Imperial College
London

Geotechnics and Energy

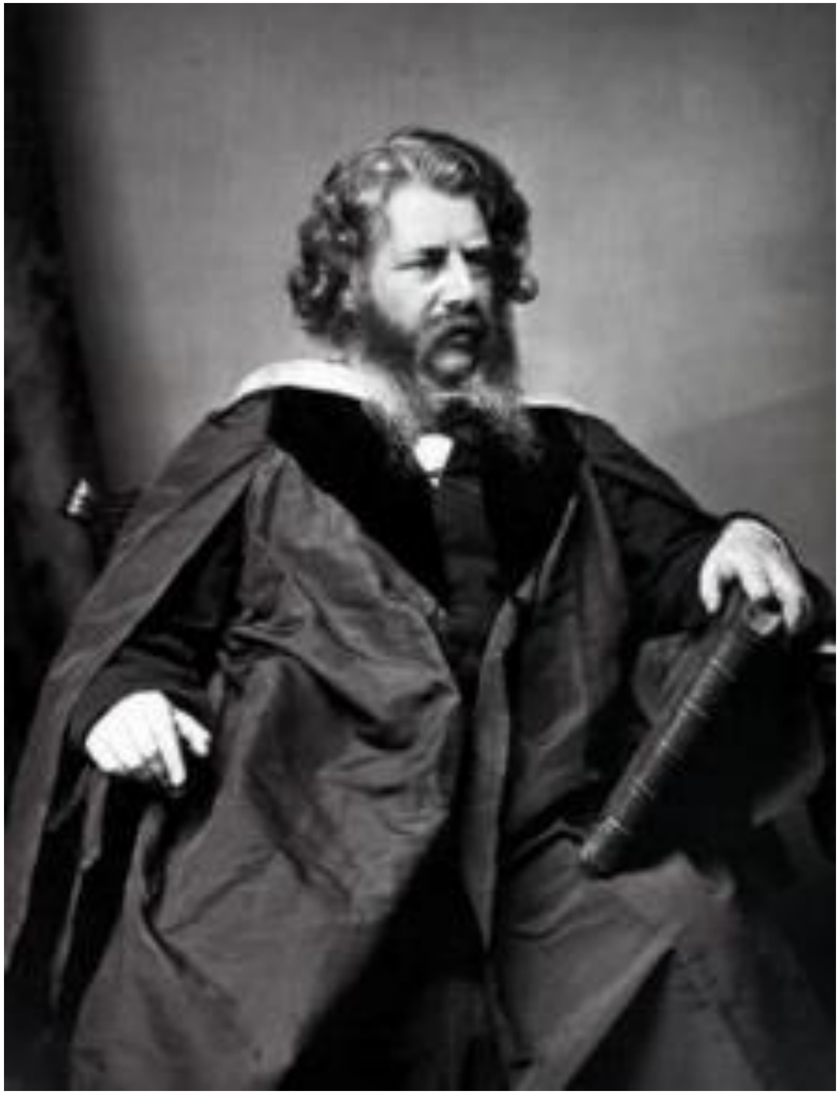
56th Rankine Lecture

Richard Jardine

Geotechniekdag 2017, Breda

7th November 2017

The energy conundrum



W J M Rankine: 1820-1872
Thermodynamics & geotechnical pioneer

Global energy demand rising 20% per decade

Imperative to cut greenhouse gas emissions

Geotechnical contributions towards resolving grand engineering challenge

Three main Parts, each with paired topics

I – Maintaining supplies: Offshore oil & gas platform foundations & deepwater landslide risks

II - Climate change: Geotechnical impact & engineering adaptation

III – Renewable energy: Mono & multi-pile offshore windturbine structures for shallow & deeper water

Broader aspects

Transferring offshore research to civil engineering

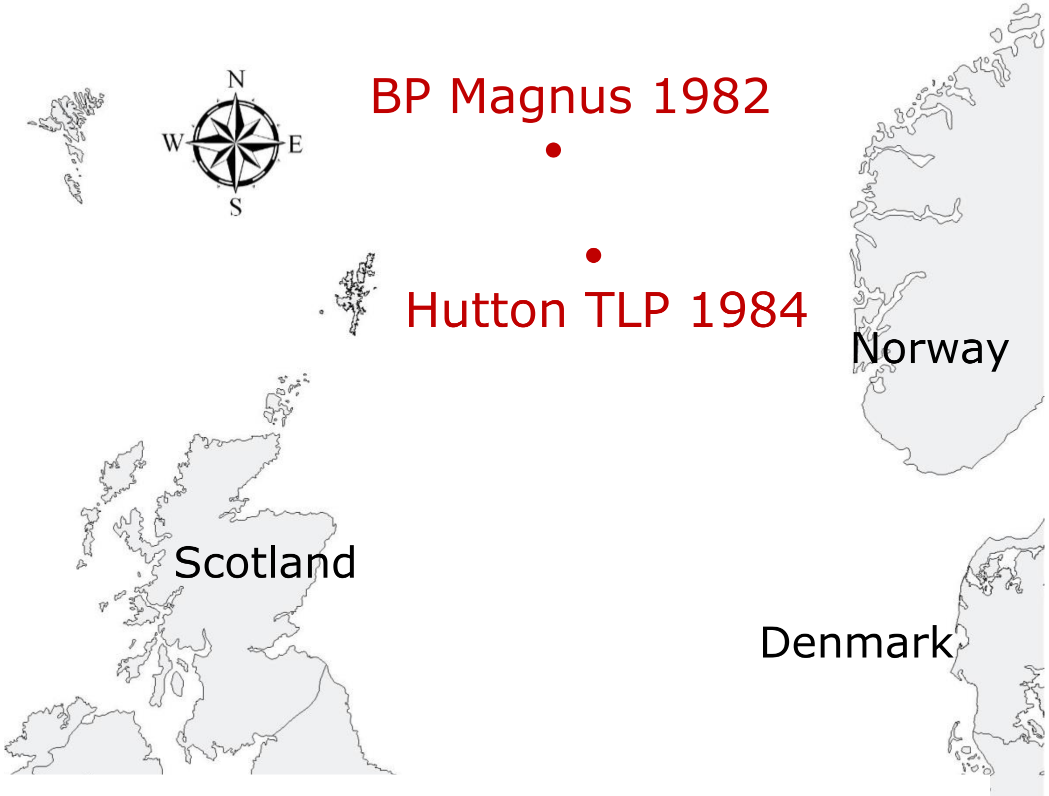
And three general geotechnical themes

Integrating geology, experiments, analysis & field observations

Collaborative research & engagement with Industry, as cited throughout

Practical tools: “As simple as possible, but no simpler”

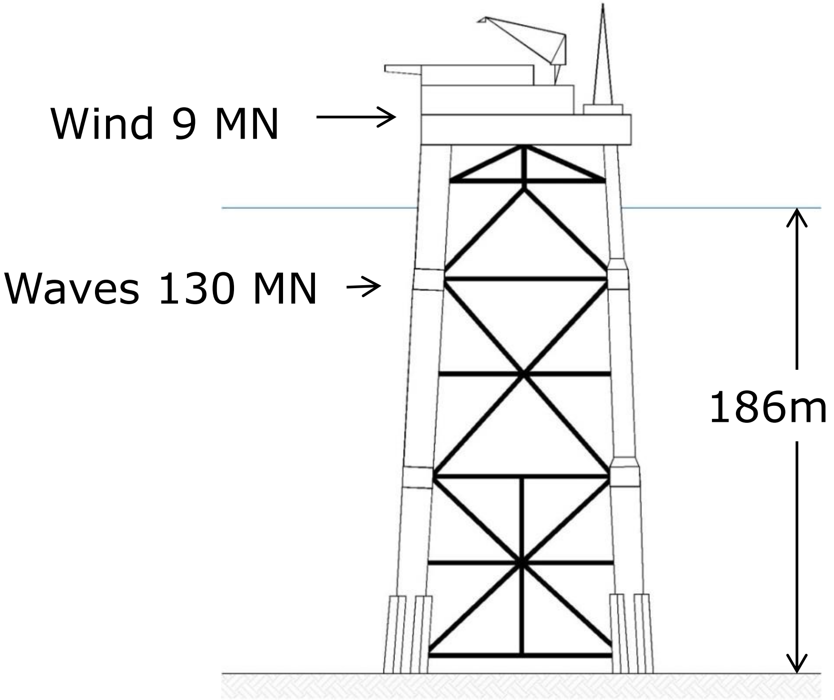
Measurements & predictions for North Sea foundations



Hutton TLP: special sensors

Similar groups, but under tension

High resolution static & storm data



Magnus: pile strain gauges & accelerometers

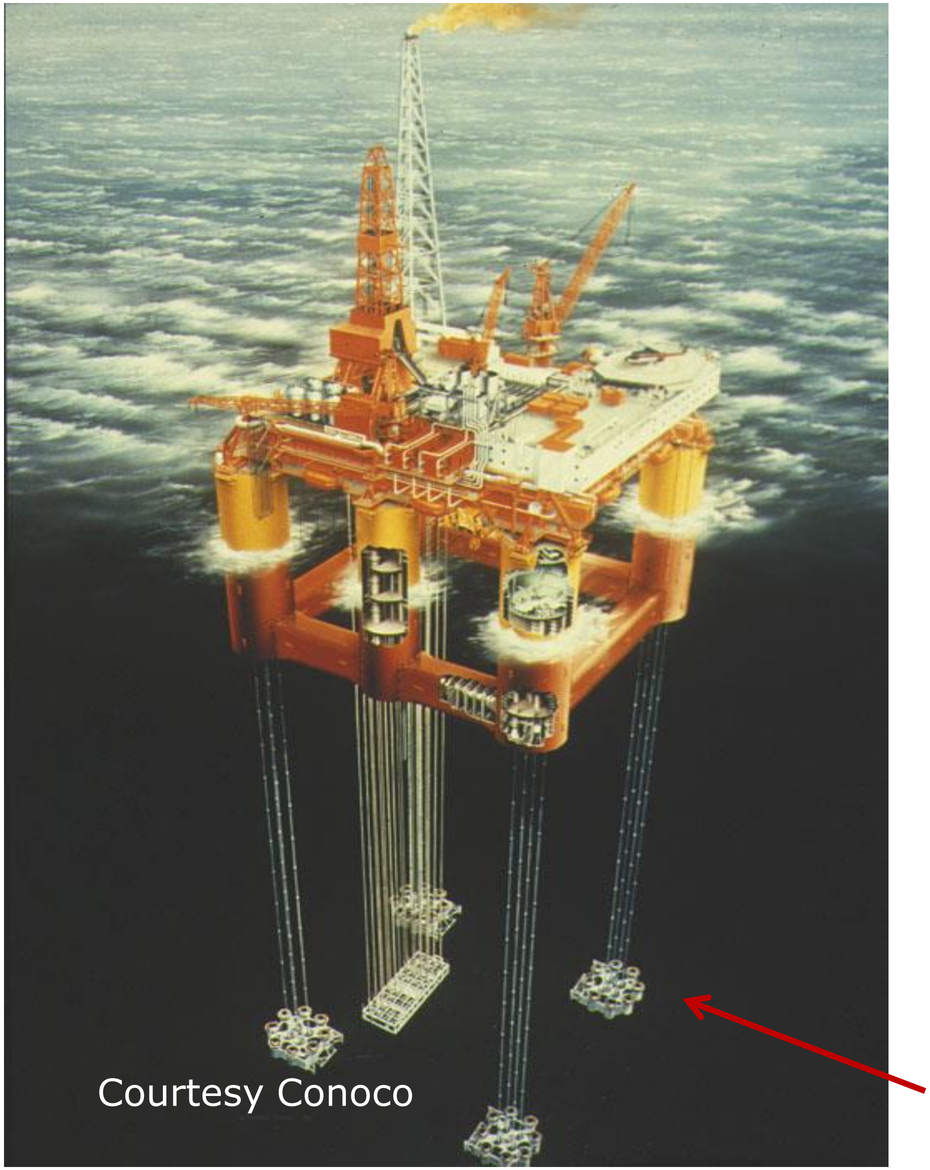
Groups of 9x2.1m steel tubes driven 82m, hard glacial tills

