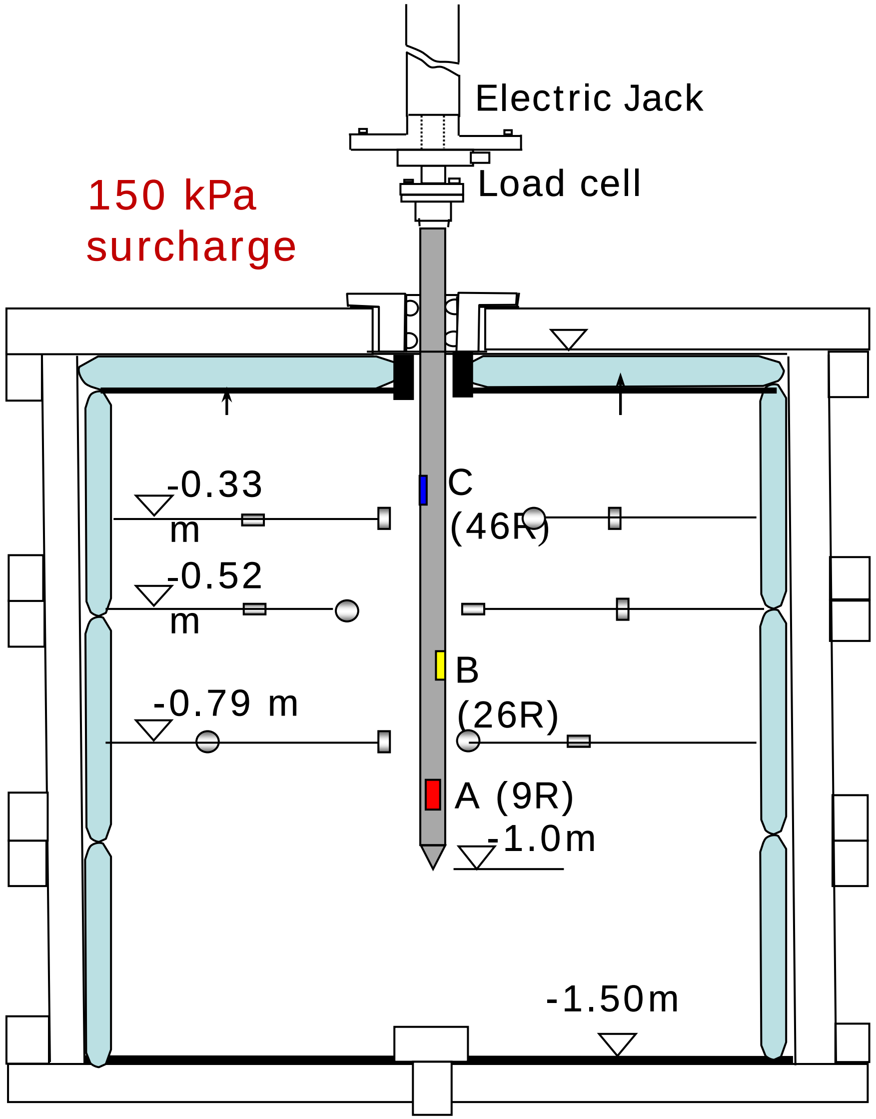
Clear evidence of σ'_r arching around pile shaft

