Imperial College London

Working with Pierre Foray to understand the behaviour of piles driven in sand

Pierre Foray Homage

27th January 2015

Richard Jardine

Background

Topic central for current large, multi € bn offshore wind-energy and hydrocarbon projects

Difficult, considered fully resistant to 'theoretical refinement' by Terzaghi & Peck

Conventional API & other approaches have poor reliability

Advances made in 25 years of Anglo-French research, last decade working with Pierre Foray and Grenoble 3S-R Lab

Continuing collaboration with France: SOLCYP, TC-209, Grenoble 3S-R and current PISA tests

Programme started in 1990 with Labenne field experiments with Prof Roger Frank's LCPC team

IC instrumented piles

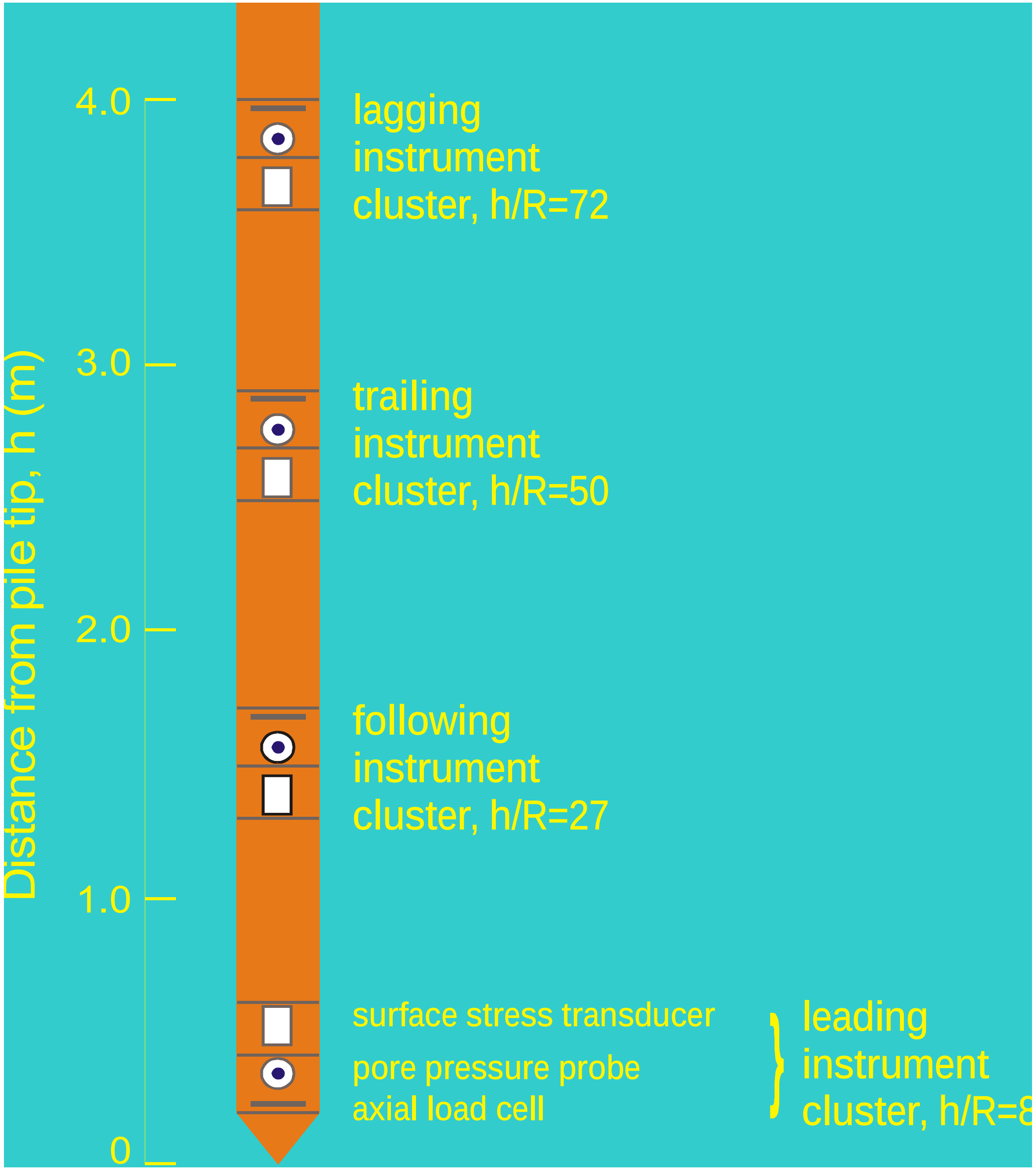
102mm diameter; up to 20m long

SSTs measure local σ_r and τ on shaft

Intensive testing in sand at Labenne and Dunkerque 1990-95

...and 4 UK clay sites 1985-96

Bond, Jardine & Dalton (1991)



The 4 + 2 Anglo-French team at Labenne, SW France, 1990

See Lehane, Jardine, Bond & Frank (1993), ASCE

Interrogating nature...

Do conventional theories work? Constant K earth pressures and N_q models? Or direct in-situ test methods?

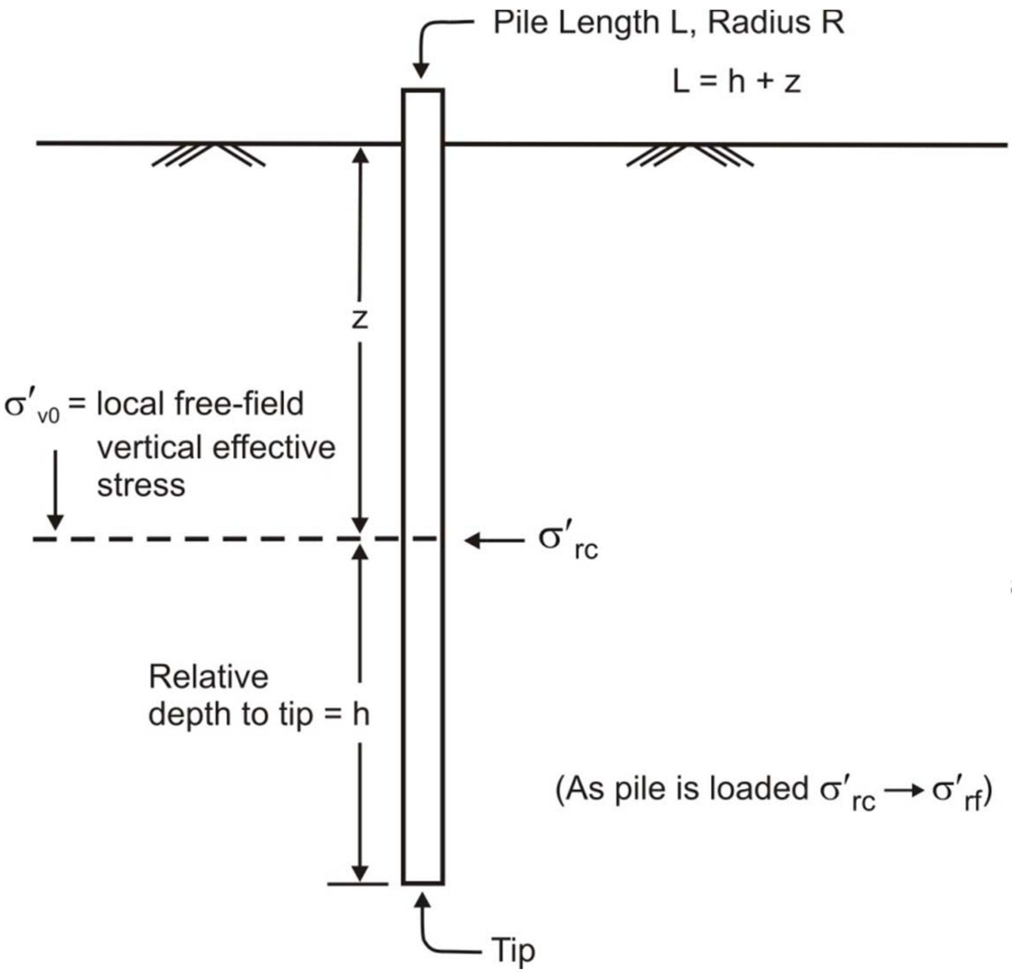
If not, what really controls failure shaft shear τ and normal σ'_{rf} stresses & end-bearing q_b?

What are the missing key variables?

Are there really upper limits to τ and q_b?

Compression versus tension loading?

ICP Configuration



Multiple tests:
Loose dune sand: Labenne
Dense marine sand:
Dunkerque

Continuous profiles of shaft radial and shear stresses, axial loads and tip resistance

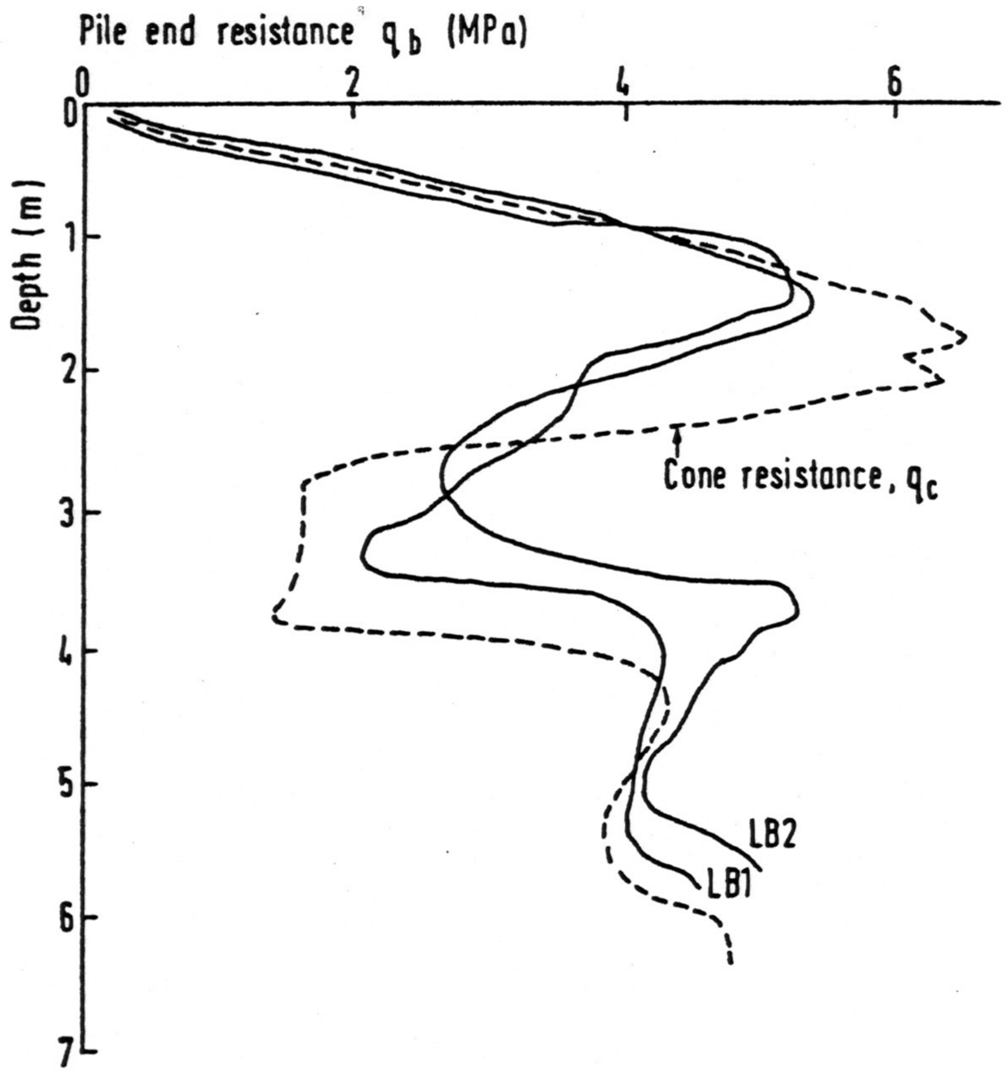
Installation, equalisation and loading to failure

Tip pressures controlled by local q_c; shaft stresses also vary with pile tip position h

Shaft stresses vary strongly during loading

Labenne: end bearing

Pile end resistance q_b mirrors CPT q_c



Local shaft radial effective stresses

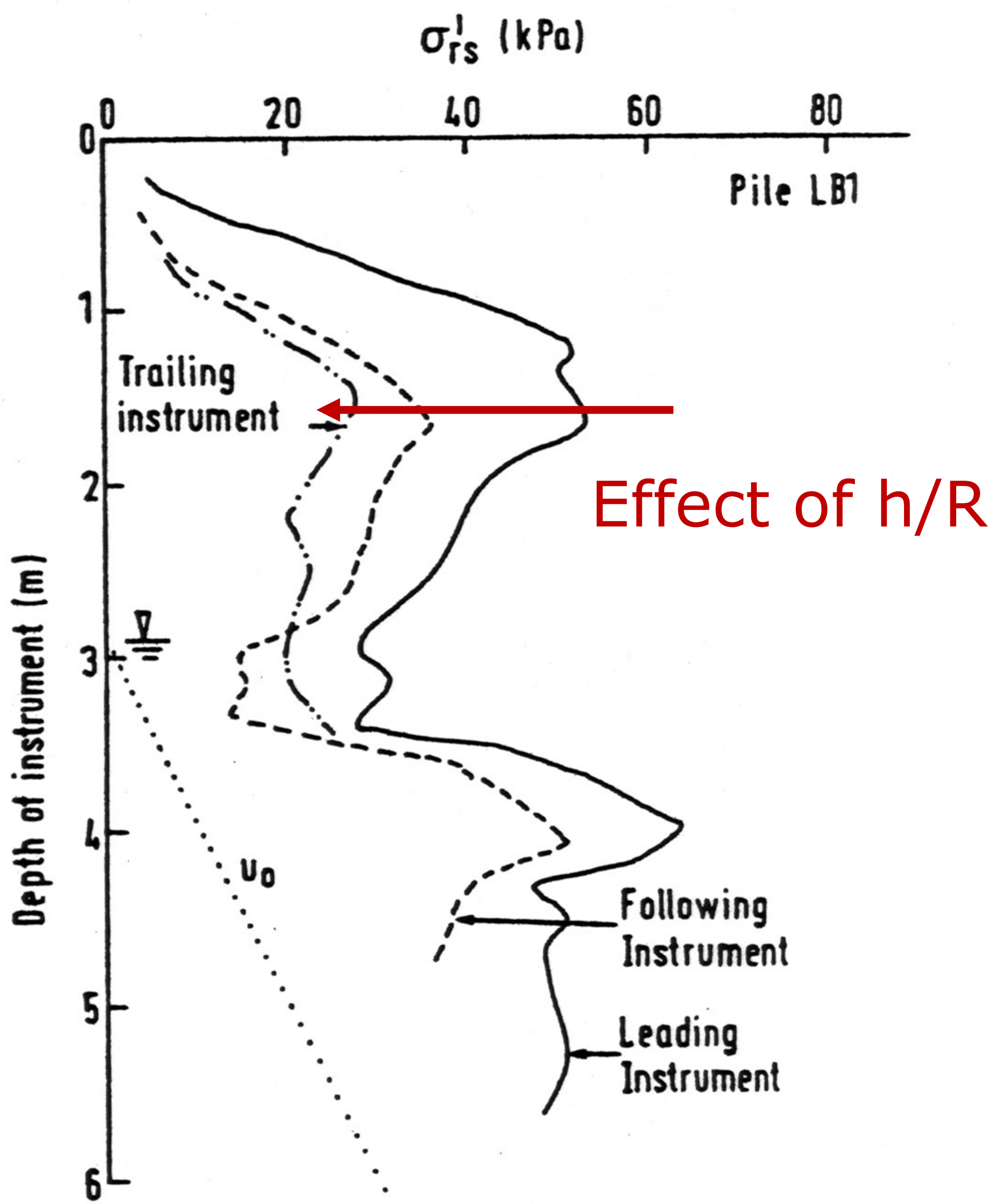
Shaft σ'_r during penetration at Labenne