Dynamic storm loading data

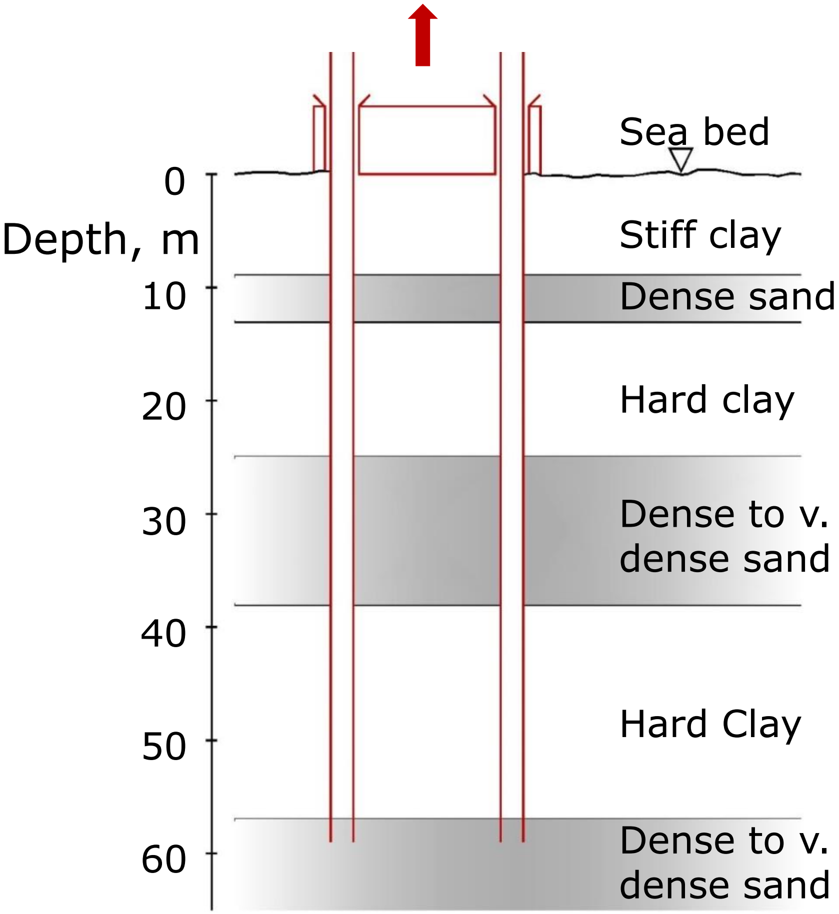
Revolutionary floating Hutton Tension Leg Platform

Load-cells, ±0.03mm IC gauges, static & storm monitoring

Jardine, McIntosh & Hight 1988



Courtesy Conoco



1.83m OD piles driven through deep glacial clays & sands

Predictive methods

Conventional API

Pile FE, t-z & p-y soil ‘spring’ curves, elastic group factors

Small strain & FE

Stress-path tests, local instruments
Non-linear stiffness

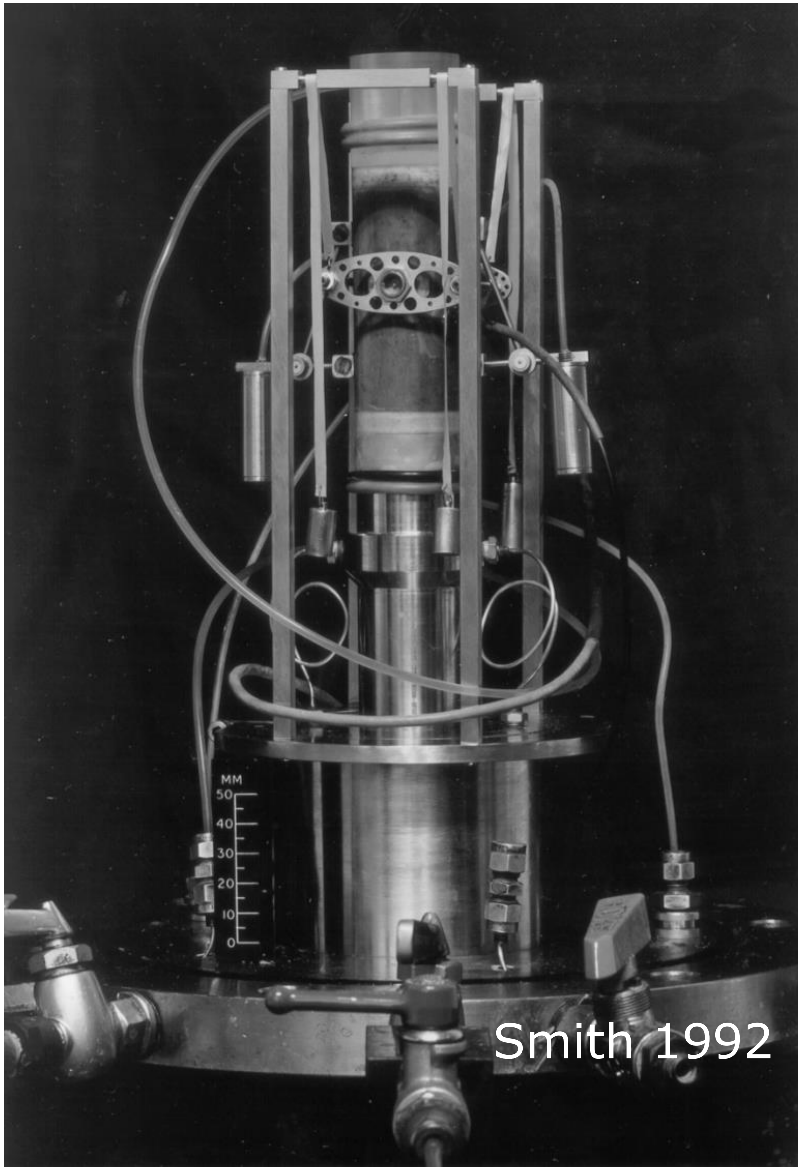
Shear $G/p' = f(\varepsilon_s)$
Bulk $K'/p' = g(\varepsilon_{vol})$

ICFEP; Mod Cam Clay & Mohr-Coulomb models

Installation & Coulomb interface

Non-linear group interaction

Jardine & Potts 1988, 1993



Smith 1992

Foundation stiffness: measurements & predictions

Conventional: 4 x too soft

"IC" predictions accurate

Also at Magnus, axial, rotational & lateral

Jardine & Potts 1993

Kenley & Sharp 1993

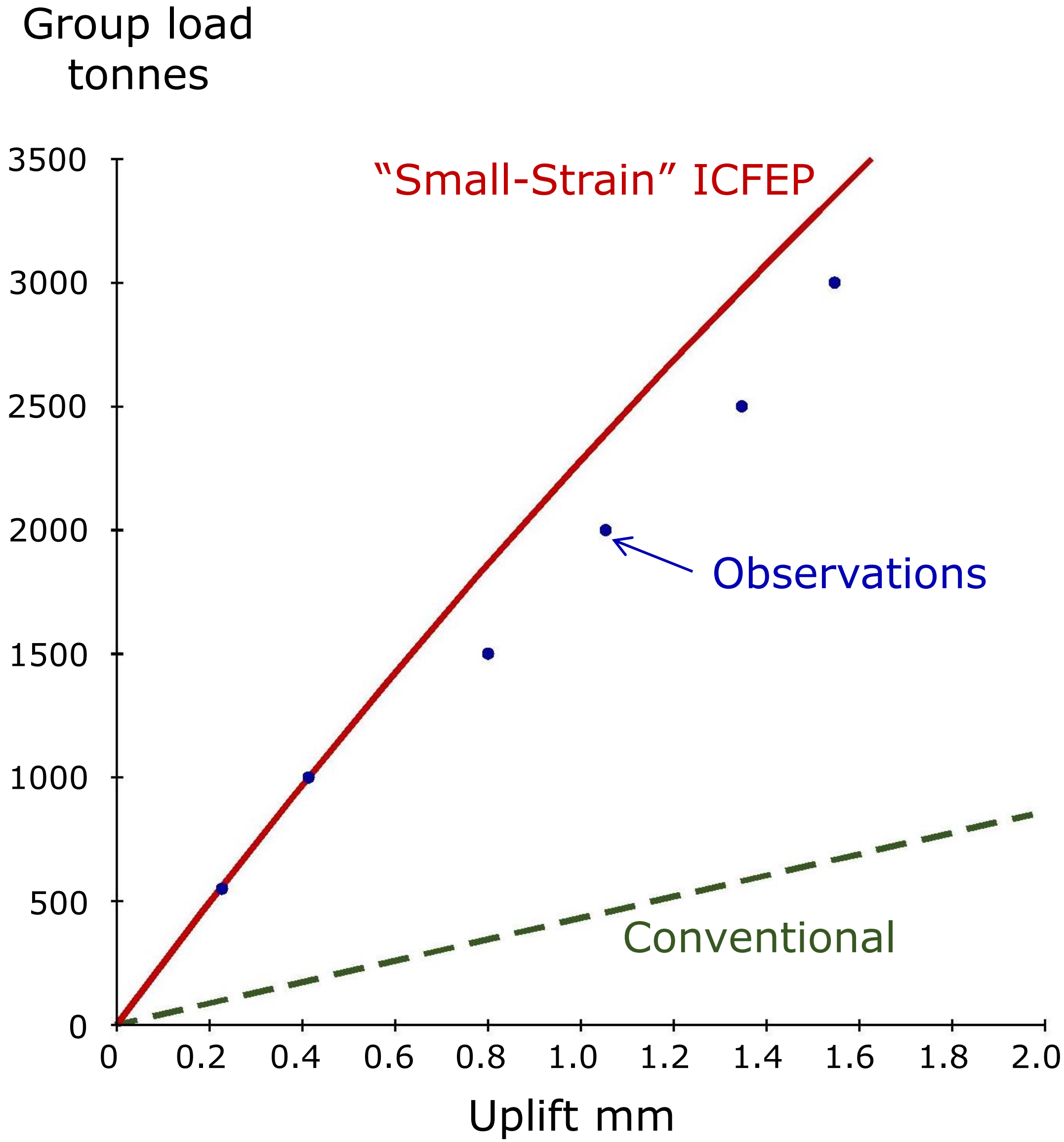
Ganendra 1994

'IC' approach used widely onshore

Less offshore use..