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

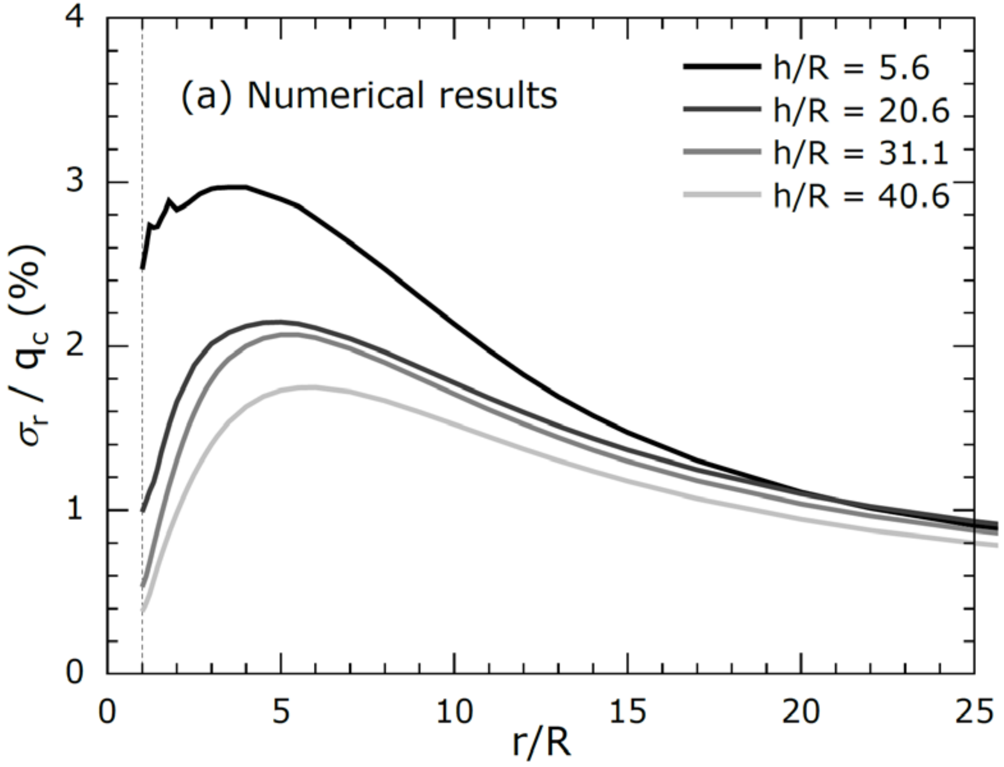


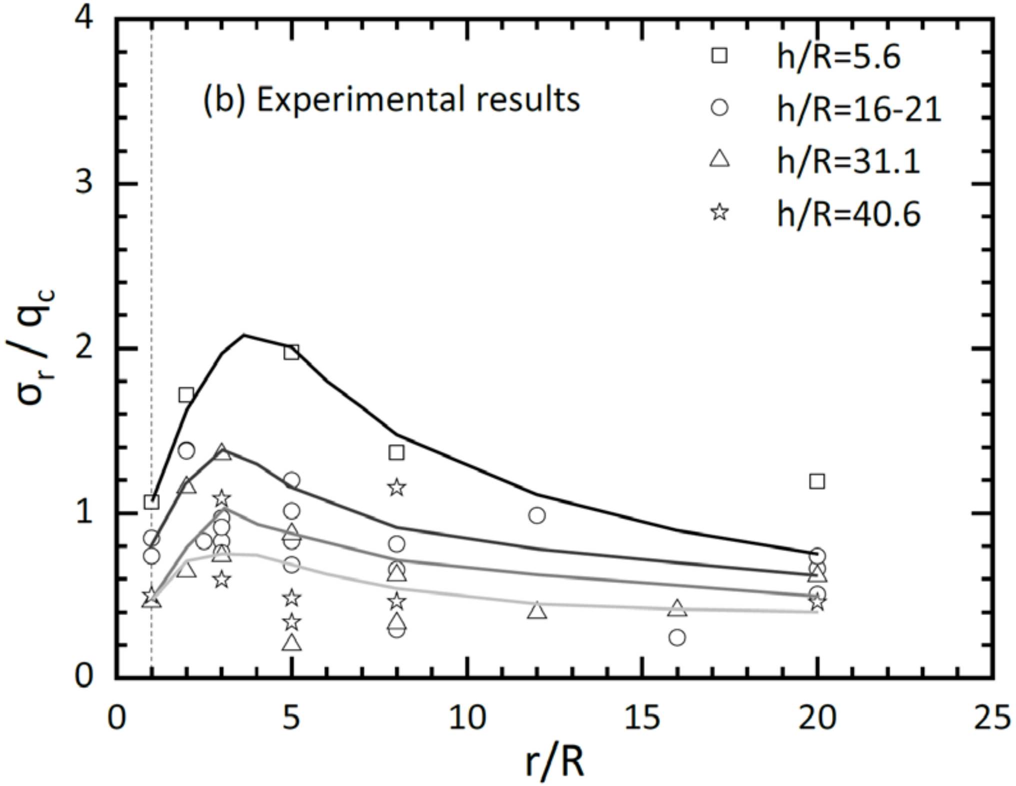
Grenoble 3S-R calibration chamber

PFEM analysis example Ye et al (2023)

Grain crushing, cyclic loading, open-ended geometry analyses; see paper

End of installation σ'_{rc} profiles, normalised by (computed & measured) CPT q_c



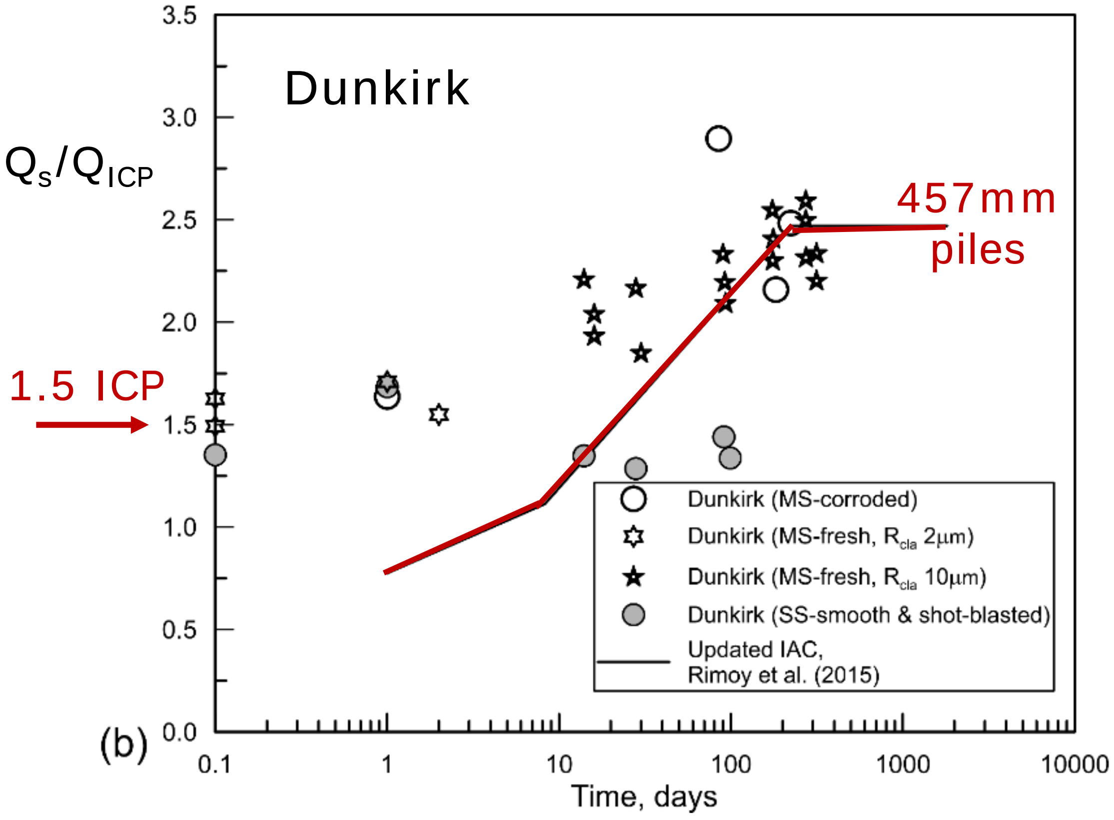


Captures most features of model tests well; quantifies & explains arching

But over-predicts σ'_{rc} & 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)