Mirror q_c profile & vary with pile tip depth h

No constant K, but

$\sigma'_r = f\ (q_c, \sigma'_{vo}, h/R)$

Confirmed in dense Dunkerque sand



Loading response & effective stress paths, similar at Dunkerque and Labenne

σ'_r varies under load

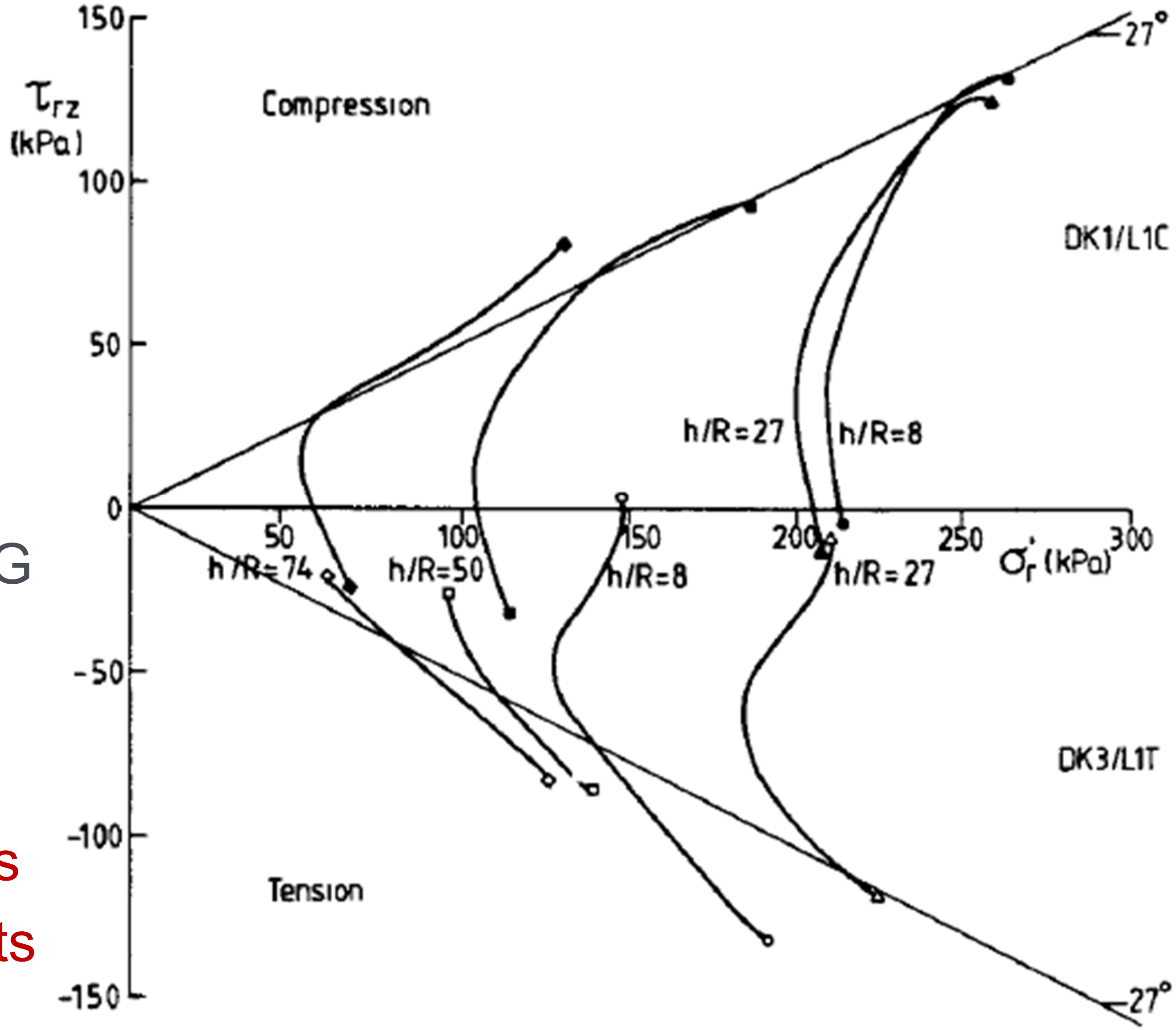
Tension ≠ compression

Simple interface law
$\Delta\sigma'_{rd} = 2G\ \delta r/R$

D_r influence is through G

δ_{cv} not affected by D_r

Tests on CLAROM piles explore open-end effects



Basis for new ICP design rules used for oil, gas & wind energy

Overy 2007

Piled tripods for Borkum West II
German N. Sea Merritt et al 2012

Practical impact: one large UK jacket based windfarm

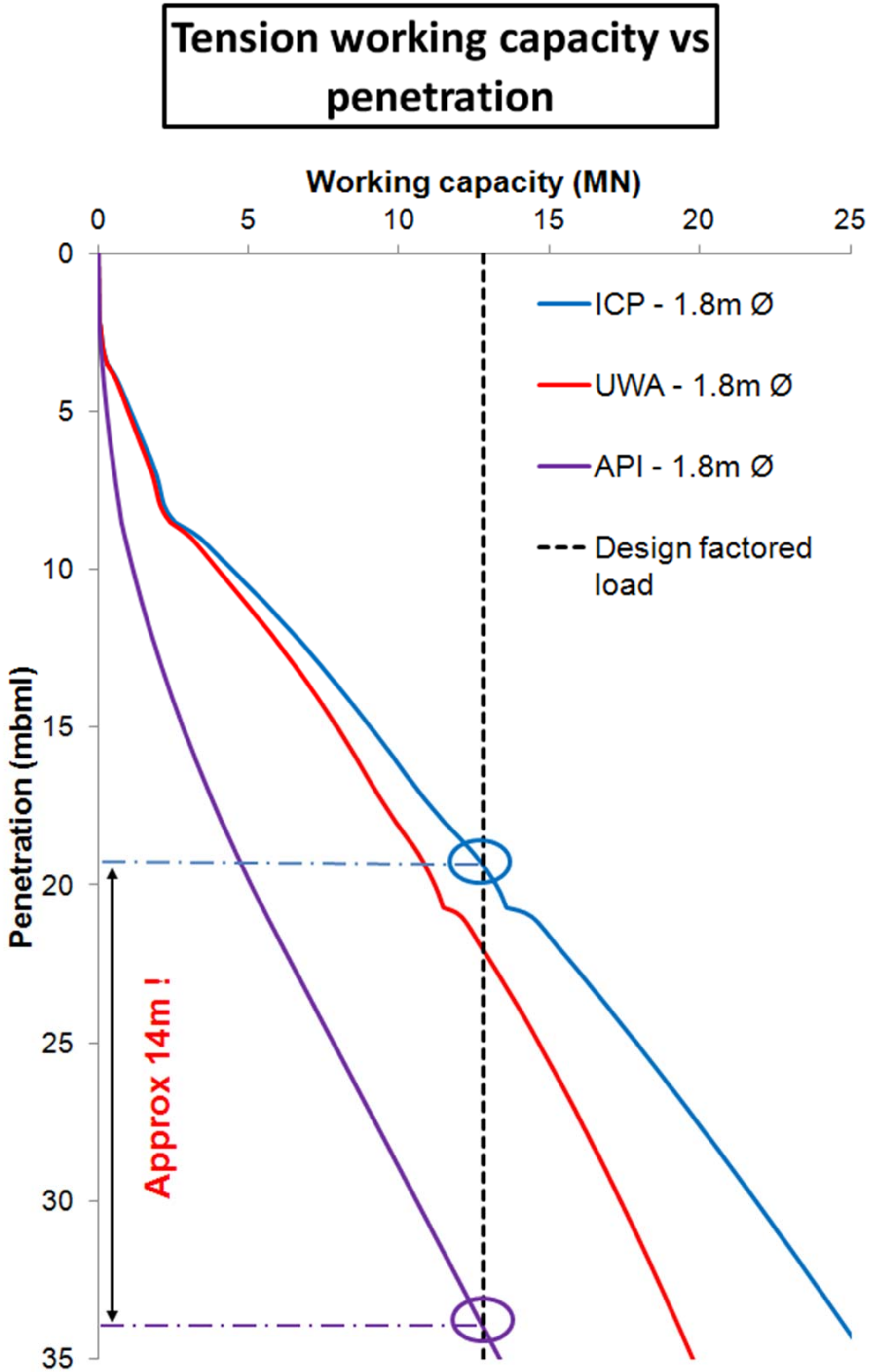
Critical economies in onshore and offshore projects

But surprising ageing results from large scale Dunkerque tests:

1994 Re-tests on CLAROM piles: Chow, Jardine, Brucy & Nauroy Geotechnique 1997

1998-9 tests on fresh GOPAL piles

And cyclic tests on GOPAL Piles



Dunkerque tests in dense marine sands: 1988-2015

CLAROM, ICP, GOPAL, SOLCYP and current PISA tests

Variable q_c profile, up to 30 MPa

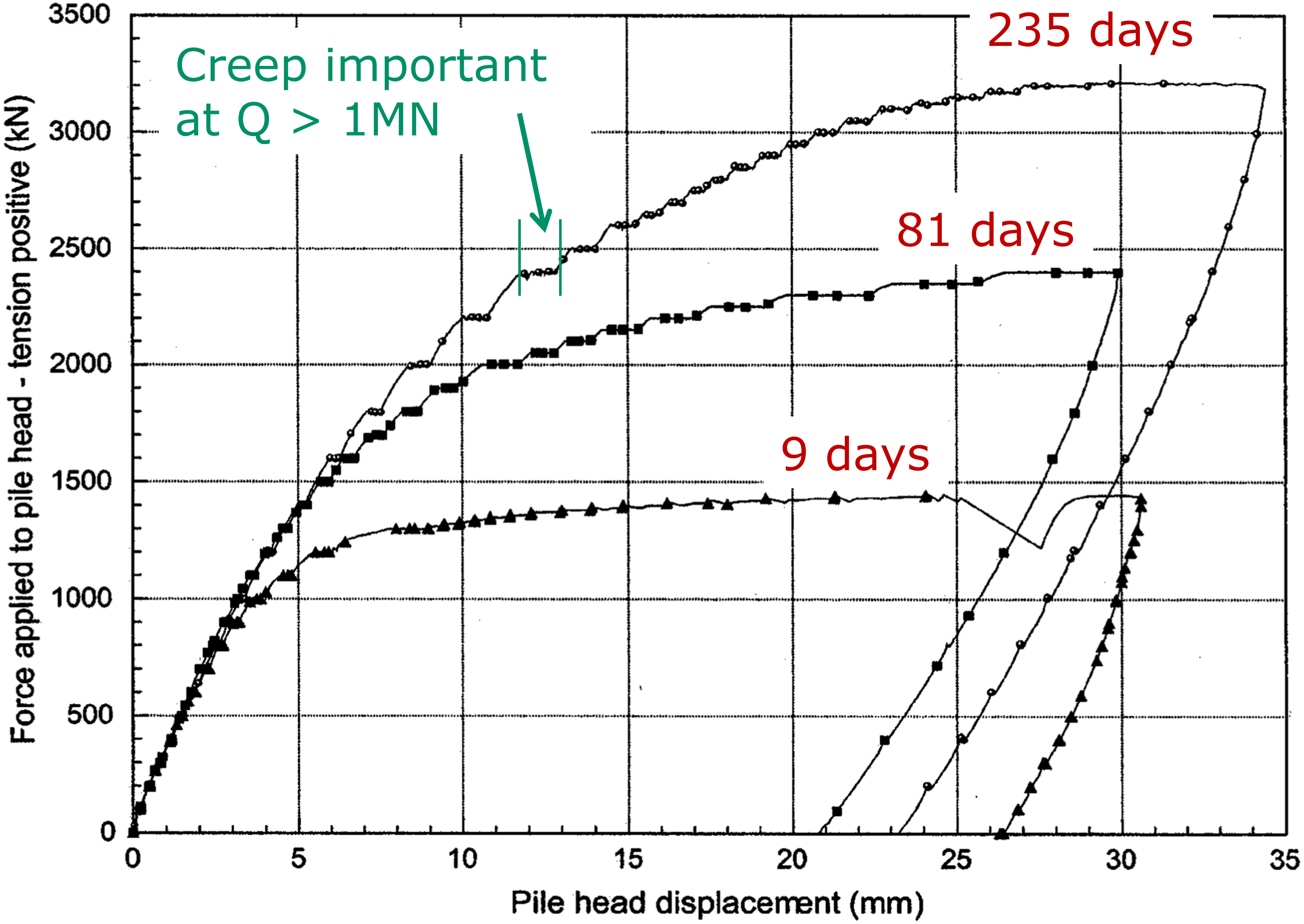
GOPAL: 8 steel pipe piles 457mm OD, 19m

Static & cyclic loading

Pile ages: 9 days to 1 year after driving

Jardine et al 2006, Jardine & Standing 2012

Ageing, creep & non-linear axial shaft stiffness,



1st tension tests varying with age

Impact of axial cyclic loading

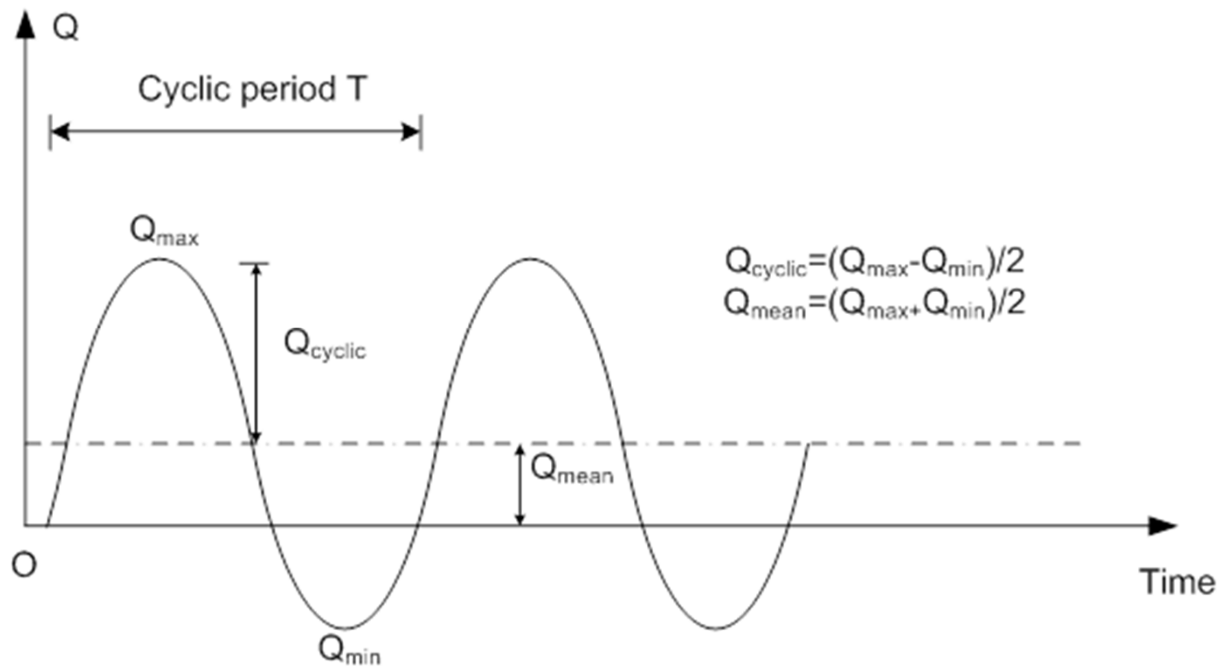
Load controlled

T = 60s

One-Way: tension

Two-Way: tension & compression

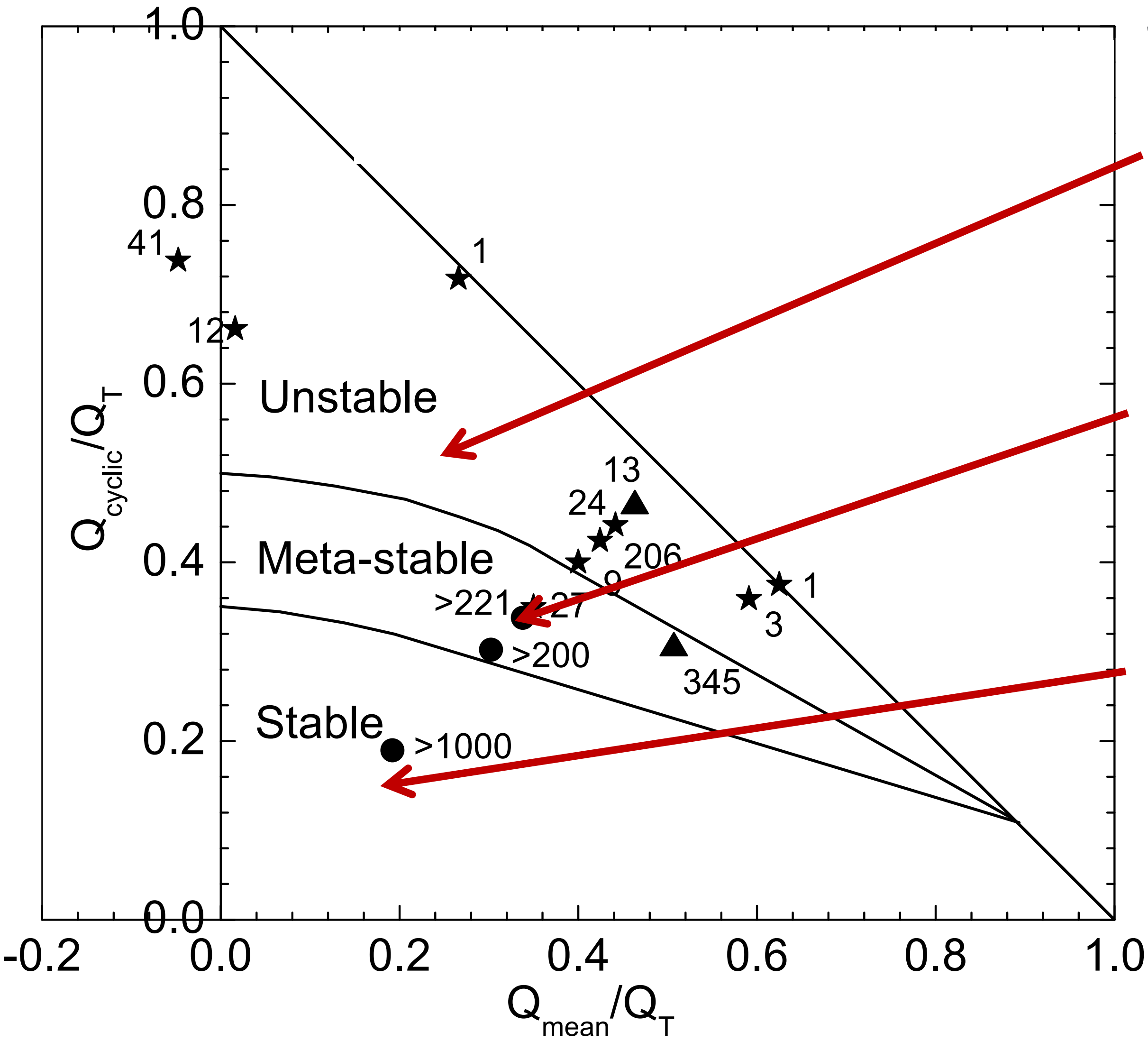
Plus: tension tests to failure



Failure depends on N, Q_{cyclic}, Q_{mean} & static tension capacity Q_T

Loads normalised Q_{cyclic}/Q_T & Q_{mean}/Q_T to allow for age & pre-testing

Impact of axial cyclic loading: can halve capacity



Jardine and Standing (2012)

Failure $N_f < 100$

$100 < N_f < 1000$

Stable to N > 1000

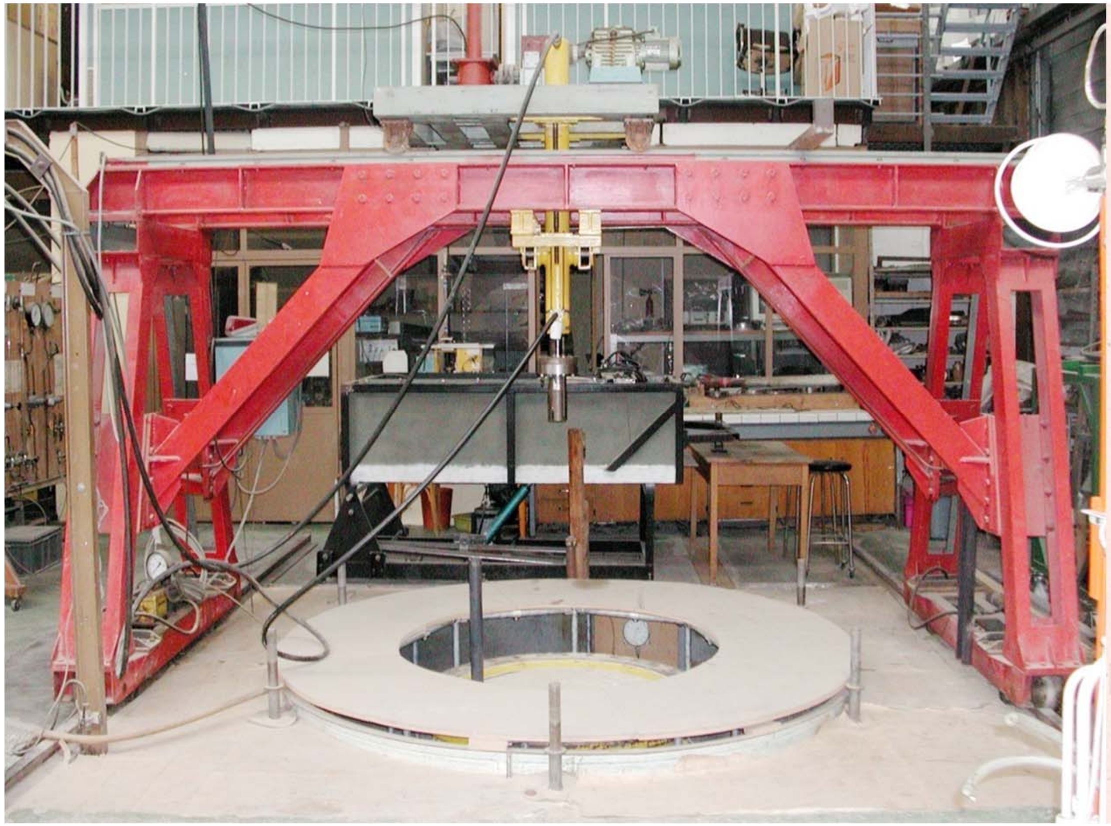
Shaft capacity grows
Cycling adds to ageing

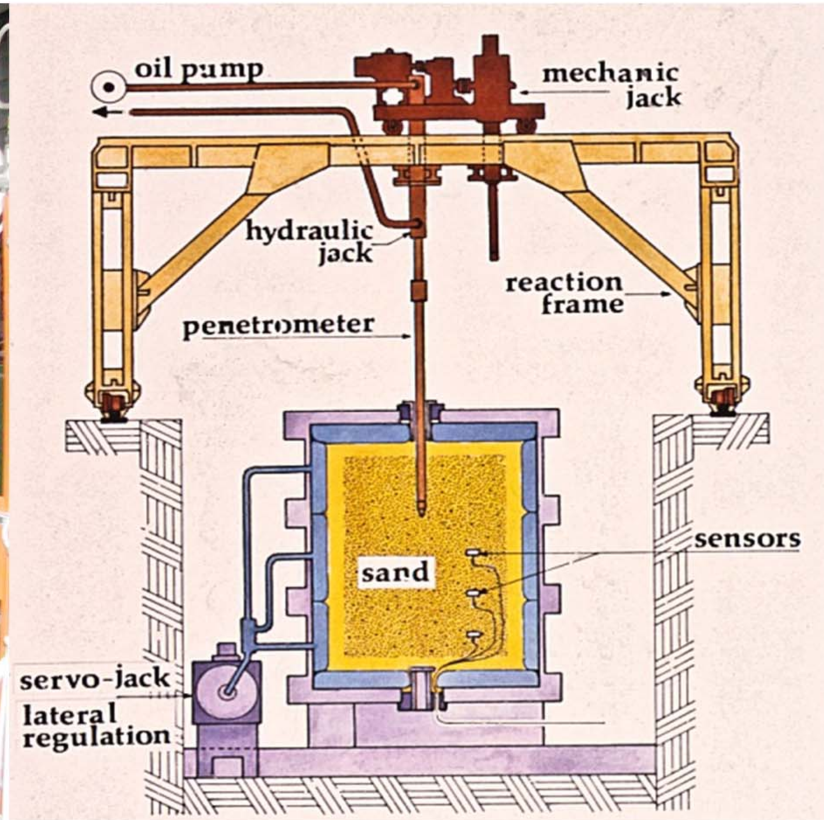
Degradation much worse with bored piles: SOLCYP, Puech et al 2013

Need for scientific exploration of these 'new' phenomena

Working with Professor Pierre Foray
2005-2014

Model experiments with Prof. Pierre Foray





3S-R chamber, temperature & pressure control

Dense NE34 sand; CPT: 20< q_c <25 MPa

Tests over months under 150 kPa

Up to 36 stress sensors

Instrumented Mini-ICP

Foray, Tsuha, Silva M, Jardine & Yang Z.X. (2010) - ICPMG, Zurich

Mini-ICP model pile

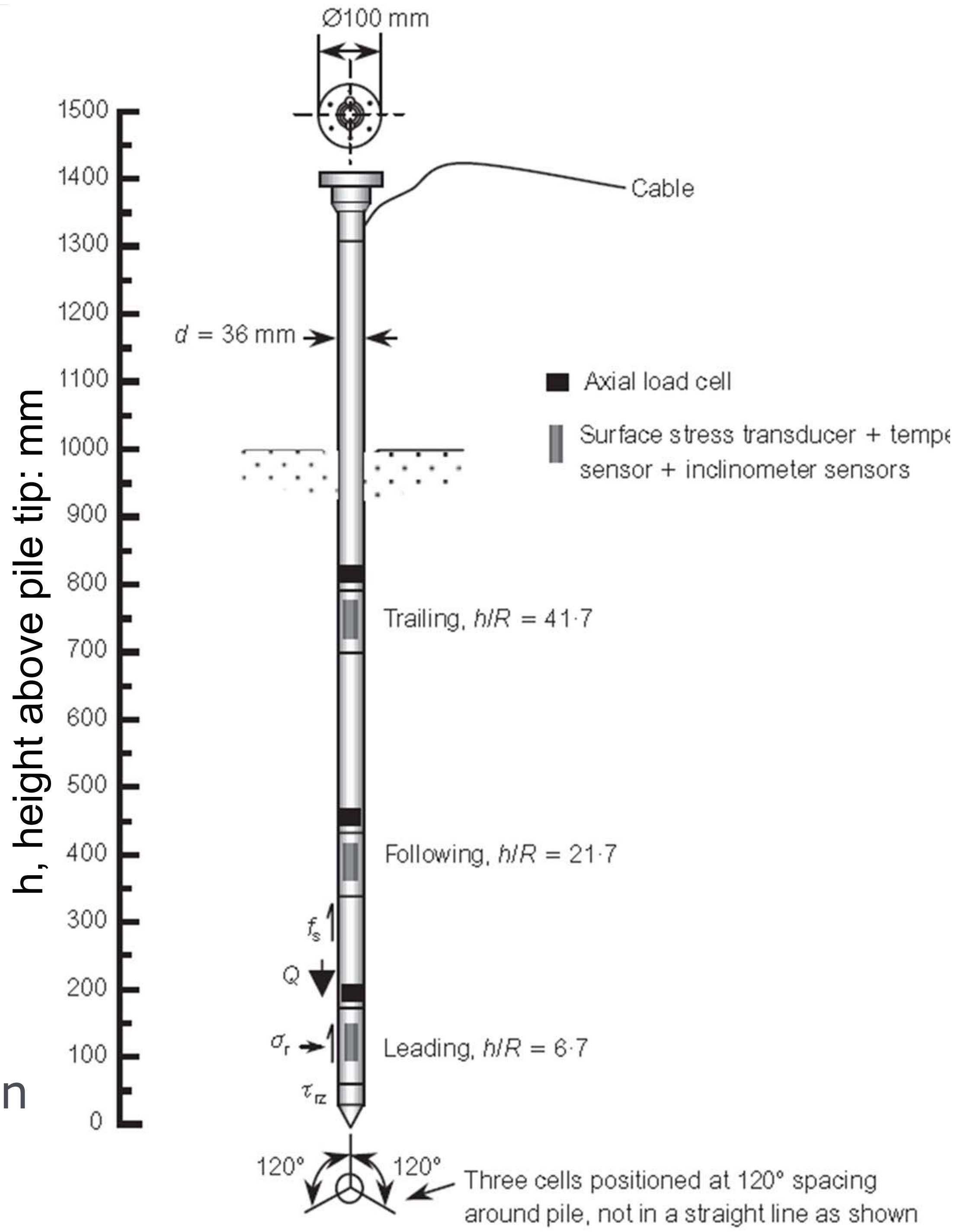
Stainless steel: 36mm OD

Cyclic jacking installation

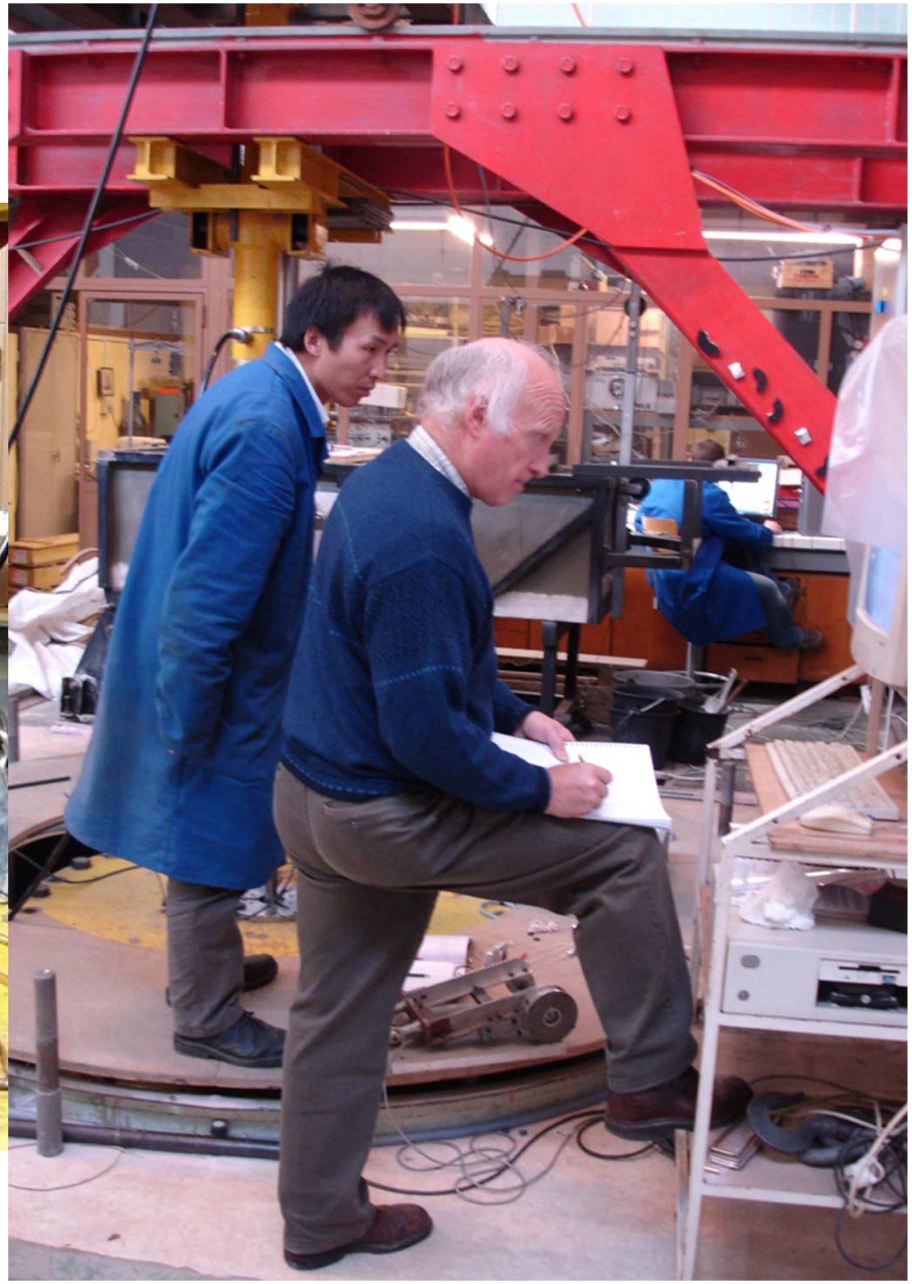
Local measurements at three h/R levels of:

- Axial load
- Surface τ_{rz} & σ_r
- Plus tip loads etc

Jardine, Zhu, Foray & Dalton (2009) Soils & Foundations



“Hands-on” with Pierre Foray in the 3S-R laboratory



“Heads-down” – problem solving...