Poor axial capacity reliability CoVs up to 70%

Axial Hutton case



Field tests with Imperial College Pile

Axial load, local σ_r , τ_{rz} & pore pressure, multiple h/R levels

Bond, Jardine & Dalton 1991

Installation, equalisation & loading

Six clay & sand sites in UK & France

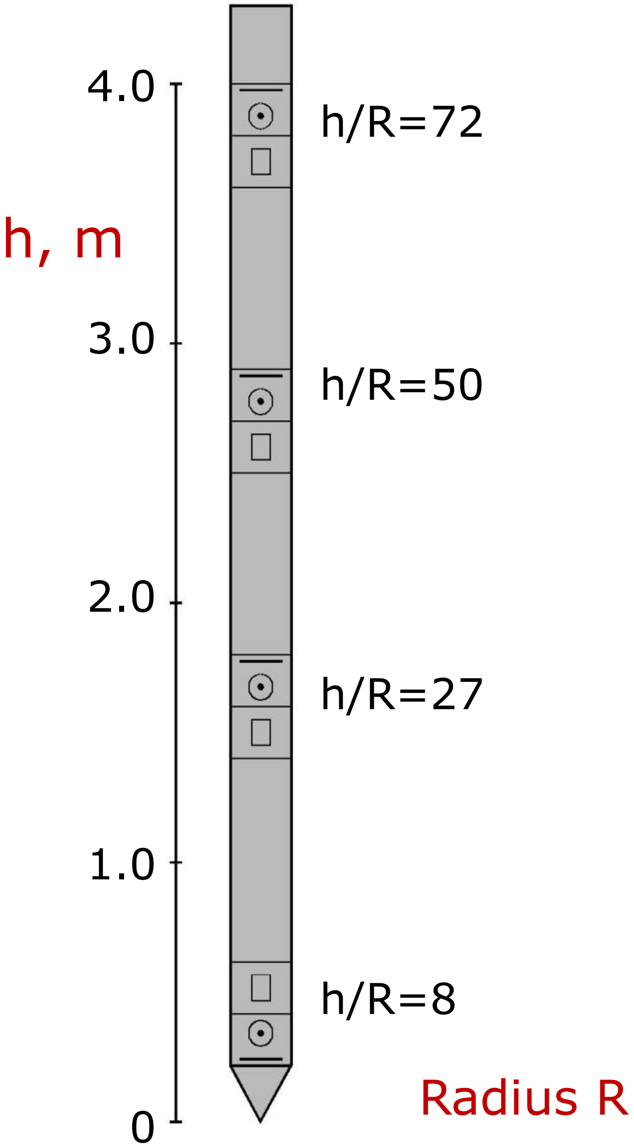
Bond 1989, Lehane 1992, Chow 1997

'ICP method' from field, lab tests & theory; Jardine & Chow 1997, Jardine et al 2005

Checks: 149 test ICP-05 database

Recent updates: With ZJU, Yang et al 2017

With NGI, UWA & Fugro, Lehane et al 2017



Greatly reduced CoVs, predictive bias eliminated

ICP précis

Field SI: CPTu q_c profiling & sampling
Laboratory: interface shear δ', σ'_{v0} & clay OCR, Sensitivity S_t

Base: $q_b = f\,(q_c)$

Shaft: effective stress failure $\tau_{rz} = \sigma'_{rf} \tan \delta'$

	Sand	Clay
Pre-loading	$\sigma'_{rc} = q_c\, f(\sigma'_{v0}, h/R^*)$	$\sigma'_{rc} = \sigma'_{v0}\, f(OCR, S_t, h/R^*)$

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

At failure

Compression	$\sigma'_{rf} = \sigma'_{rc} + \Delta\sigma'_{rd}$	$\sigma'_{rf} = 0.8\, \sigma'_{rc}$
Tension	≈ 25% lower	same

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

δr = pile roughness $G = f(q_c, \sigma'_{v0})$

Applications & checks

All Shell platforms from 1996

Instrumented driving & storm response monitoring

Field performance assessed: 13 case histories, Overy 2007

Courtesy P van Esch, Heerema

Goldeneye

Courtesy R Overy, Shell

Better reliability & economy, reduced installation risks

Critical to marginal projects

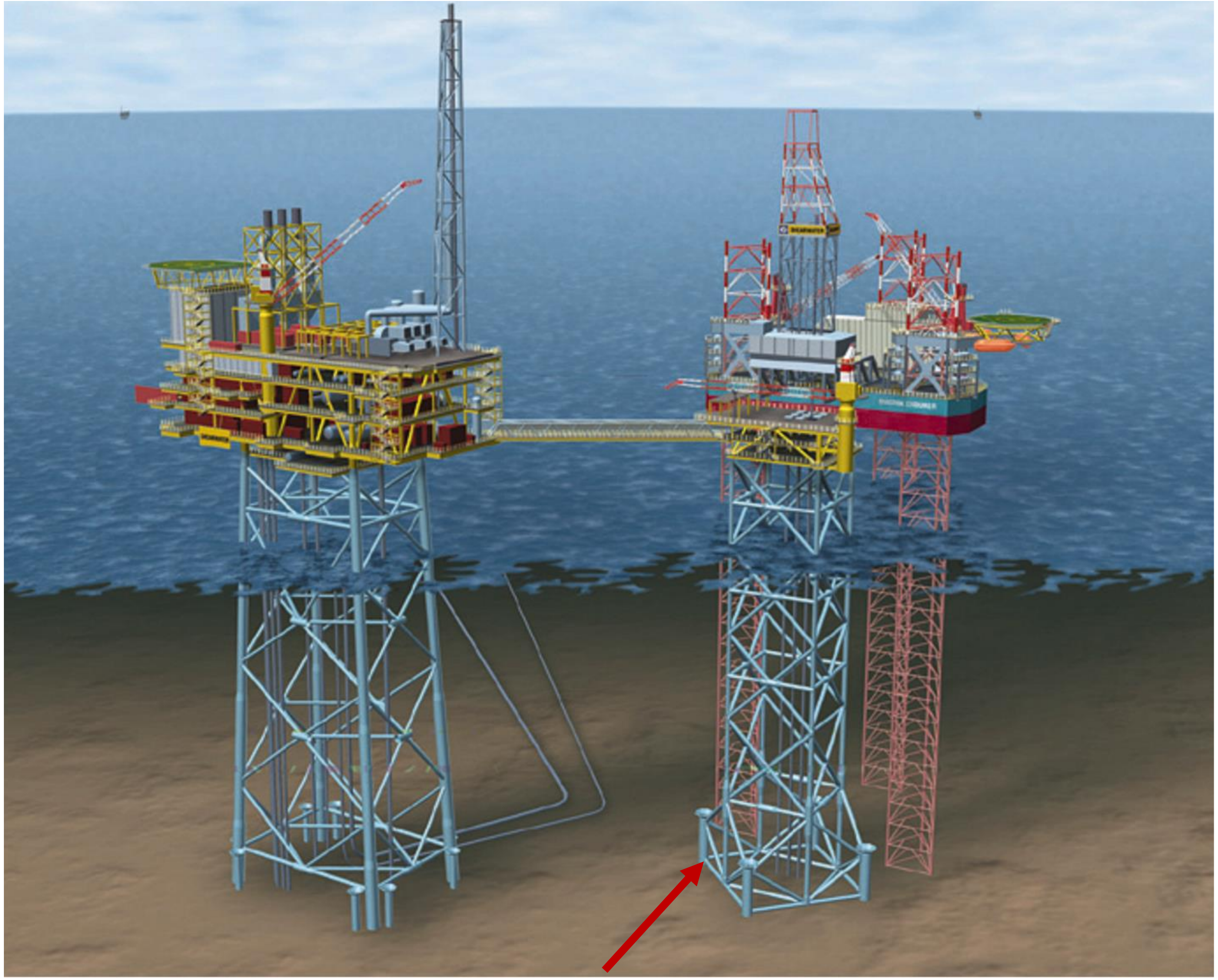
Overy & Sayer 2007

Sand method:

API RP2 GEO and ISO

Storm performance?

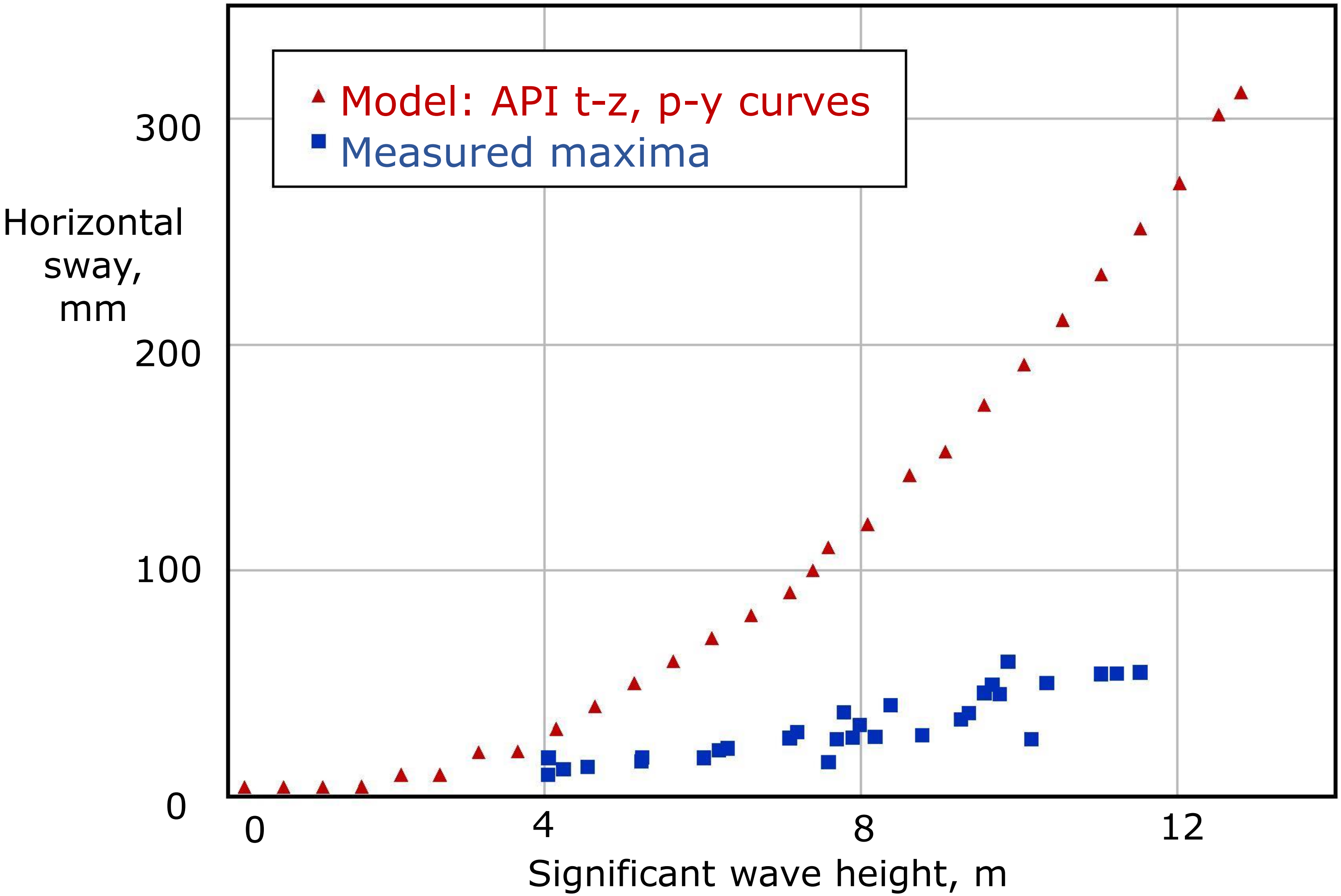
Shearwater A; piles driven in 1997
Response to ≈20 year storm, December 27th 1998



2.13m OD, 51m: hard clays & dense sand

Waves at Tern

Single piles push & pull, deck sways; Hunt 1999



As at Magnus & Hutton, field far stiffer than API model
1+ year after driving & cyclic loading

Research questions posed by field experience

Ageing after full pore pressure equalisation?

Stiffness & capacity?

Cyclic loading?

Impact & assessment for design?

Full stress regime around driven piles?

Poorly understood, beyond accurate analysis?

