Imperial College London

The 2nd Bishop Lecture

Advanced laboratory testing in research and practice

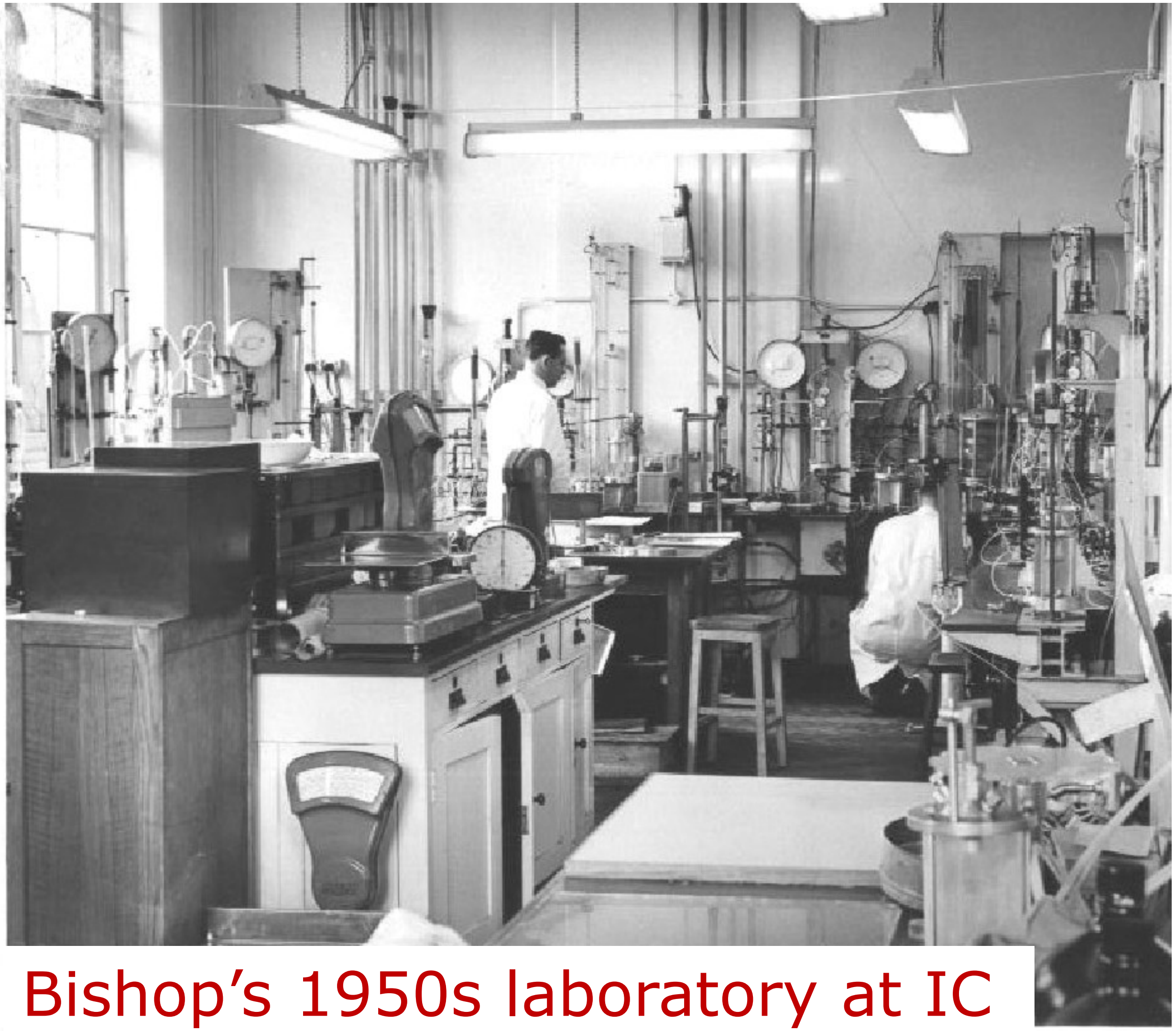
Paris ICSMGE, 2nd September 2013

Richard Jardine

Legacy

TC-101 honouring
Prof A W Bishop
1920-1988

Analyst,
Experimentalist,
Equipment designer



Bishop's 1950s laboratory at IC

Life, work and archived papers:
www.cv.ic.ac.uk/SkemArchive/index.htm

Bishop's last keynote: Stockholm ICSMFE 1981:

With 70 former and current IC group members

Sampling & Advanced Laboratory testing:

Equipment & techniques

Rigour, meticulous attention to detail, engineering application

Lecture themes

Following Bishop & TC101: special capabilities & practical value of Advanced Laboratory Testing

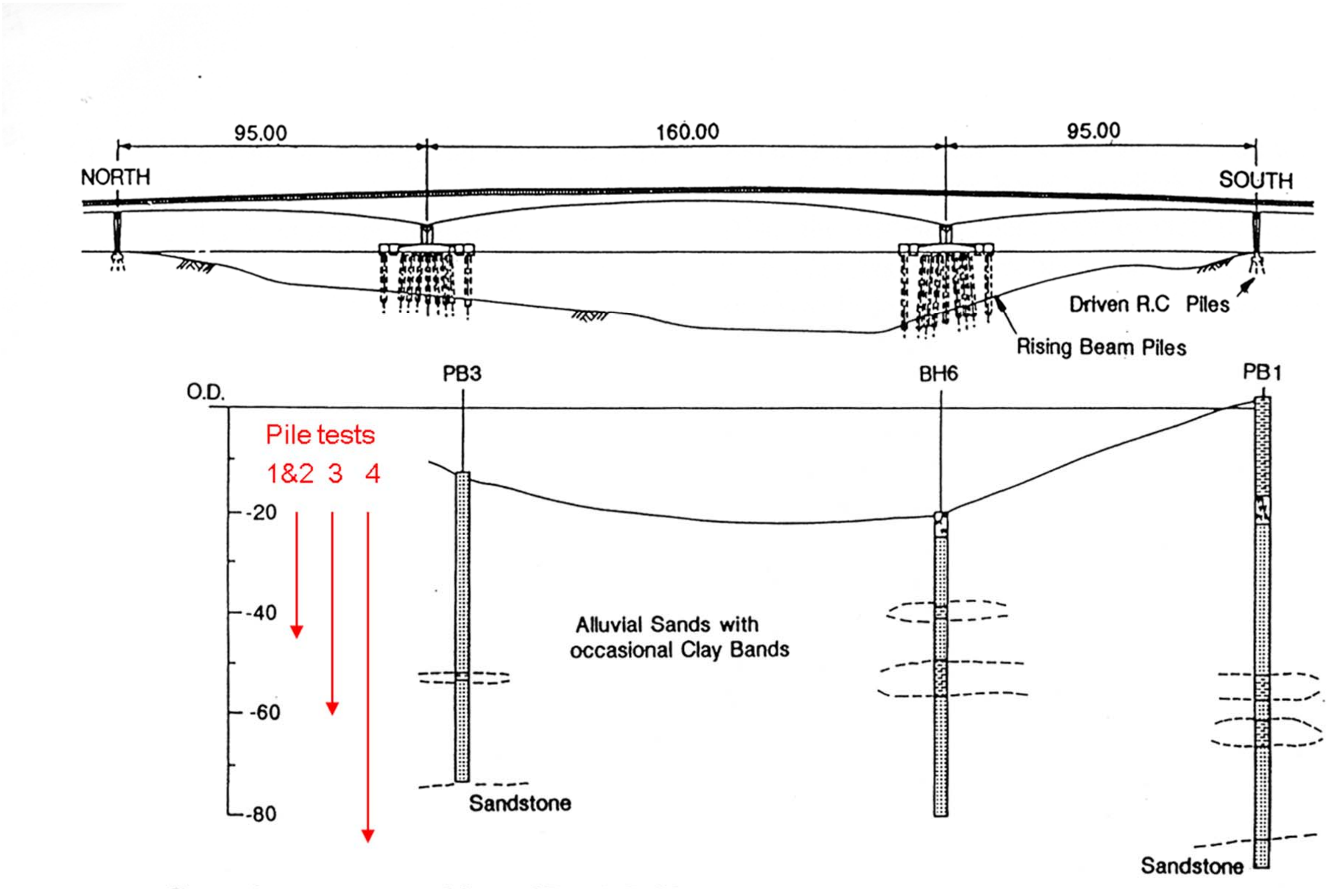
Contributions: Author, colleagues & French co-workers

Integration of laboratory & field research with analysis

Example of application considered fully resistant to ‘theoretical refinement’: Piles driven in sand

For clays: see Jardine et al 2012

Mainstream Civil Engineering: see Williams et al 1997



Sungai Perak, Malaysia: 160m central span

Offshore Energy applications

Oil and gas platforms

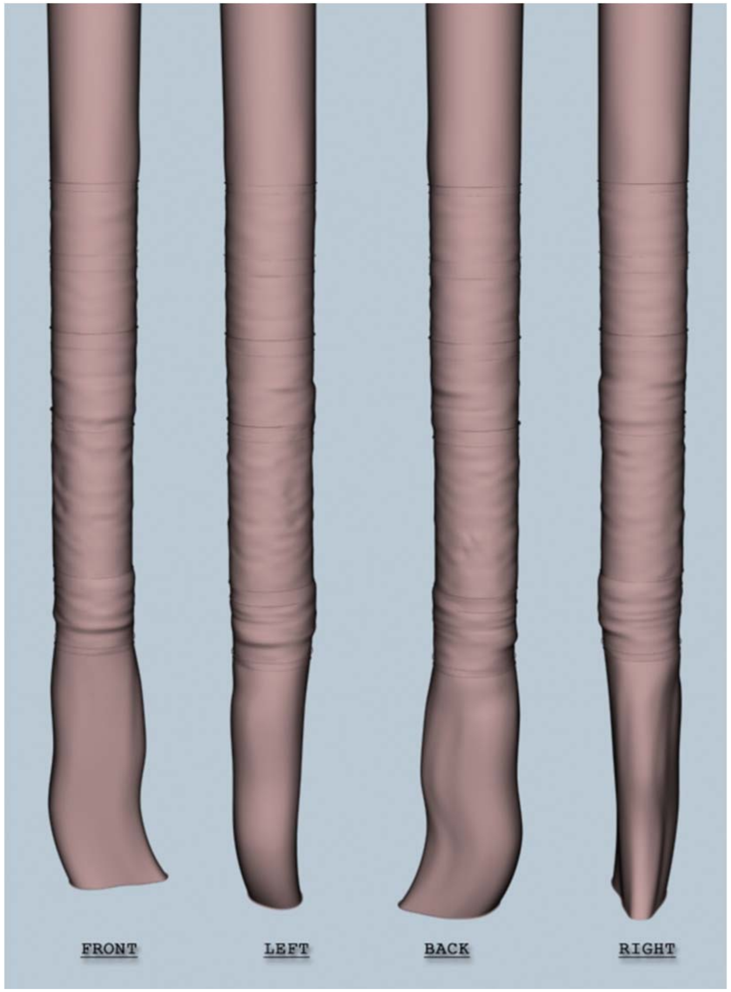
Overy 2007

Piled tripods for Wind-turbines:
Borkum West II German N. Sea
Merritt et al 2012

Research agenda: set by field experience

Axial capacity - improved after field research in France: Lehane et al 1993, Chow 1997, ICP-05 (Jardine et al 2005)

Installation stresses? Tip buckling



Other observations revealed by large-scale Dunkerque tests

Creep & ageing: affects axial capacity & stiffness

Non-linear stiffness: axial, lateral & rotational

Cyclic loading: potential impact

Dunkerque programme:

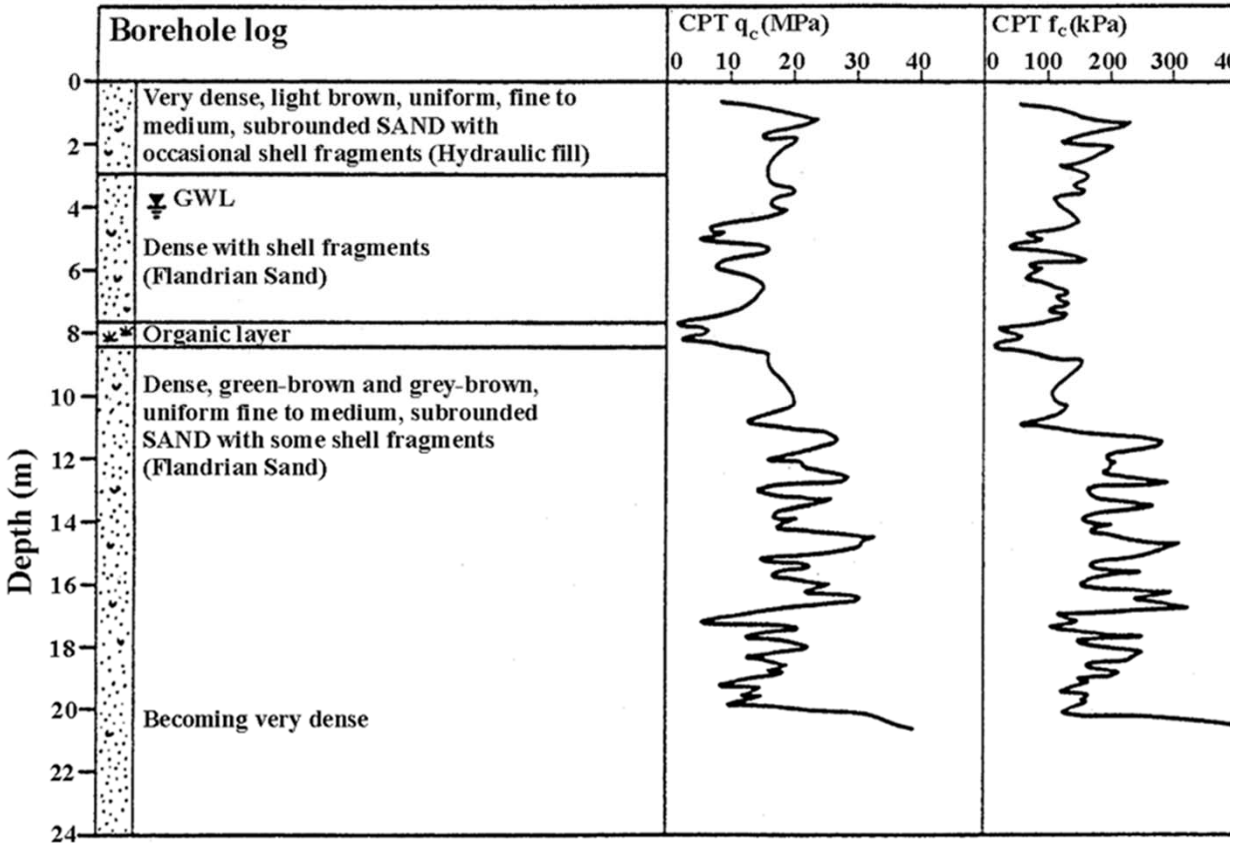
Dense marine sand

Eight steel pipe piles
457mm OD, 19m

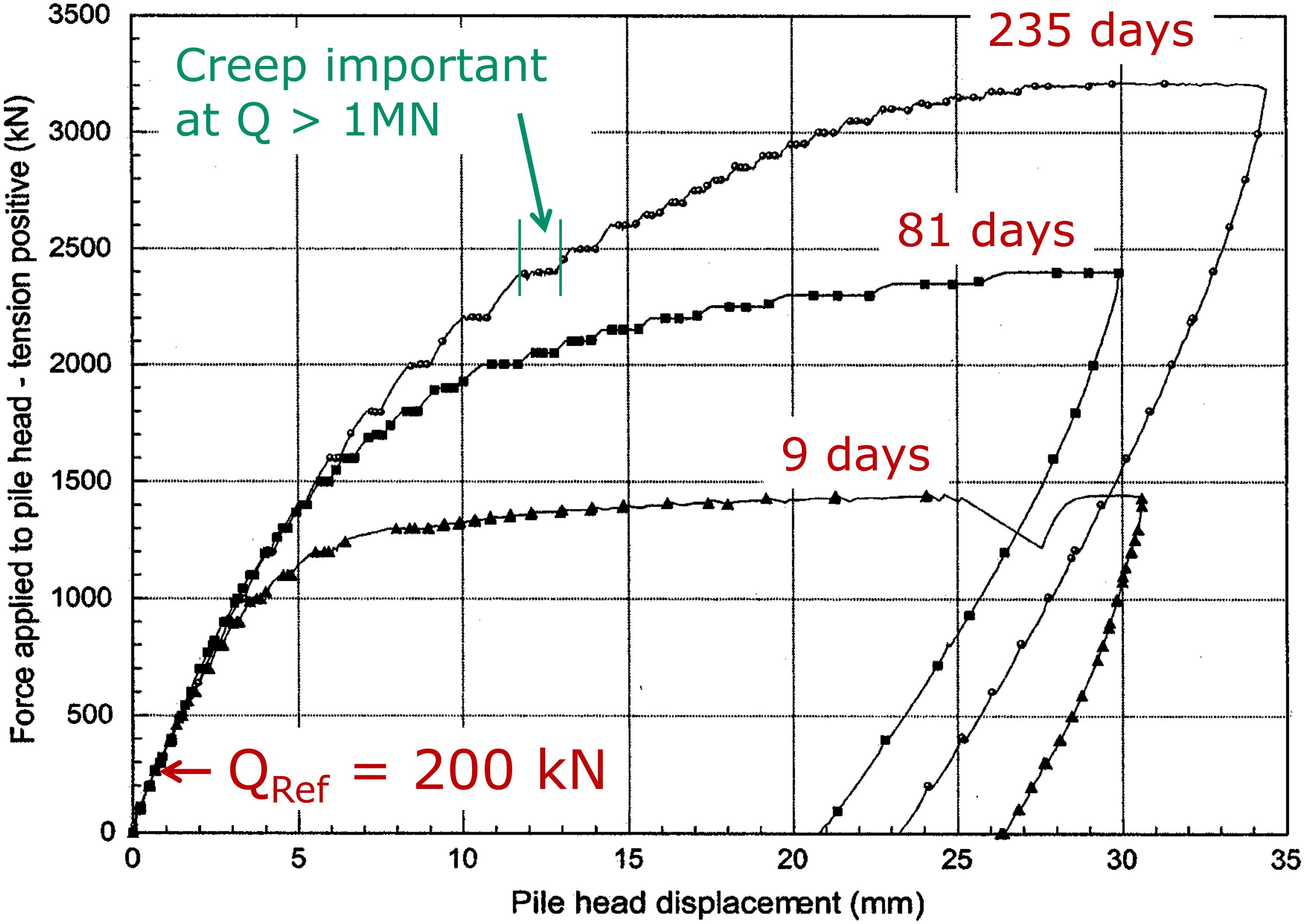
Static & cyclic loading

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

Non-linear axial stiffness: first time tension tests

Head loads Q, displacements δ

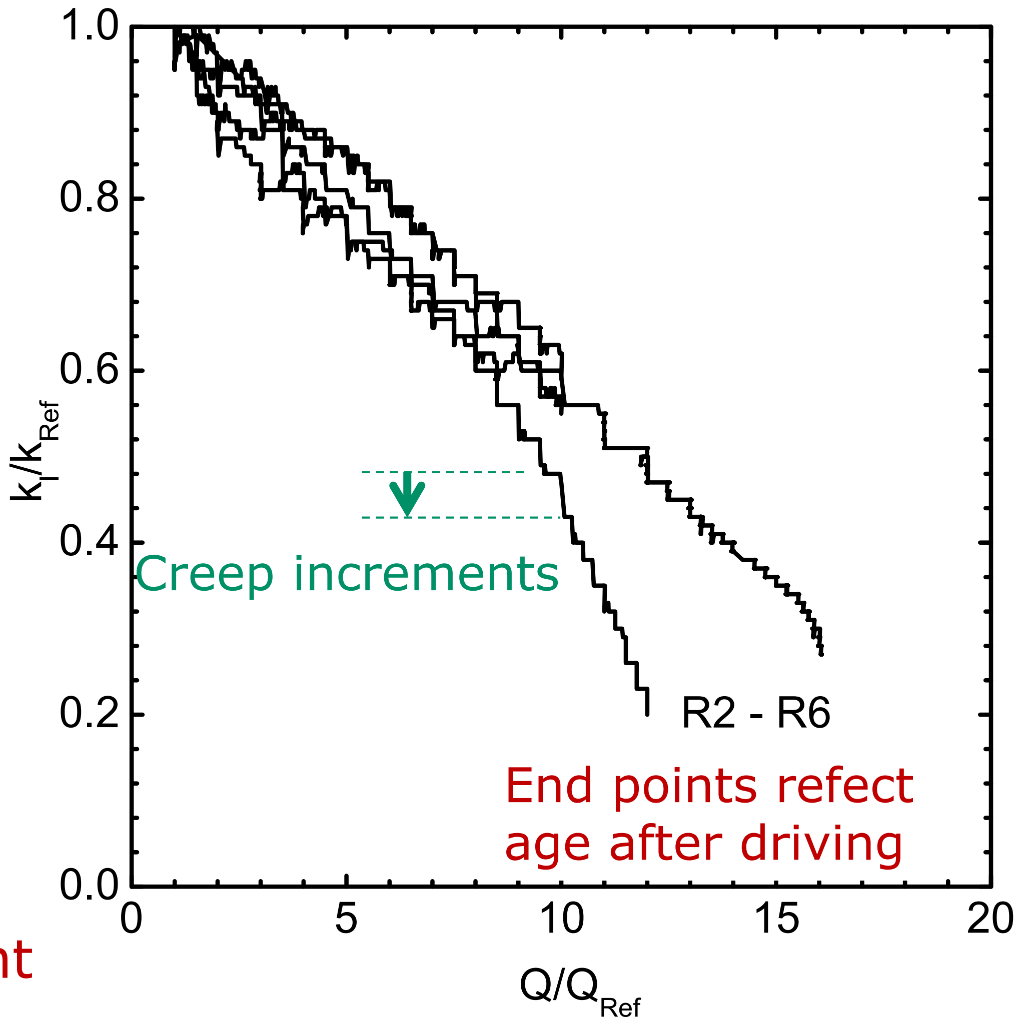
Pile stiffness $k = Q/\delta$

$Q_{Ref} = 200$ kN

k_{Ref} = stiffness at Q_{Ref}

No 'linear-elastic' plateau
Stiffness falls with Q/Q_{ref}

Creep & ageing: very significant



Rimoy et al 2013

Impact of axial cyclic loading

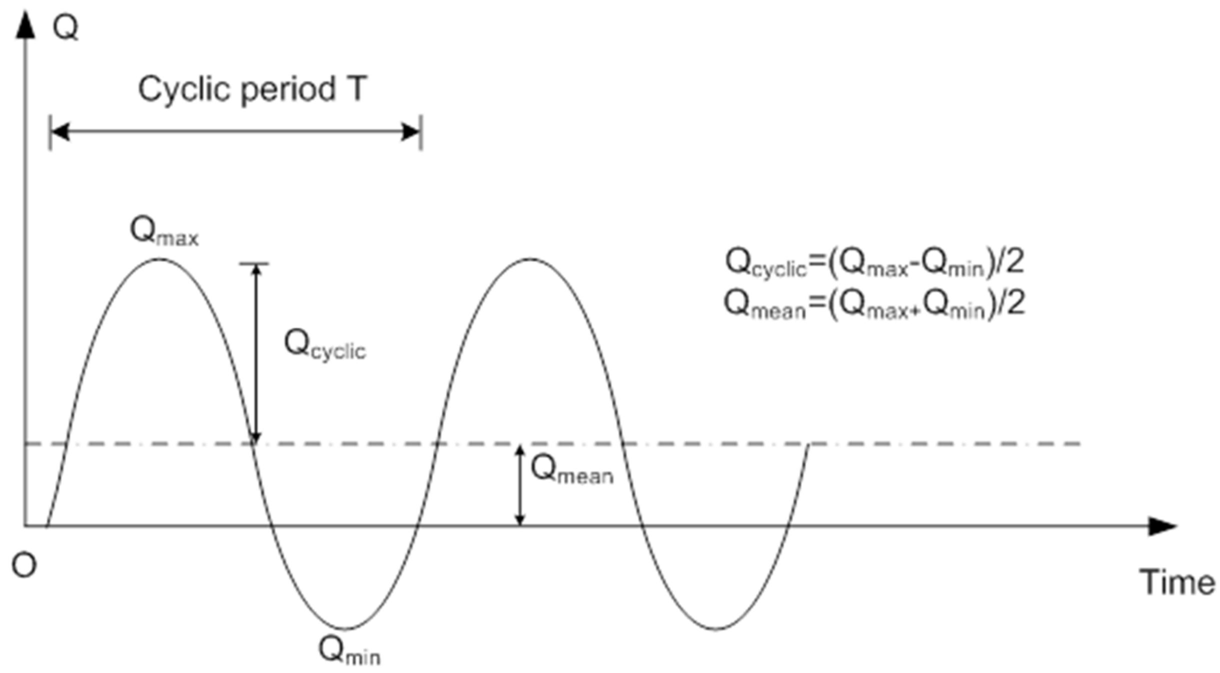
Load controlled

T = 60s

One-Way: tension

Two-Way: tension & compression

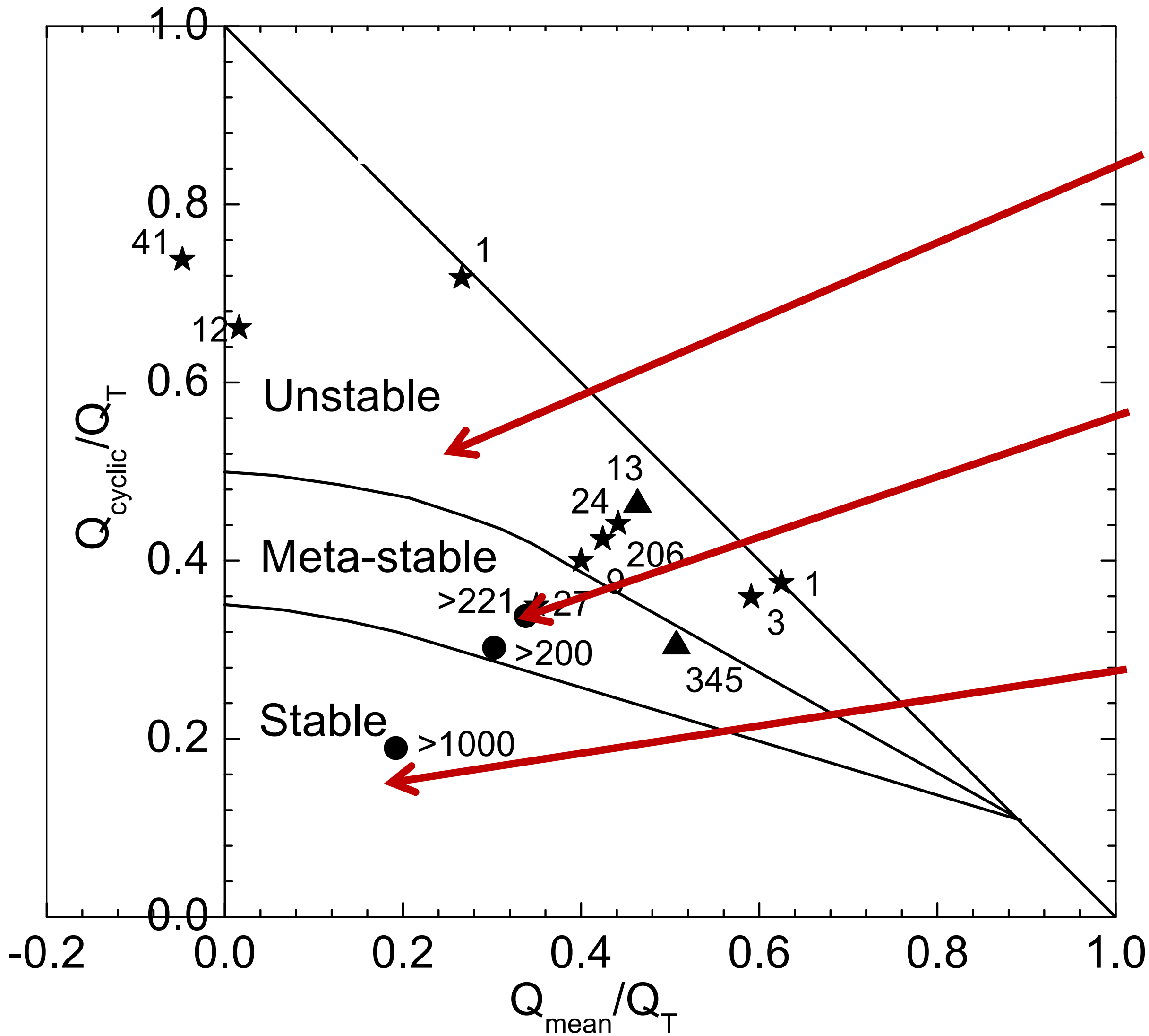
Plus: tension tests to failure



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



Failure $N_f < 100$

$100 < N_f < 1000$

Stable to $N > 1000$

Shaft capacity grows
Cycling adds to
ageing

Research to improve understanding & predictive scope

1. Non-linear stiffness from advanced laboratory tests

2. Lab-based FE predictions & field trends

3. Stress path studies of creep & ageing

4. Installation soil stresses: laboratory model

5. Interface-shear & grain-crushing experiments

6. Lab results & ‘breakage’ FE analysis

7. Cyclic loading: towards lab-based design

Theme 1

Stress-path experiments

Pluviated Dunkerque, Ham River (Thames Valley) & Fontainebleau NE 34 sands

Sub-angular, 0.2< d_{50} <0.3mm, silica media

Stress path test: Kuwano 1999

'Bishop & Wesley' cell:
200 x 100mm specimens

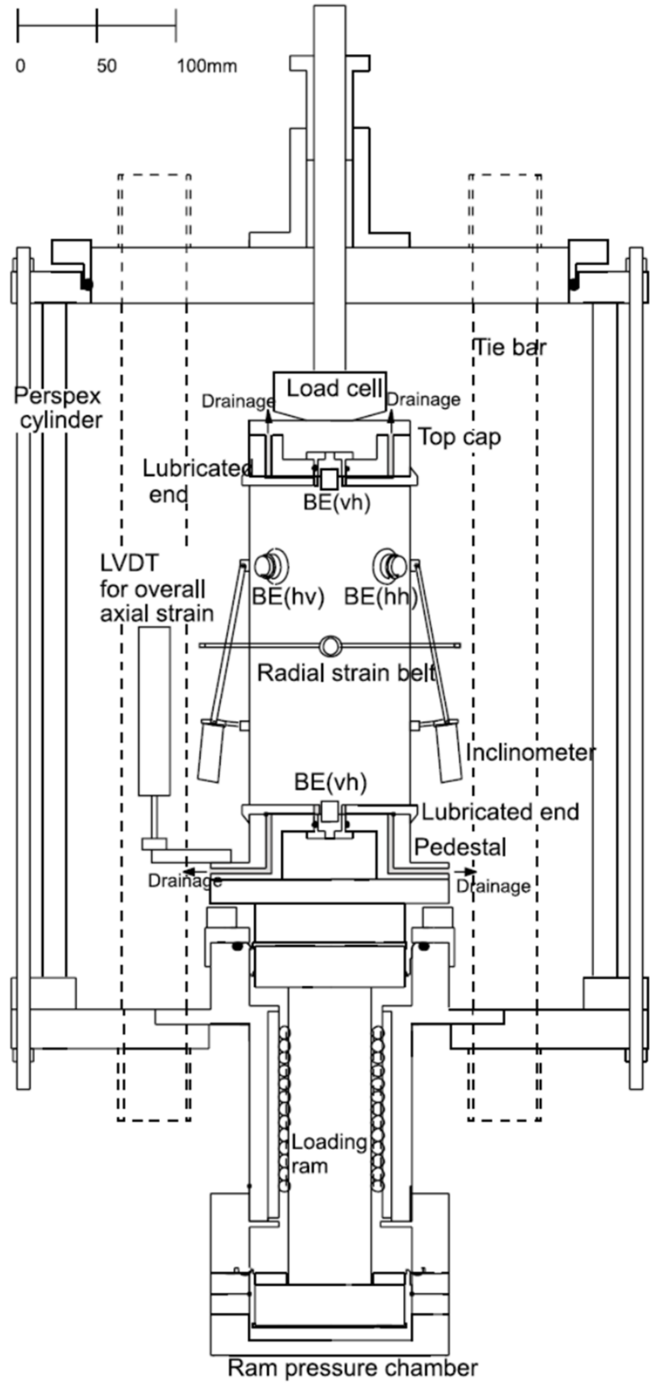
Automated stress & strain options

High resolution local strain gauges
multi-axial Bender Elements (BE)

Elasticity & kinematic yielding

Non-linearity & anisotropy

Time dependency



Elasticity & Kinematic Yield Surfaces: KYS

Elastic Y_1 KYS

Stiffness depends on σ′ level
Usually anisotropic
Plastic & non-linear if Y_1 engaged

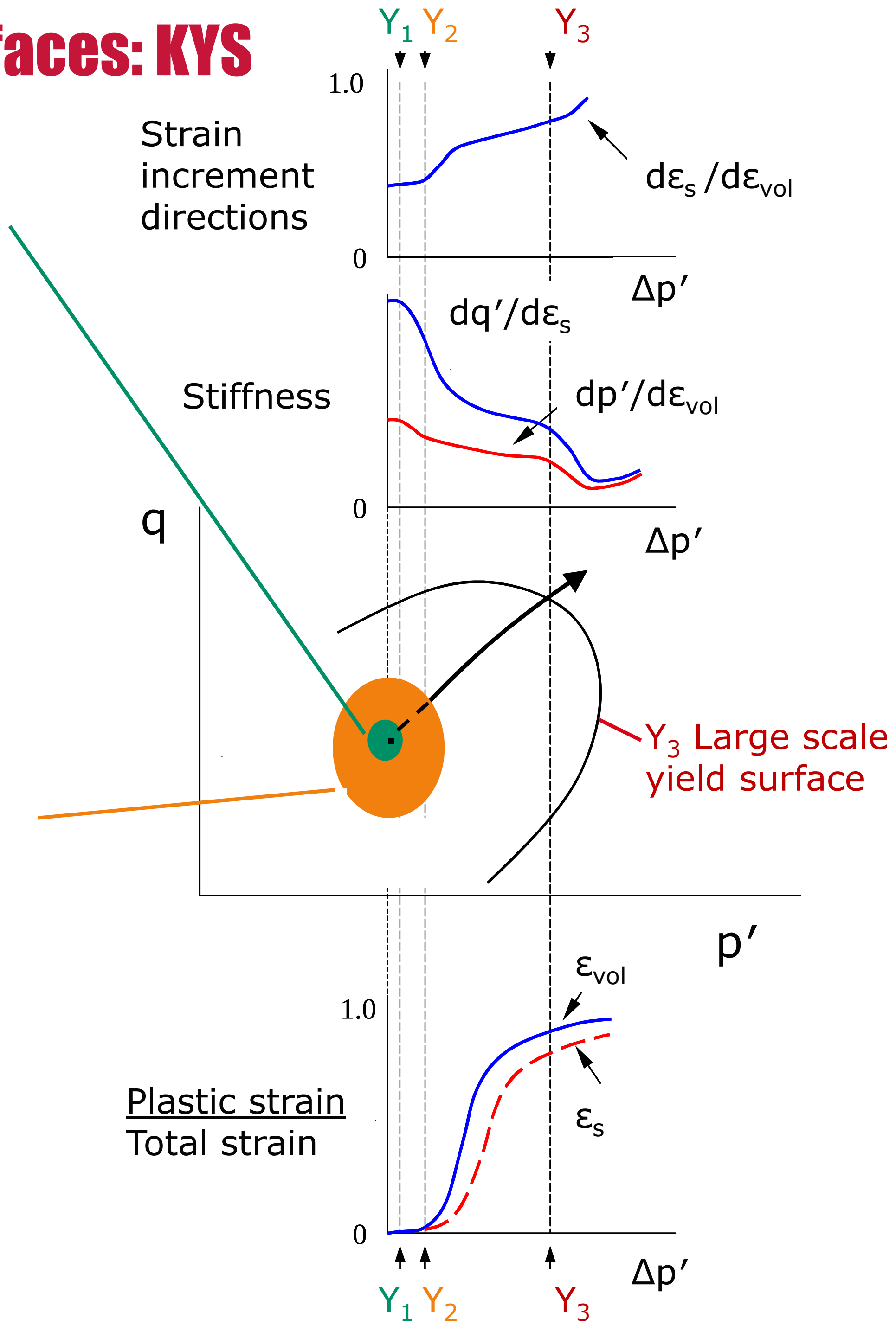
KYS dragged with q, p′
Conforms to outer Y_3
Scales with p′

Intermediate Y_2 KYS

Strain increment direction changes

Onset of time/rate dependency

Cyclic threshold: sharp increase in permanent strain accumulation and/or undrained p′ drift



Elastic property measurement techniques

Bender Element shear wave velocities:

Vertical, polarised horizontally – S_{vh}

Horizontal, polarised vertically - S_{hv}

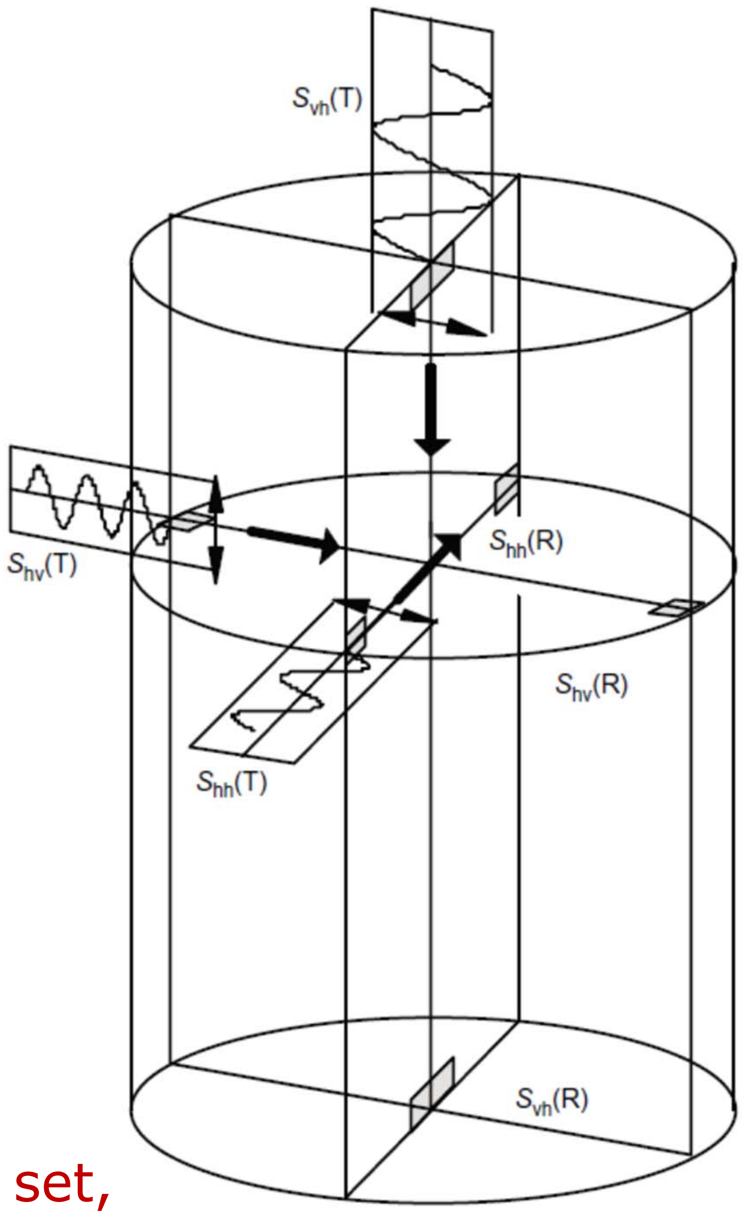
Horizontal, polarised horizontally - S_{hh}

And vertical P-Waves

Vertical & radial static probing tests

Range of conditions, keeping within Y_1

Full cross-anisotropic elastic parameters set, assuming rate independence



Resonant column & static Torsional Shear (TS) HCA tests

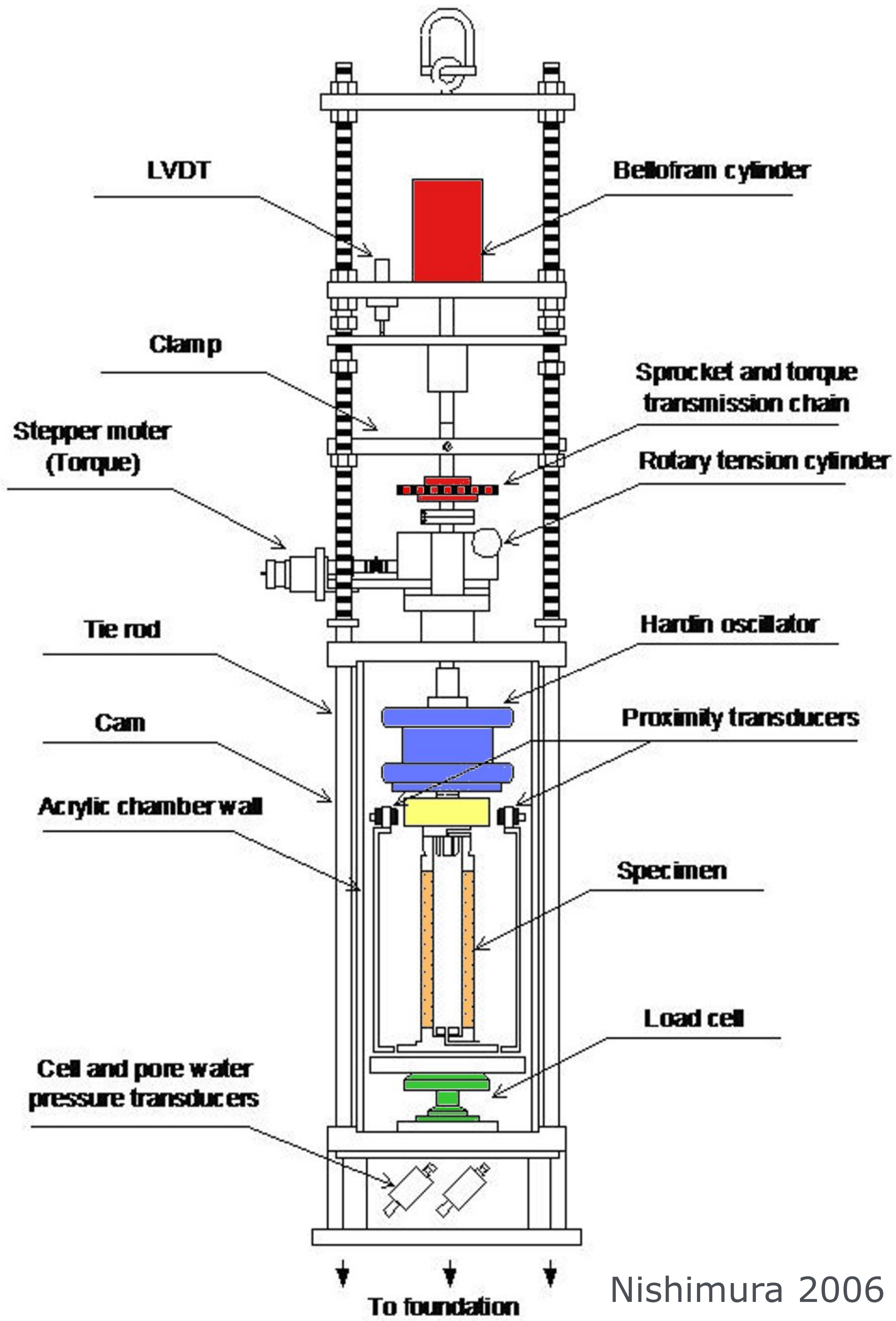
Porovic 1995 & Connolly 1998

Dynamic & static G_{vh}
Wide range of conditions

HRS & Dunkerque sands:

h =170, d_i = 38 & d_o= 70 mm

Correlated with BRE's field seismic CPT & DMT G_{vh} tests at Dunkerque



Nishimura 2006

Cross anisotropic behaviour within Y_1 KYS

Kuwano 1999, Jardine & Kuwano 2003

Stiffnesses vary with σ′ components & void ratio (e)

$$E_u = f(e).\ A_u\ .\ (p'/p'_r)^{B_u}$$

$$E'_v = f(e).\ A_v\ .\ (\sigma'_v/p'_r)^{C_v}$$

$$E'_h = f(e).\ A_h\ .\ (\sigma'_h/p'_r)^{D_h}$$

$$G'_{vh} = f(e).\ A_{vh}\ .\ (\sigma'_v/p'_r)^{C_{vh}}\ .\ (\sigma'_h/p'_r)^{D_{vh}}$$

$$G'_{hh} = f(e).\ A_{hh}\ .\ (\sigma'_v/p'_r)^{C_{hh}}\ .\ (\sigma'_h/p'_r)^{D_{hh}}$$