Working even with a geo-endoscope

Many successful tests over 2007-2013 main programme

International team:
Academics, Post-Doc, PhD, MSc & technicians

Members from:

Brazil
Chile
China
France
Italy
Tanzania
United Kingdom

What did we find?

Distributions of σ'_r σ'_z & σ_θ around piles

Key to modelling ageing, cyclic response,
group effects..

Supported by IC-Grenoble laboratory element
& particle scale studies

Installation σ'_r trends in sand mass:

1000s data contoured

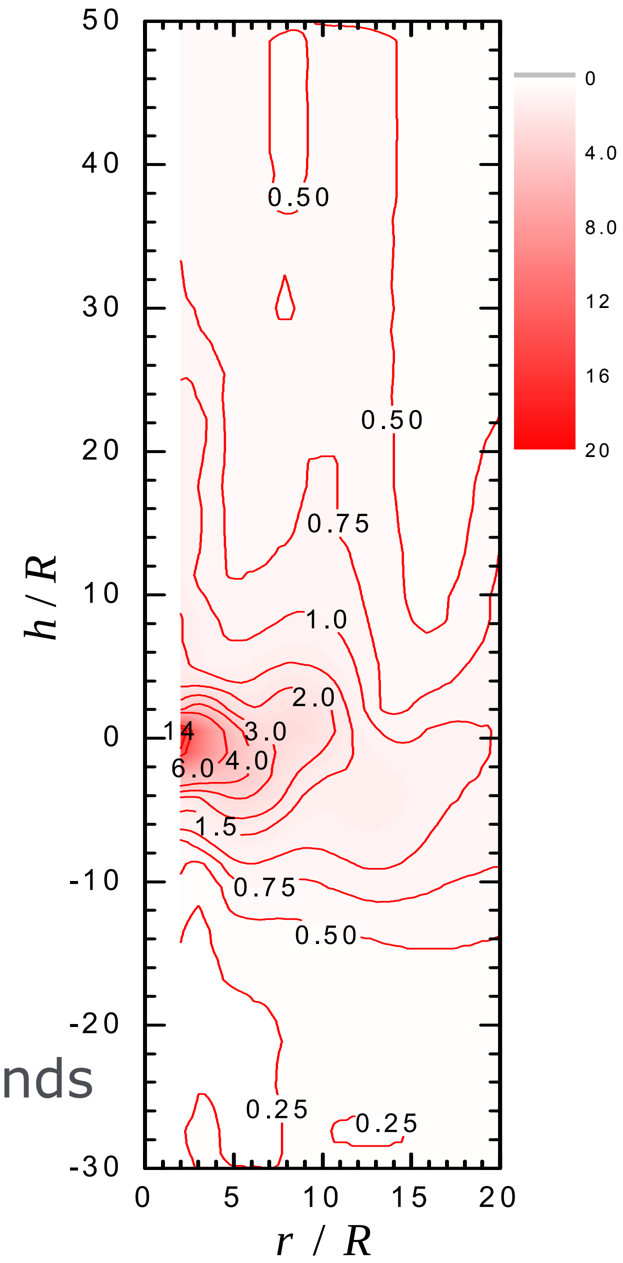
$\sigma_r/q_c = f(h/R, r/R, \sigma_{zo})$

Intense tip concentration
Unloading above tip

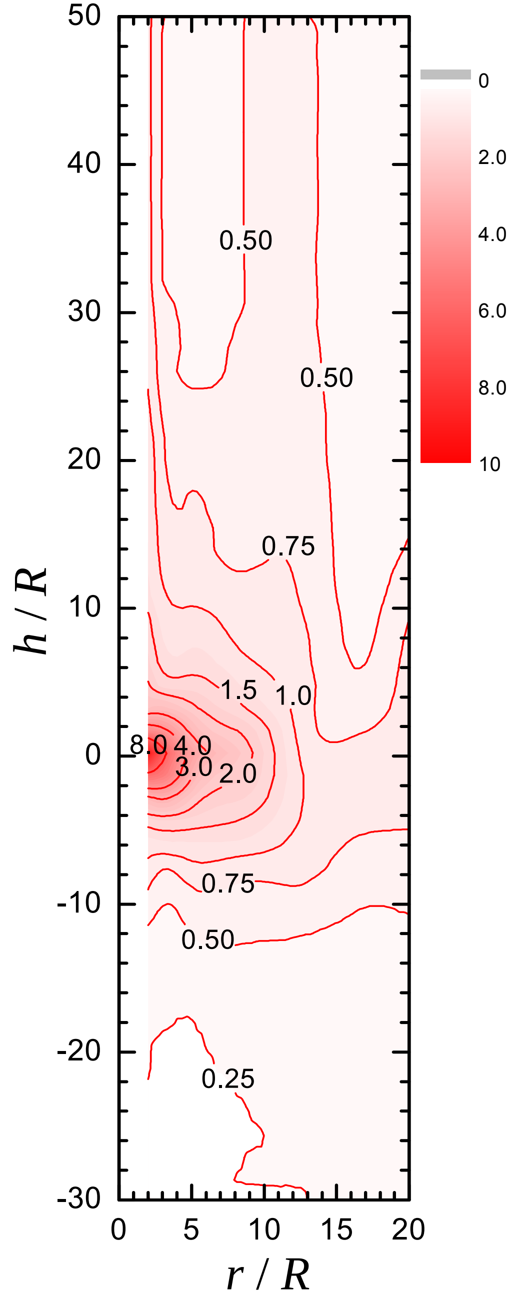
Sharp changes over each jacking cycle

Corresponding σ_z & σ_θ trends

Jardine, Zhu, Foray & Yang 2013 Geotechnique

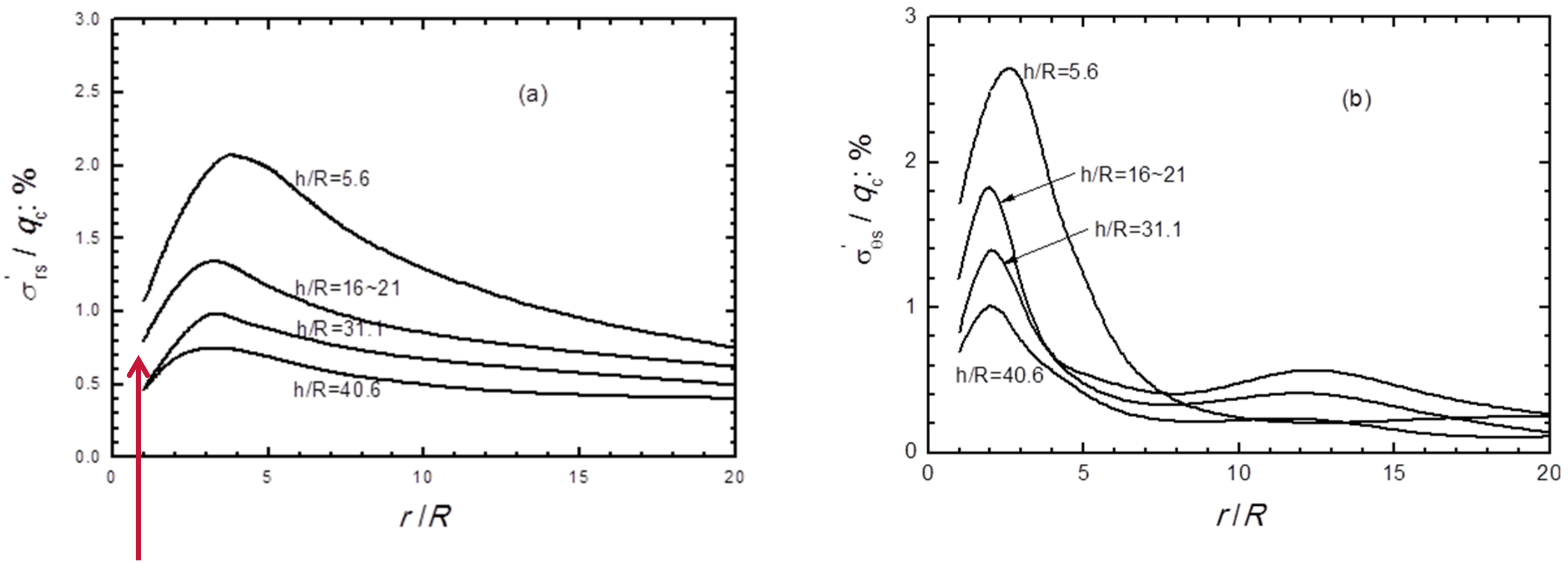


End of push



End of pause

Radial profiles of σ'_r/q_c and σ'_θ/q_c shortly after installation



Radial stresses measured on pile face – far below installation maxima

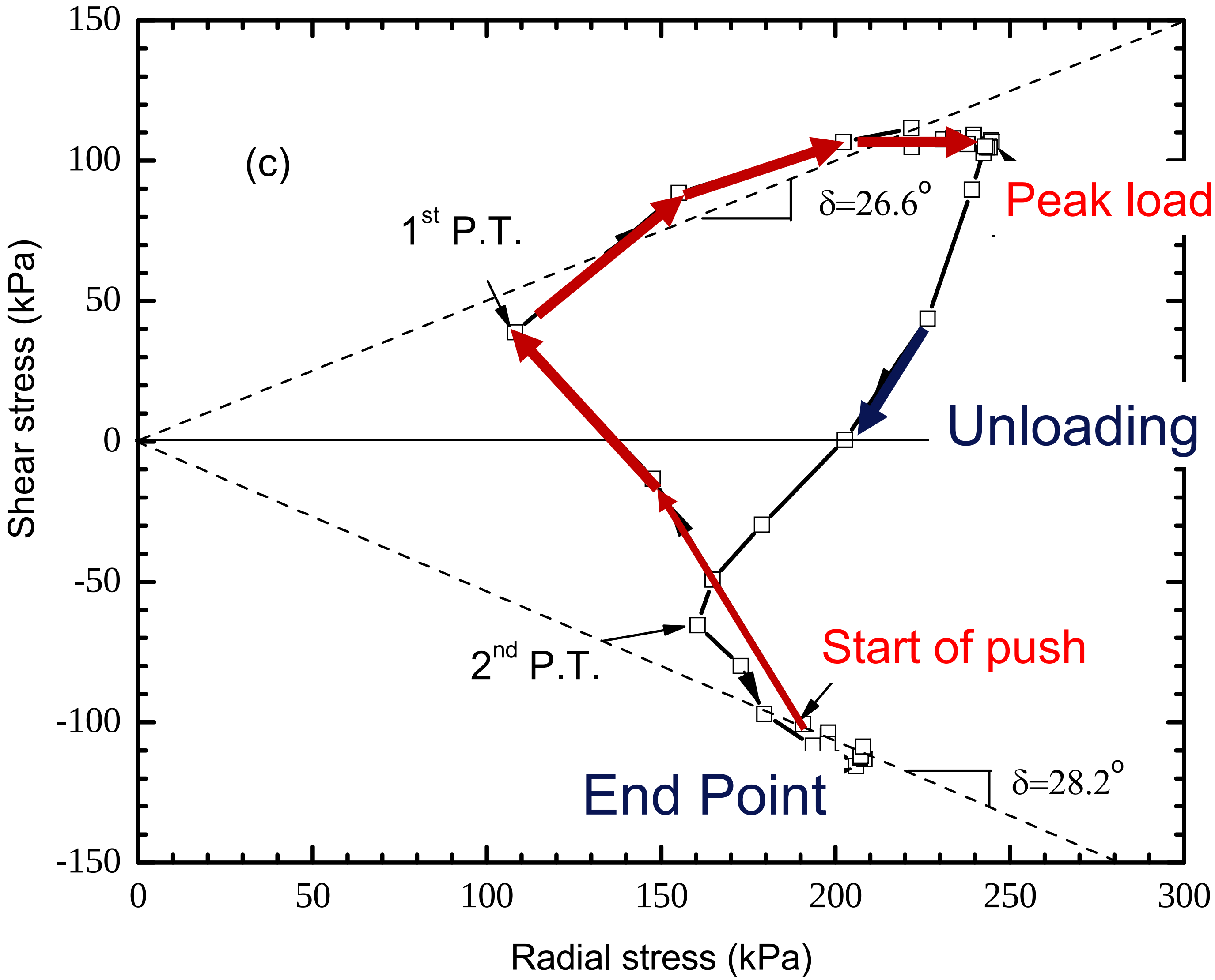
σ_r and σ_θ profiles interlinked, peaks in at $2 < r/R < 4$

Critical to shaft capacity ageing theories

Compared later to advanced analysis

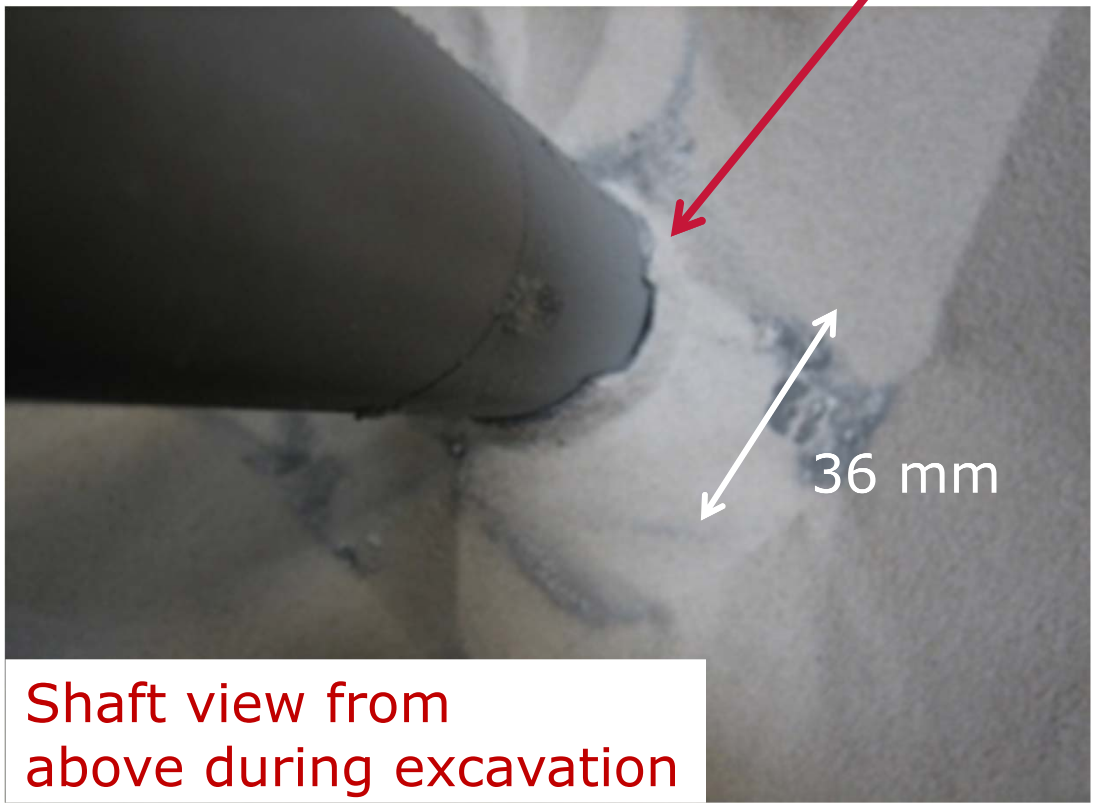
Local stress paths at Leading pile instrument