Field: ageing study in dense Dunkirk sand

Steel pipe piles
457mm x 19m
Parker, Jardine,
Standing & Xavier 1999

Driving is key:
Bored piles
behave
differently!
Puech et al 2013

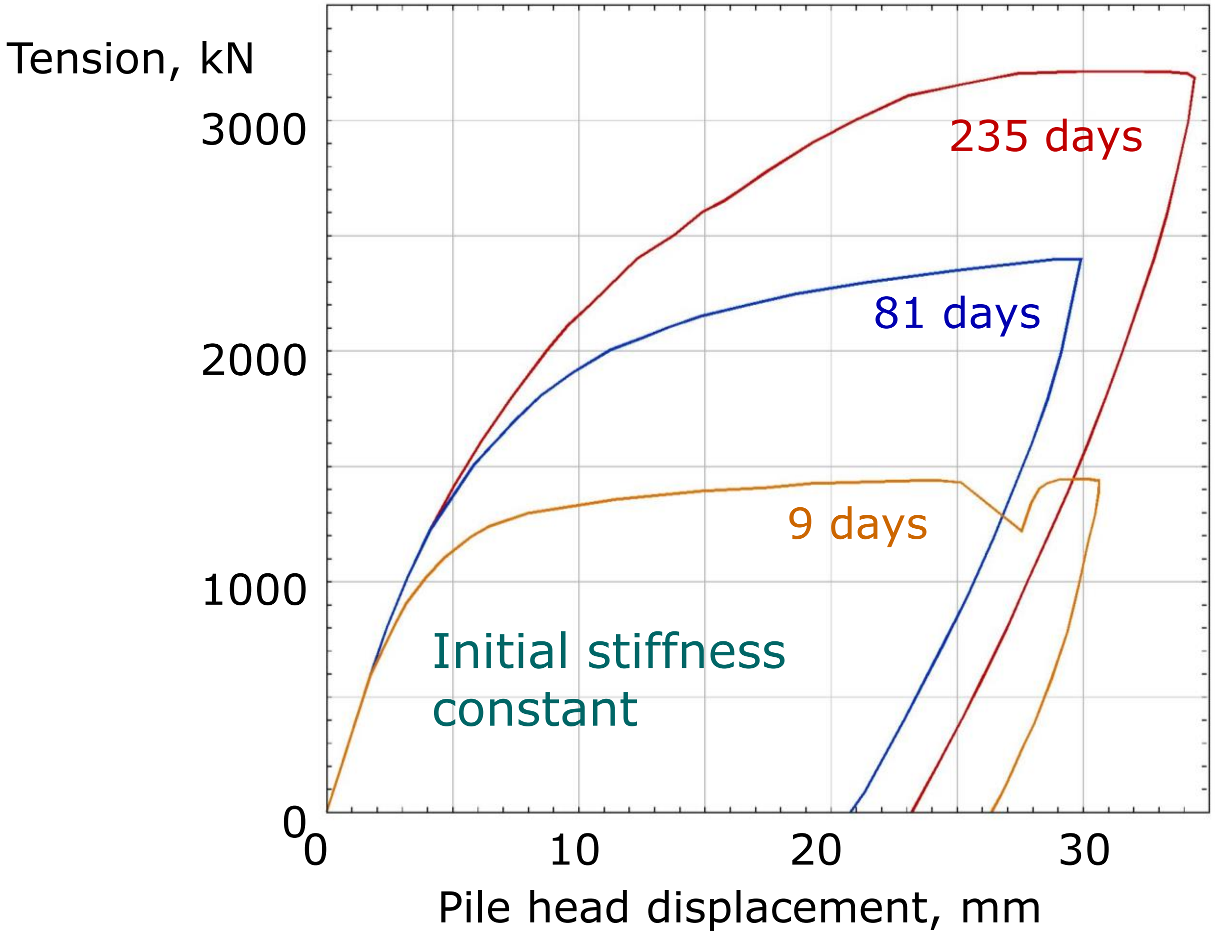
With HSE & PMC

Jardine & Standing 2000, 2012; Jardine, Standing & Chow 2006

Shaft capacity from 1st time tests

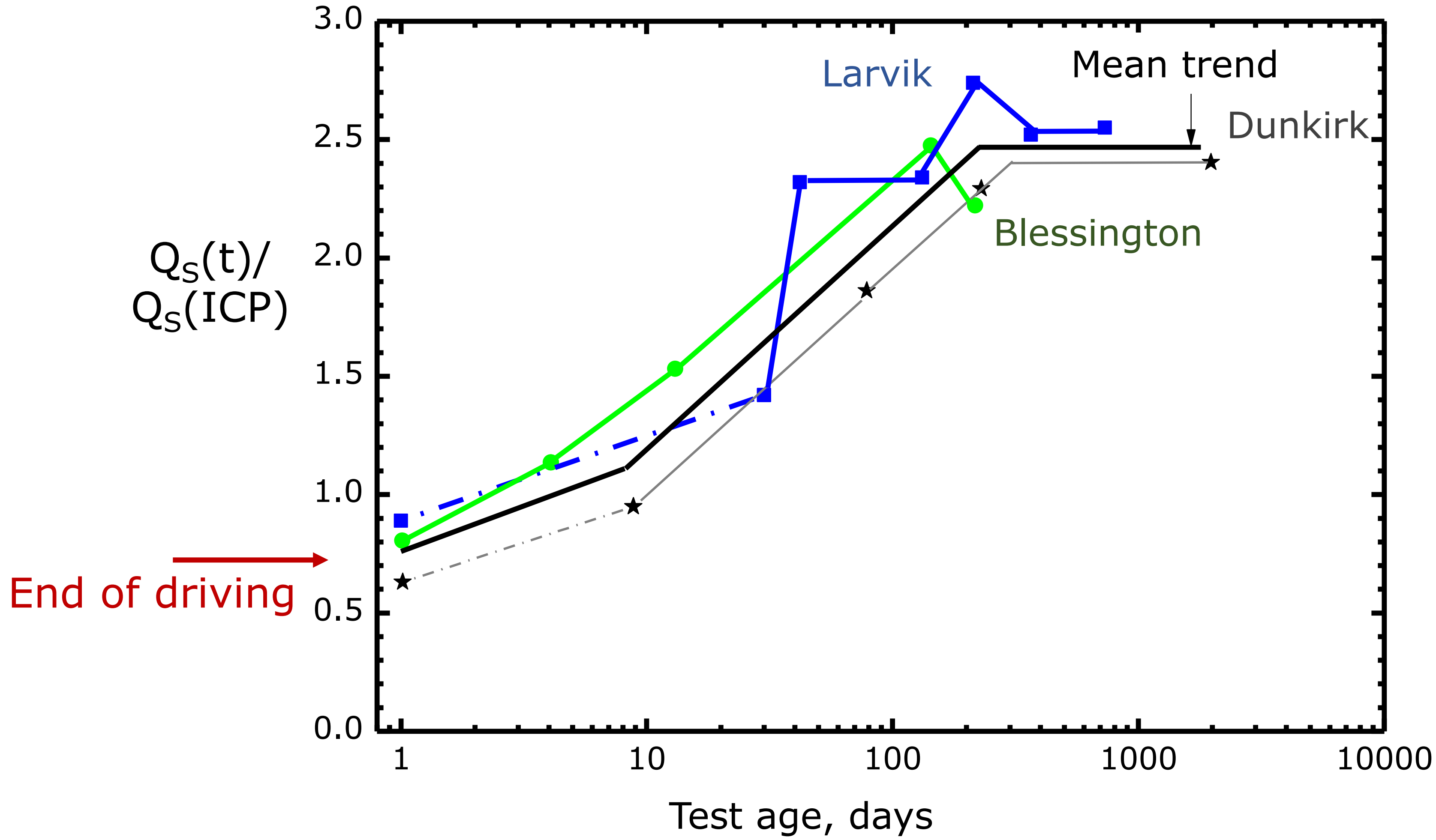
Capacities grow markedly over months after driving

Re-tests: more complex & disrupted trends



Adding tests by Gavin et al 2013 & Karlsrud et al 2014

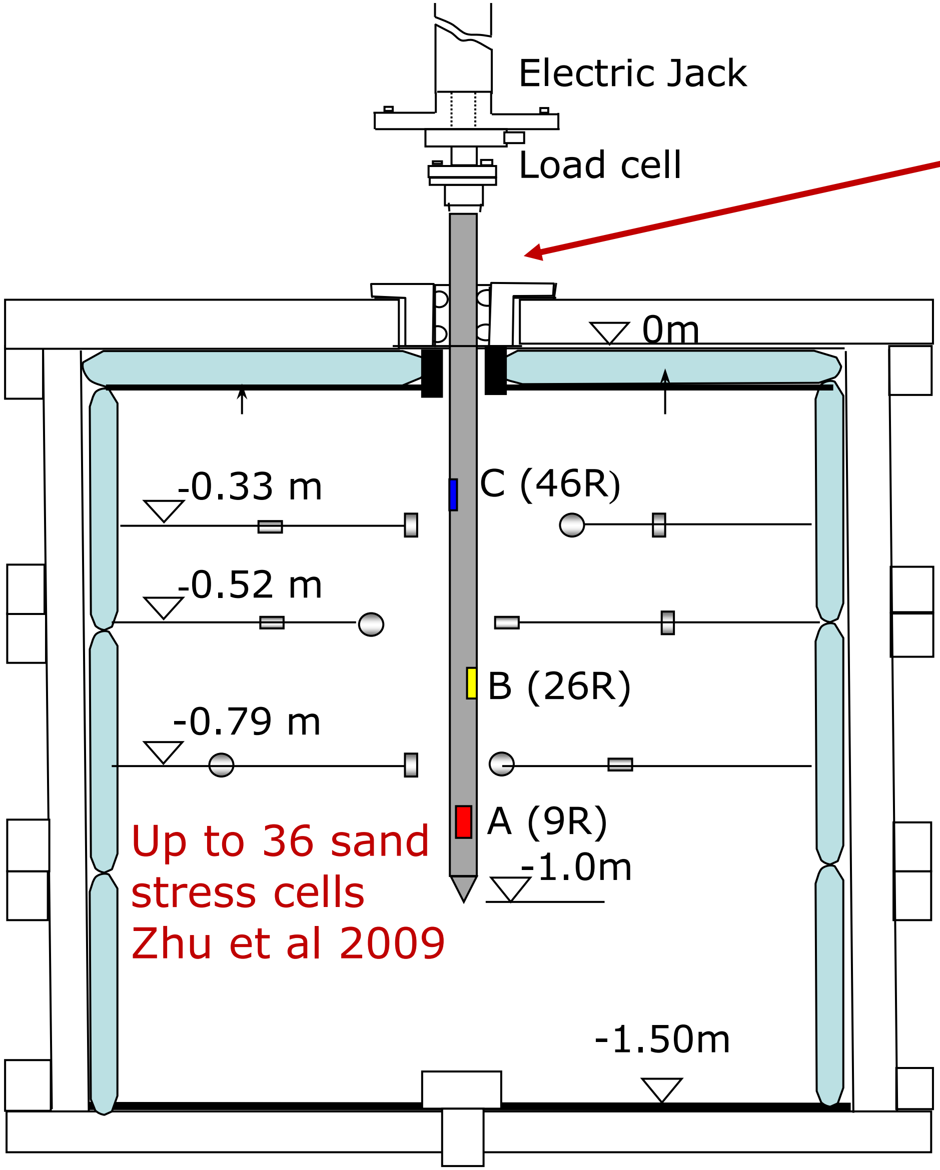
1st time tension 0.3<OD<0.5m steel piles



Governing processes, necessary conditions?