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

Exhumed after 2 years above water table

Stainless piles show no further setup, like lab

Bonded sand grains, anoxic shaft conditions

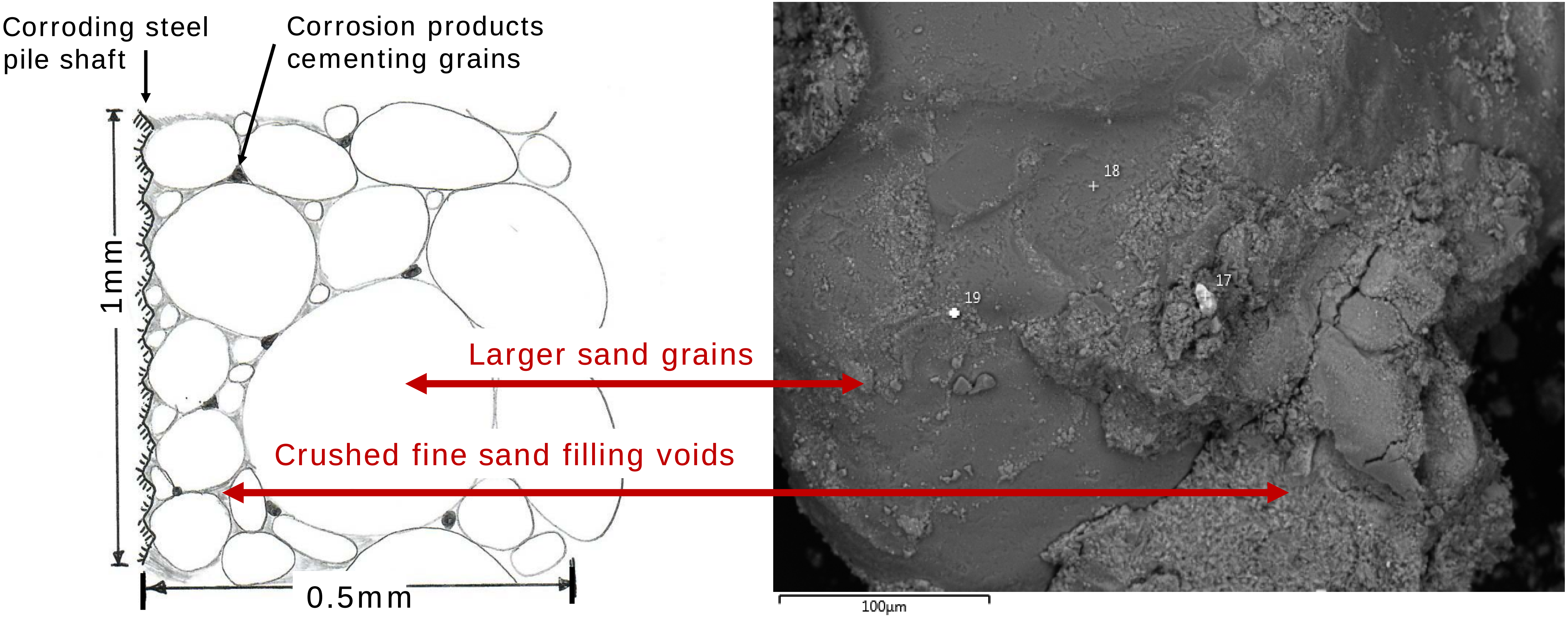
Mild steel piles setup markedly to similar final Q_s/Q_{ICP} as 457mm piles, but lower Λ

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



Shaft failure mechanism pushed out into surrounding sand

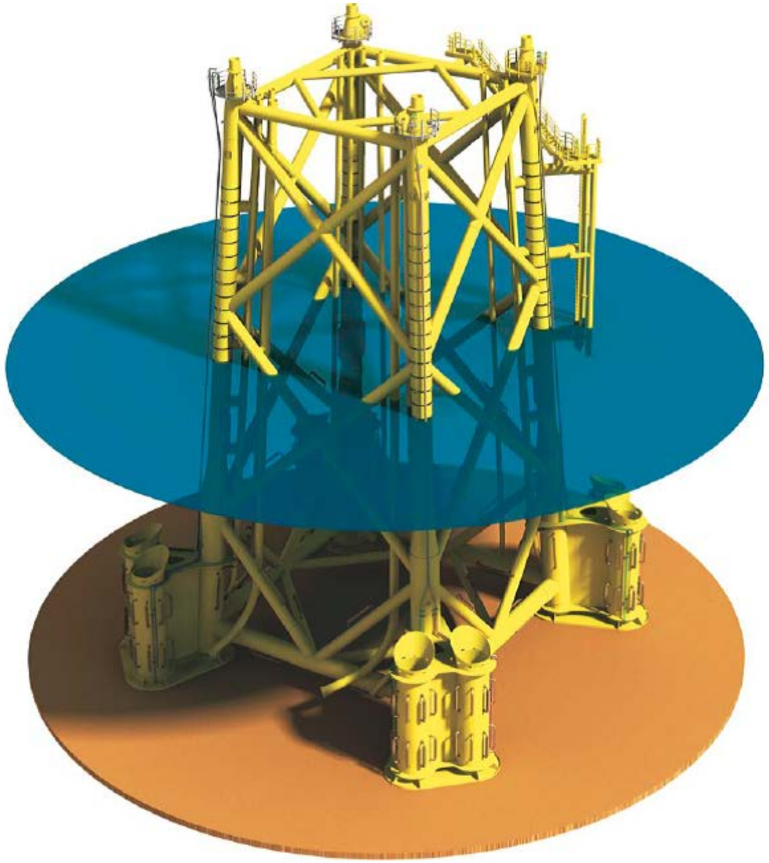
Interface shear tests show dilation displacement steps up from ≈$2R_{CLA}$ to exceed d_{50} see paper