One cycle towards end of installation



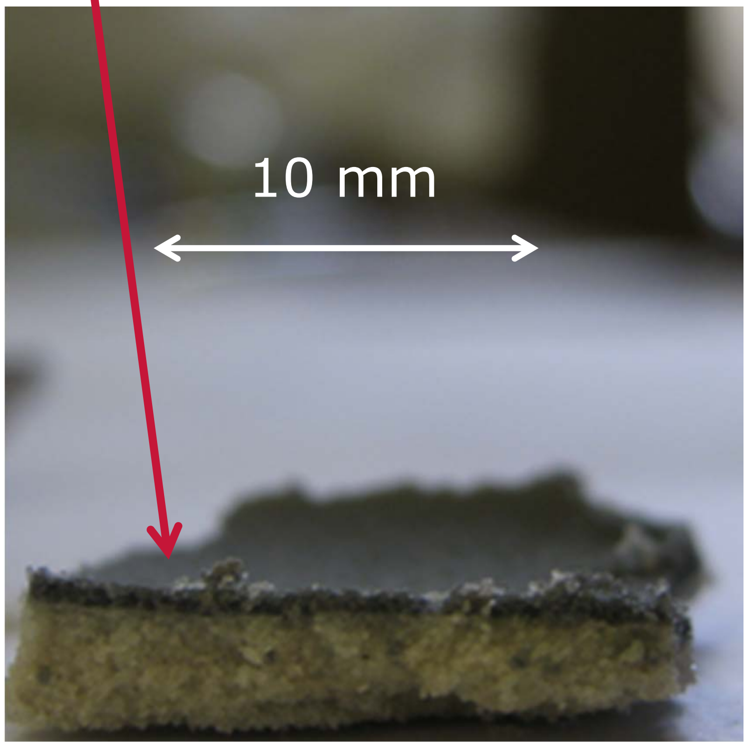
Interface shear zone; Yang, Jardine, Zhu, Foray & Tsuha 2010; Geotechnique

Grey dense fractured shear zone 'crust'
0.5-1.5mm thick, growing with h
Not present if $q_c < 6$ MPa



Shaft view from above during excavation

Side view of vertical sample from shaft



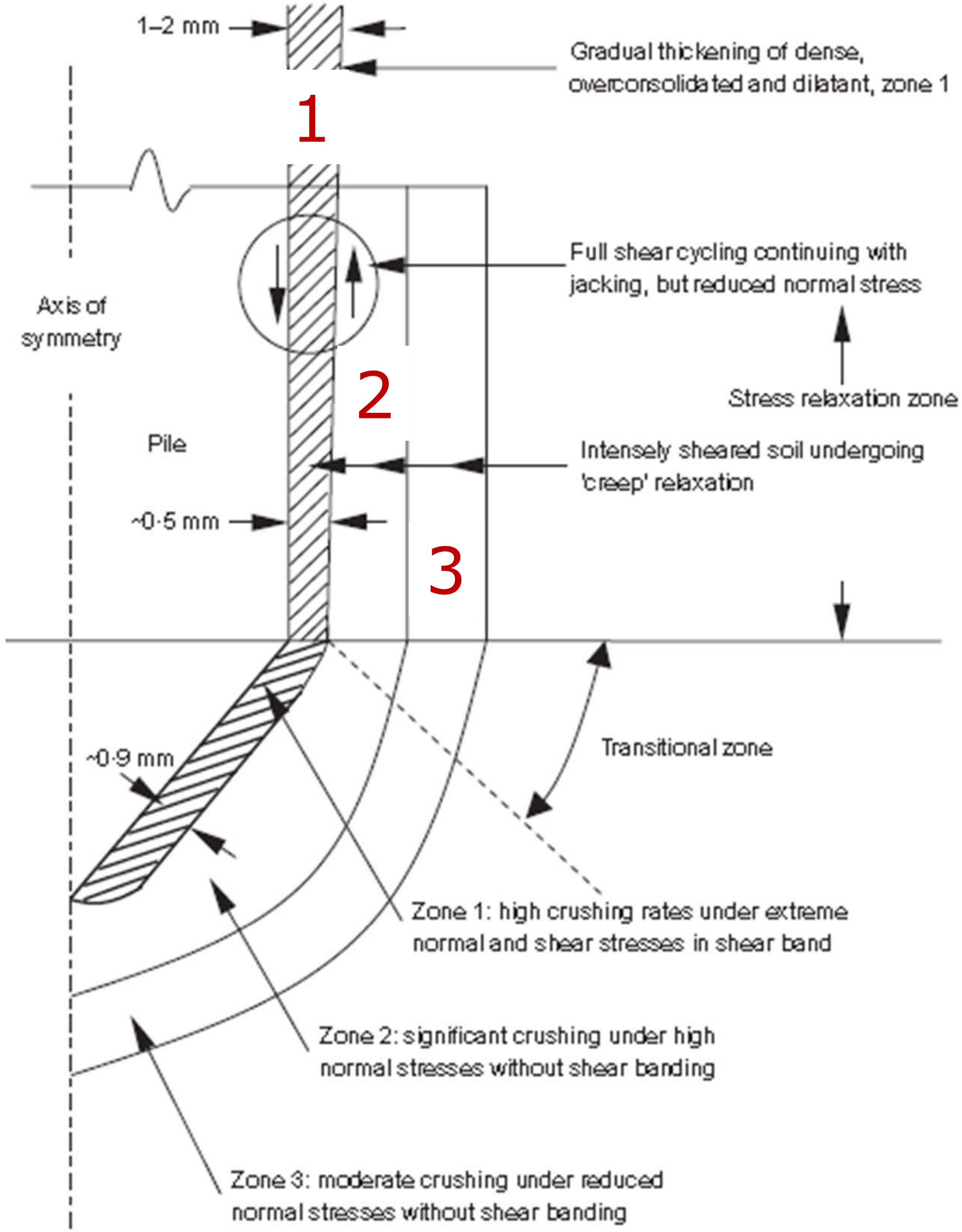
Breakage Zones 1, 2 & 3

Breakage starts under tip
$\sigma'_v > 20$ MPa

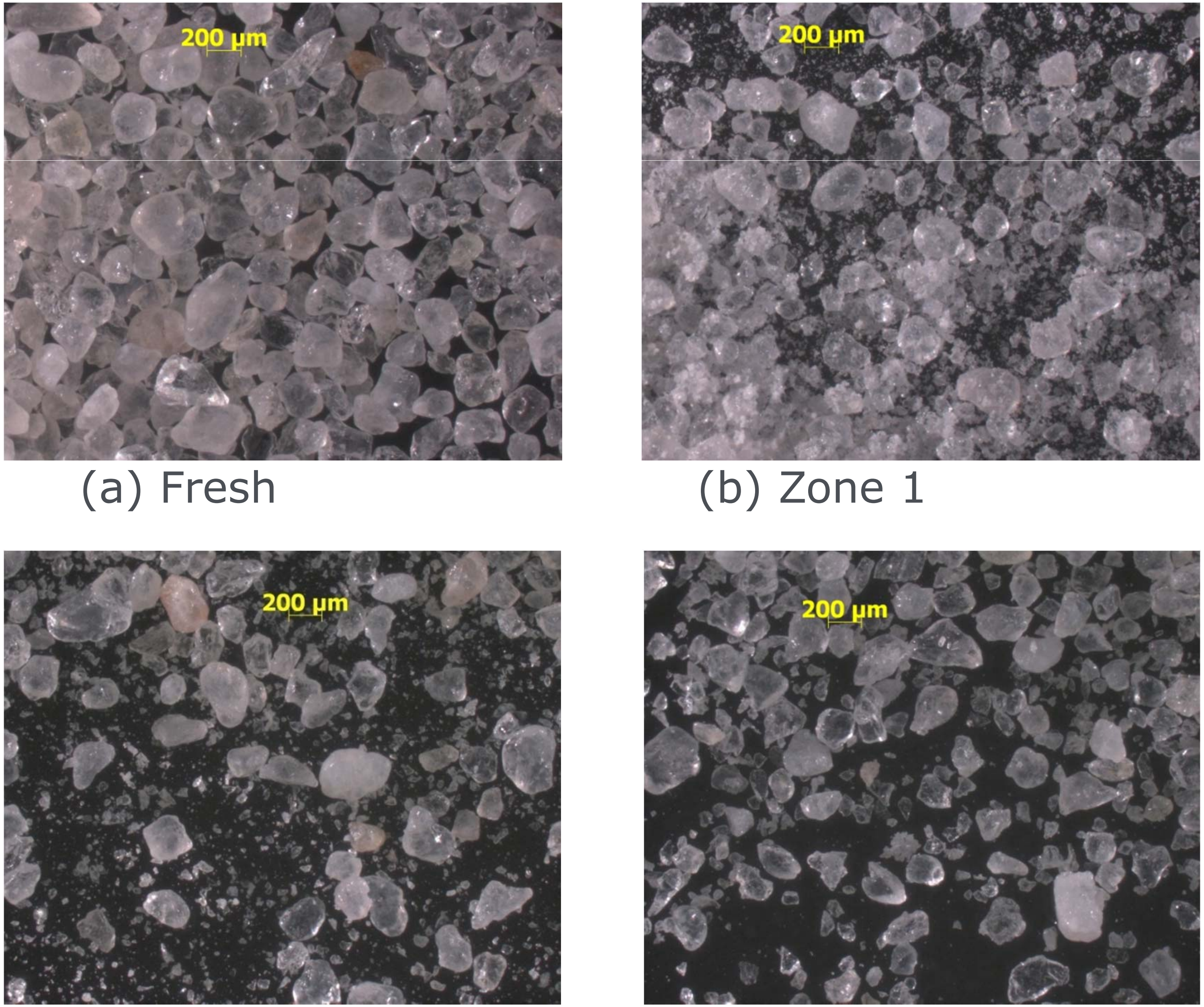
Fractured sand displaced & spread over shaft: Zone 1

Further abrasion on shaft

Partial fracturing in outer Zones 2 & 3



Micro analysis of progressive grain crushing

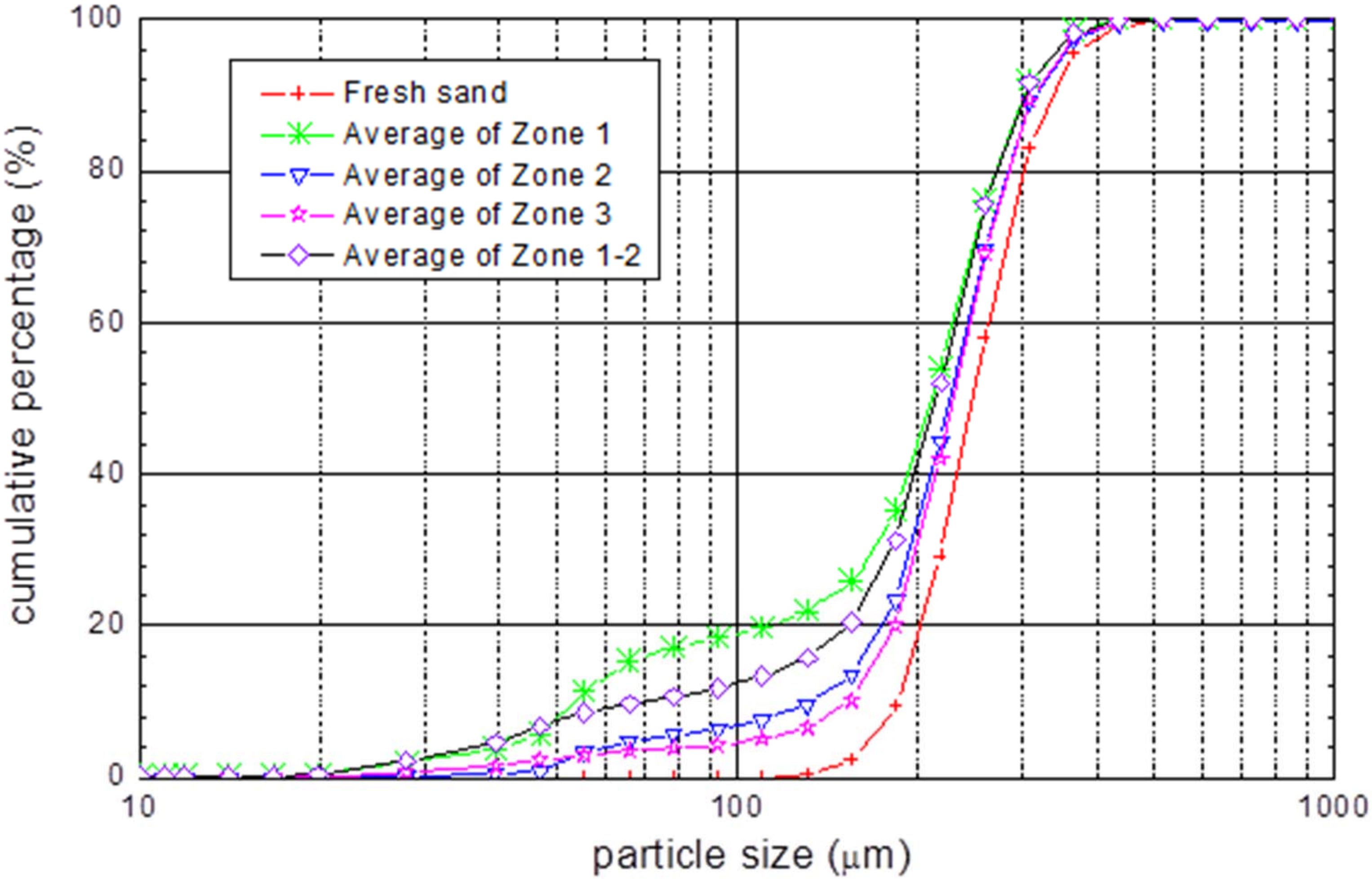


(a) Fresh (b) Zone 1

(c) Zone 2 (d) Zone 3

Qic-Pic laser analyses of small samples:

Progression from fresh sand to Zone 1 'crust'



Breakage most severe in Zone 1, less in Zones 2 & 3

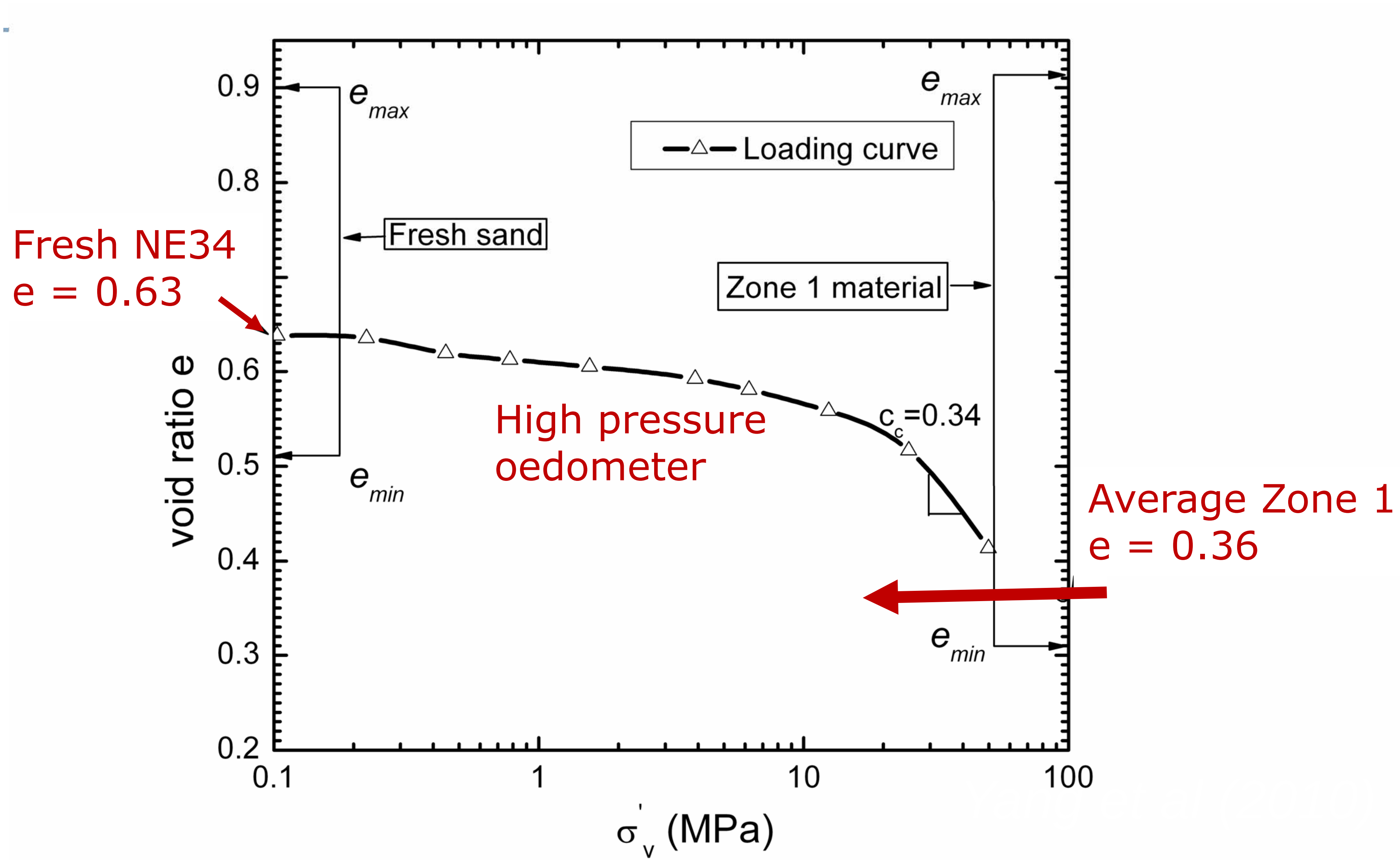
Related laboratory tests at Imperial College