Rimoy, Silva, Jardine, Foray, Yang, Zhu & Tsuha 2015

Model: Grenoble calibration chamber experiments with Pierre Foray



36mm OD ICP; Jardine et al 2009

Up to 36 sand stress cells
Zhu et al 2009

Fontainebleu NE34 & GA39 sands
Wet & dry, Dunkirk I_D range

150 kPa surcharge
Constant stress, rigid or ‘active’ radial boundaries

Stainless & mild steel piles,
Driven & jacked

Post-docs: M Emerson, B Zhu, Z Yang, C Tsuha; PhDs: Rimoy 2014, Silva 2015

Model: radial stresses in NE34

Heavily pre-loaded sand

Intense loading under tip radius r & h = 0

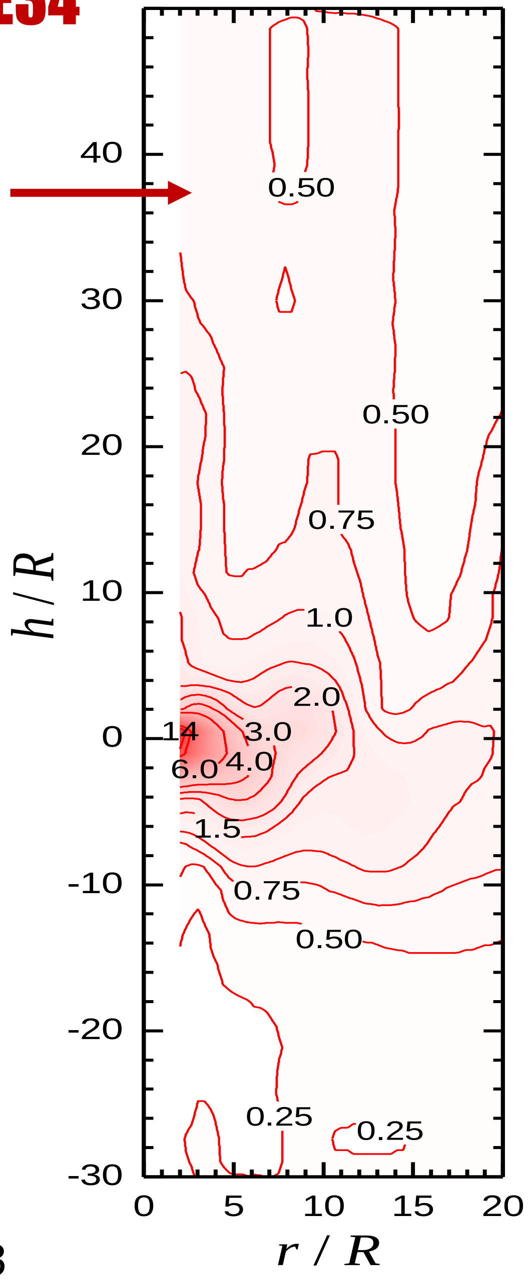
$\sigma'_z \approx q_c \approx 20$ MPa
$\sigma'_r \approx q_c/3$

σ'_r/q_c contours in % decay with r/R & ± h/R

And pre-cycled

Quite unlike bored piles

Jardine, Zhu, Foray & Yang 2013

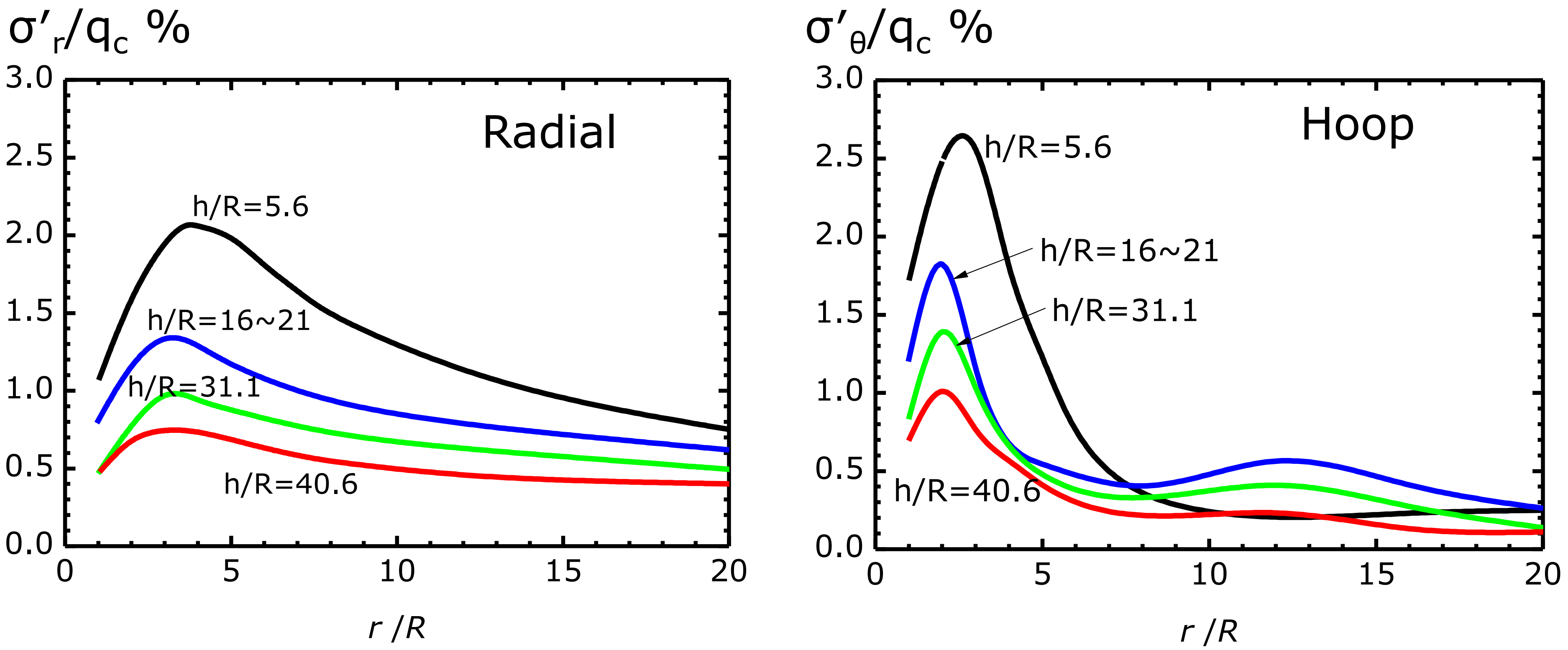


Pile penetrating

Model: arching round shaft after installation

Adding SST shaft σ'_r data

Reveals σ'_r maxima at $2 < r/R < 4$



If arch relaxes through creep σ'_r & shaft capacity rise

Benchmarks for numerical analyses

Yang et al 2014, Rimoy et al 2015

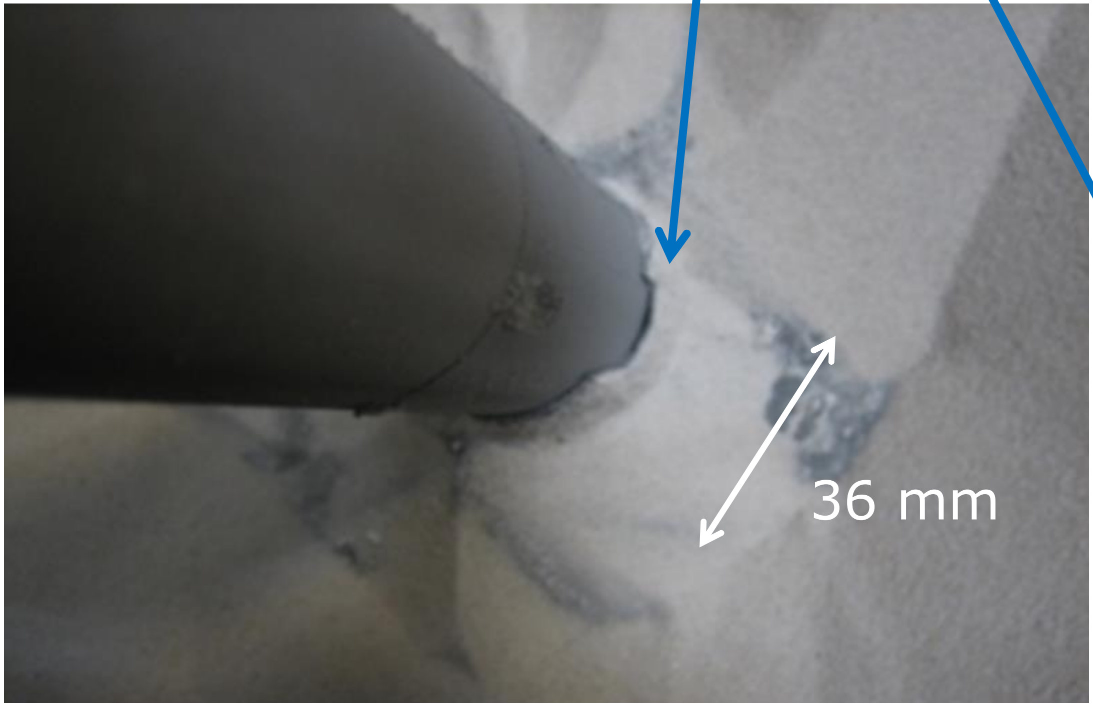
Dataset includes micro-mechanical observations