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 Λ = 1.45
Jardine et al. (2015)



Followed by PAGE JIP

PAGE JIP Cathie et al. (2022)

25 unpublished, well-characterized, offshore cases
$76\% \leq I_D \leq 100\%$ (mean 85%). Mainly silica sands provide ≥75% Q_s & all Q_{base}

Piles
1.37 to 3.35m diameter: 2.8m mean ≈ 80 times mini-ICP
$8 \leq L/D \leq 53$ (16 mean)
18 to 67 D/t_w (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 $D < 0.8$m

New analyses of published EURIPIDES, Horstwalde, Tokyo Bay, Los Angeles port & other cases

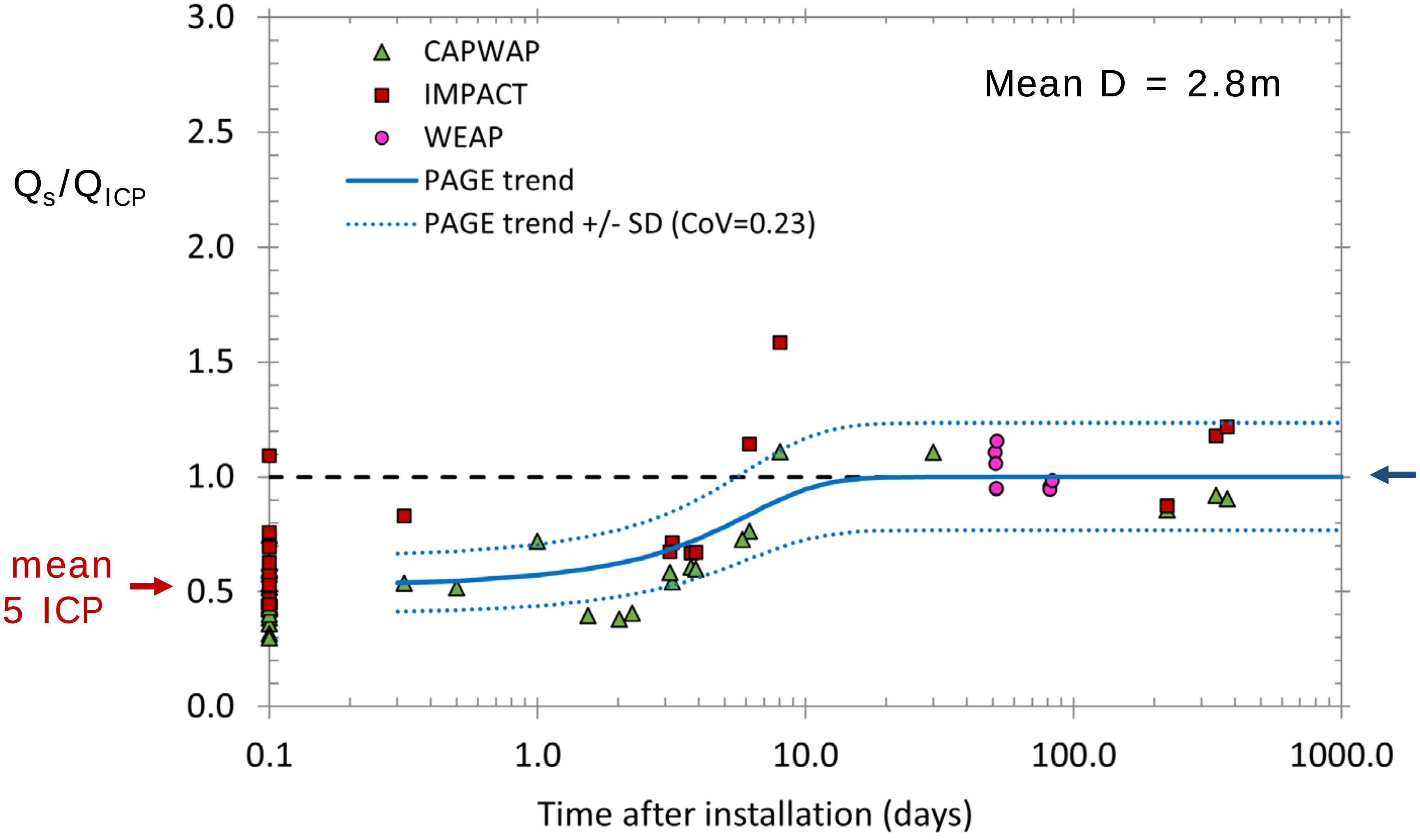
Base resistances: dynamic far lower than static