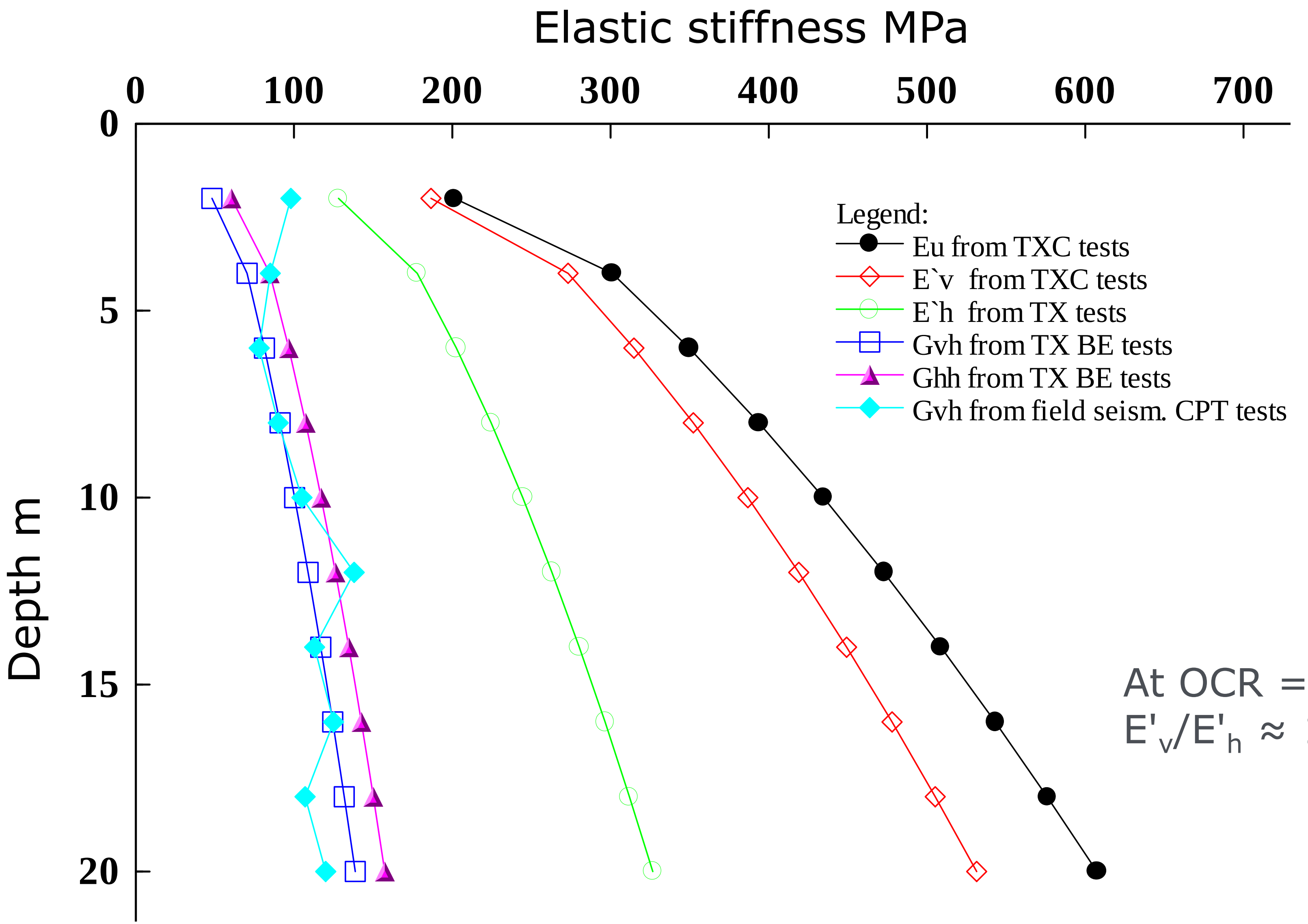
$$f(e) = (2.17 - e)^2/(1 + e)$$

p_r is atmospheric pressure

A_{ij}, B_{ij}, C_{ij} & D_{ij} non-dimensional material constants

Stress level exponents B_u and $[C_{ij} + D_{ij}] \approx 0.5$ to 0.6

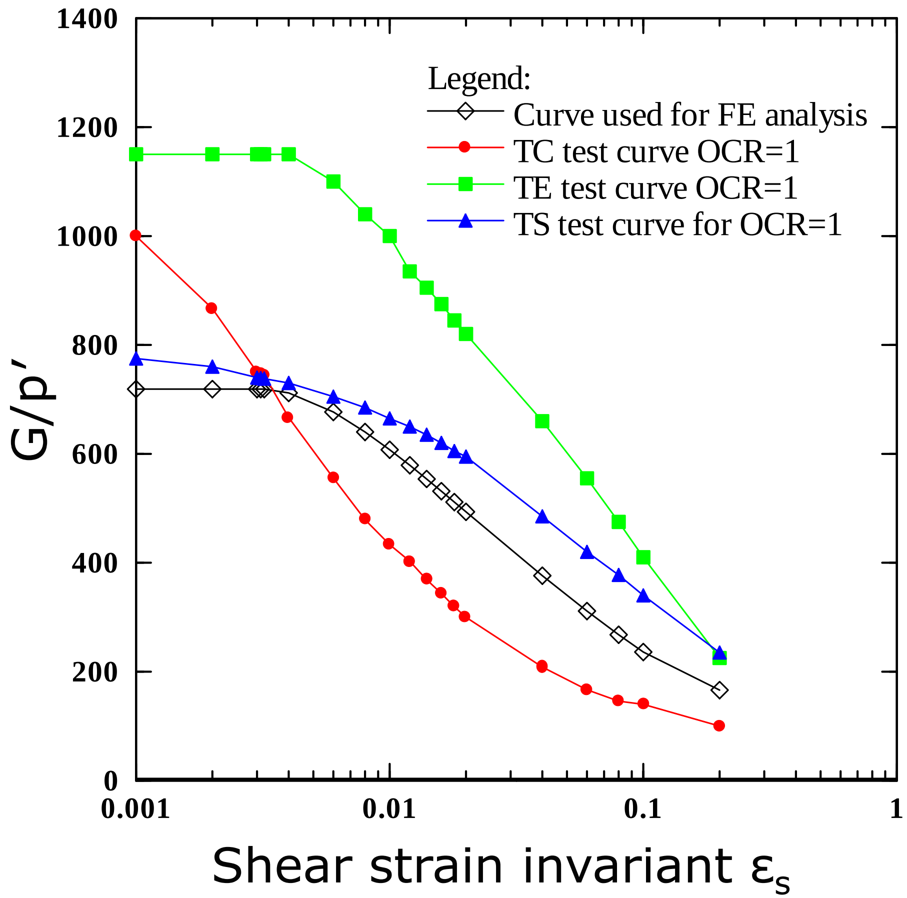
Anisotropic Y_1 stiffness profiles: Dunkerque



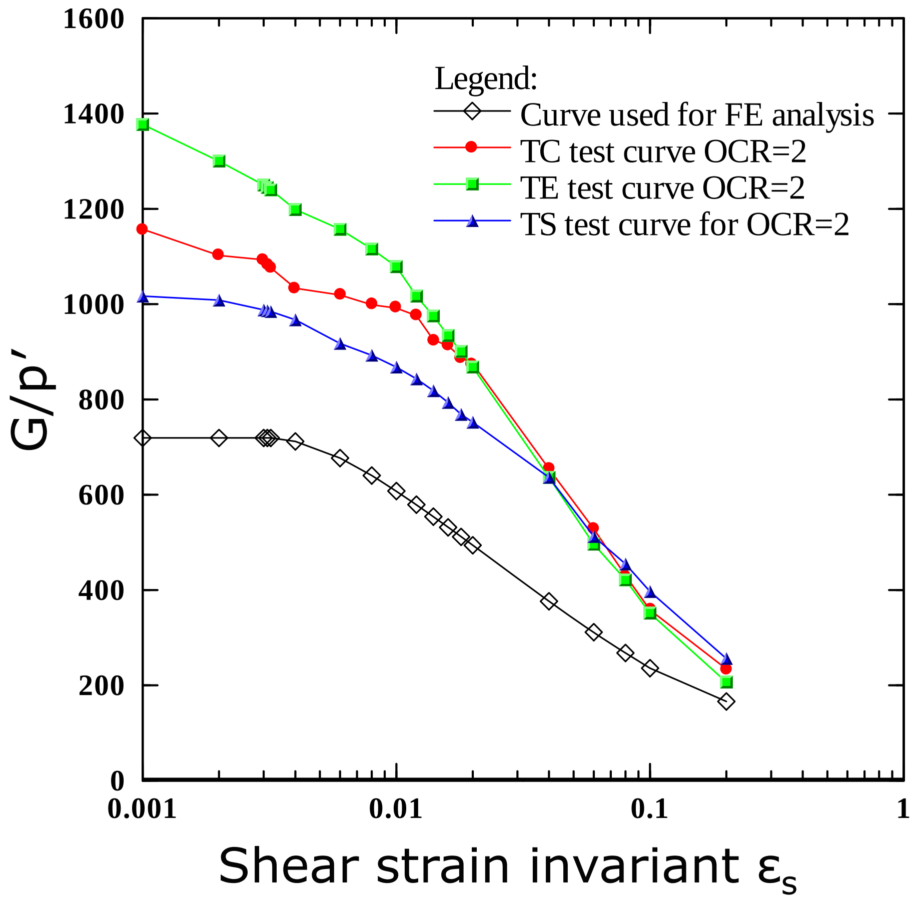
At OCR = 1 K_0
$E'_v/E'_h \approx 1.7$

Field seismic & laboratory G_{vh} measurements agree within ≈ 10%

Anisotropy post Y_1 in non-linear range: Secant shear stiffnesses: dense Dunkerque sand



OCR = 1, K_0 consolidation



OCR = 2, K_0 consolidation

Theme 2

Lab-based ICFEP predictions for Dunkerque tests

Predictive tools: ICFEP; Potts and Zdravkovic 1999

Elastic pile displaced axially to failure

Sand: non-linear & σ′ dependent tangent stiffness between Y_1 & Y_3 yield surfaces

$G = f(p', \varepsilon_s)$ fitted to OCR = 1, G_{vh} trends

$K' = g(p', \varepsilon_{vol})$

Y_3 : non-associated Mohr-Coulomb, depth-variable φ′ & Ψ

Interface: effective-stress Coulomb, δ from interface shear tests

Can be extended: anisotropy, stress reversals or ‘bubble’ models…

Non-linear predictions for 81 day tension test

19m, 457mm OD, steel pipe pile

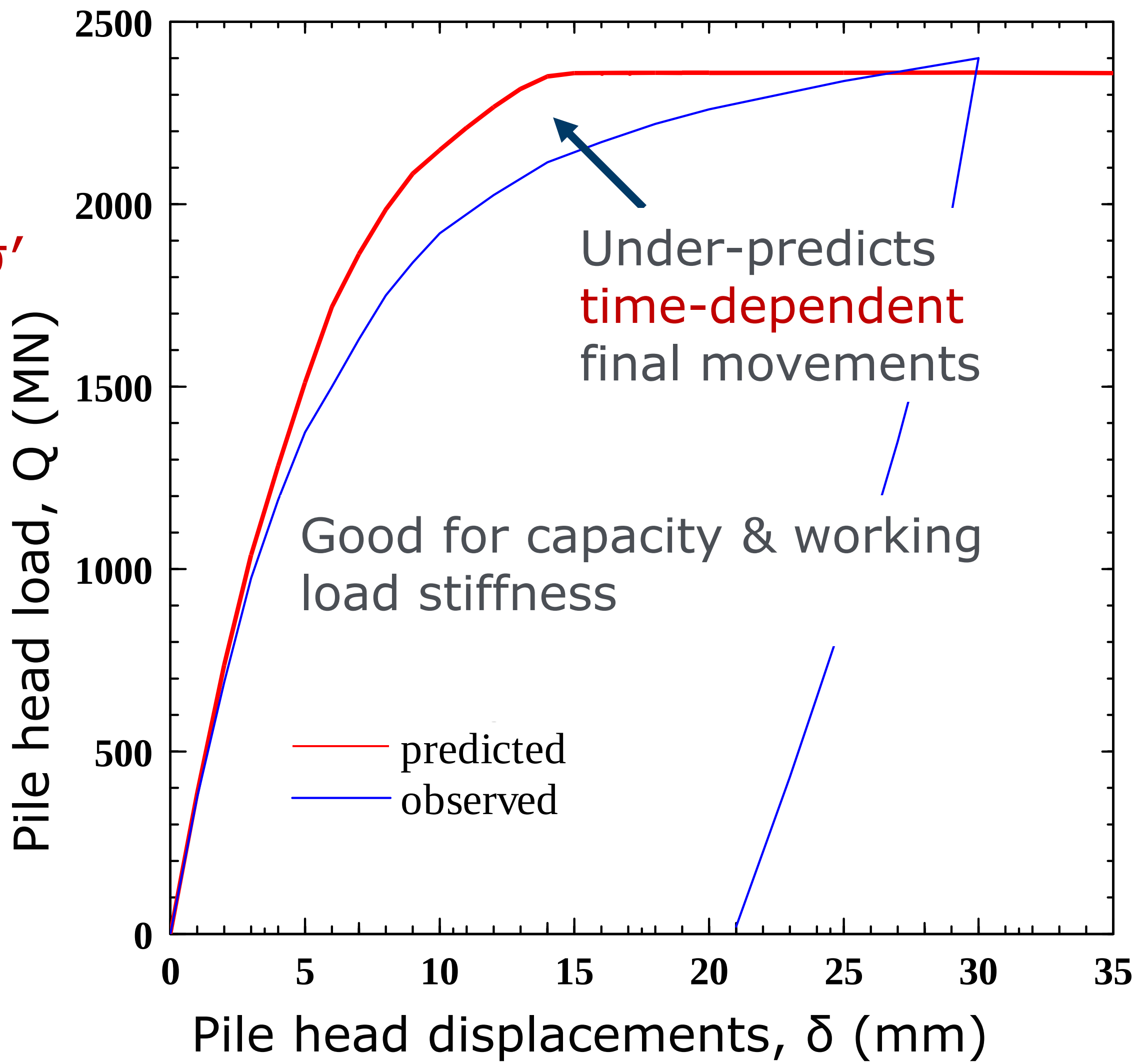
Shaft σ'_{rc} from ICP-05 approach

Estimates for other soil σ′ components…

Pile ageing: adjustment from field trends…

Creep & time – not modelled

Jardine et al 2005b

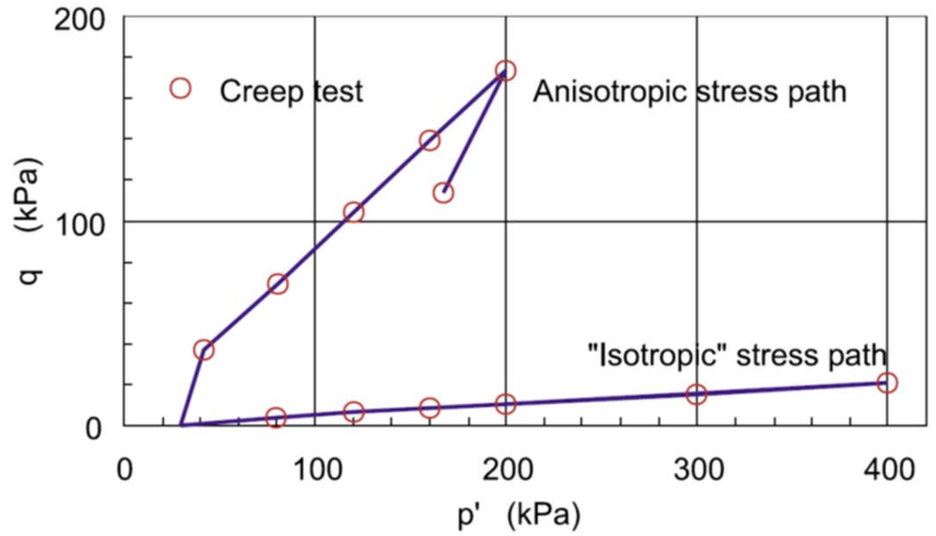


Theme 3

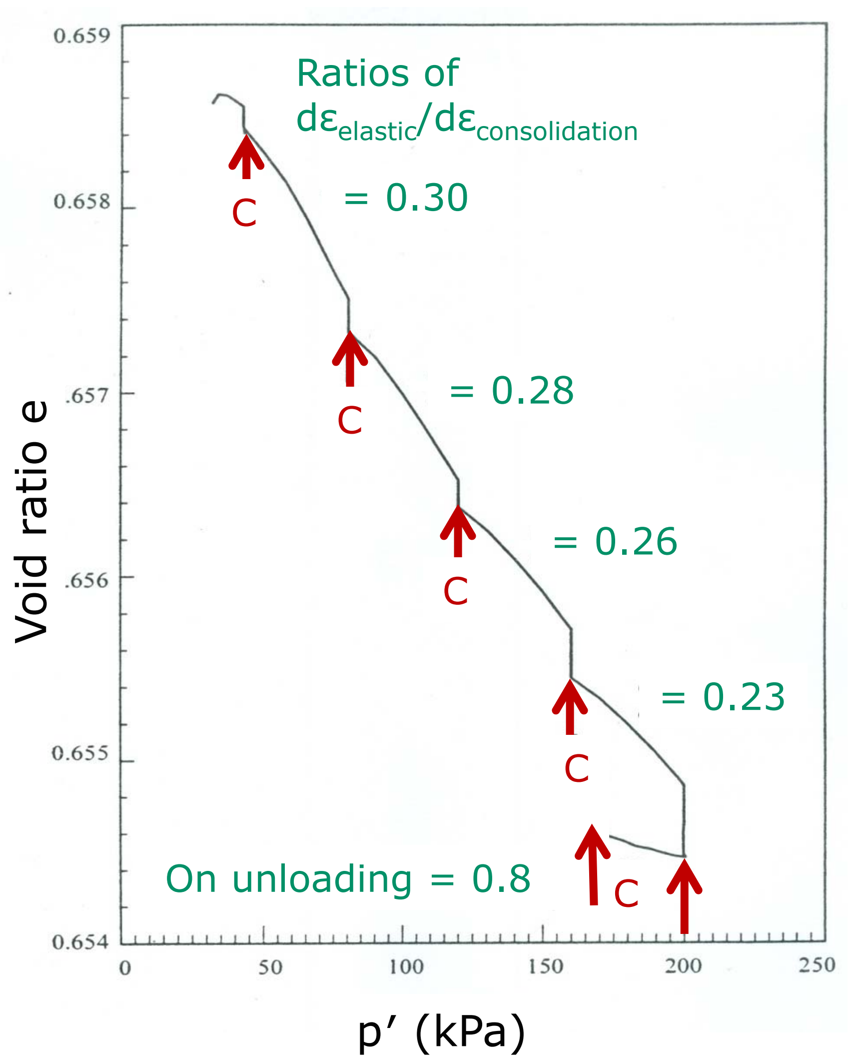
Creep and time effects

Need: stable high resolution instruments, careful calibrations, accurate stress path & temperature control

Isolating elastic, plastic & medium-term creep strains



K_0 test on med. dense HRS



dp′/dt≠0 ‘consolidation’ sections

$\varepsilon_{consolidation} = \varepsilon_{elastic\text{-}plastic}$

Elasticity from stiffness functions

$d\varepsilon_{elastic}/d\varepsilon_{consolidation}$ falls with p′, increases on unloading