Matching pile conditions in lab tests

Oedometer, interface ring-shear,
high-to-low pressure stress path
& cyclic experiments

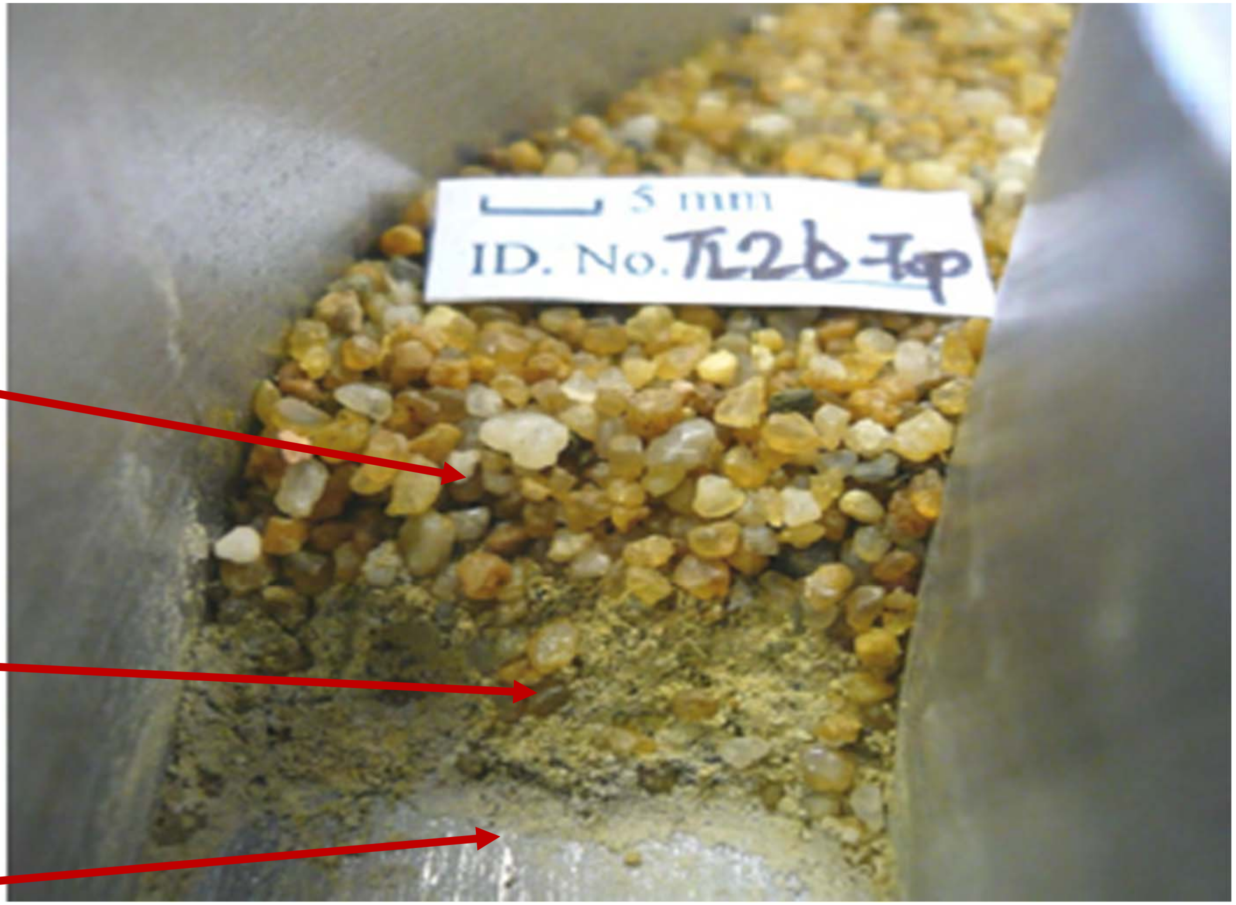
High pressure oedometer compared to Zone 1

Void ratios, limits & sand states



Replicating shear zones: 'Bishop' ring-shear interface tests

Coarse example of sands sheared against steel for metres
σ'_n up to 800 kPa; Ho et al 2011



Intact sand

Crushed sand

Abrading steel interface

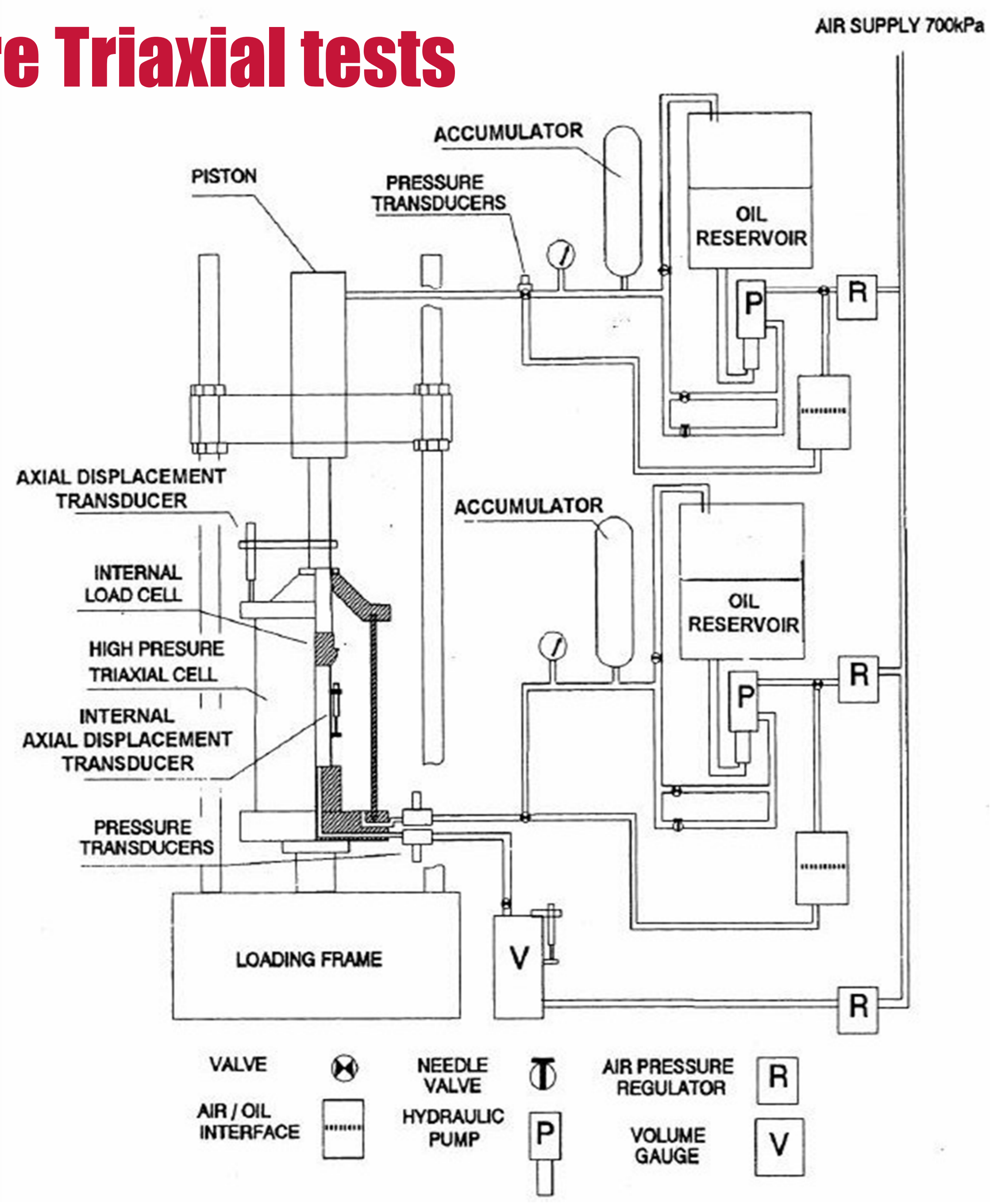
Wide range of sands: different trends to direct shear interface tests

High-to-Low Pressure Triaxial tests

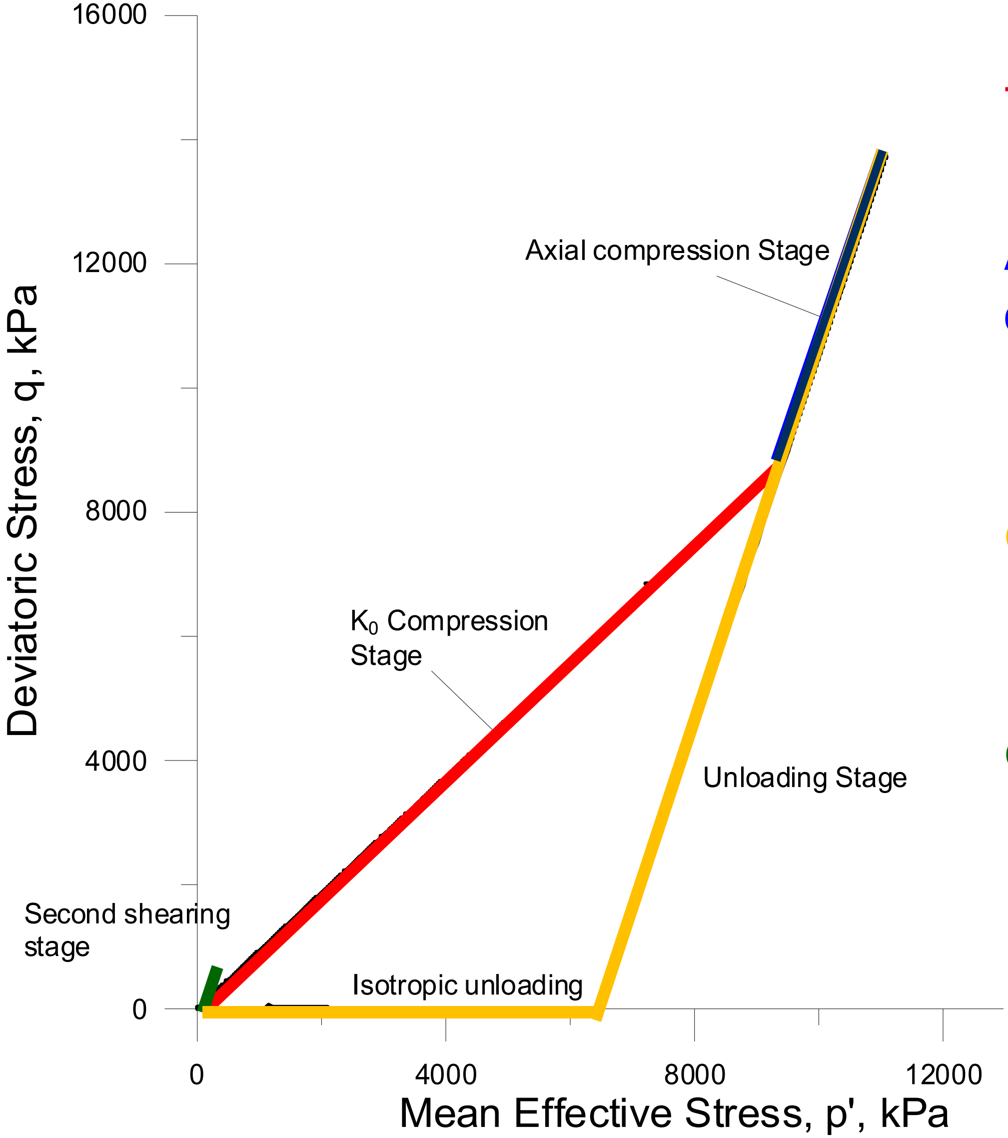
High-to-Low pressures, without dismantling & changing soil fabric

Matching model pile installation stress paths

Altuhafi & Jardine 2011



High-to-Low pressure stress-path tests



K_0 compression: tip advancing from above

Active shearing: tip arrival with $\sigma'_v > 20\text{MPa}$

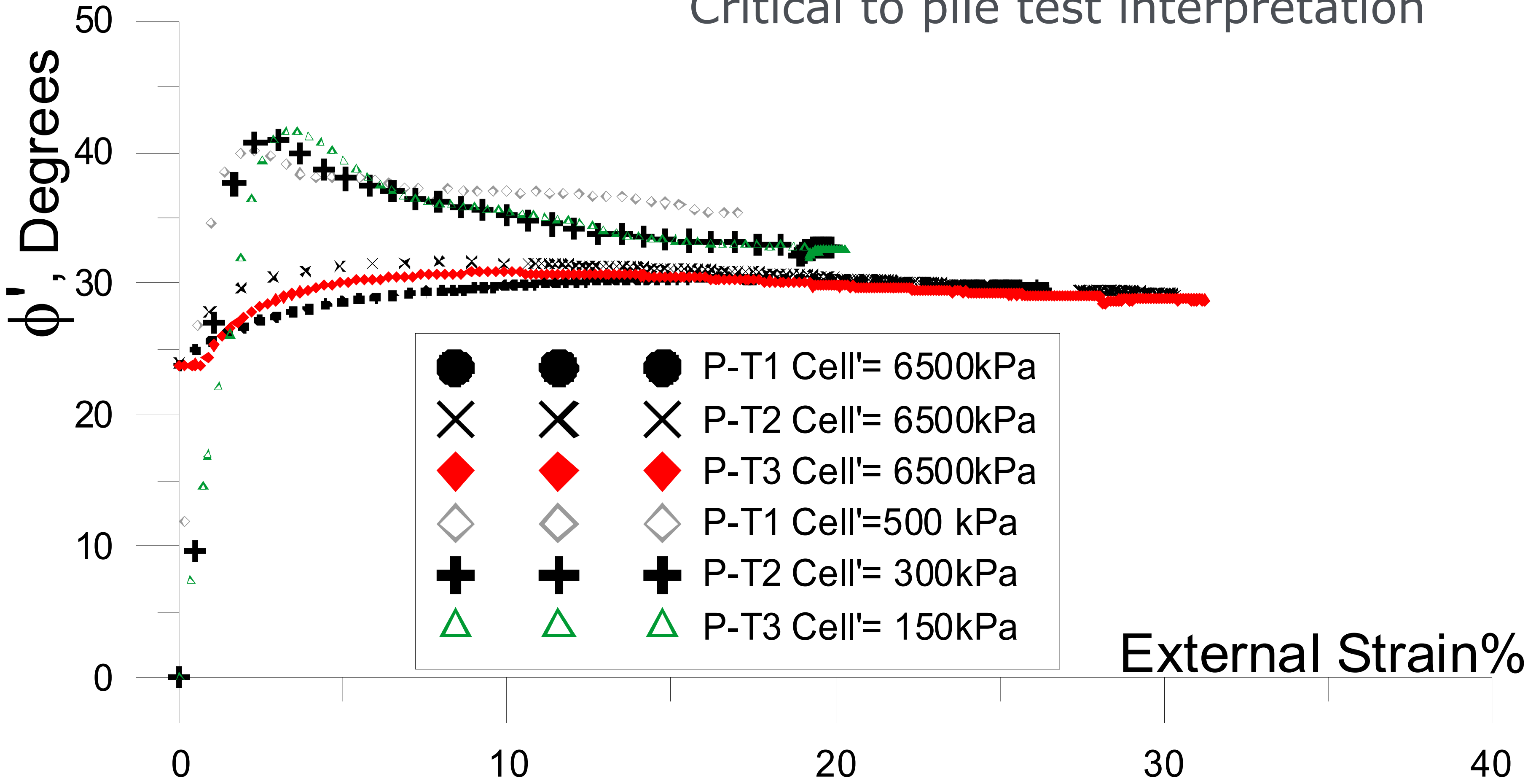
Unloading, tip advancing to greater depth

Re-shearing, in compression or extension at high 'OCR'

Effects on angle of shearing resistance?