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

EoD mean = 0.5 ICP

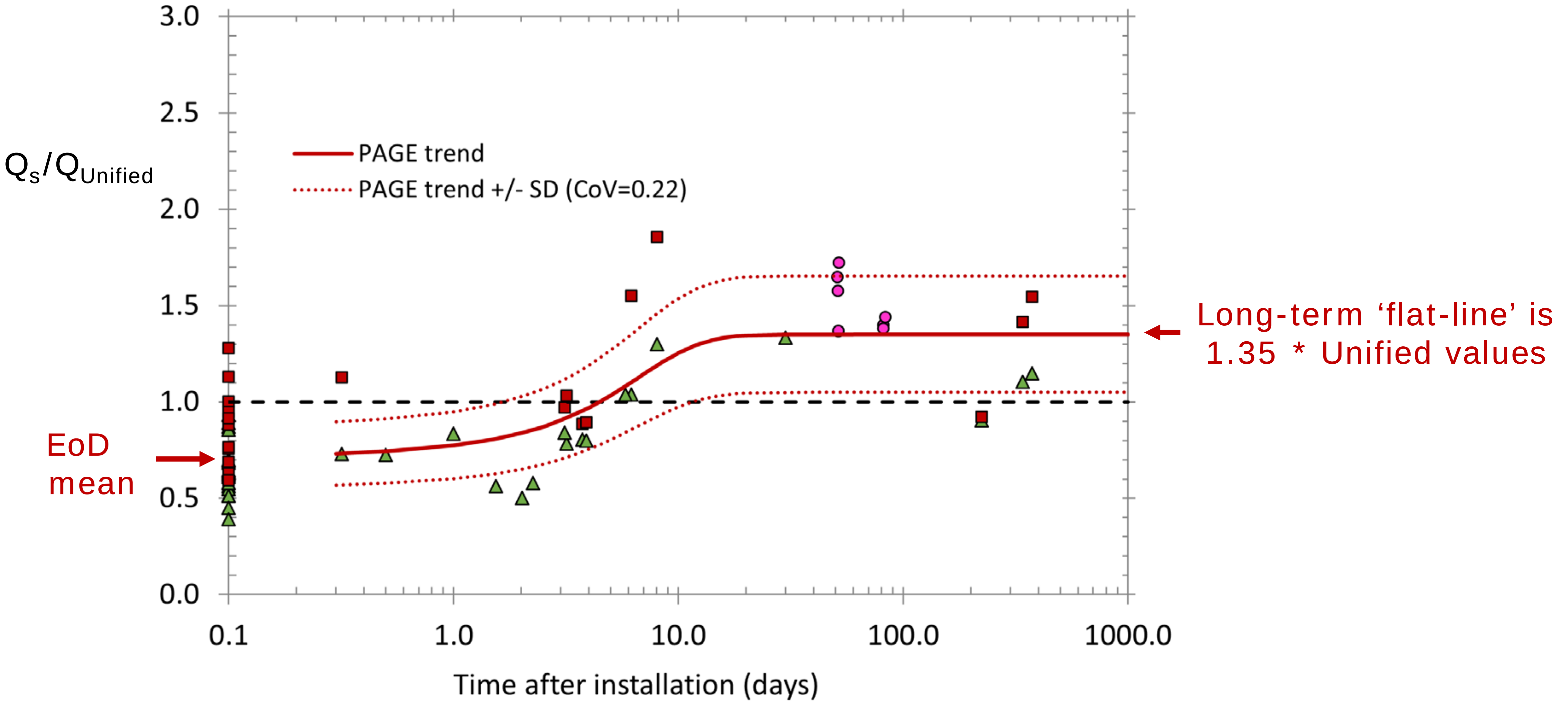


Long-term resistances 'flat-line' at ICP Q_s values

Shaft ageing offshore normalised by Unified method

Mean EoD resistance ≈ 0.7*Unified, long-term close to 1.35*Unified

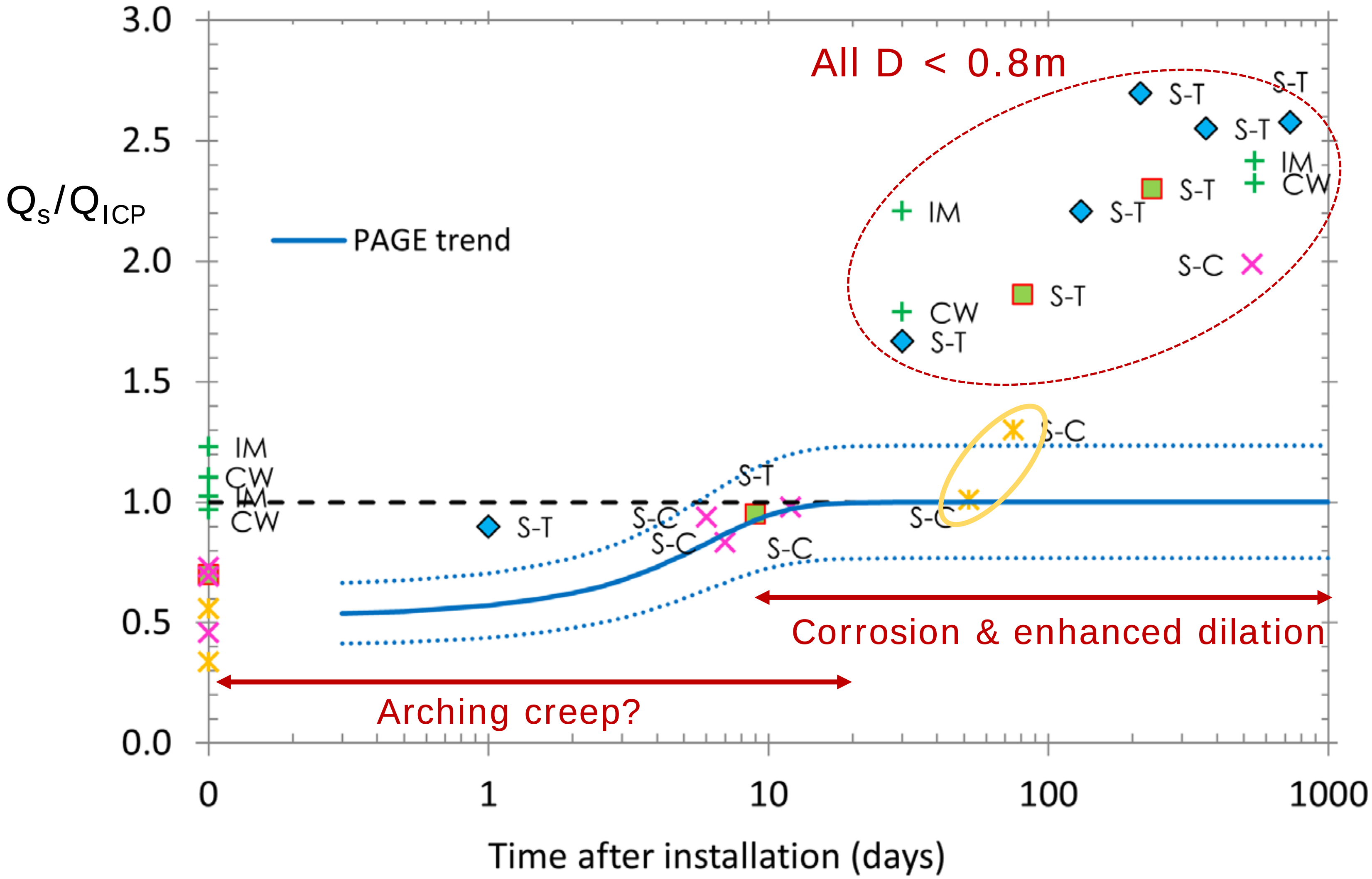
Surprising 35% difference with ICP explored by Scarfone et al. (2023)