Creep from dp′/dt=0 pauses

Kuwano 1999, Jardine & Kuwano 2002

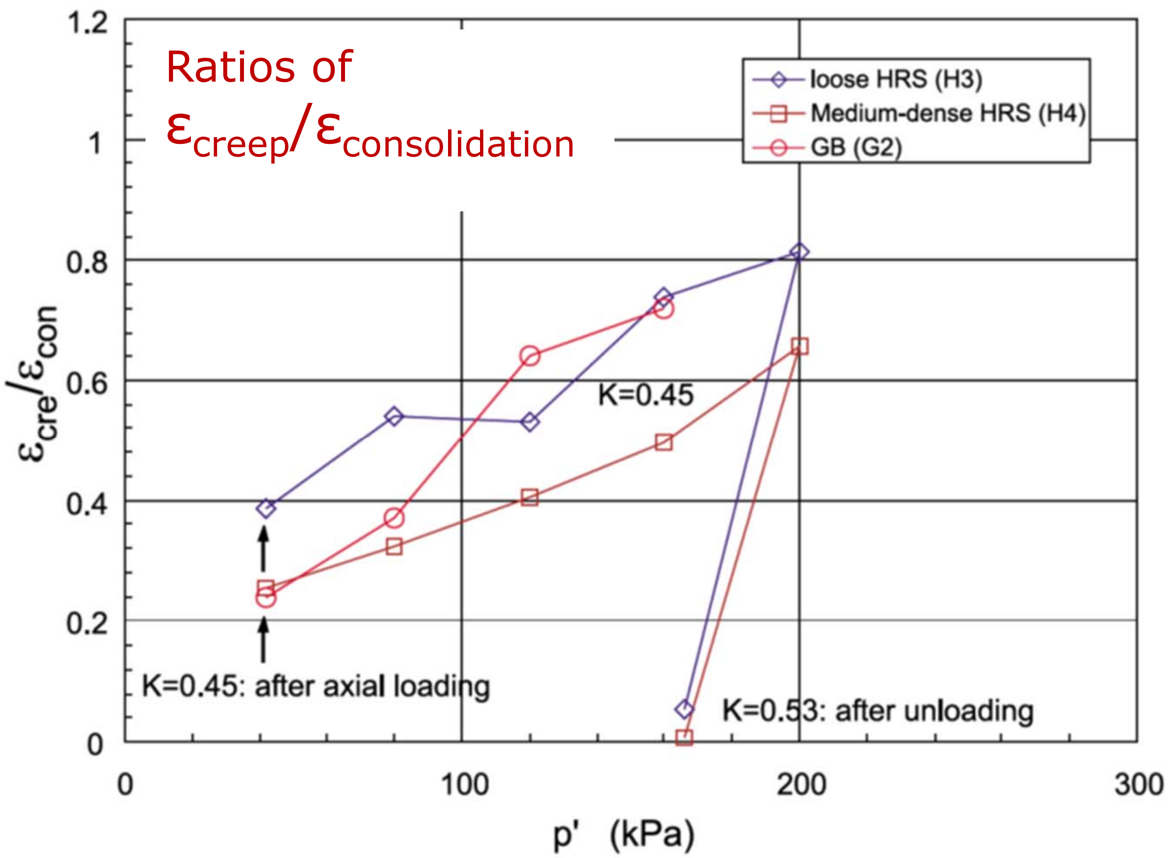
'Consolidation' and medium term creep

$\varepsilon_{creep}/\varepsilon_{consolidation}$ grows large with p' & time

Falls with $K = \sigma'_h/\sigma'_v$

Falls with I_D

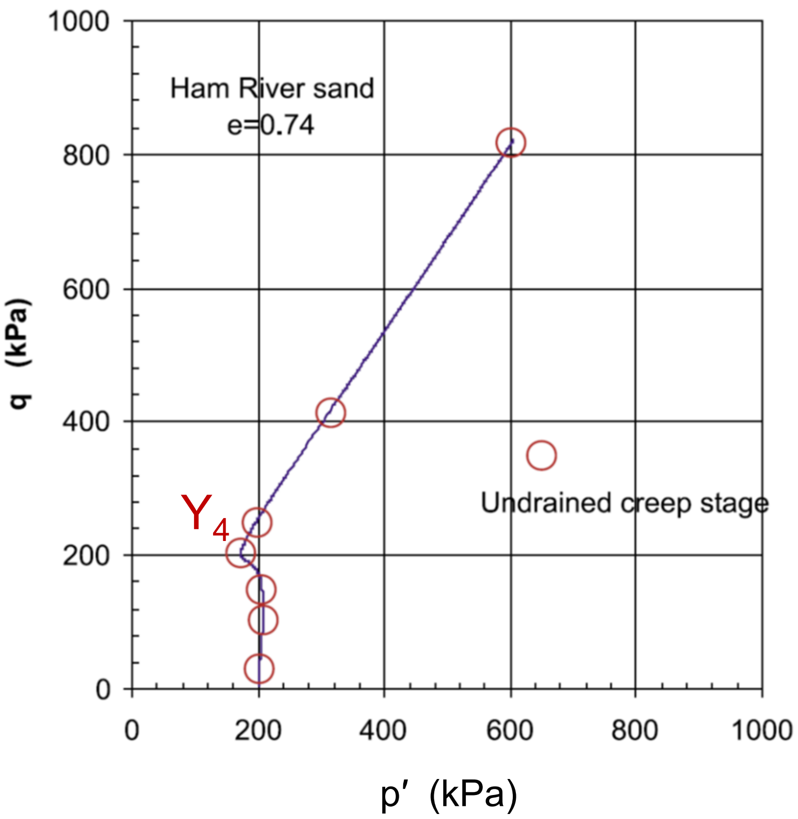
Falls on unloading



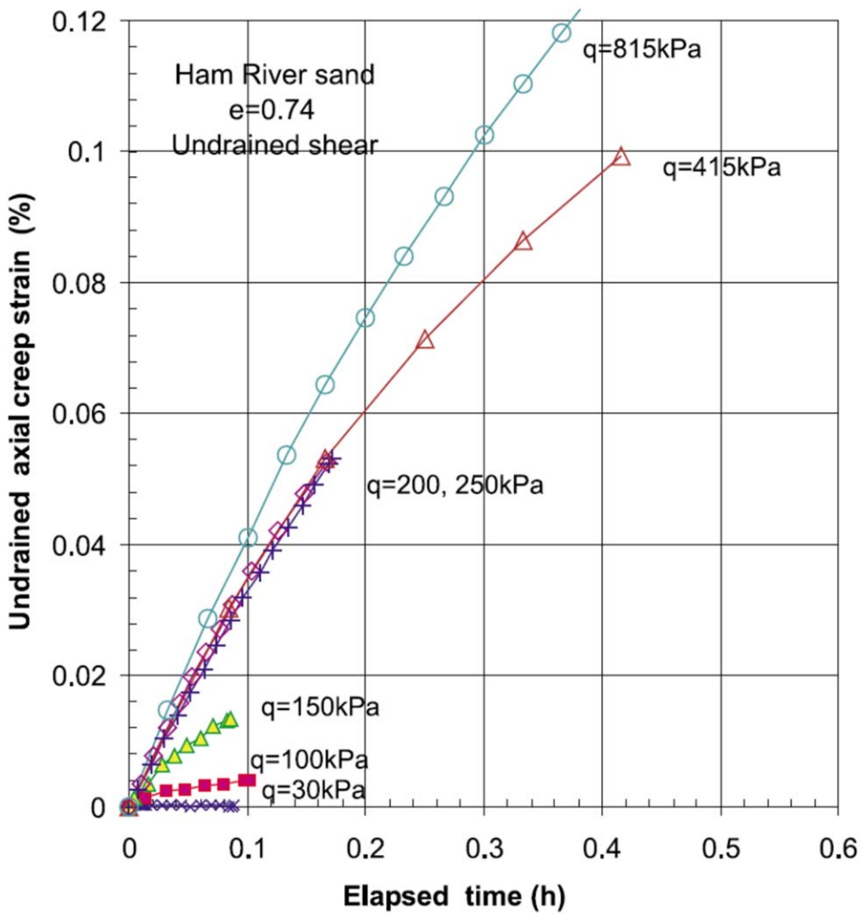
Kuwano & Jardine 2002

Creep: HRS under undrained triaxial shearing

Stress path & creep stages



Early creep-time curves



Creep negligible until Y_2 engaged
Increases steadily post Y_2
Stabilises after phase transformation - Y_4

Rimoy's tests: updated equipment

200 x 100mm, dense TVS

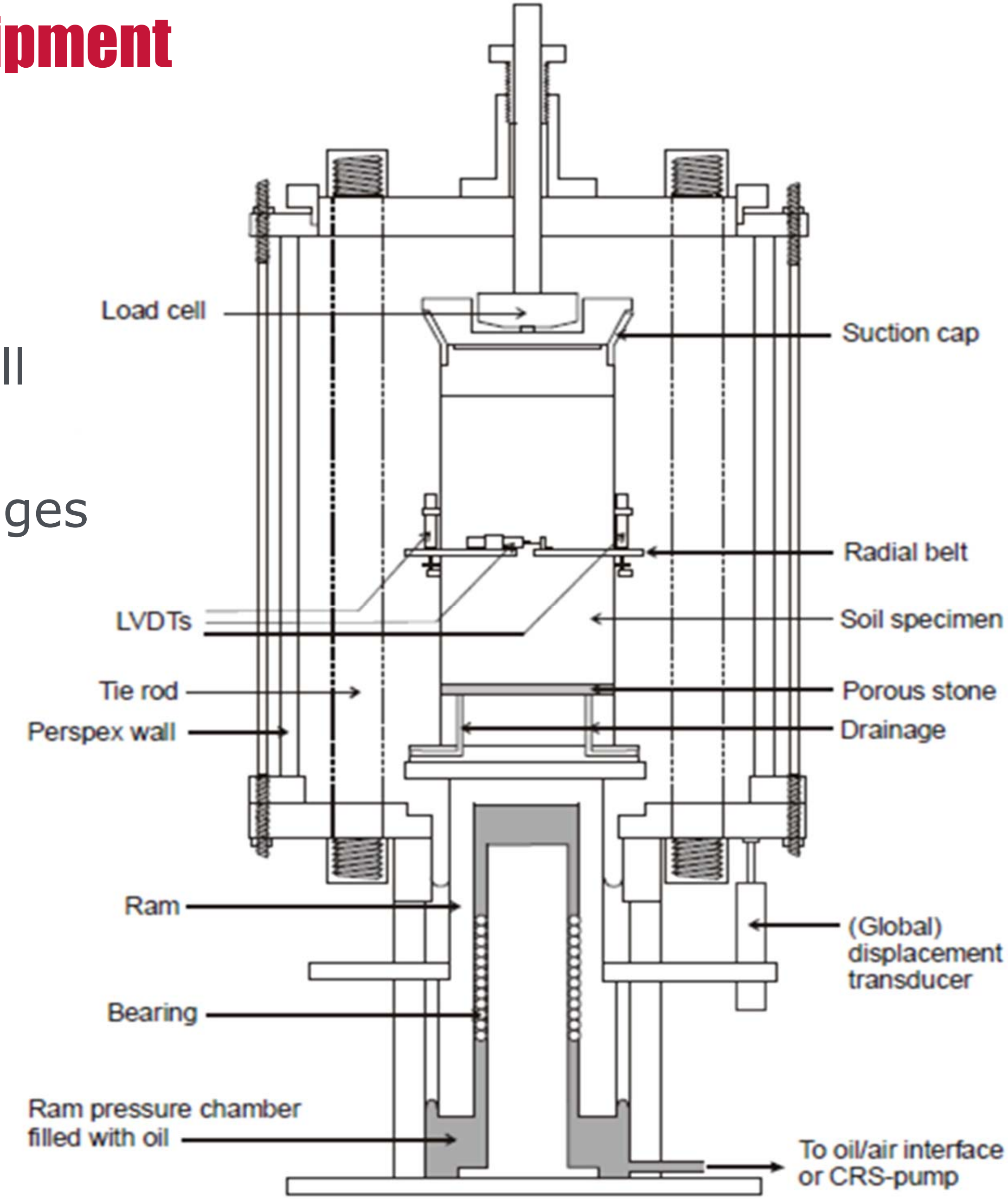
New 'Bishop and Wesley' cell

Higher resolution strain gauges

Accurate cyclic loading

Longer term creep tests

Interactions with cycling



Rimoy & Jardine 2011

Medium dense TVS tests: K_0 paths, OCR = 1

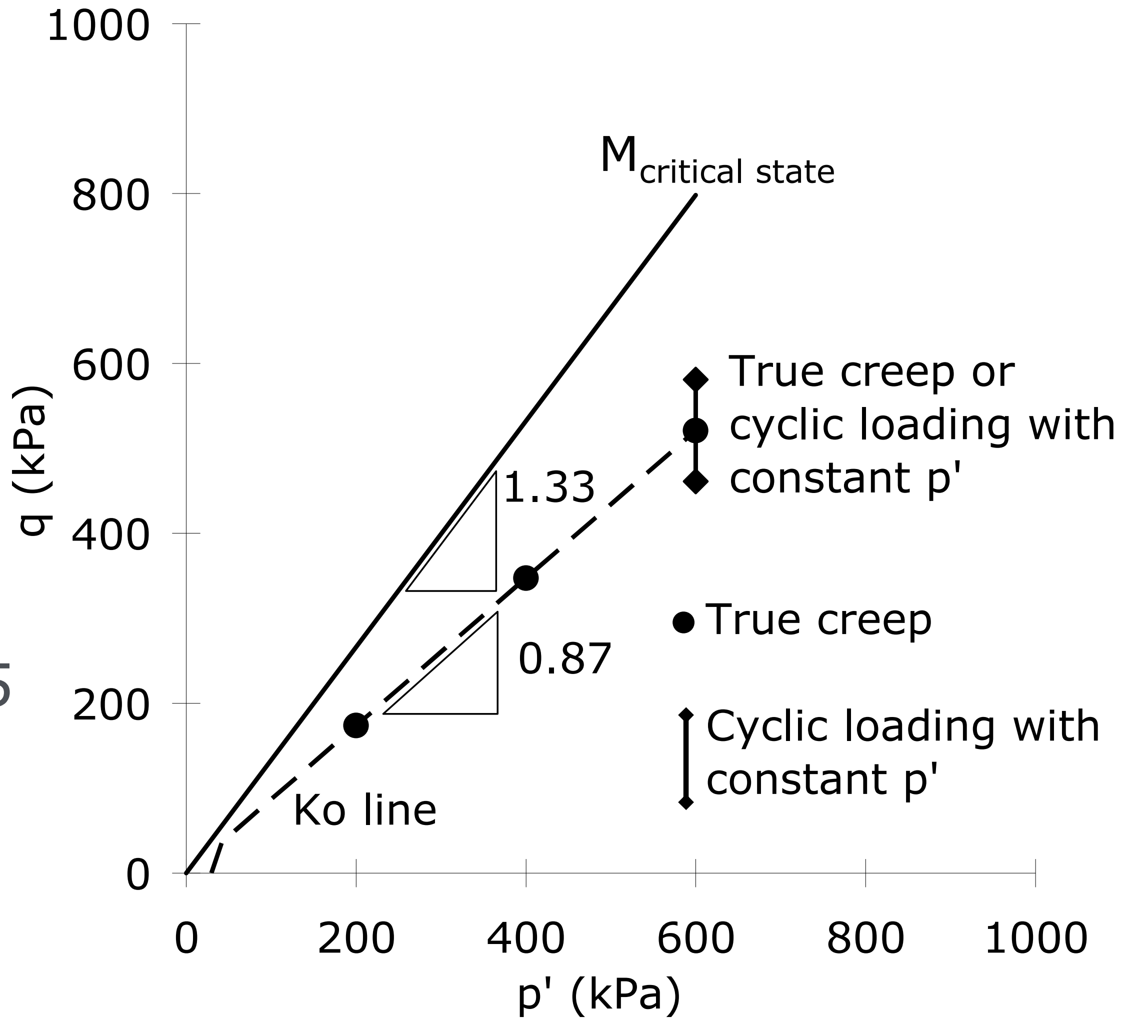
‘True’ creep and ‘Creep plus low-level cycling’

Extended ‘creep’

p′ = 200, 400, 600 kPa

Extended cycling:

q_{cyclic}/p' = 0.015 to 0.05



Rimoy & Jardine 2011

Creep straining patterns

Invariant shear strains:

ε_s increases monotonically,
$d\varepsilon_s/dt$ increases with p′

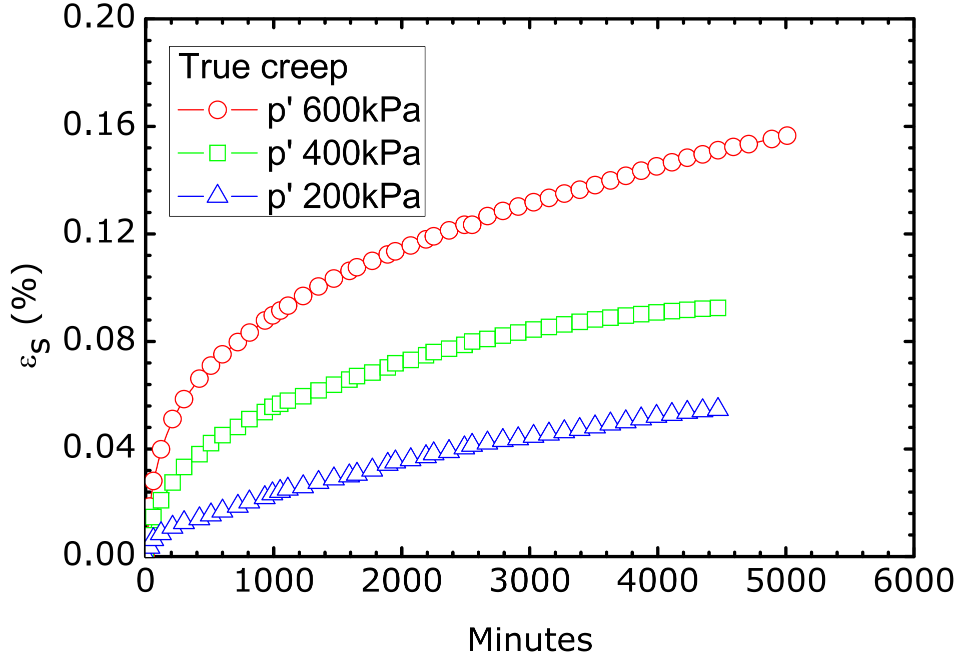
Volume strains:

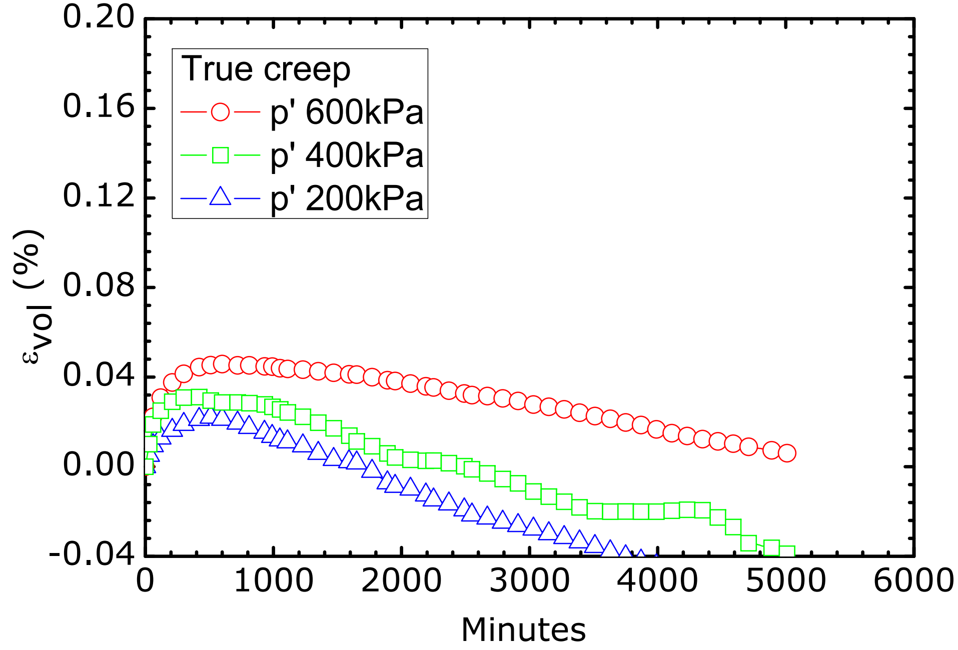
K_0 pattern initially:
$d\varepsilon_{vol}/d\varepsilon_s = 3/2$

Then reverses, negative $d\varepsilon_{vol}/dt$
less dilatant at higher p′

Y_2 KYS:

Moving/changing with time

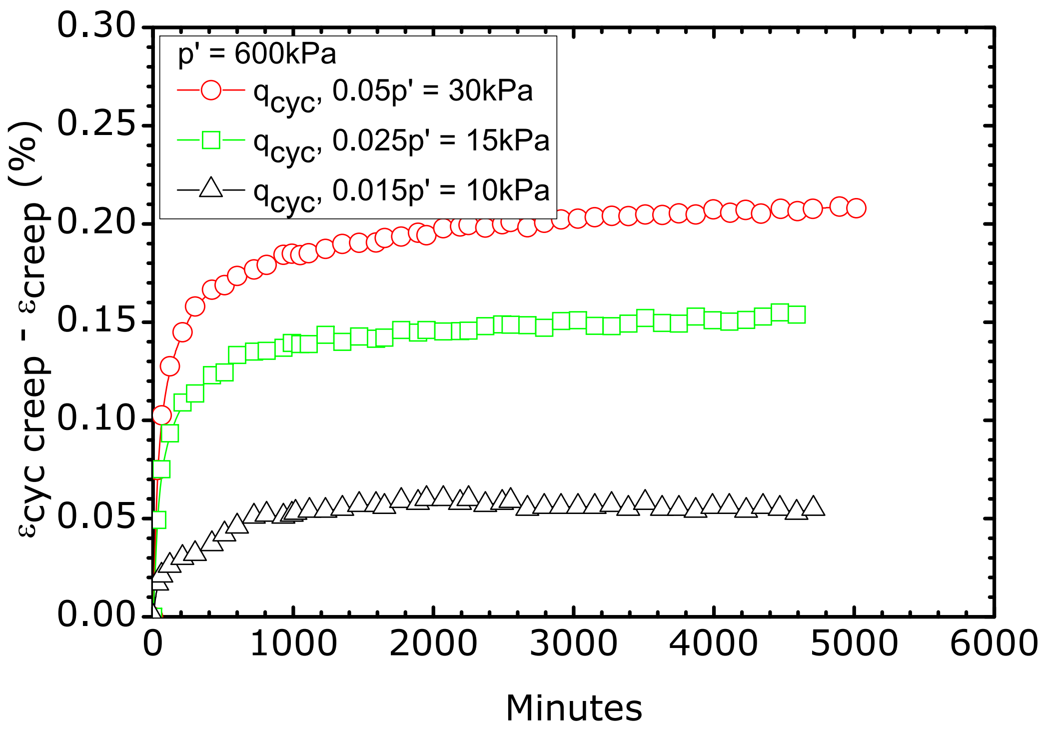


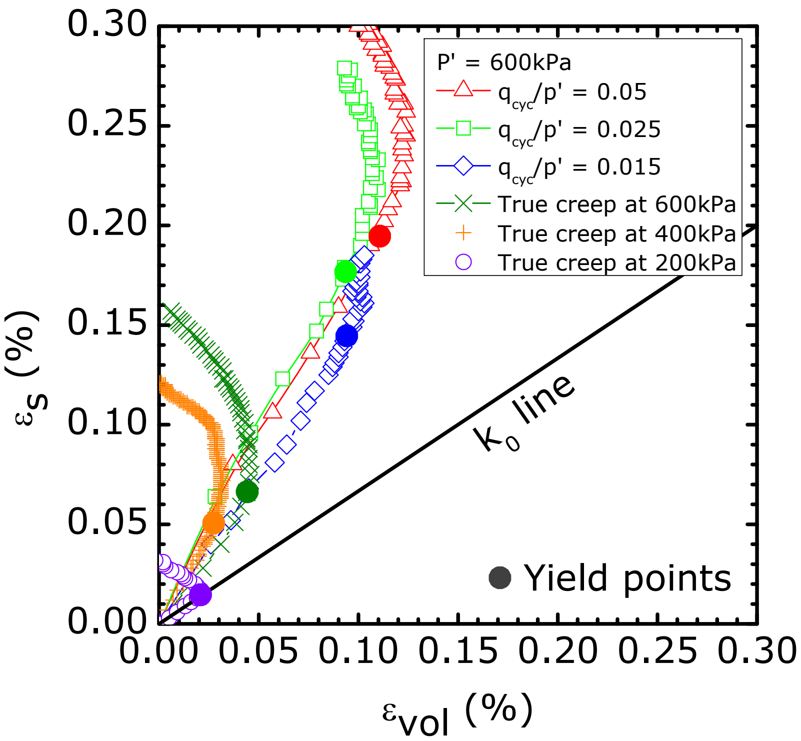


Adding low level cyclic perturbations

Applying $q_{cyclic}/p' = 0.015$ to 0.05 — Augments straining

Also changes straining pattern: — Reduces & retards dilation





Creep & yielding: affected by stress state, time & background cycling

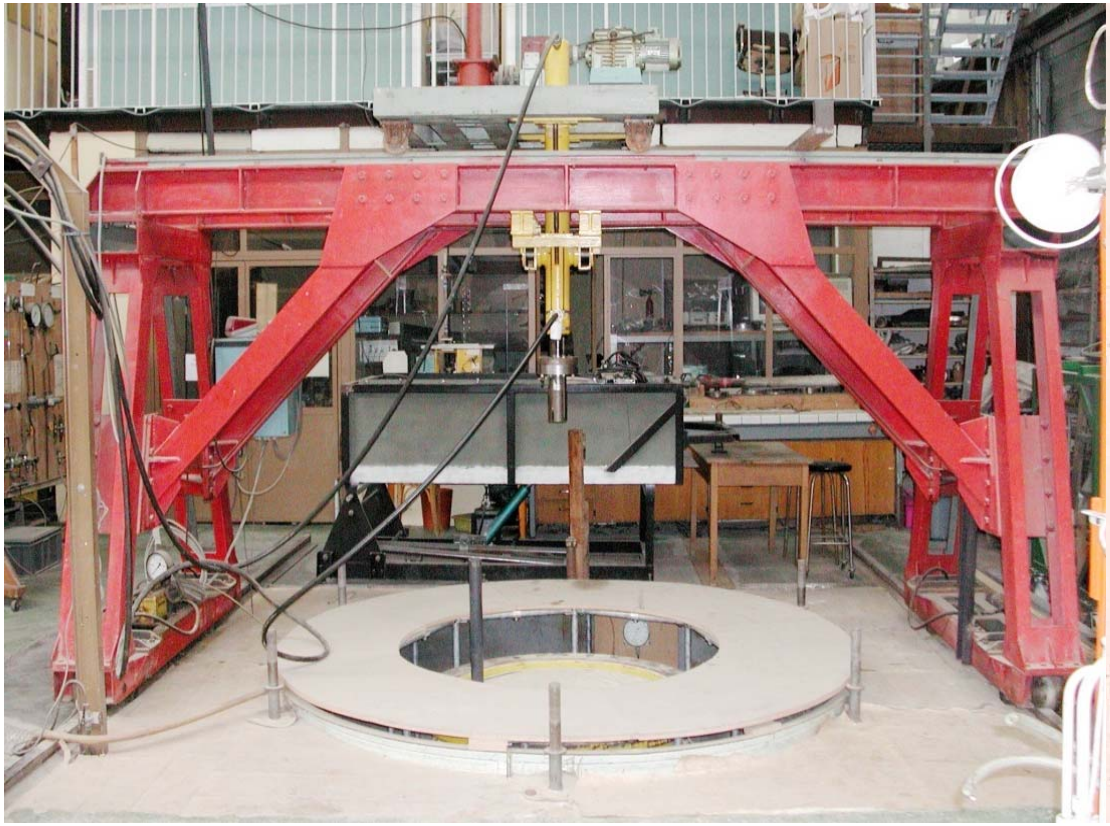
Theme 4

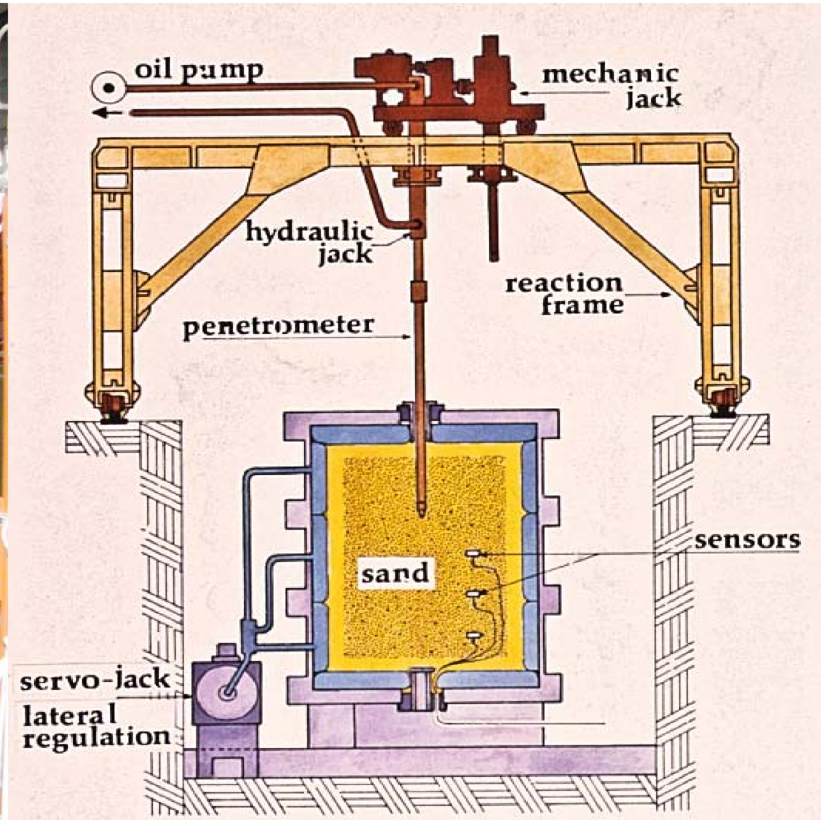
Distributions of σ'_r σ'_z & σ'_θ around piles?

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

IC-Grenoble laboratory model & particle scale studies

Model experiments with Prof. Pierre Foray





1.3 x 1.5m chamber with close temperature & pressure control

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

Tests over months under 150 kPa

Up to 36 stress sensors in sand

Multiple tests with instrumented Mini-ICP

Jardine et al 2009, Zhu et al 2009

Mini-ICP model pile

Stainless steel: 1.4m x 36mm

Cyclic jacking installation

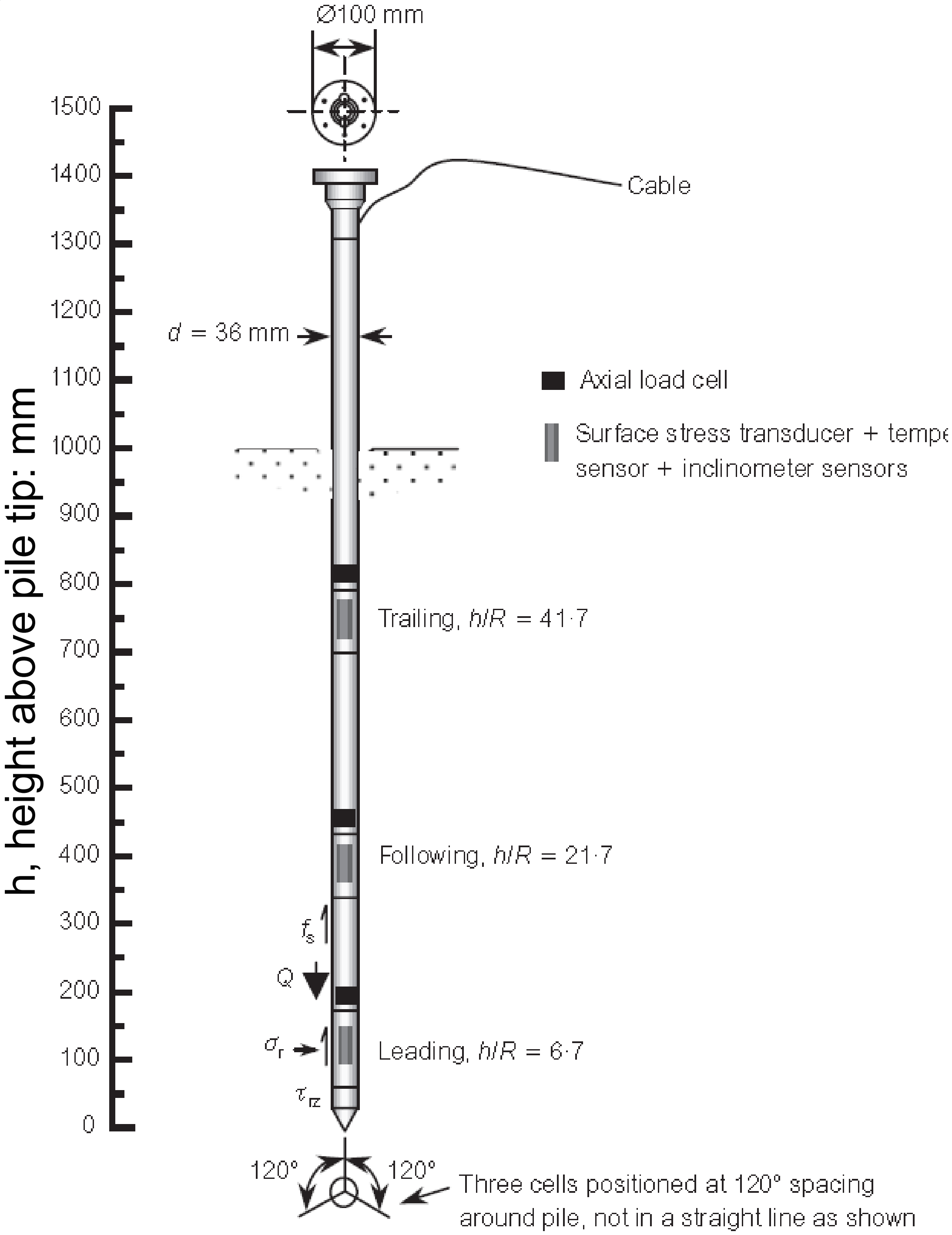
Traces shaft effective stress paths and tip loads

Local measurements of:

- Axial load
- Surface τ_{rz} & σ_r

At three h/R levels

Jardine et al 2009



Installation σ'_r trends in sand mass:

1000s data contoured

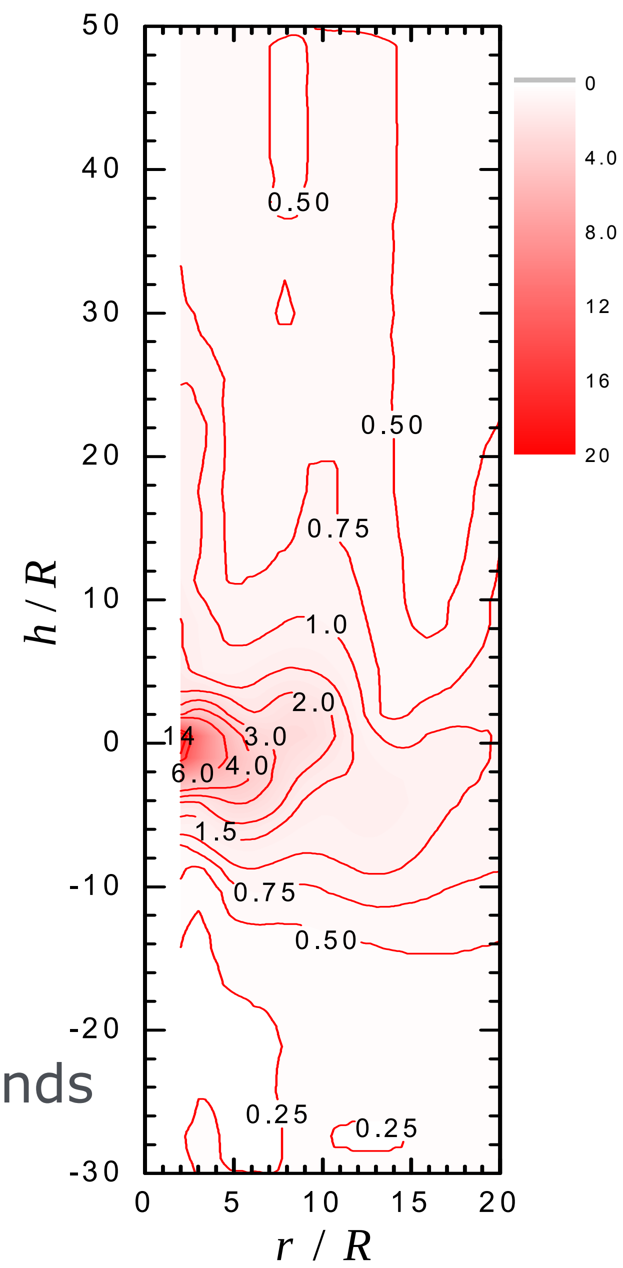
$\sigma'_r/q_c = f(h/R, r/R, \sigma'_{zo})$

Intense tip concentration
Unloading above tip

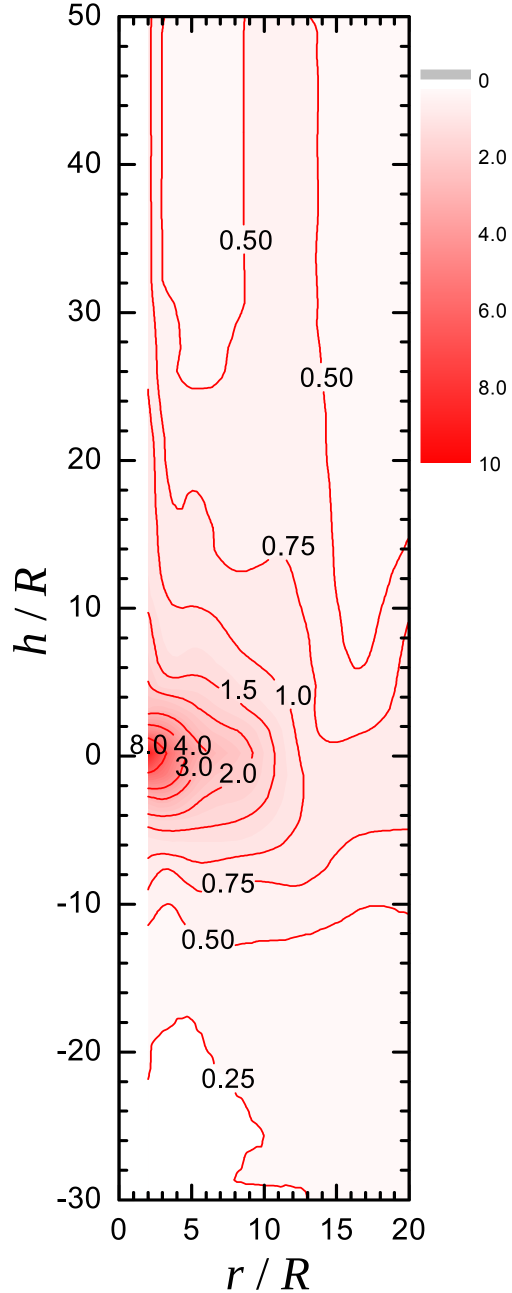
Sharp changes over each jacking cycle

Corresponding σ'_z & σ'_θ trends

Jardine et al 2013b

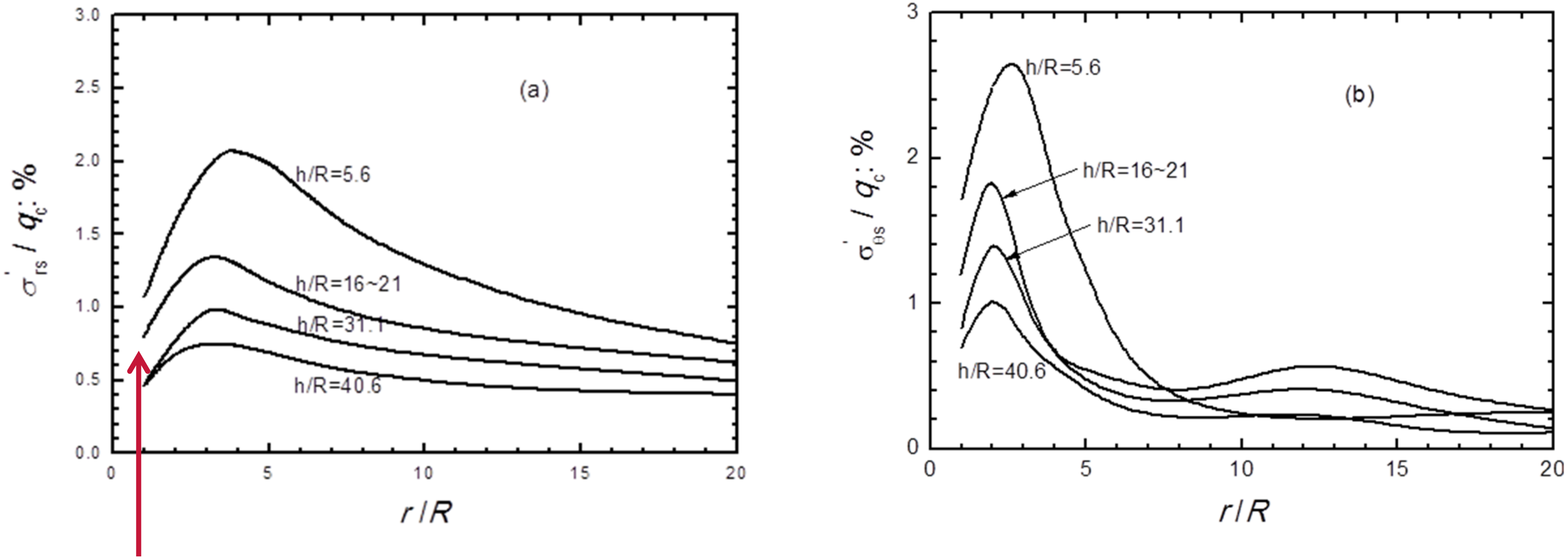


End of push



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

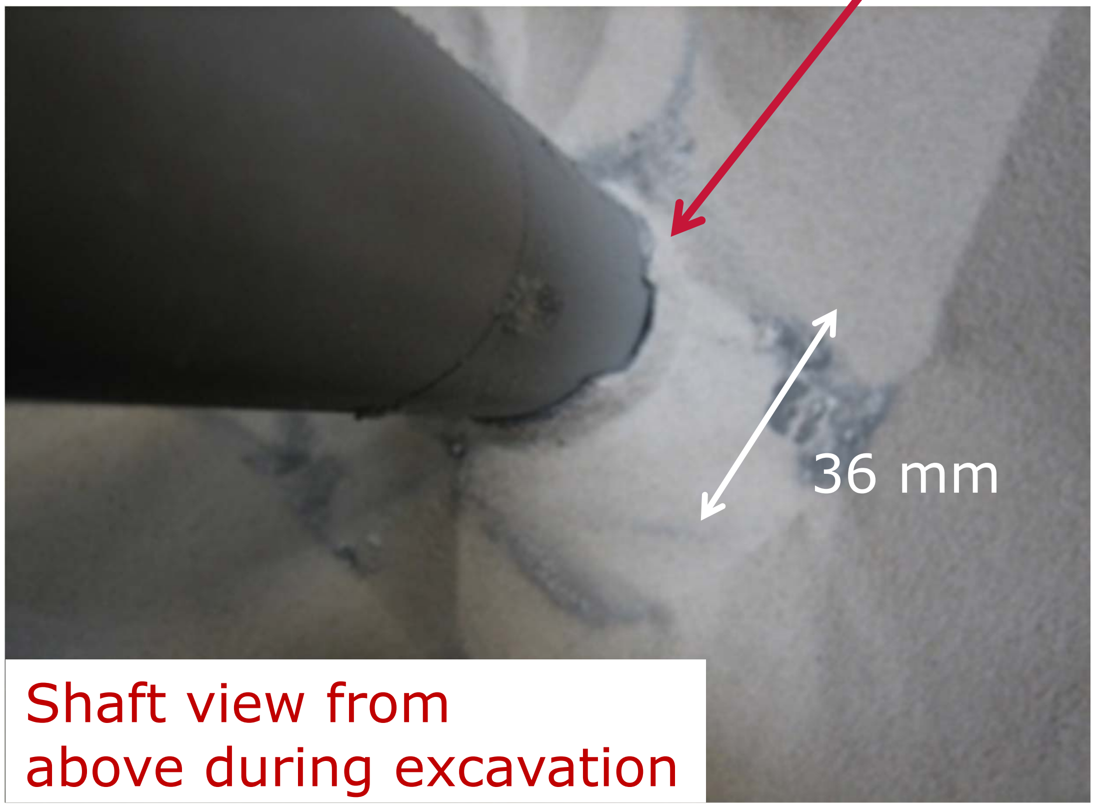
Compared later to advanced analysis

Interface shear zone; Yang et al 2010

Grey dense fractured shear zone ‘crust’