High pressure 1st shearing: Ductile response low peak φ′

Low pressure re-shear: Brittle and much higher peak φ′
Critical to pile test interpretation

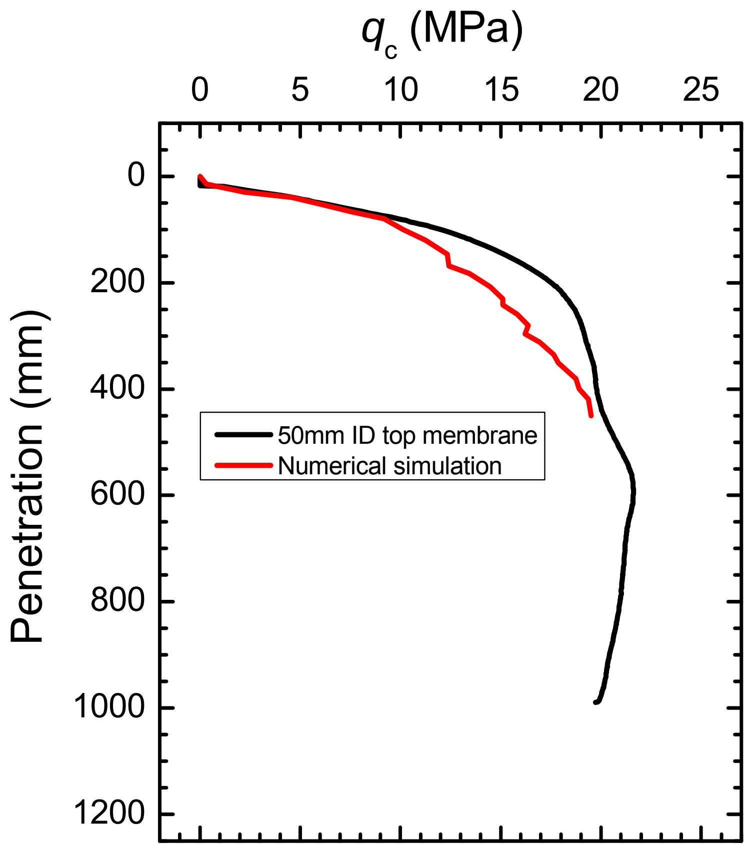


Ongoing research

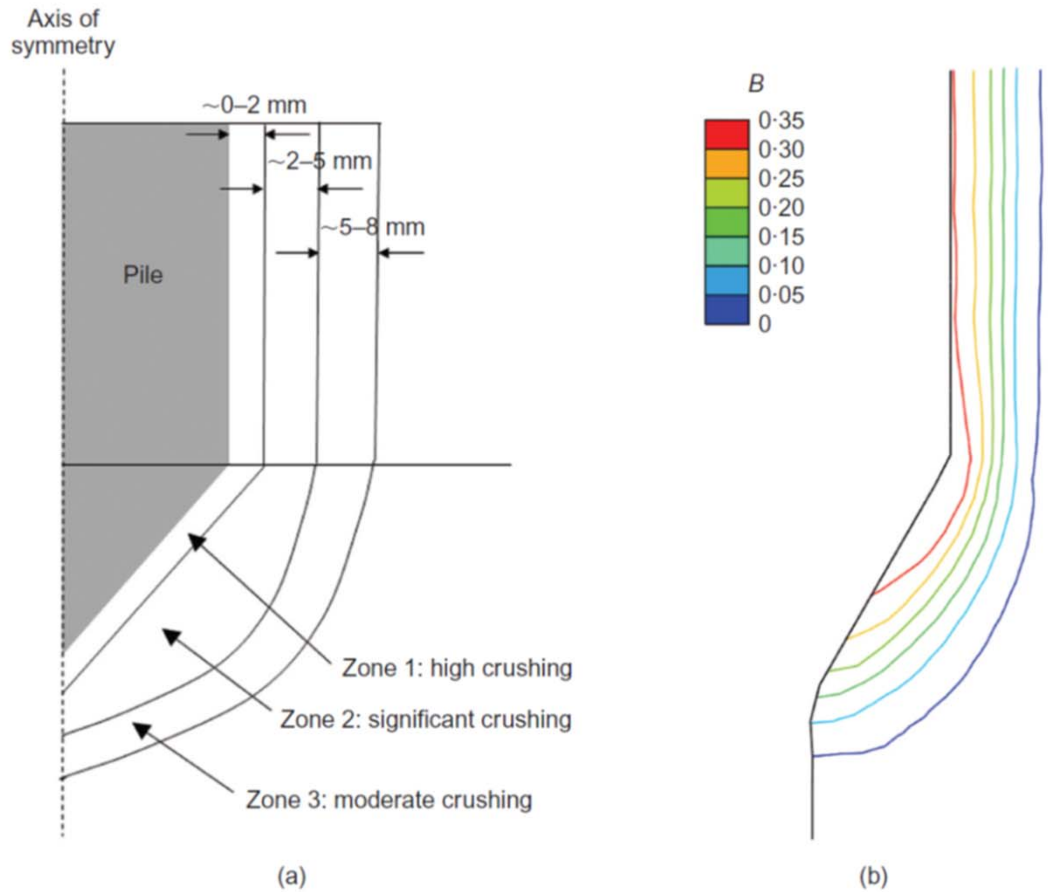
Ageing studies in lab and field
Rimoy, Silva, Jardine, Foray, Yang, Zhu & Tsuha (2015)
Under Review, Geotechnique

Simulating crushing and pile installation stresses
'ALE' Finite Element method with breakage mechanics:
Zhang, Yang, Nguyen, Jardine & Einav (2014)
Geotechnique Letters

End bearing and breakage: Zhang et al's predictions

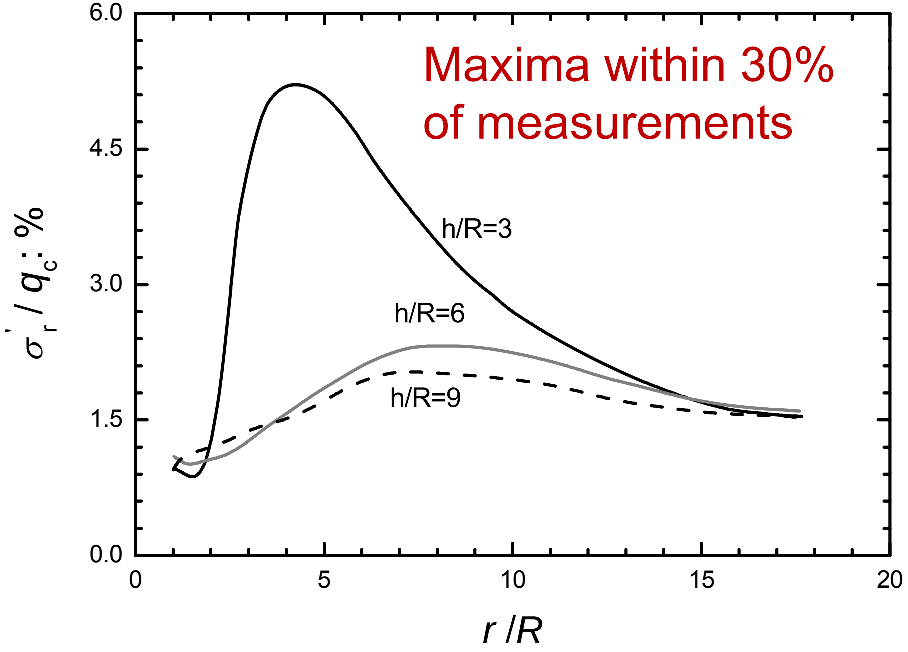


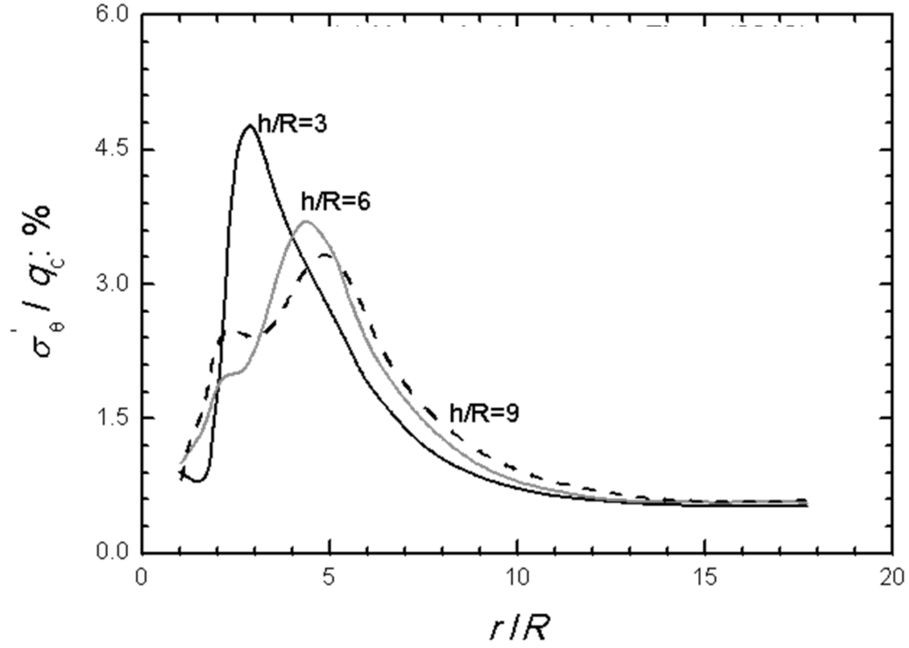
Predicted and measured pile tip stresses q_c



Contours of breakage parameter B:
Fresh sand B = 0, fully fractured B = 1

σ'_r/q_c and σ'_θ/q_c profiles predicted during installation





Encouraging agreement with cyclic penetration model pile tests

But predictions steady at h/R > 10, while shaft σ_r/q_c measurements keep falling with h/R

Improve by modelling shaft abrasion & cyclic penetration?

Second main theme in 3S-R experiments

Cyclic axial loading

Model pile lab tests: similar overall trends to Dunkerque field experiments, new insights