Plotting supplementary PAGE case points over offshore trend curves

17 piles with D<0.8m 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



EoD/ICP reductions with D
Imply greater arching?

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

Marked longer-term Λ of <0.8m piles, not seen at offshore scale

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

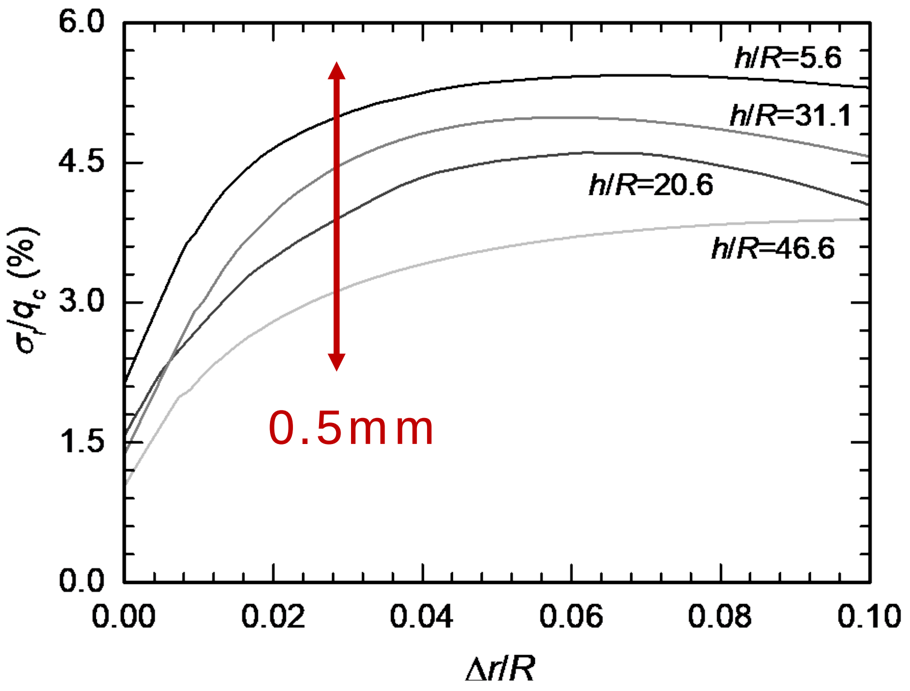
Also limited by p_{lim}?

Reconciling multi-scale outcomes see paper for details

Interpretation of dozens of micro-pile tests at 3 sites identified upper limit to mean σ'_{rf}
Maximum mean σ'_{rf} = [3.2 ± 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