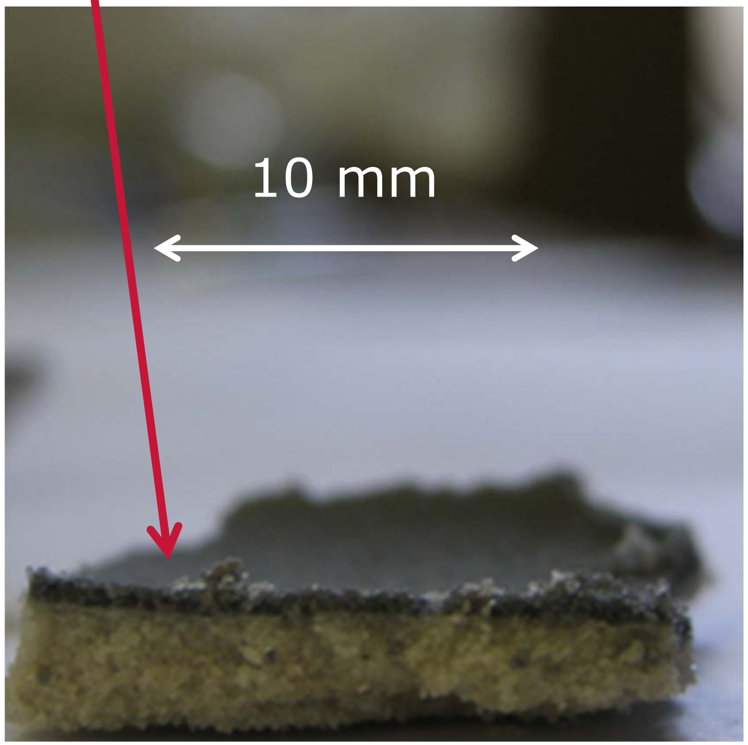
0.5-1.5mm thick, growing with h

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

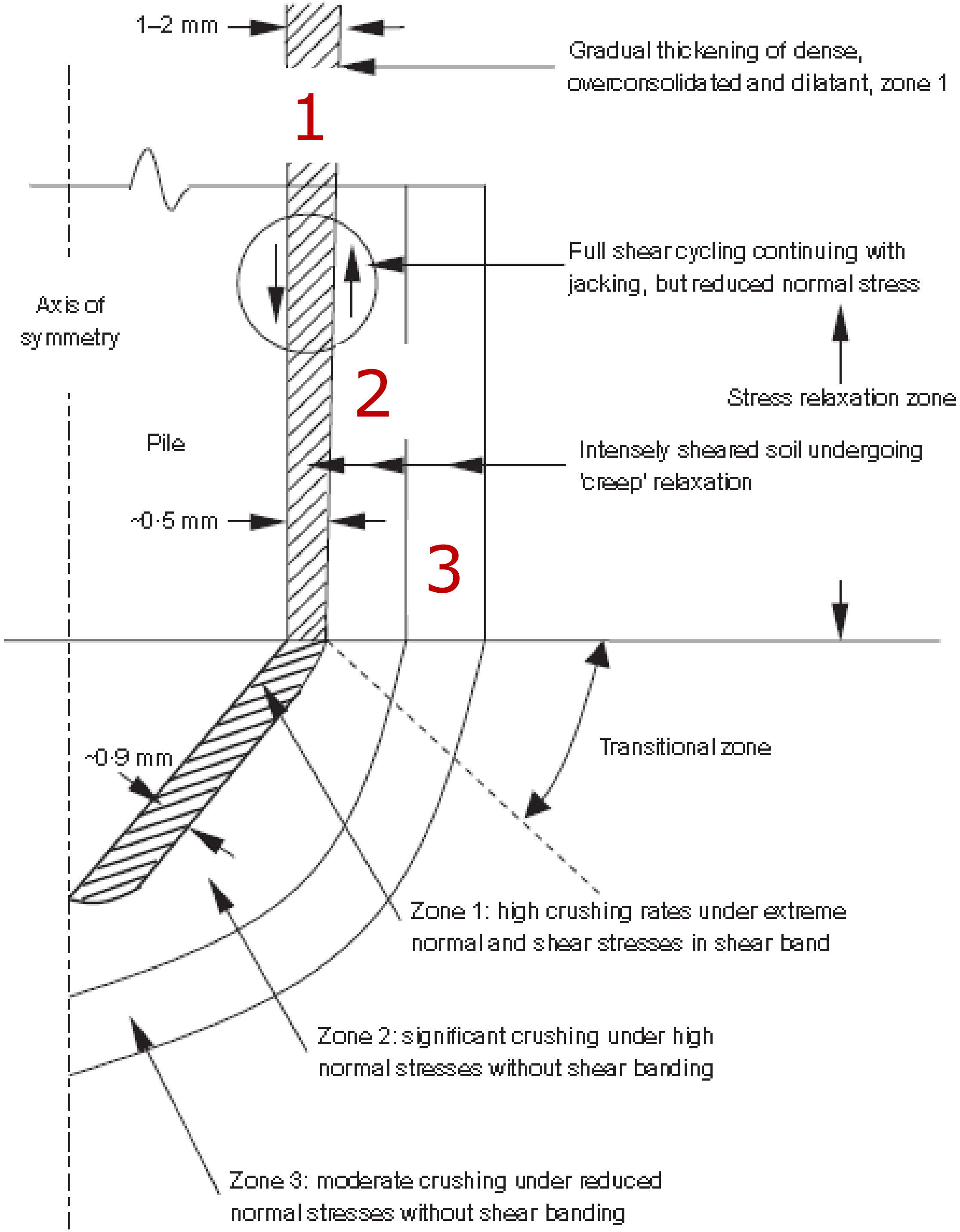
Breakage starts under tip
$\sigma'_v > 20$ MPa

Fractured sand displaced & spread over shaft: Zone 1

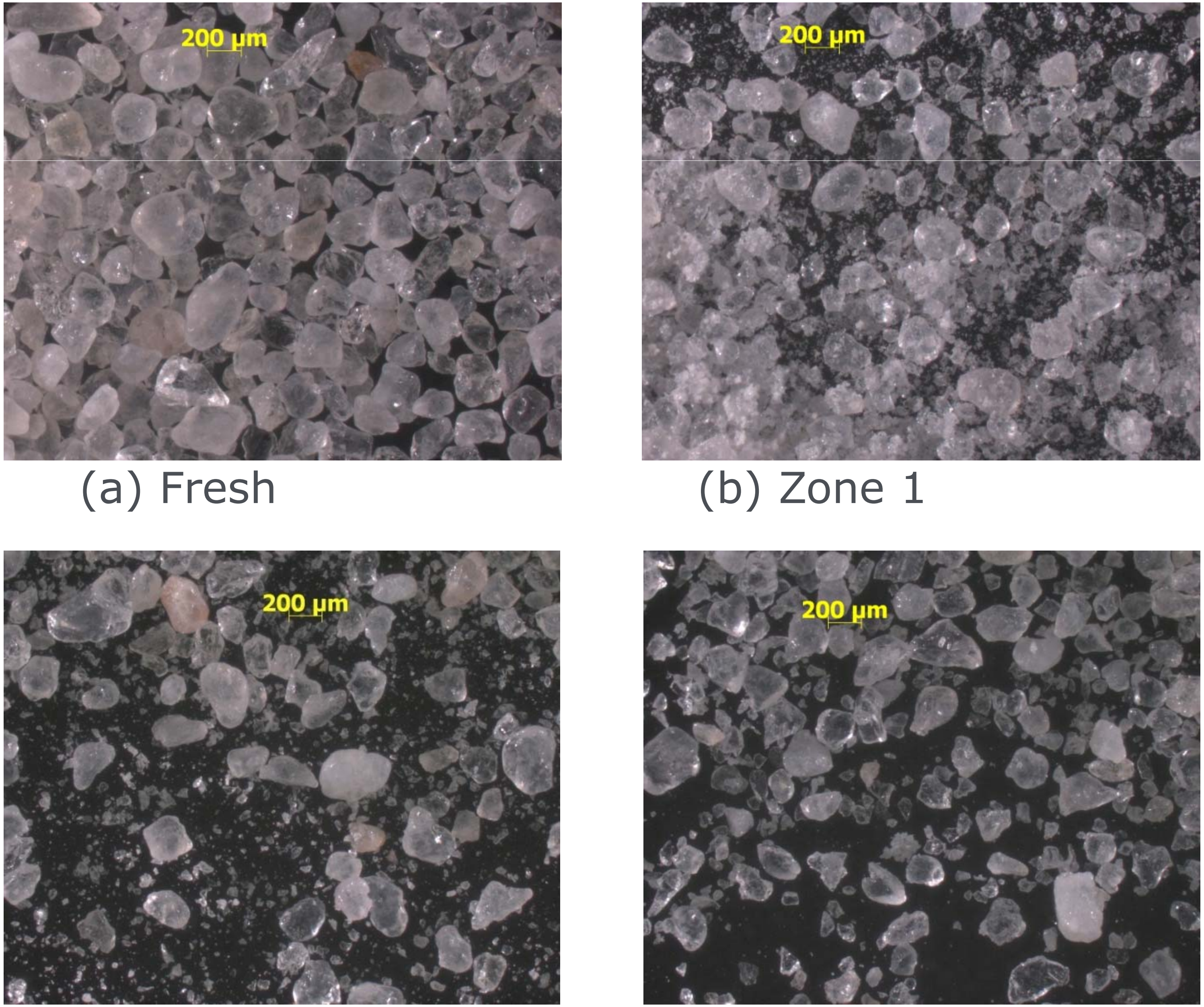
Further abrasion on shaft

Partial fracturing in outer Zones 2 & 3

Yang et al 2010



Micro analysis of progressive grain crushing



(a) Fresh

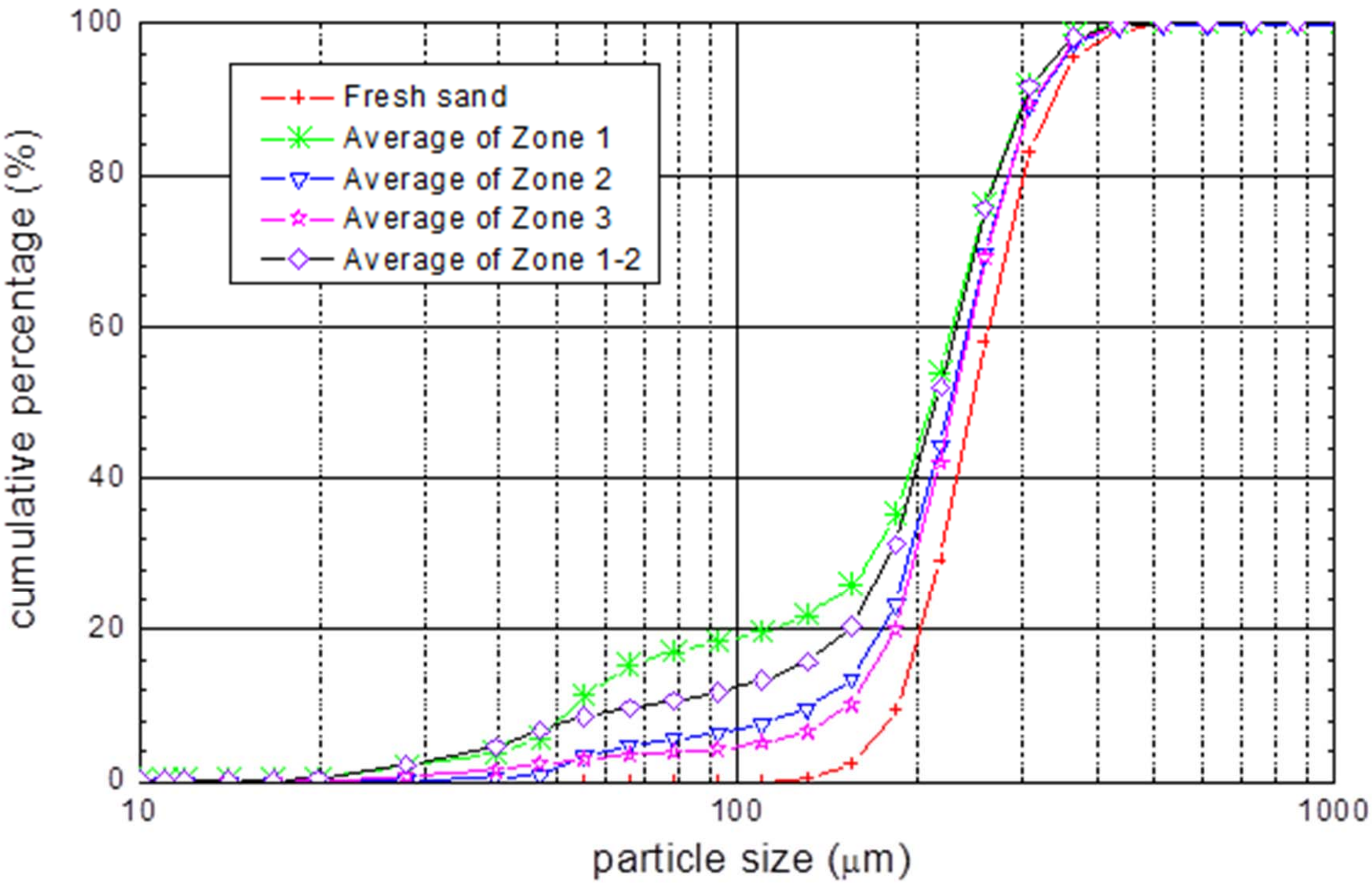
(b) Zone 1

(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

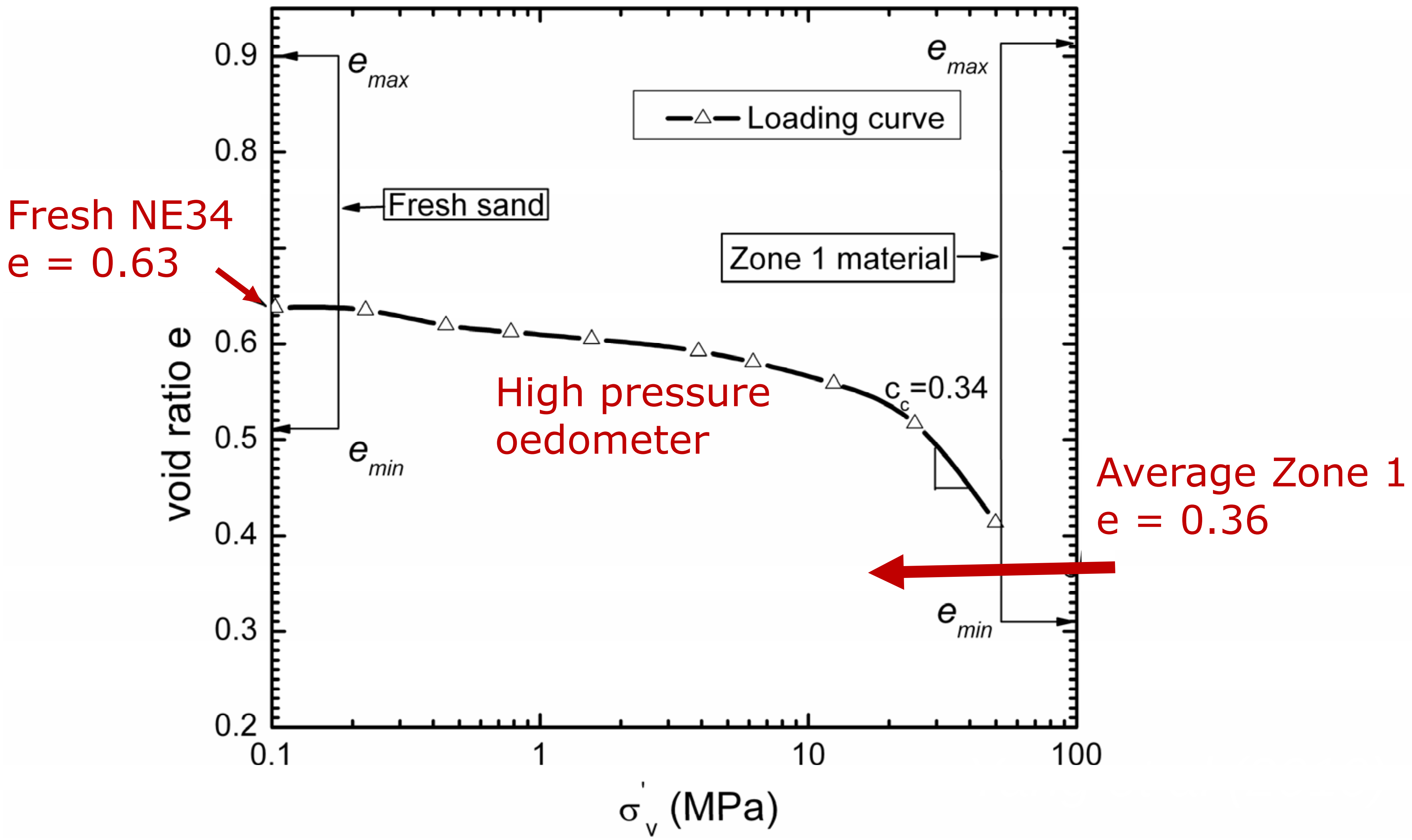
Theme 5

Matching pile conditions in lab tests

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

High pressure oedometer compared to Zone 1

Void ratios, limits & sand states



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

Sands sheared against steel for metres
σ'_n up to 800 kPa; Ho et al 2011

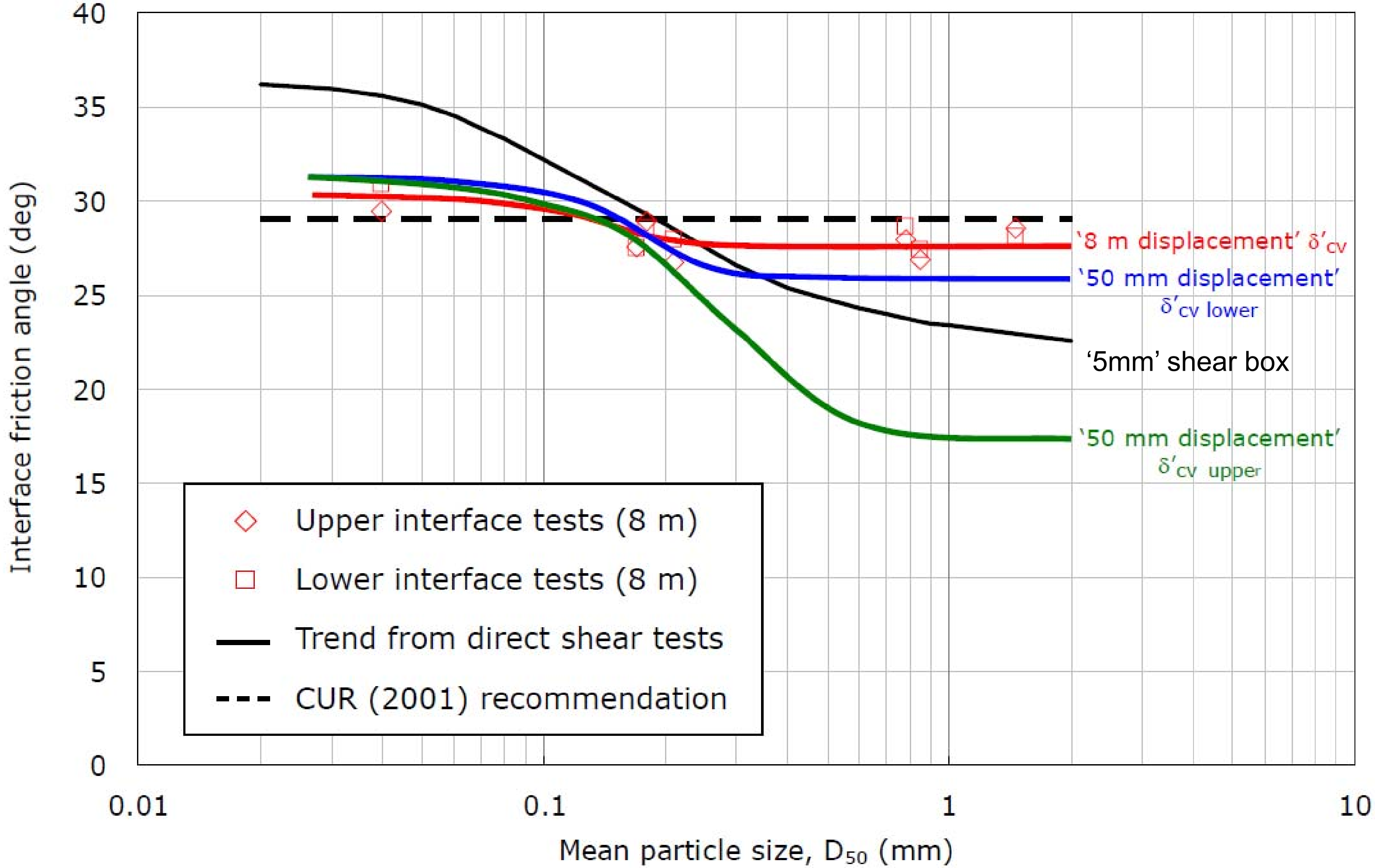
Intact sand

Crushed sand

Abrading steel interface

Wide range of silica sands: coarse example

Interface shear angles vary with shear displacement



Large displacement δ angles: independent of I_D and vary less with d_{50} & interface configuration