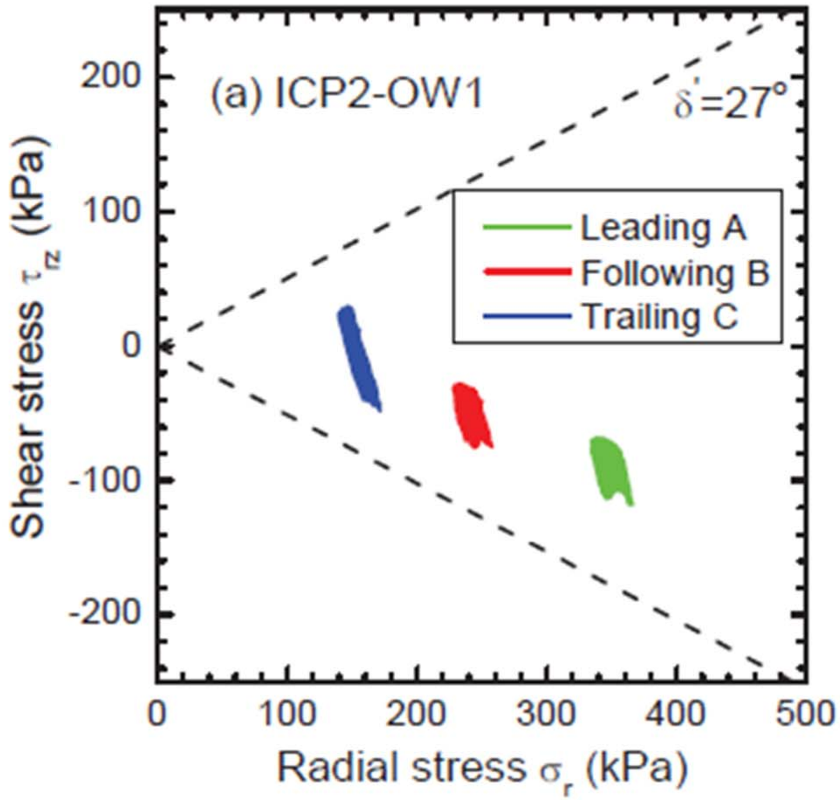
Parallel cyclic lab element testing

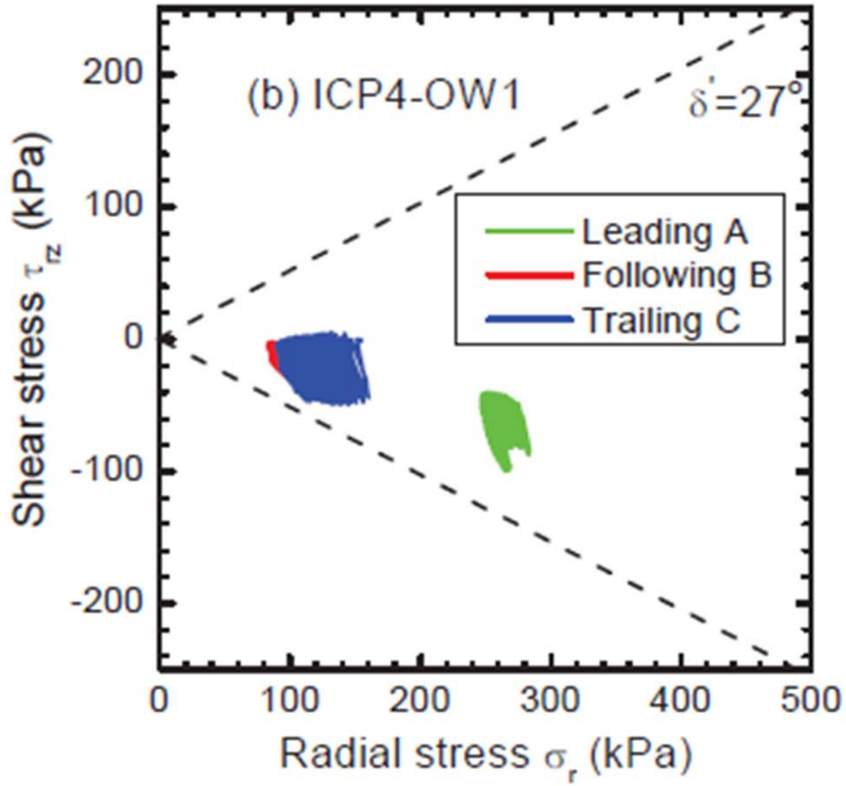
Integration into practical design

Stable Mini-ICP cycling: interface stress paths

Load-controlled to N > 1000

Stresses remain within Y_2 shaft capacity rises





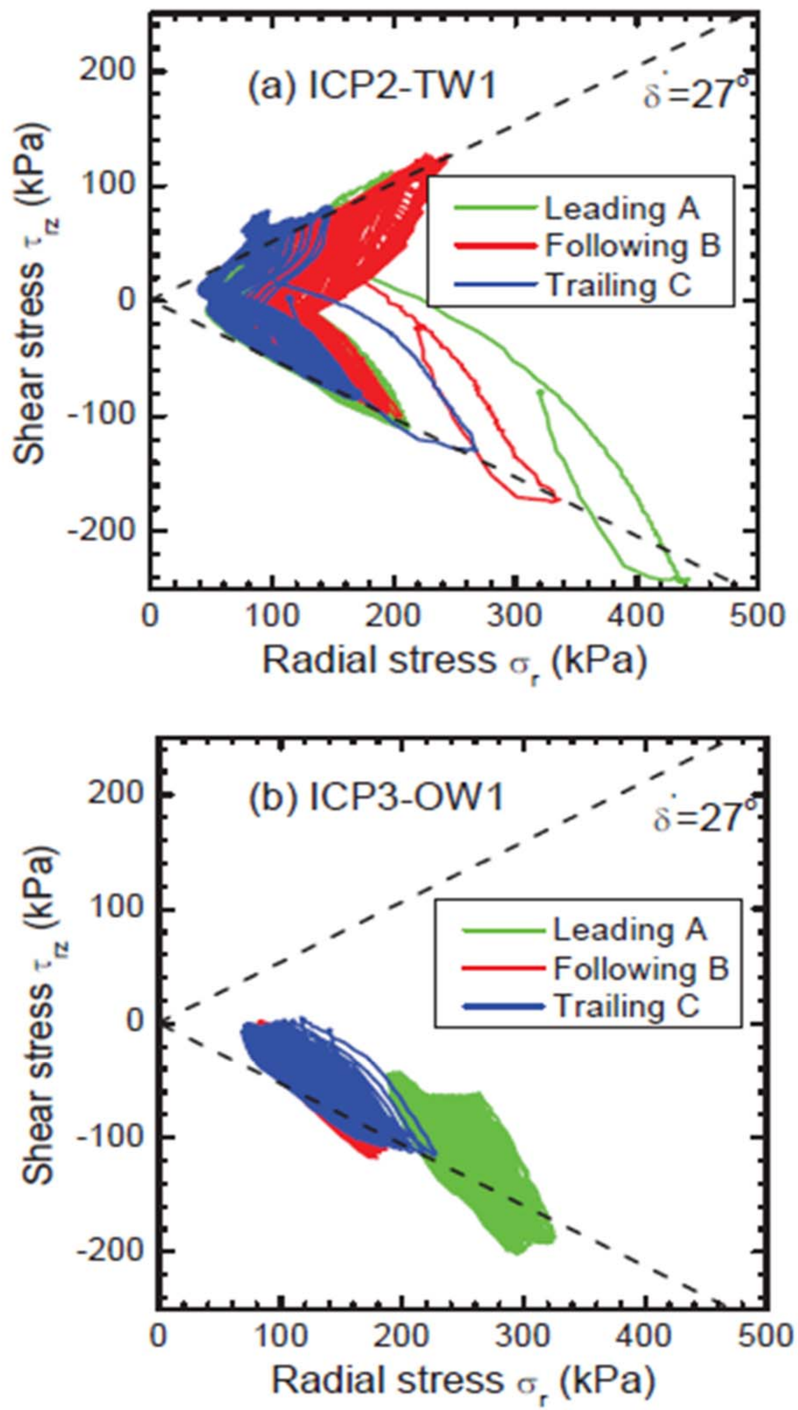
Tsuha, Foray, Jardine, Yang, Silva & Rimoy (2012) Soils & Foundations

Unstable stress paths
Mini ICP tests failing with N < 100

Displacement-controlled
Two-Way tests engage Y_3 and Y_4
Phase transformation at interface

Load-controlled
One-Way tests engage Y_2
Drift towards interface failure

Shaft capacity falls markedly



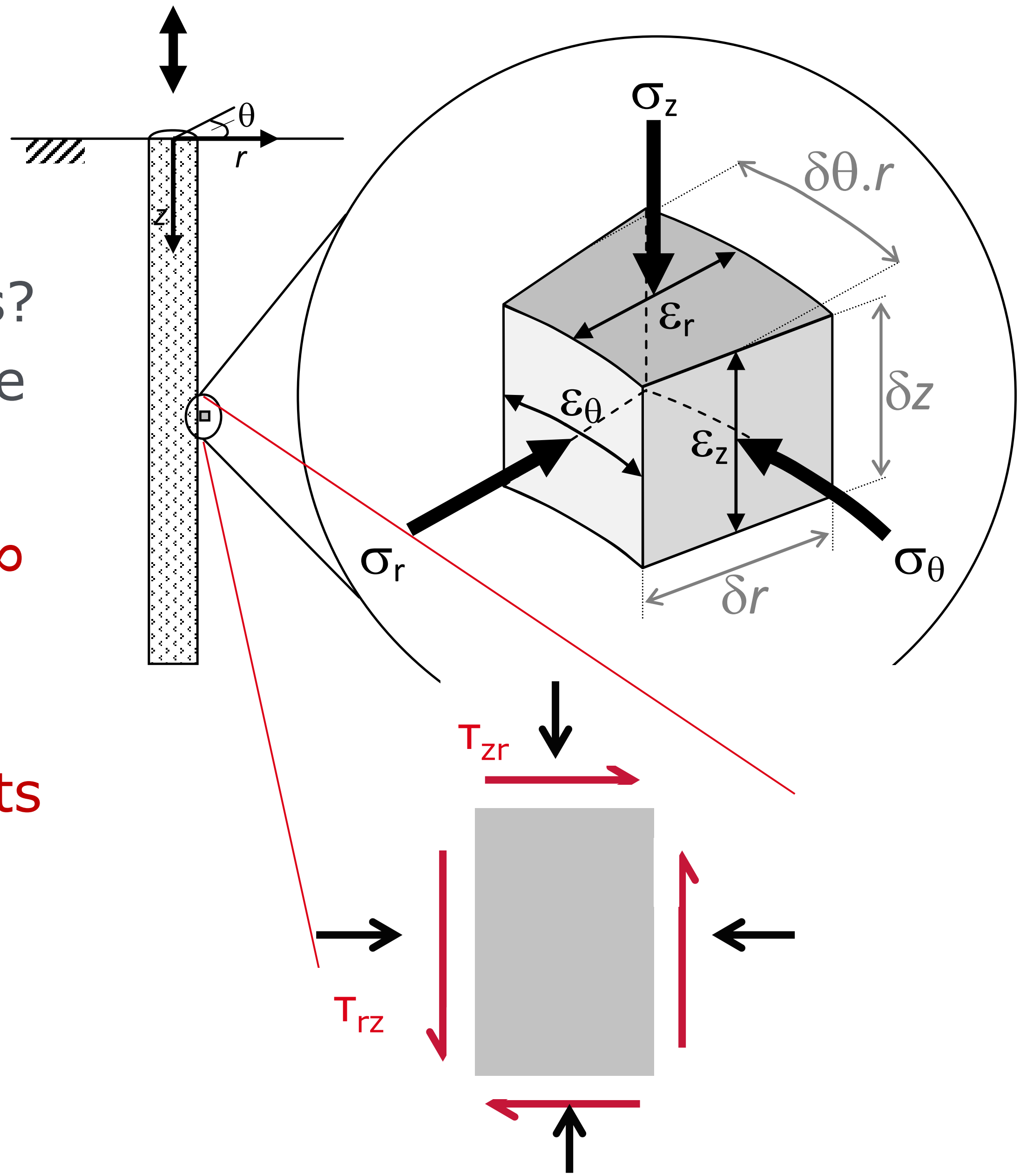
Matching cyclic conditions in lab element tests

Interface $\delta\sigma'_r/\delta r = 2G/R$
Constant Normal Stiffness?
$G \neq$ constant, R = variable

Apply undrained CNS = ∞
in Cyclic Triaxial CTX

Or Simple Shear CSS tests
Best performed in HCA

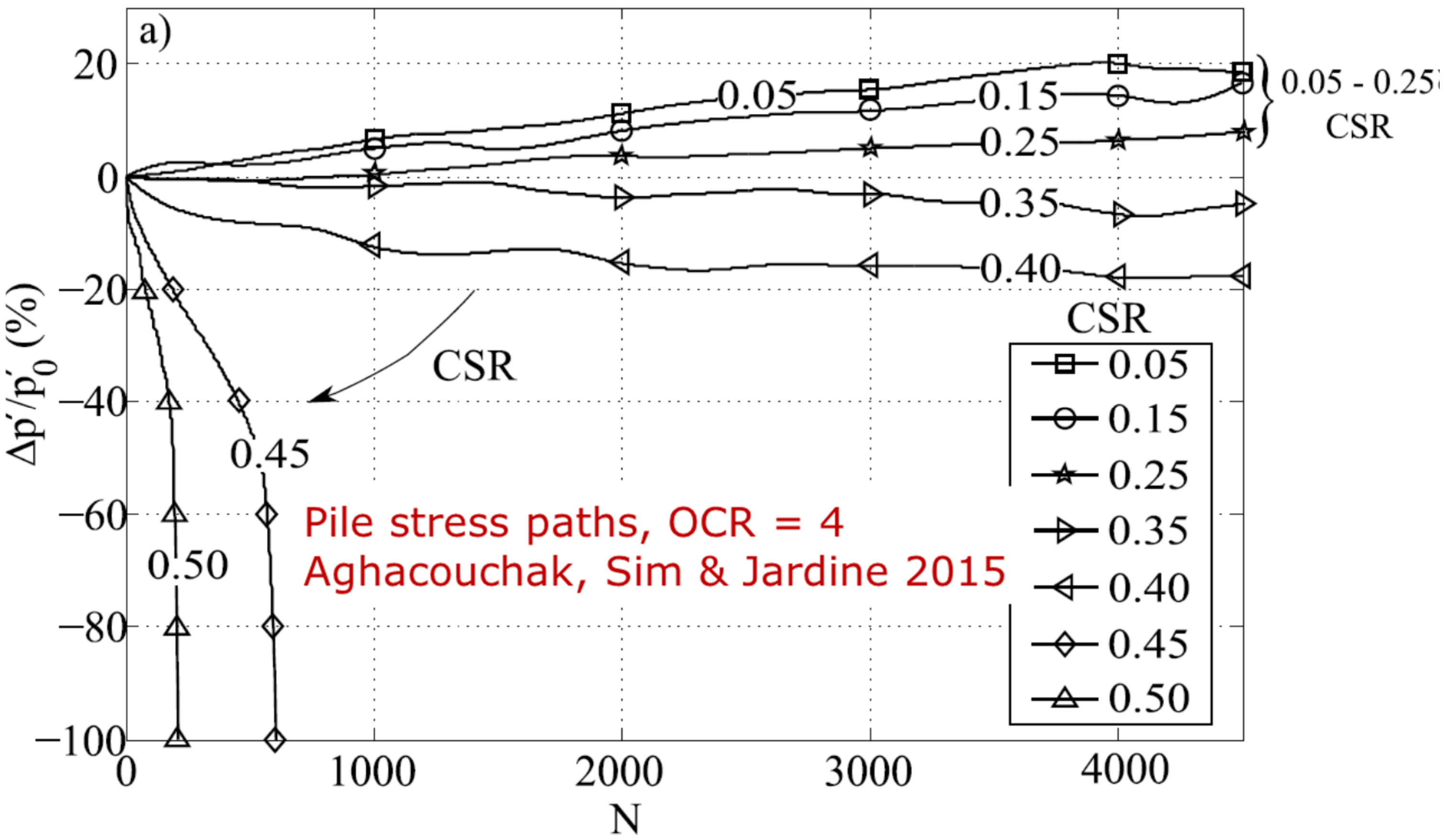
Pre-cycling stress path?



Undrained cyclic element tests: NE34 & Dunkerque sands

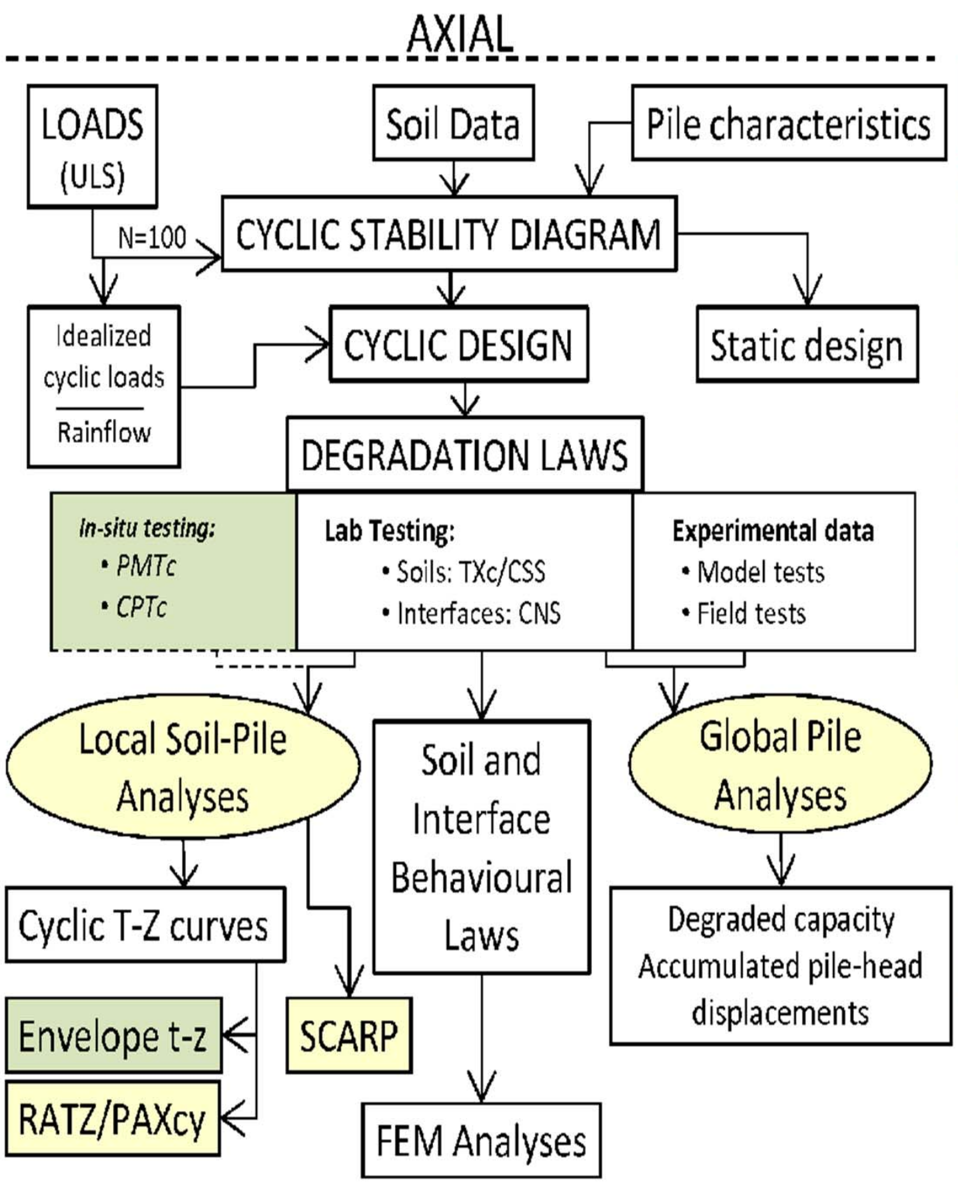
Yielding patterns and p′ drift rates depend on:

- CSR = q_{cyclic}/p' and N
- Shearing mode (TXL or HCA-SS)
- OCR & pre-cycling; creep & ageing periods



SOLCYP and applications

SOLCYP: Puech et al 2013



SUT 2012, Paris 2013 workshop

Jardine, Puech & Anderson 2012
Anderson, Puech & Jardine 2013

ICP static and cyclic methods for Borkum West II; Merritt et al 2012

Image from www.heavyliftspecialist.com

Summary

- Challenges posed by field behaviour. New scientific insights needed into ageing & cyclic response
- Critical investigations with Pierre Foray into pile installation stresses, grain-crushing, interface-shear & cyclic behaviour
- Intensively instrumented laboratory model experiments integrated with field, soil element & analytical research
- Results applied in major projects
- Still problems to solve:
  - Effect of scale on driven pile ageing?
  - More field tests needed: at Dunkerque, Larvik or Blessington?
  - Lateral/moment loading – new PISA programme underway: monopiles, tripods, jackets etc

Professor Pierre Foray 1949-2014

Other acknowledgments

Sponsors & partners: BP, BRE, CNRS, IFP, EPSRC, Exxon, INPG 3S-R, HSE, Shell, SOLCYP, Total and others

Current and former co-workers: Steve Ackerley, Fatin Altuhafi, Francoise Brucy, Andrew Bond, Fiona Chow, Roger Frank, Itai Einav, Tony Ho, Reiko Kuwano, Barry Lehane, Alain Puech, Siya Rimoy, Matias Silva, Cristina Tsuha, Jamie Standing, Zhongxuan Yang, Bitang Zhu and many others