Dense fractured 'crust' forms around shaft - as in field

From above

0.5 to 1.5mm thickness

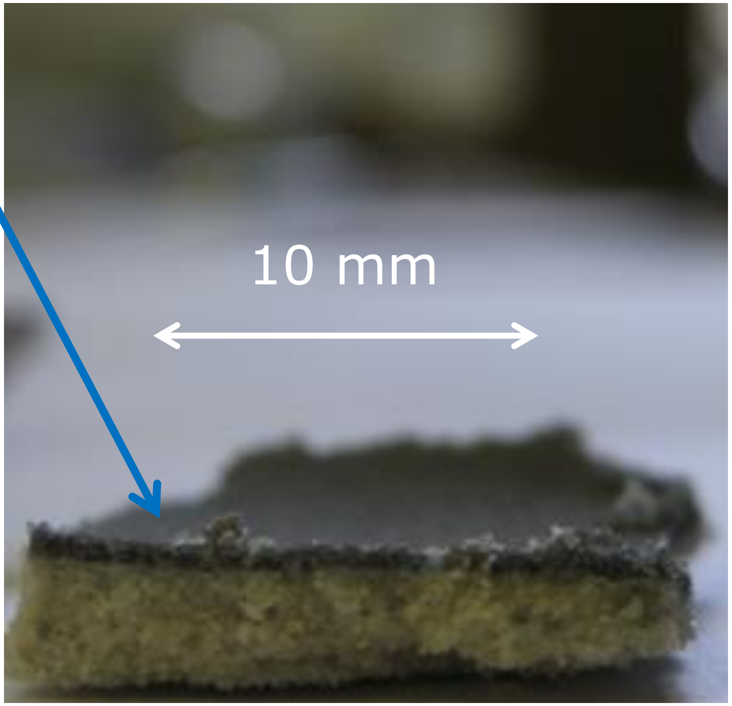
Grows with d_{50} & h



Side view

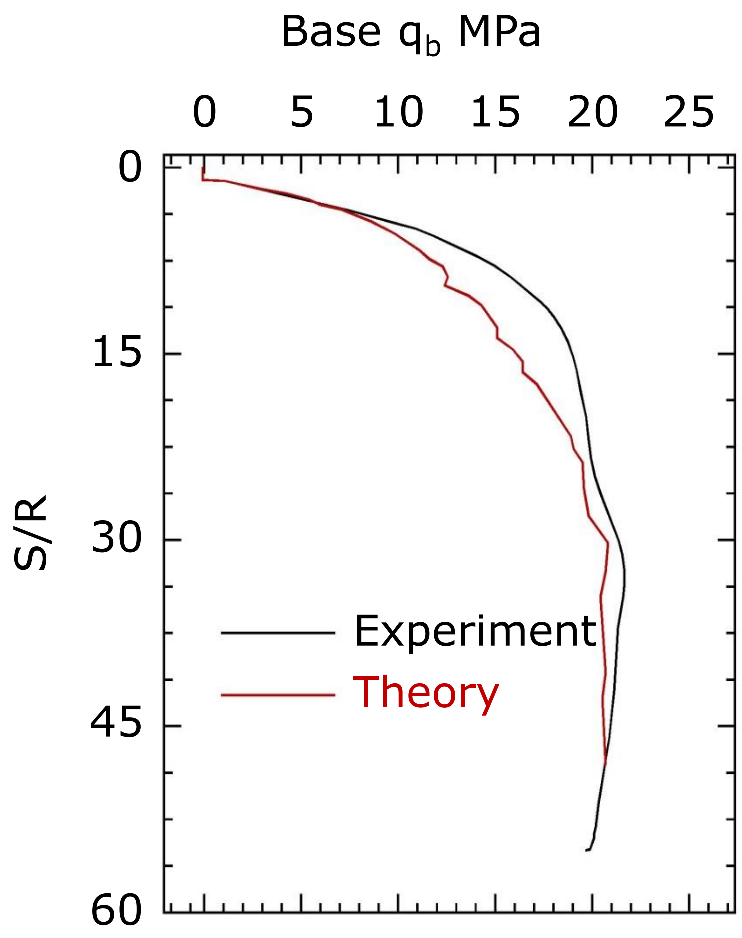
Laser analysis of breakage

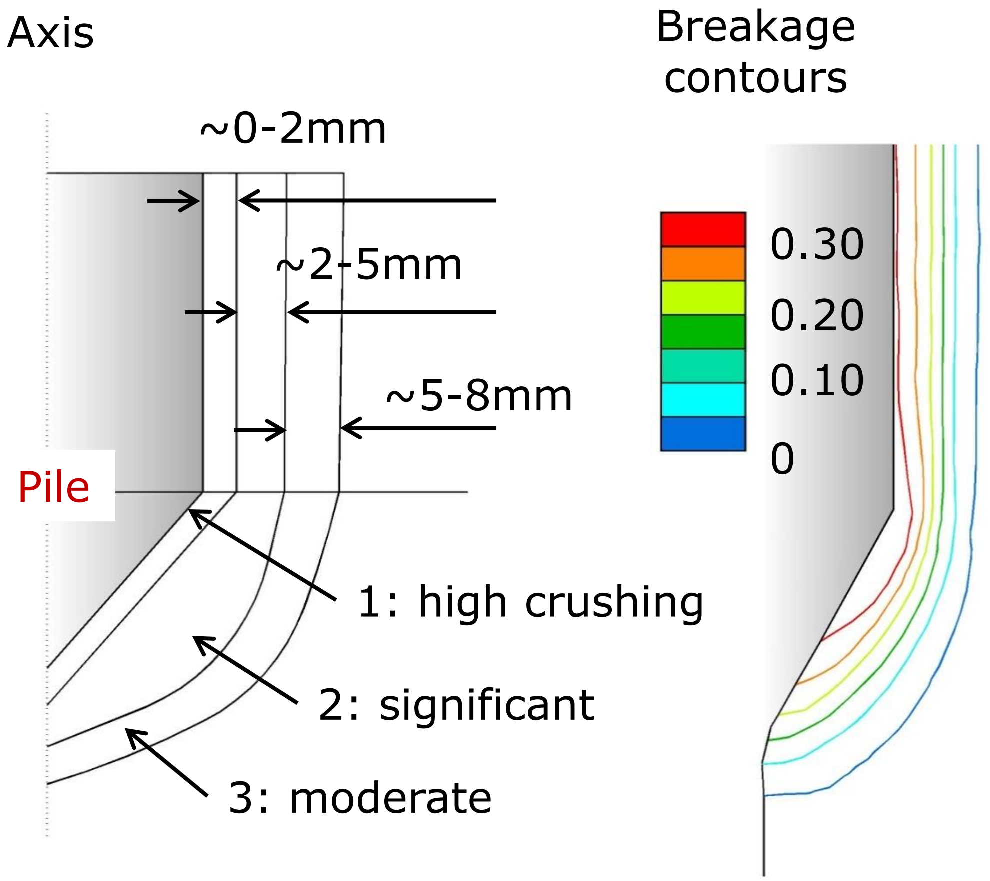
Porosity measurements



Yang, Jardine, Zhu, Foray & Tsuha 2010

Analysis: Arbitrary Lagrangian-Eulerian FE, with grain crushing



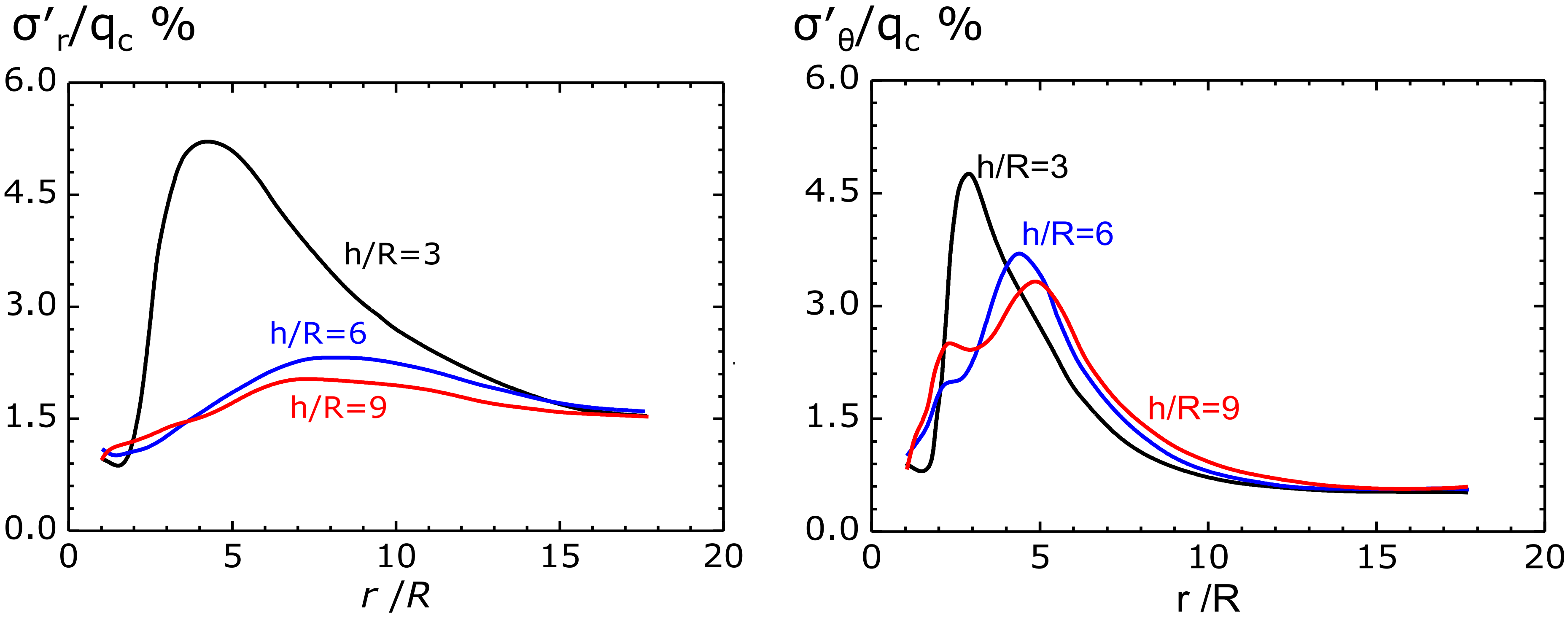


S = tip penetration depth
R = pile radius

Grain breakage
None B = 0, Full B = 1

Zhang, Nguyen & Einav 2014

‘ALE’ FE predictions of arching



Similar to σ measurements, maxima within 30%

Add shaft abrasion & cycling to improve predictions?

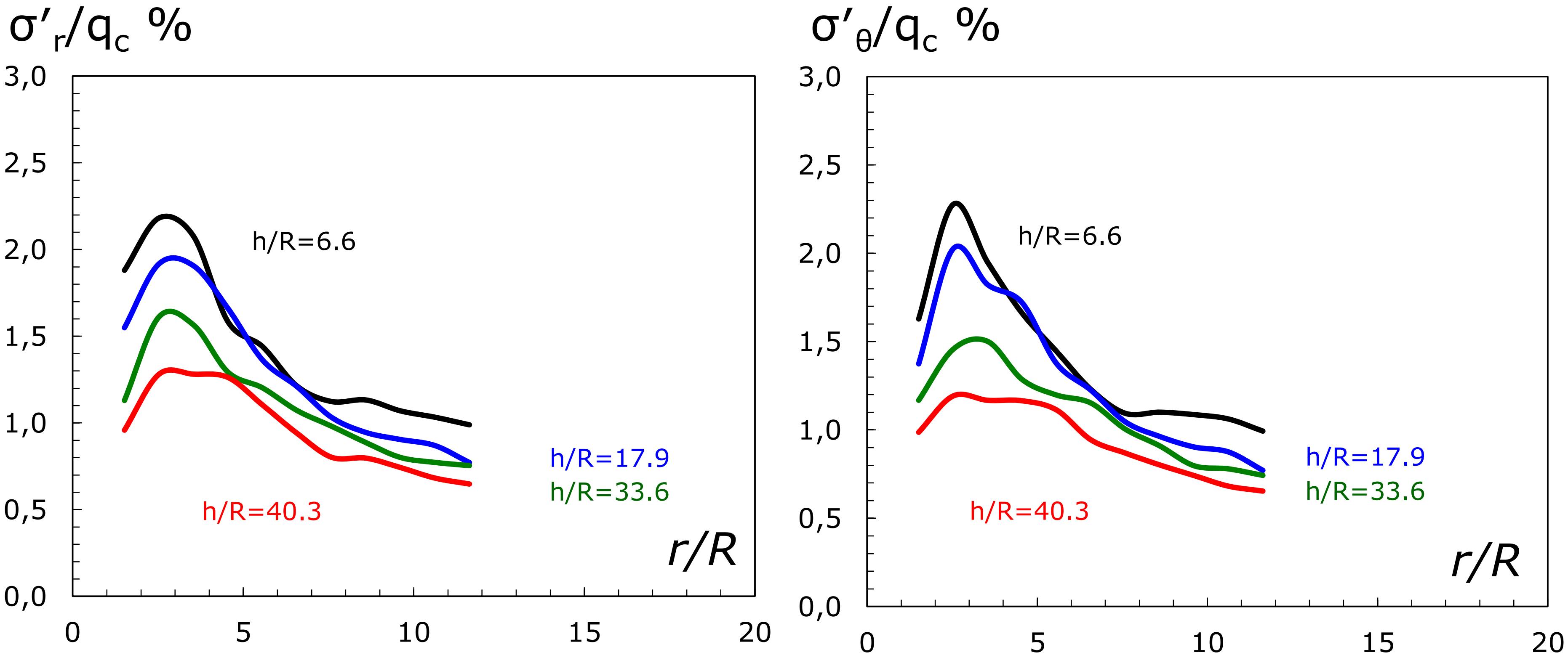
Or tackle with Discrete Element Method?

Zhang, Yang, Nguyen, Jardine & Einav 2014

DEM analysis: Ciantia et al 2017

0.4m x 1m 'sand mass' - 5×10^5 crushable d_{50} =8.5mm grains

Matches q_b – penetration curve & arching stresses



Better h/R trends

Analysis converging towards experiments

Influence of pile & grain diameters?