High-to-Low Pressure Triaxial tests

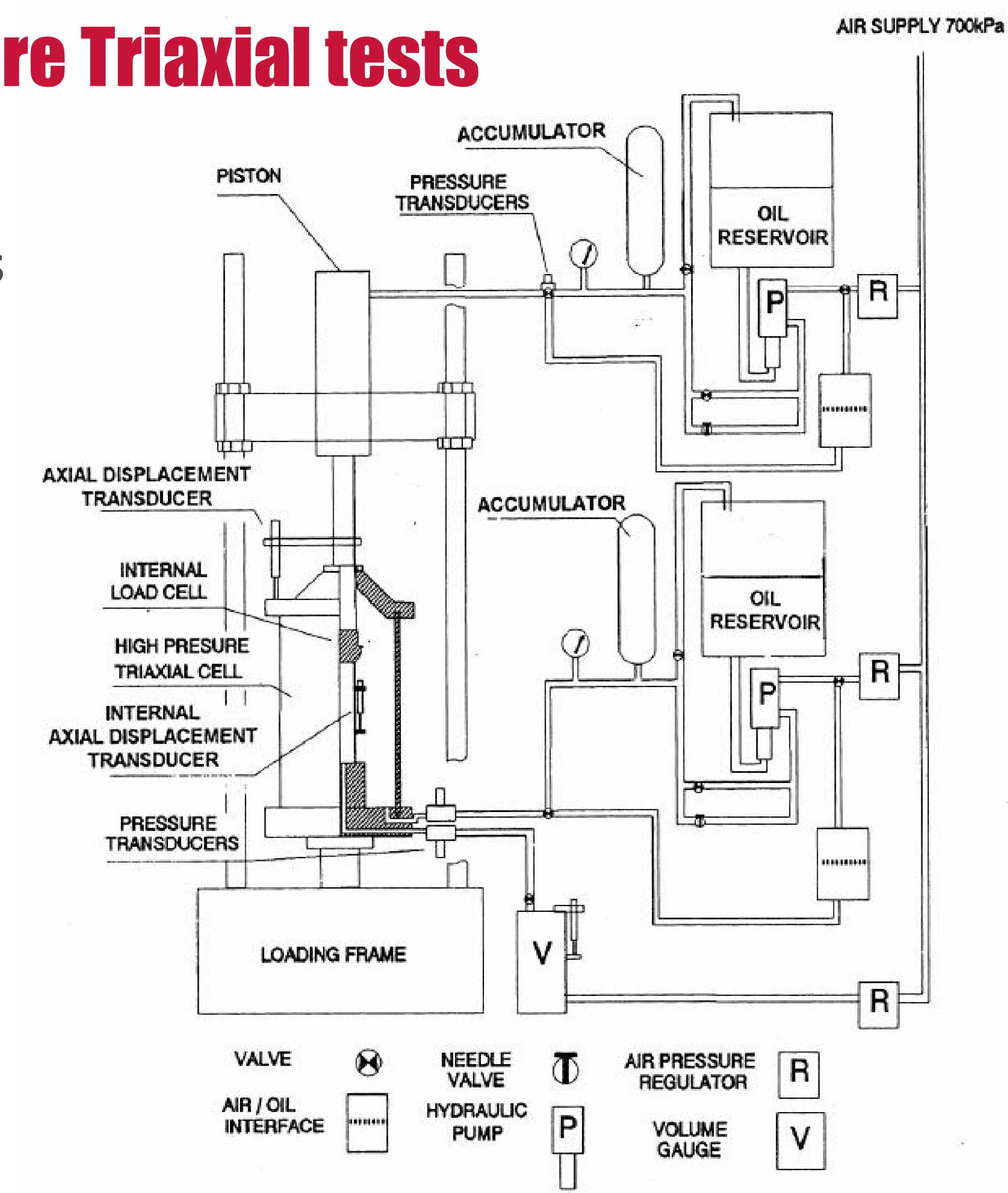
50mm D, 100mm L

Dense NE 34 specimens

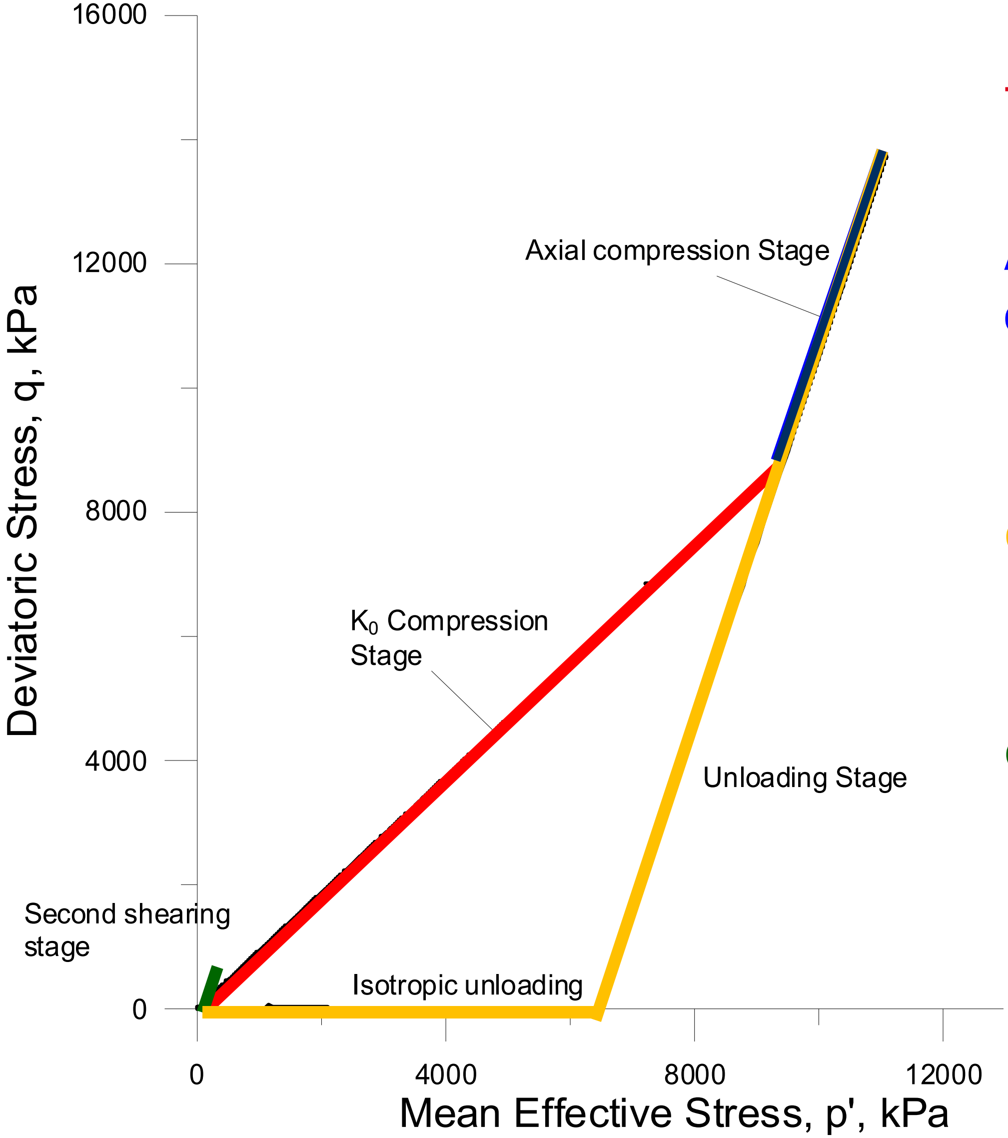
Cuccovillo and Coop 1998 test system

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

Matching model pile installation stress paths



High-to-Low pressure stress-path tests



K_0 compression: tip advancing from above

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

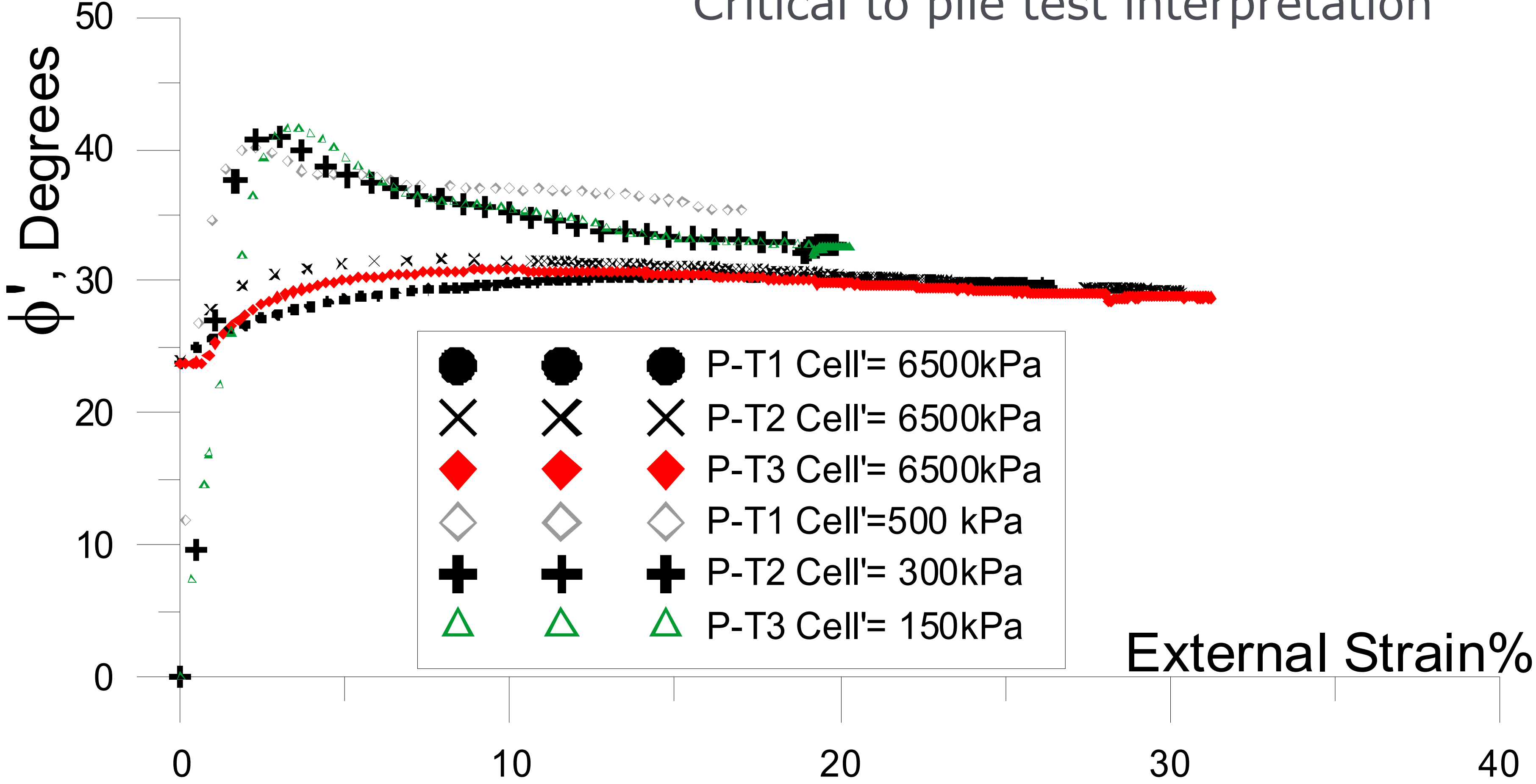
Unloading, tip advancing to greater depth

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



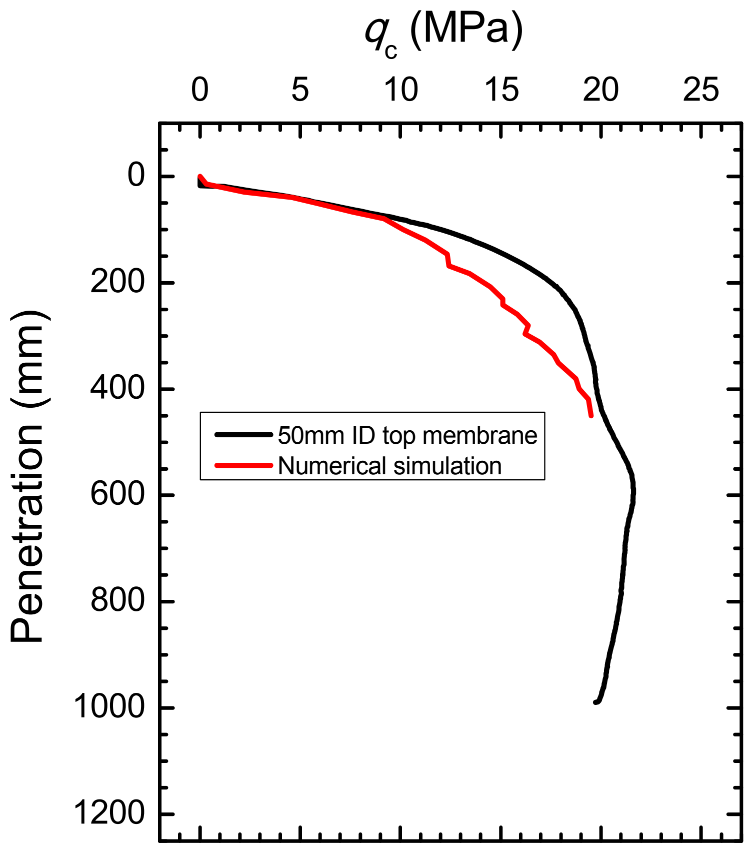
Theme 6

Simulating crushing and pile installation stresses

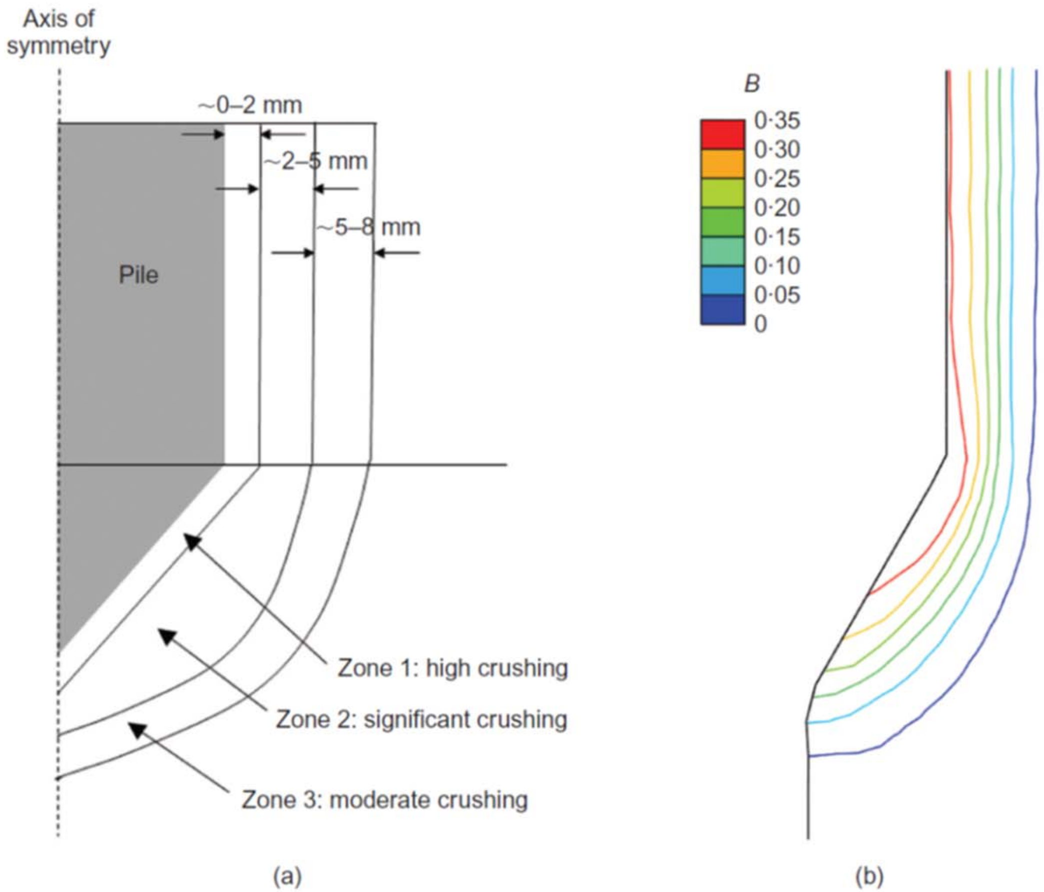
'ALE' Finite Element method; Zhang et al 2013a, b

Monotonic penetration with 'Breakage' mechanics model from standard lab tests

End bearing and breakage: Zhang et al 2013's predictions

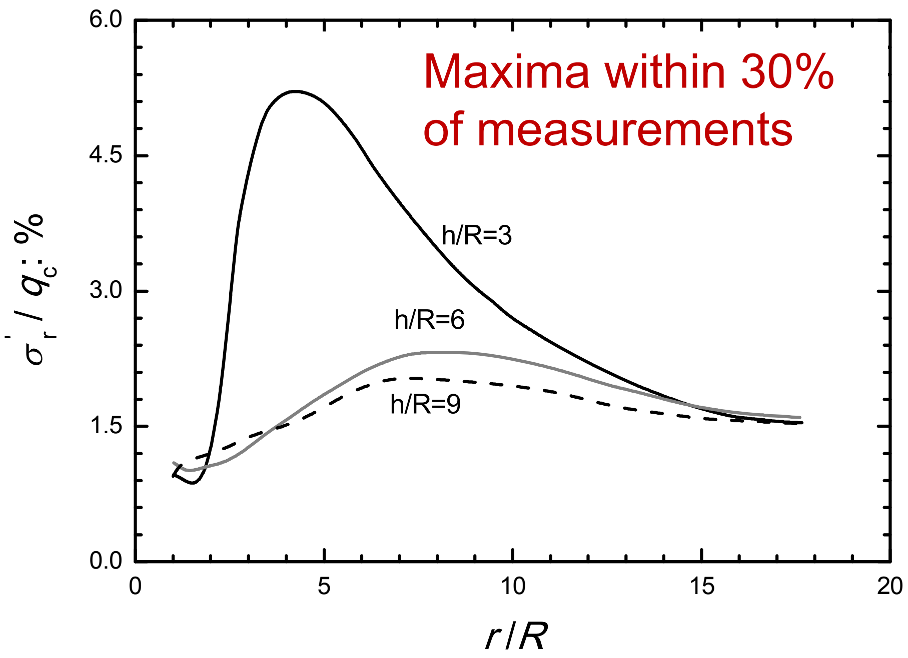


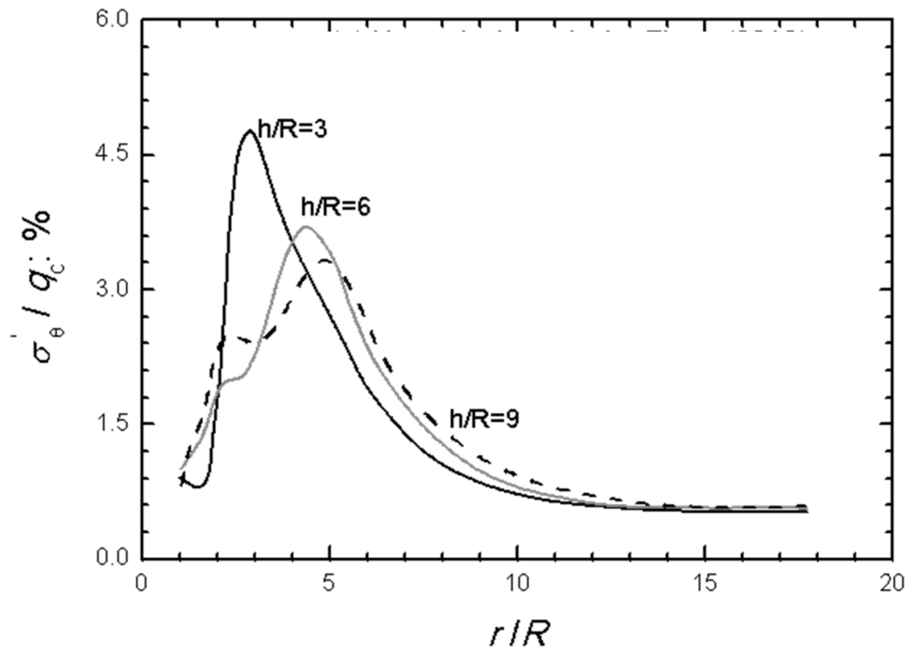
Predicted and measured pile tip stresses q_c



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?