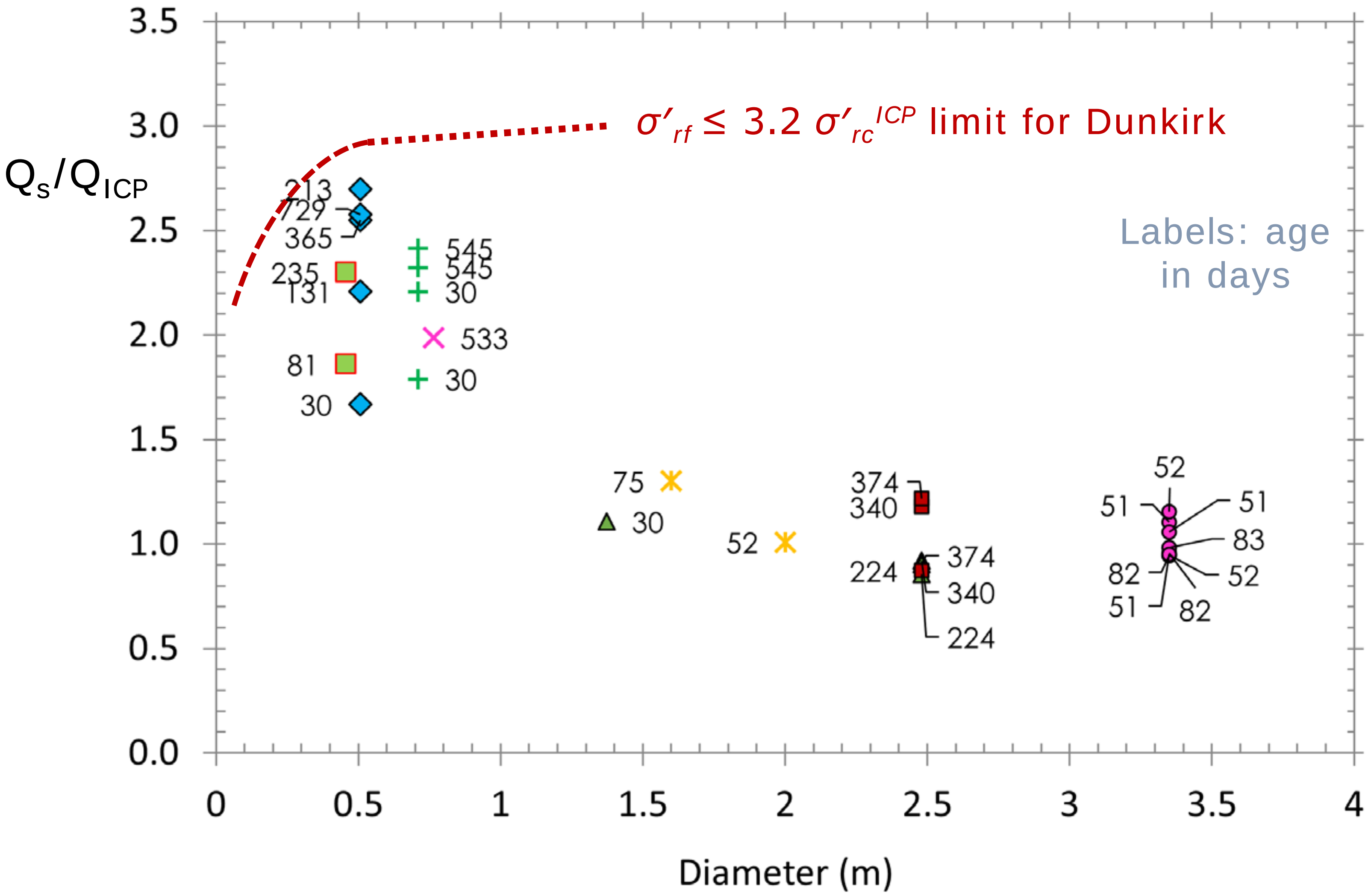
Steep σ'_r/q_c gains develop initially

Low gradients after 0.5mm
Final p_{lim} = 4.6 (±0.7)% q_c ≈3 σ'_{rc}

Analytical result broadly compatible with limit interpreted from micro-pile tests

Next: look for diameter dependency in PAGE data

Q_s/Q_{ICP} - D trend for all 30⁺ day age piles with D ≥ 0.45m



1. Apply $\sigma'_{rf} \leq 3.2\ \sigma'^{ICP}_{rc}$ limit

   Impact on Q_s/Q_{ICP} illustrated for Dunkirk piles

   Less significant when D > 0.5m

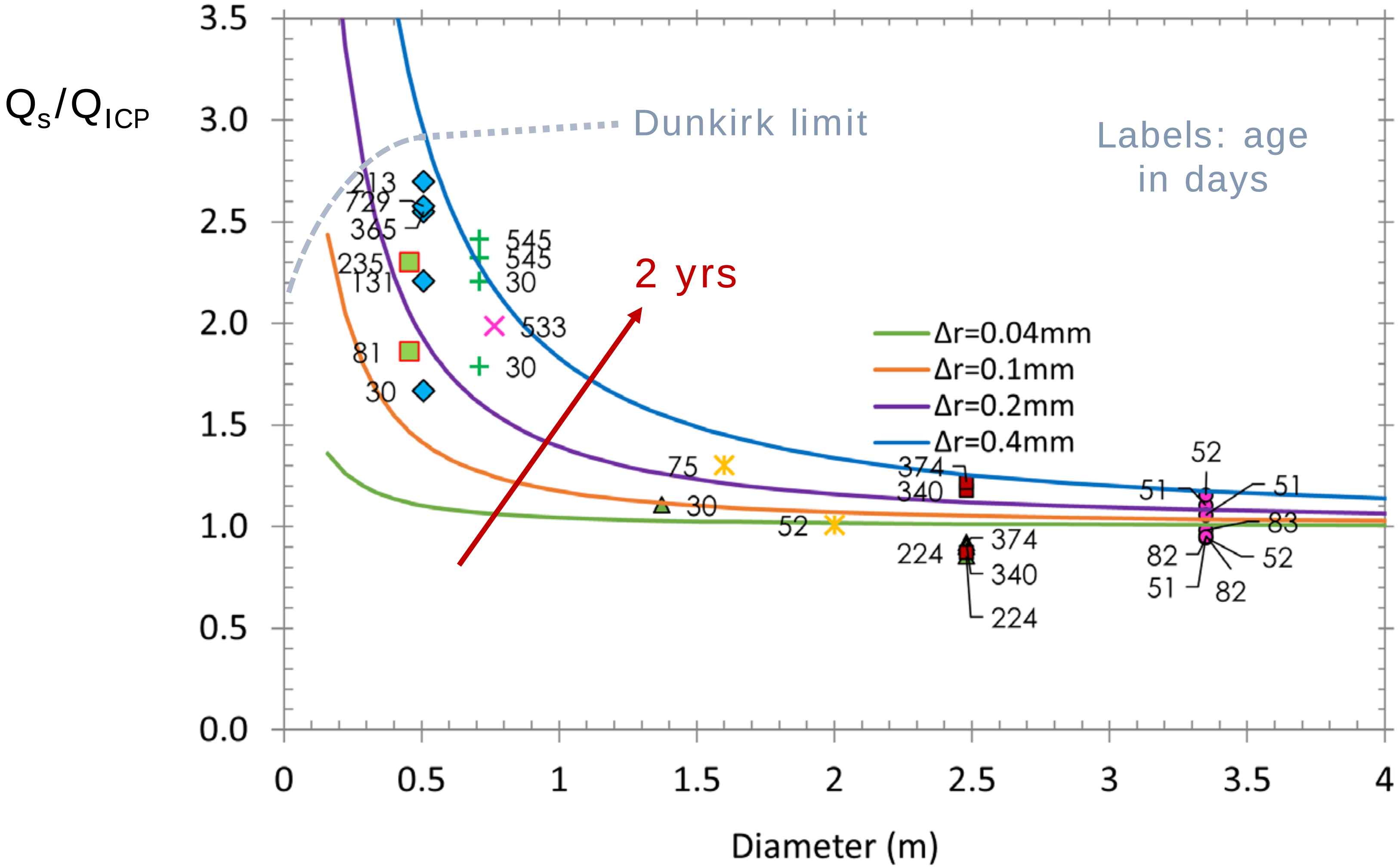
2. Assume ICP predicts 1 month capacities taking Δr = 0.02mm, as indicated in database studies