Interface shear zone controlled by d_{50}

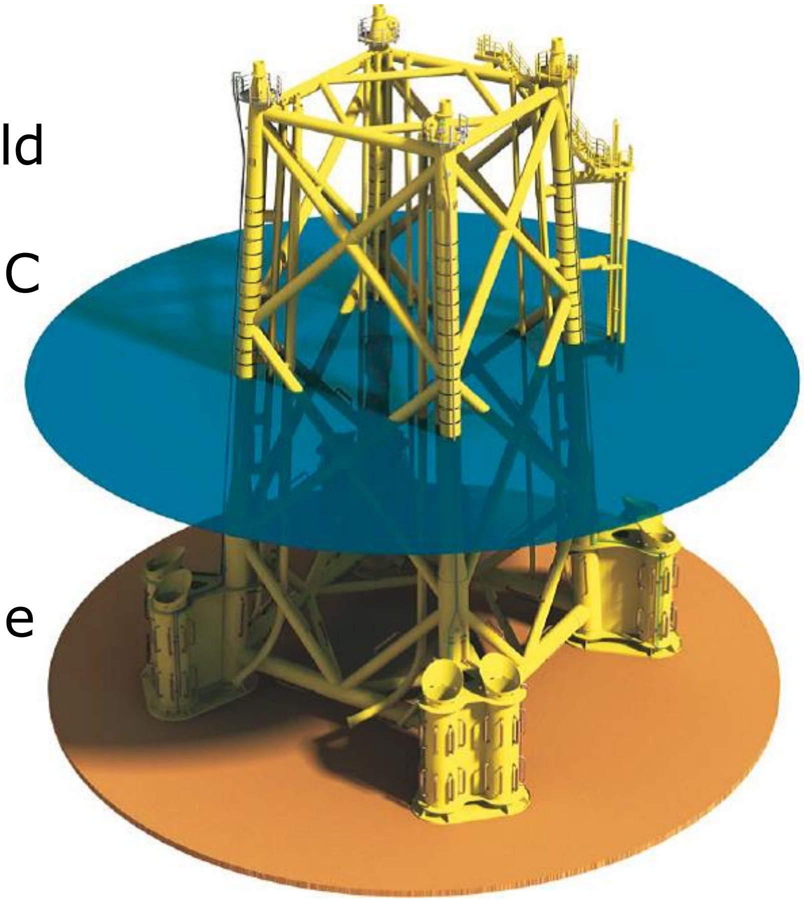
Mini-ICPs: less capacity growth than field

New field tests: NGI, UCD & Grenoble-IC

Also offshore re-drive checks

Confirm shaft capacity growth over time

Next objective: stress regime around tubular driven piles?



2.13m OD, 38.5m, very dense sand

Borkum Riffgrund, German North Sea

Jardine, Thomsen, Mygind, Liingaard & Thilsted 2015

Parallel axial cyclic research

Field: Dunkirk piles’ global response

Model: local stresses in calibration chamber

Laboratory: cyclic element tests

Analysis: simplified procedure

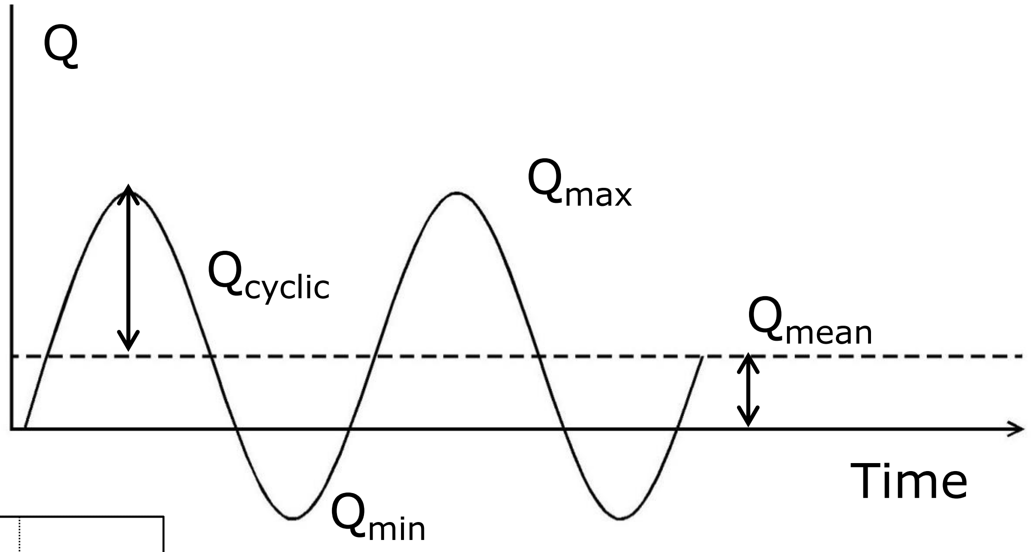
Practical application: sands & clays

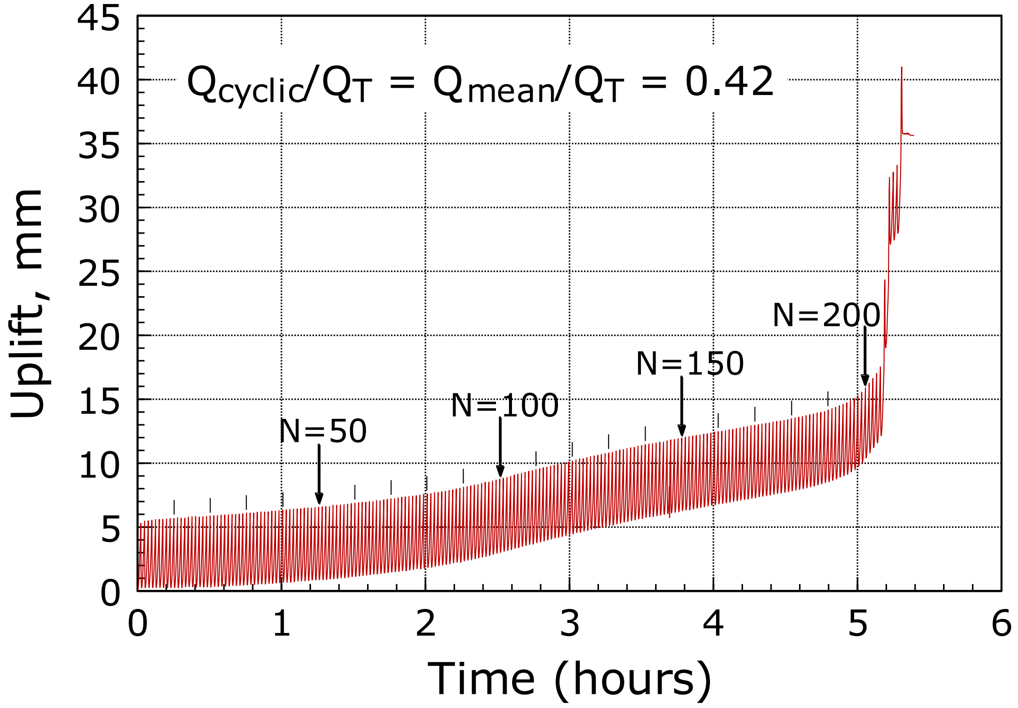
Dunkirk field piles:
Unstable, Stable or Metastable global response?

Depends critically on:

N, Q_{cyclic} & Q_{mean}

Related to tension capacity Q_T





Drained pore pressures

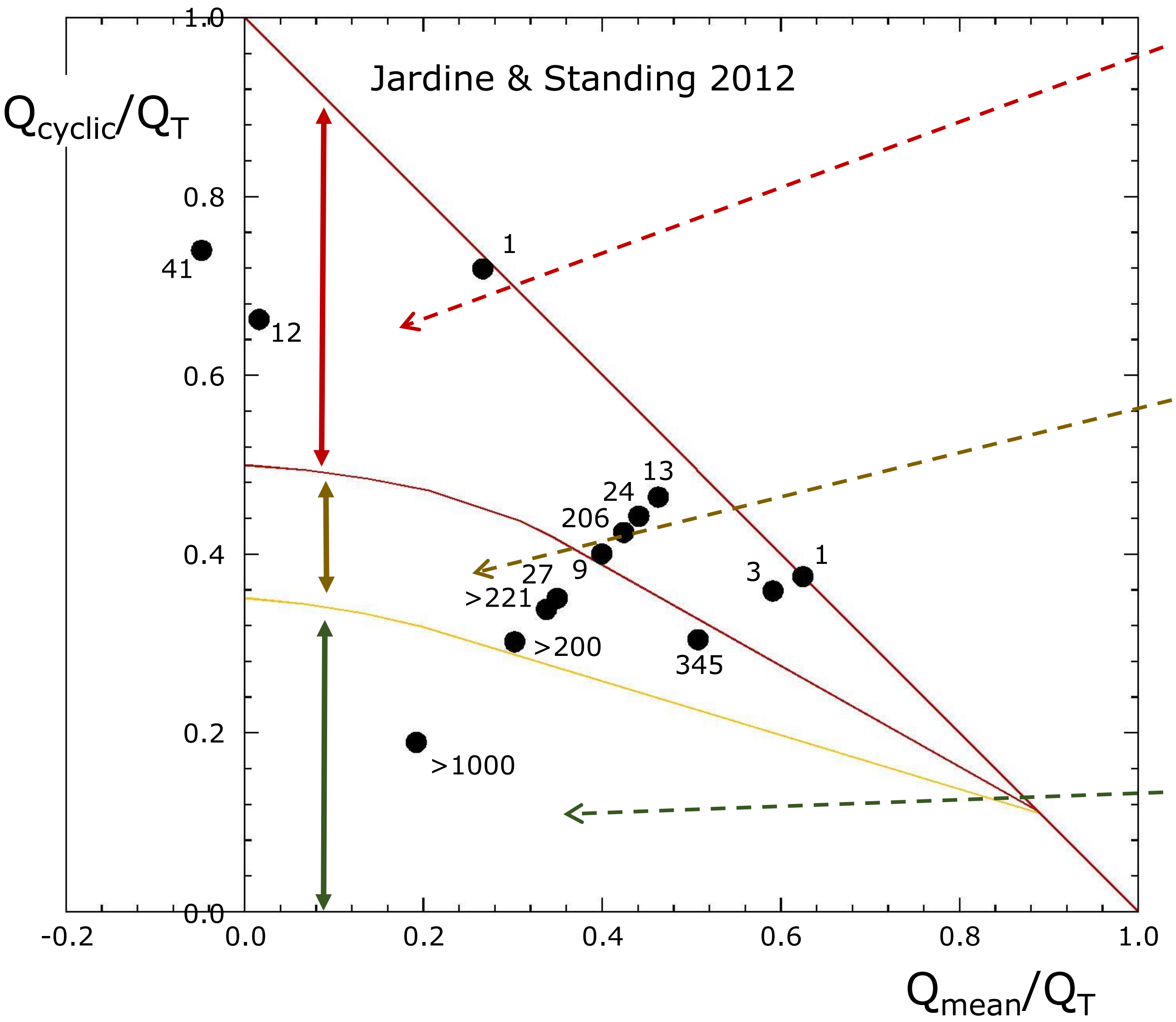
Marginally Metastable example

Little effect until N>50

Failure at $N_f = 206$

16% capacity loss

Global response: 14 Dunkirk field tests



Unstable

$N_f < 100$

Rapid degradation

Meta-stable

$100 < N_f < 1000$

Modest damage

over tens of cycles

Stable

$N > 1000$

Capacity grows,

stiffness constant

Local stress response? Mini-ICP experiments

Model: mini-ICP in dry NE34 sand at Dunkirk I_D

Local interface stress paths

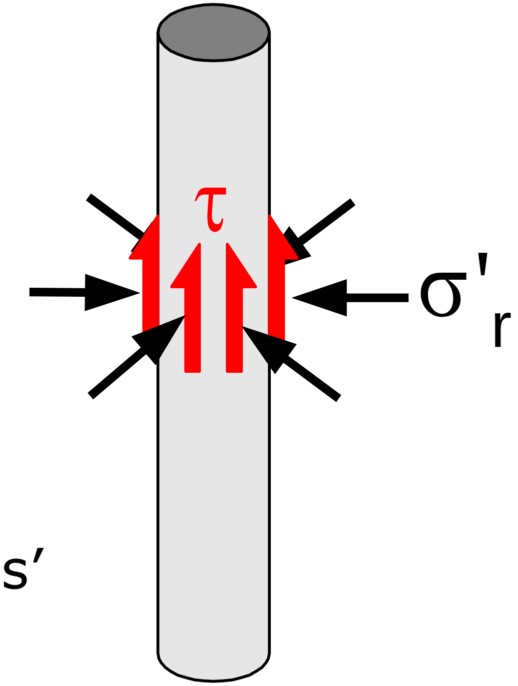
Stable: 1000s cycles, capacity grows
No drift in σ'_r or displacements

Intermediate load controlled cases: σ'_r drift rates tracked precisely

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

Analysis: simple approach from ICP tests

Metastable & Unstable τ_{rz} cycles compact sand near shaft, σ'_r unloads, paths drift towards interface failure



Locate metastable, stable boundaries?