Theme 7

Cyclic axial loading

Model pile lab tests extending Dunkerque field experiments

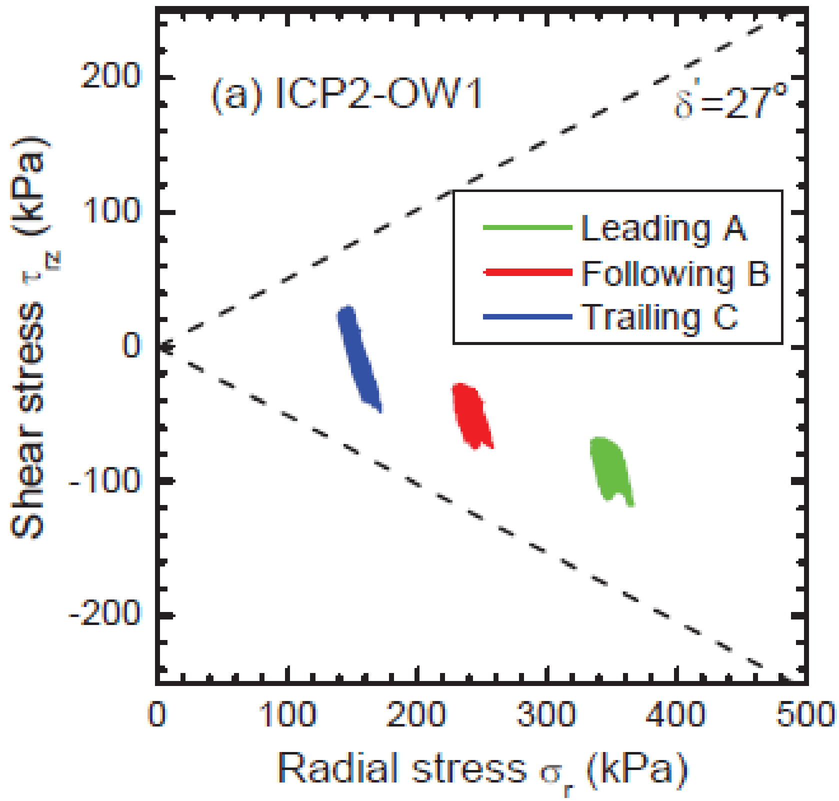
Parallel cyclic lab element testing

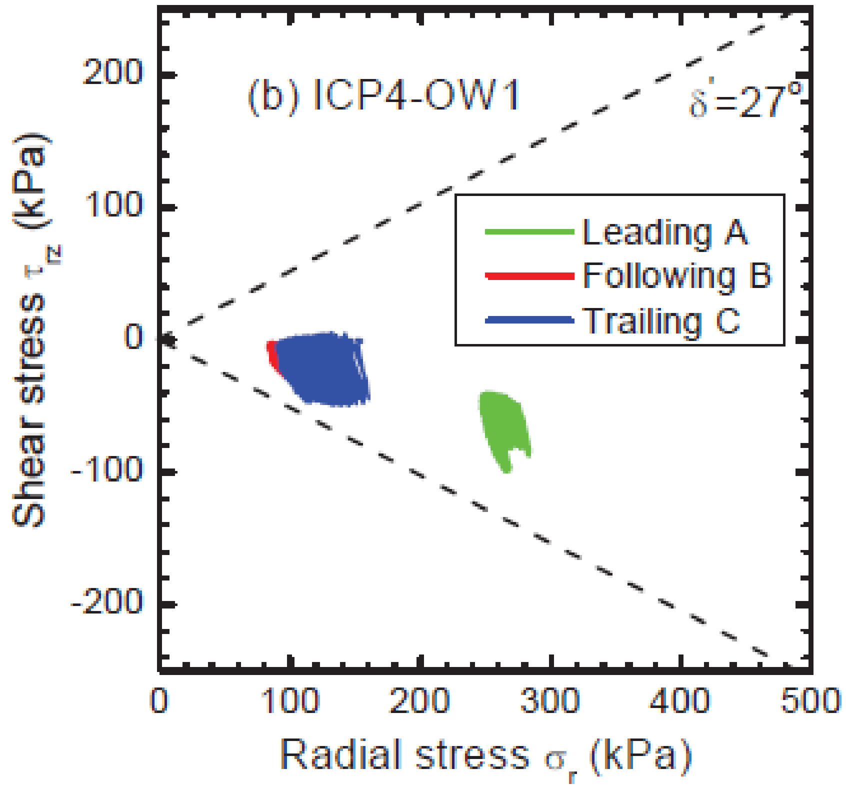
Integration into practical design

Stable Mini-ICP cycling: interface stress paths

Load-controlled to N > 1000

Stresses remain within Y_2 shaft capacity rises

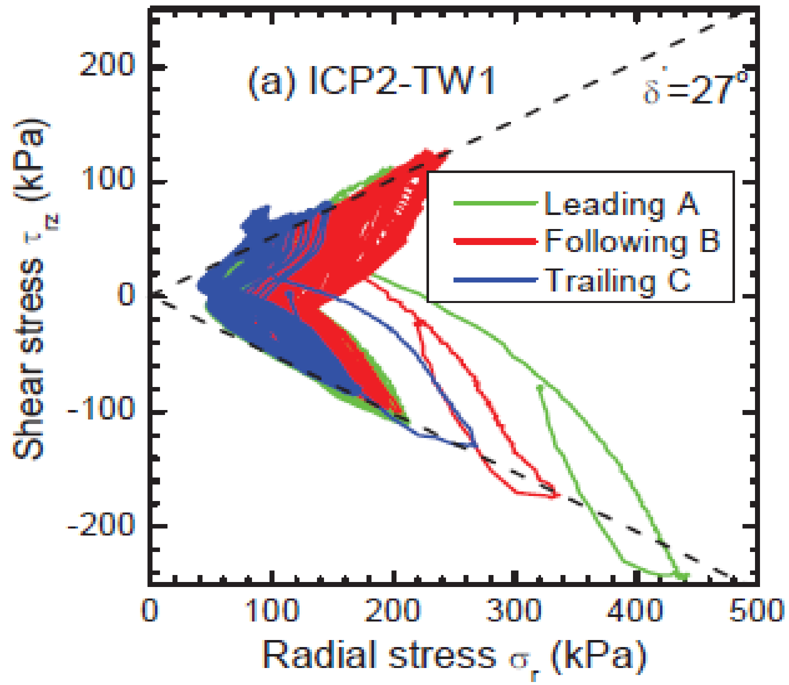




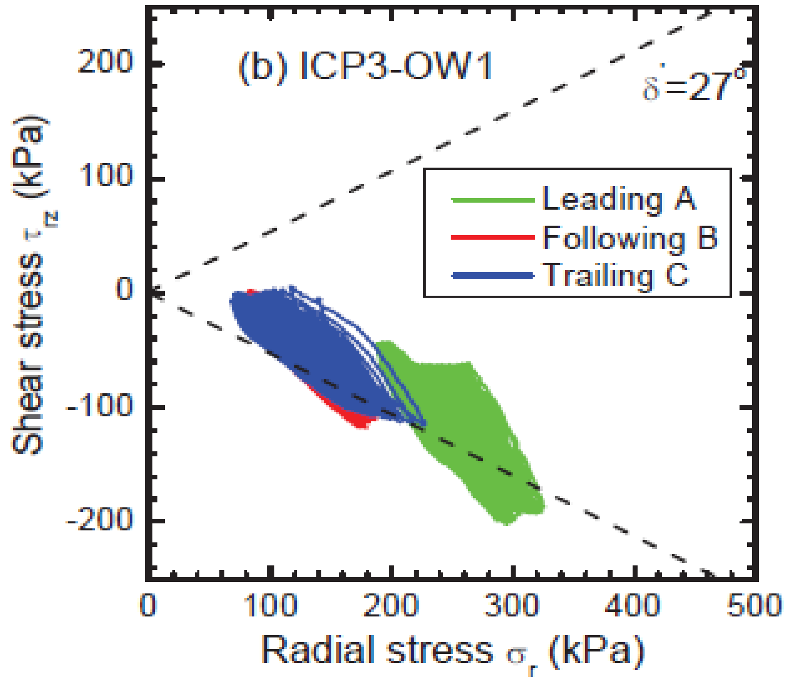
Tsuha et al (2012)

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

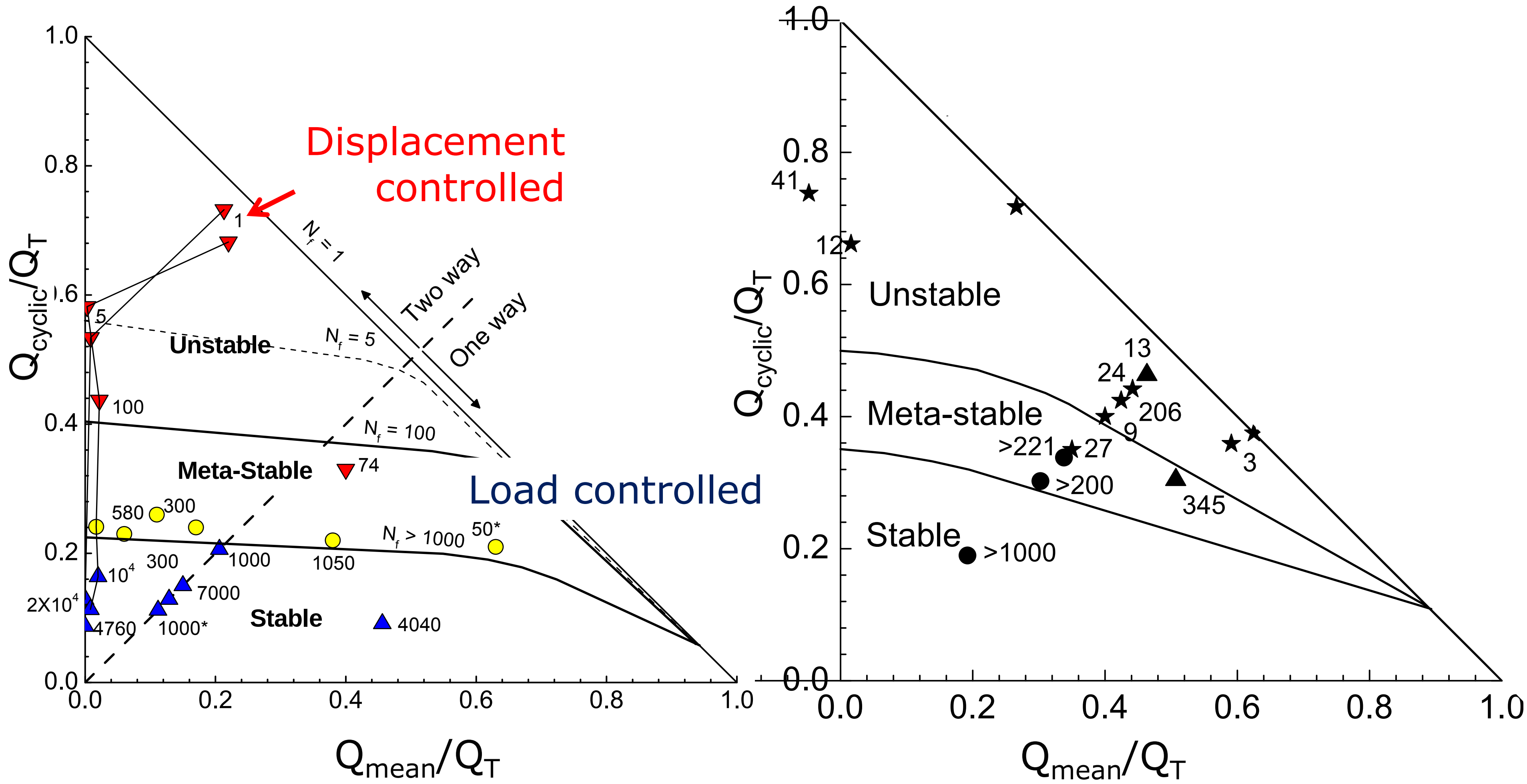


Shaft capacity falls markedly

Tsuha et al (2012)

Cyclic failure interactions: model & field cases

Mini-ICP & NE34 | Dunkerque full scale



Comparable trends; field response marginally more robust

Matching cyclic conditions in lab element tests

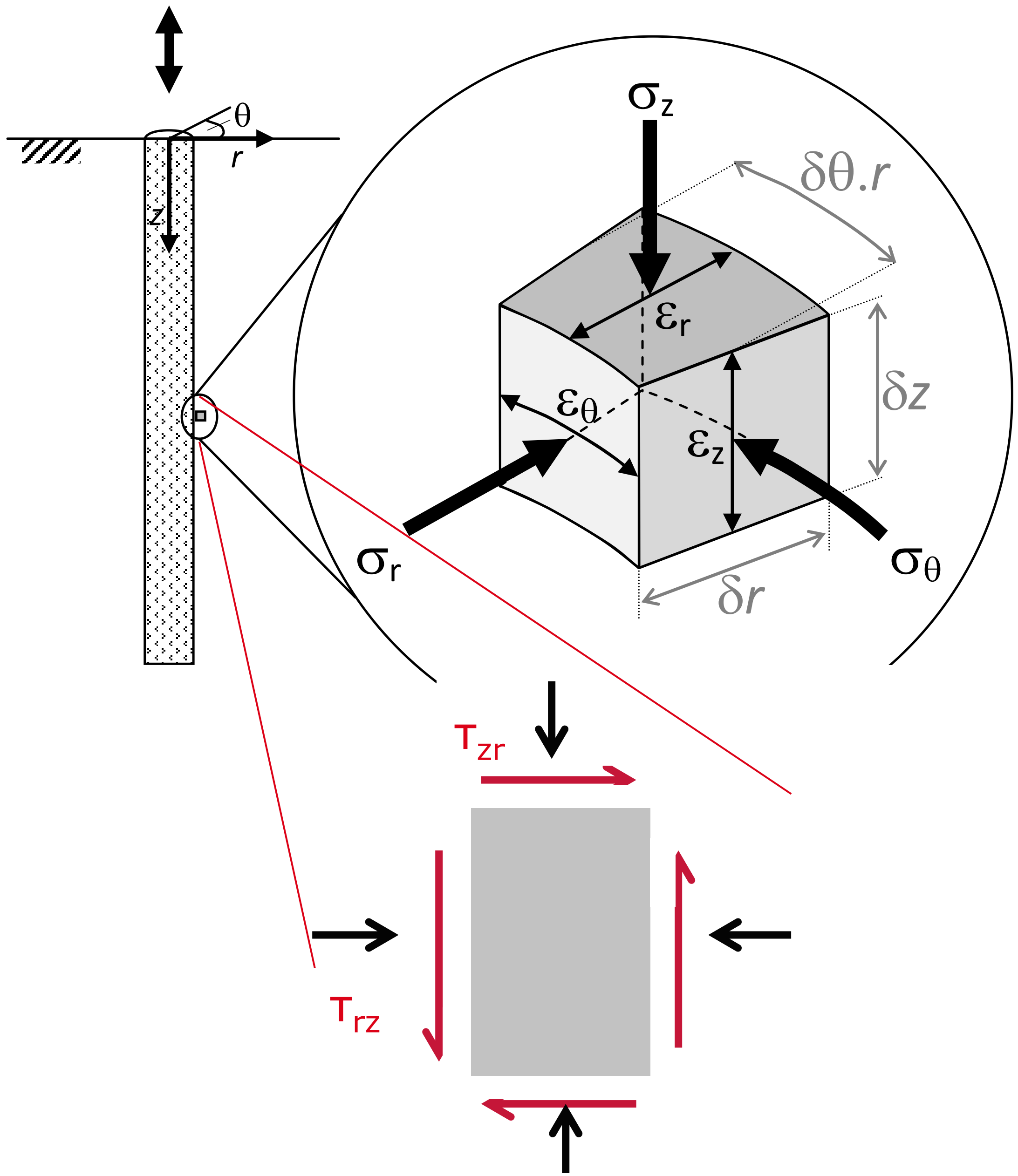
γ_{rz} shearing dominates
$\varepsilon_\theta = 0$, ε_z is small
ε_r constrained by soil mass

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

Apply undrained CNS = ∞
Cyclic Triaxial CTX or
Simple Shear CSS tests

CSS tests in HCA?

Pre-cycling stress path?



Undrained cyclic element tests: NE34 & Dunkerque sands

Y_2 yielding and p′ drift rates depend on:

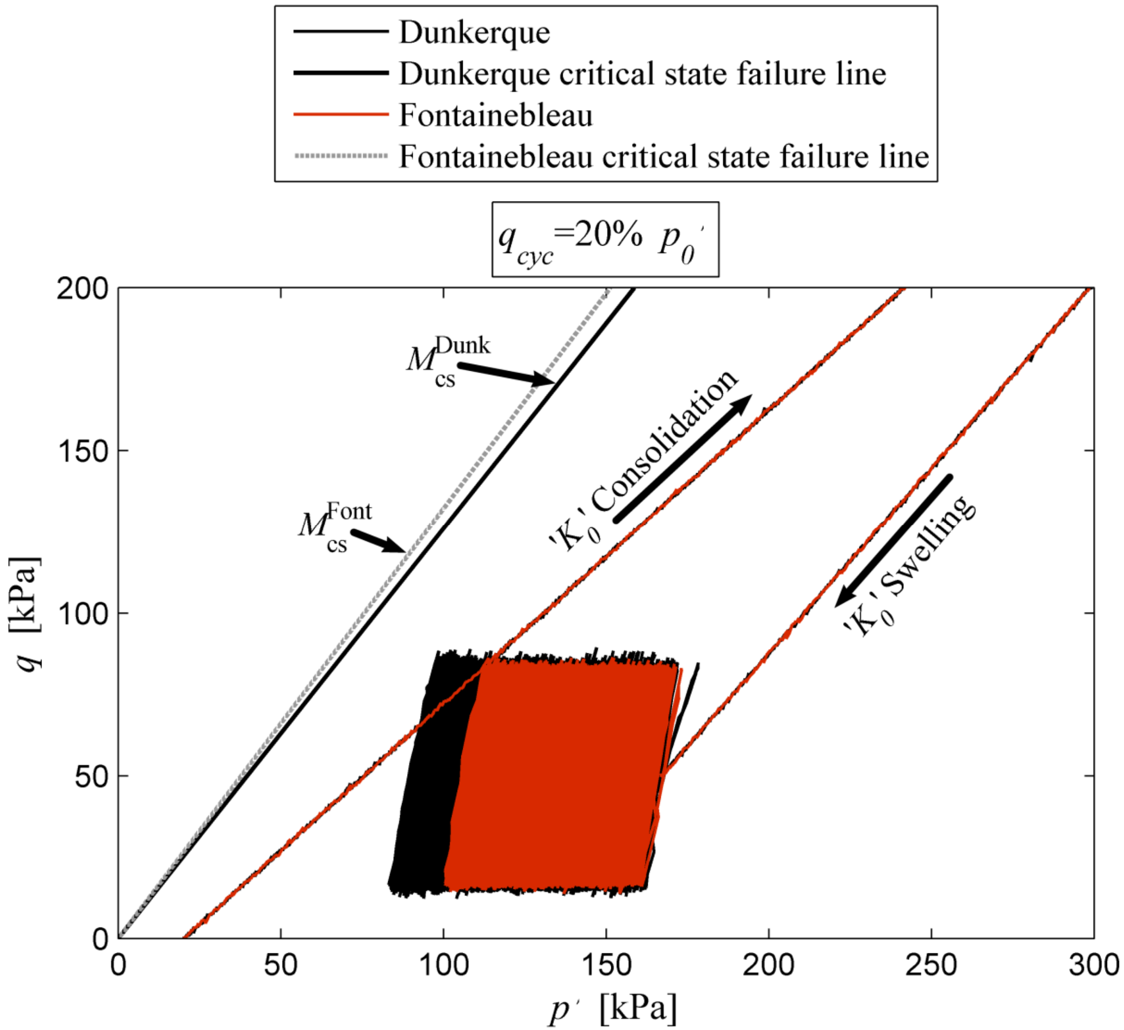
q_{cyclic}/p' and N

CTX or HCA CSS mode

OCR & pre-cycling

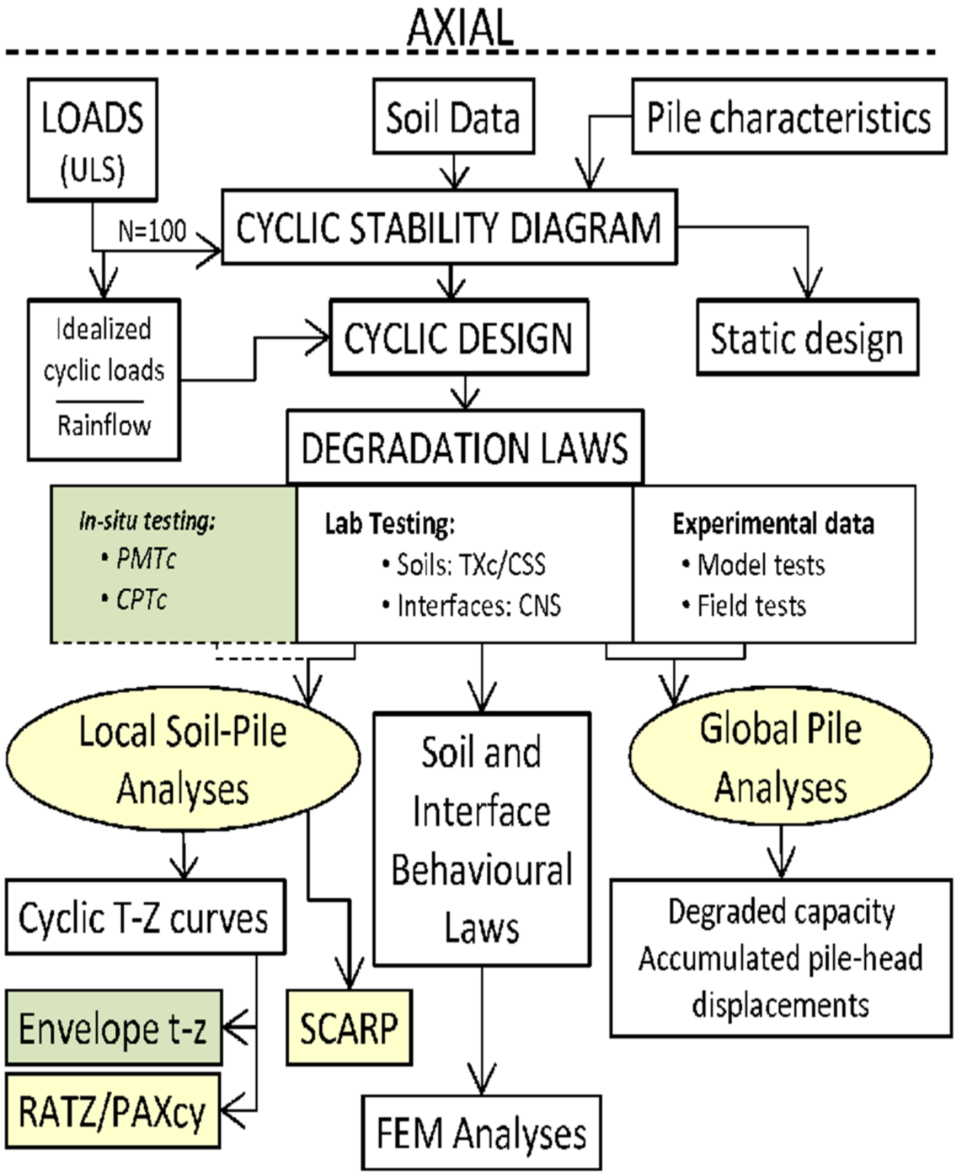
Creep & ageing pauses

1500 cycle CTX tests from OCR = 4



Sim et al 2013

Practical Application: Wednesday TC-209 workshop



Borkum West II; Merritt et al 2012

Jardine et al 2012
Andersen et al 2013
SOLCYP – Puech et al 2013

Bishop Lecture: Summary and Conclusions

- Challenges posed by field experience & observations
- Advanced Lab testing: permits scrutiny of Elastic, Plastic, Anisotropic, Kinematic Yielding, Time-dependent and Cyclic soil behaviour in precise experiments
- Also critical to investigating pile installation stresses, grain-crushing, interface-shear & cyclic behaviour
- Endorse Bishop's approach: integrate laboratory experiments with field & analytical research - and help apply the results in practice

Imperial College London

Acknowledgements

Current & former IC colleagues, particularly: S. Ackerley, A. Aghacouchak, F. Altuhafi, R. Kuwano, F. Chow, T. Ho, S. Rimoy, WW. Sim, J. Standing, Z. Yang, and B.T. Zhu

Co-workers and collaborators, particularly: C. Dalton, I. Einav, P. Foray, J. Powell, A. Puech, M. Siva and C. Tsuha

Funding from: Atkins, French CNRS, Chinese NSF, Commonwealth Commission, UK EPSRC, HSE, Royal Society, Shell, Total and others