3. Predict subsequent ageing by raising Δr input in $\Delta\sigma'_r = 2\ G\ \Delta r/R$ ICP term

Adjusting ICP calculations to capture ageing up to 2 years after driving

Q_s predictions made raising ICP Δr 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



Δr = 0.4mm 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

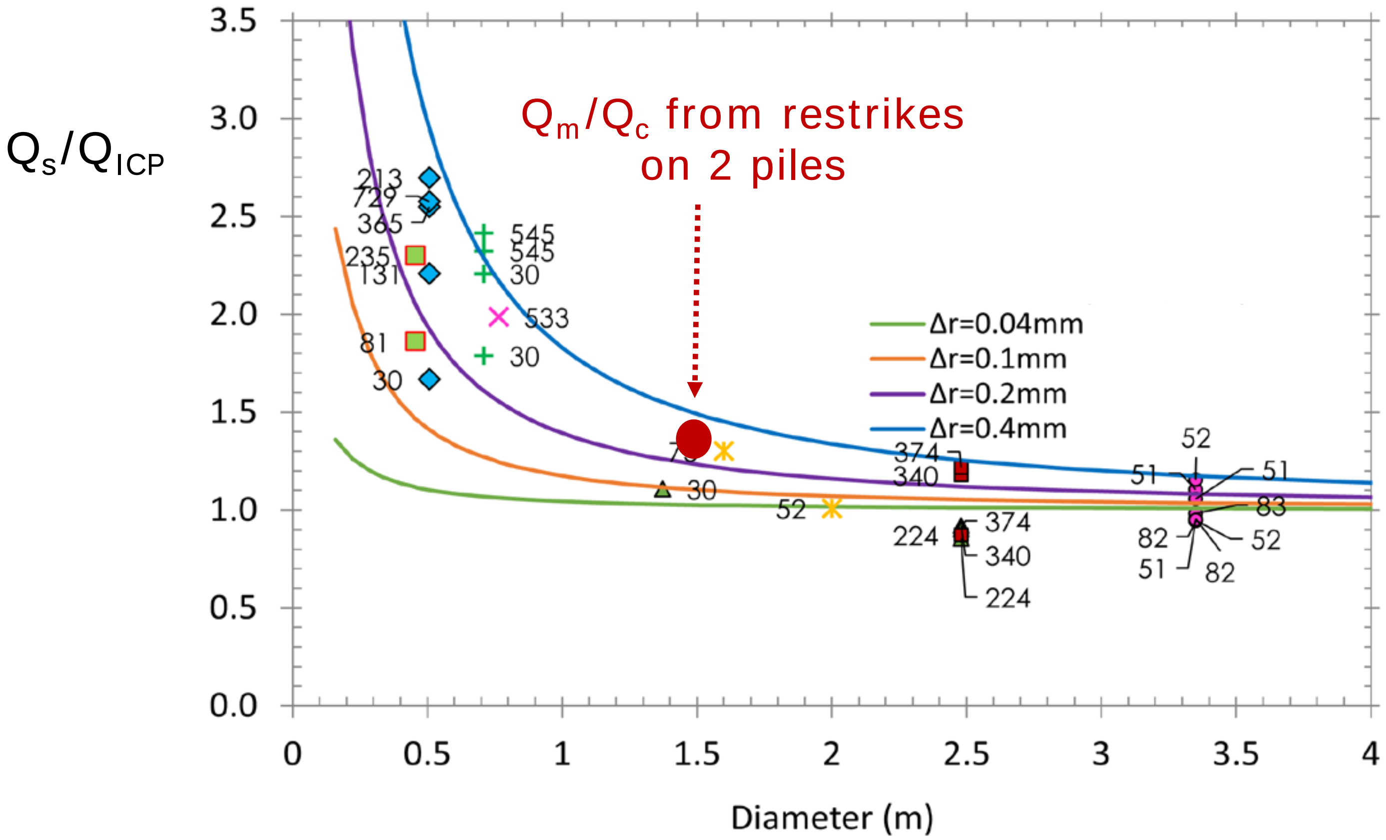
See paper for details

Taiwan Strait tests looser silty sands, silts & clays; higher *L/D* Shonberg et al. (2023)

Re-strikes after ≈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

Courtesy Orsted



Outcomes compatible with *Δr* ≈0.3mm

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 φ′ 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 δ' angles in clays, fracturing important in chalk

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

Interface dilation: Δr 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

Closing remarks

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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