Relate σ'_r drifts to cyclic loads & N?

Element, model or field pile tests?

Design storm:

Rainflow & ‘Equivalent Number of cycles’

Bored piles far more susceptible to cycling

Tests must model driven pile installation

Triaxial tests: modelling 'pile' paths

Conditioning

Pre-stressed 'OC installation' stress path: ABD

Creep & ageing at B & D

Pre-cycling at C

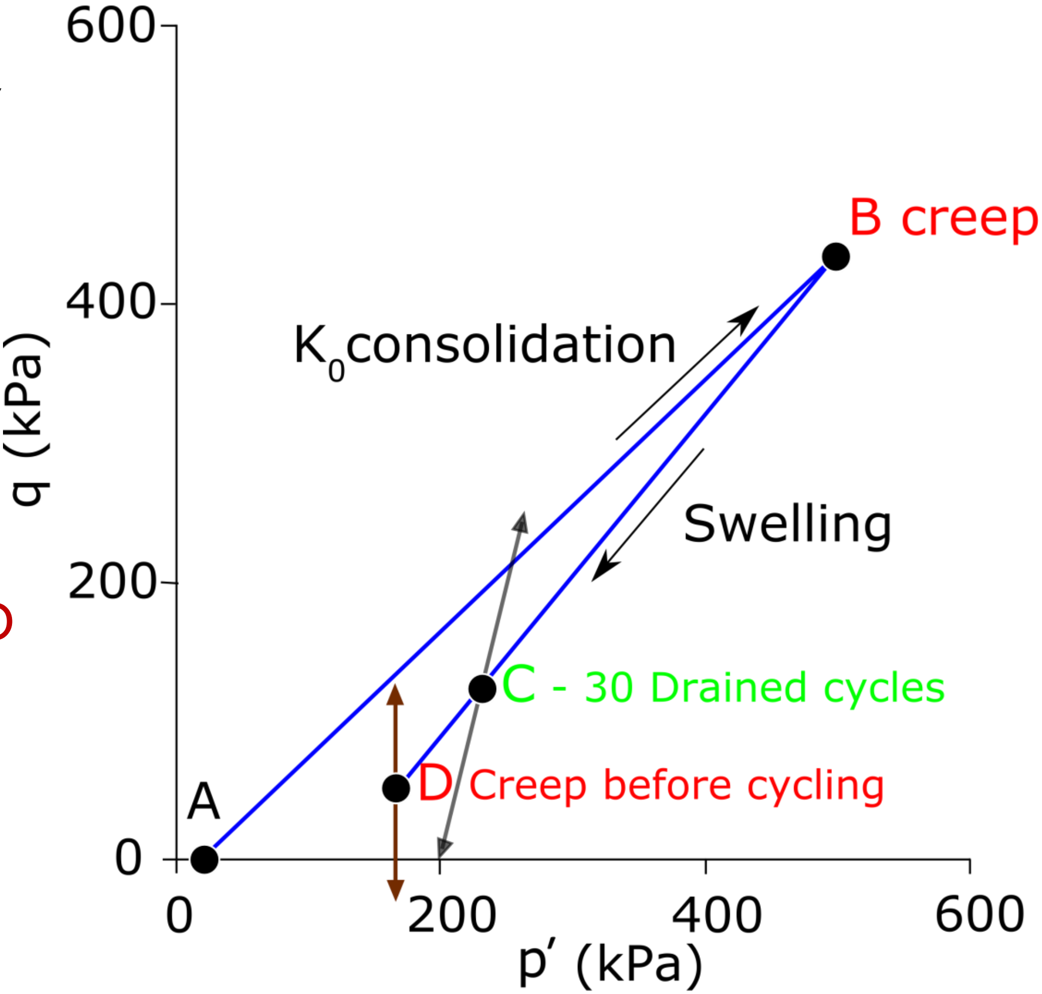
Constant volume cycling at D

Vary Cyclic Stress Ratio

CSR = Δq/ p´

Δq = half peak to trough

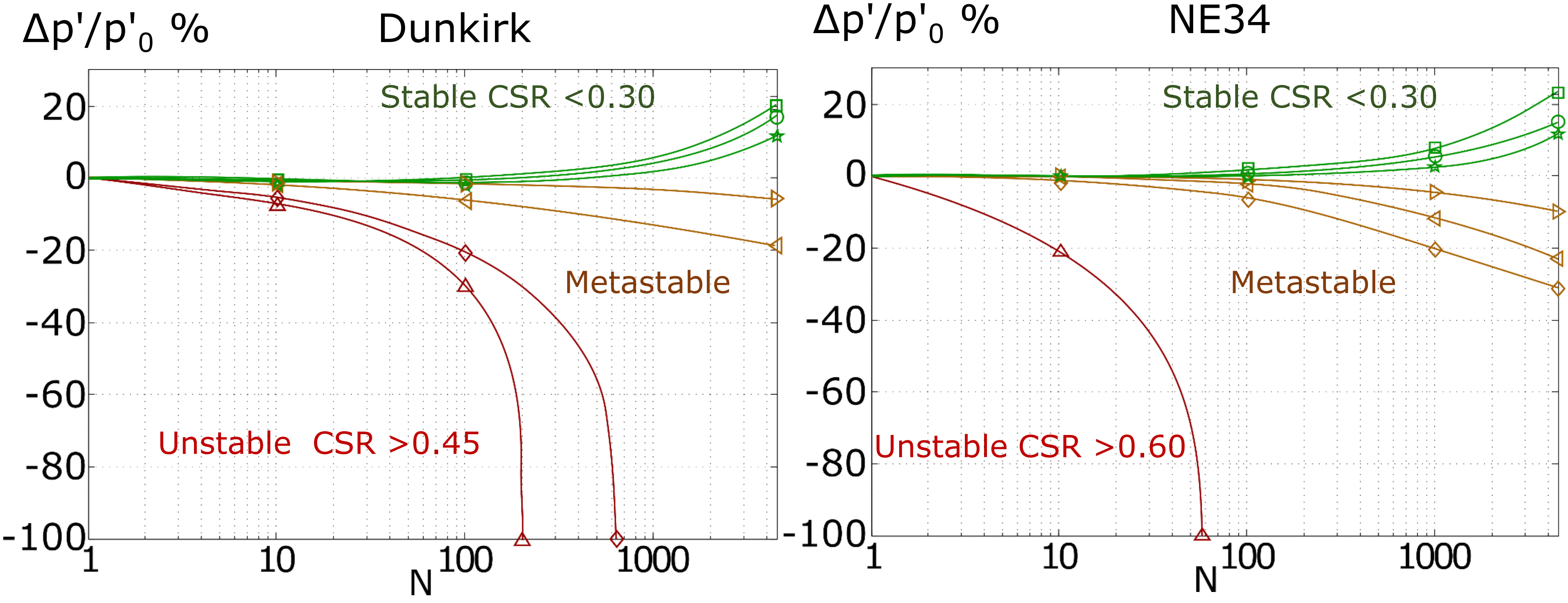
Drifts in effective stress Δp´ strains & stiffness?



‘Driven pile’ triaxial tests: p' drifts over 4500 cycles

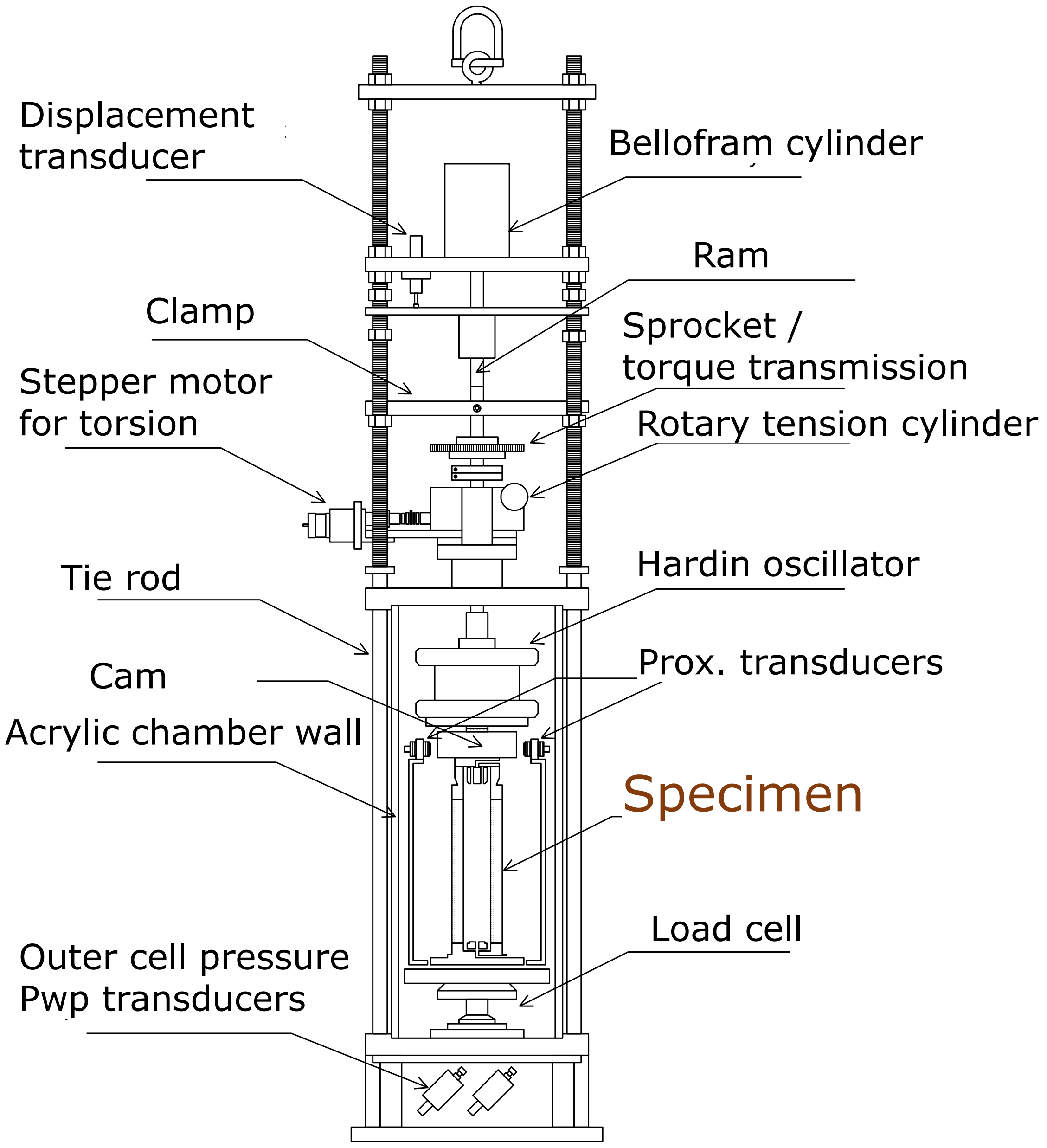
Seven CSRs: $0.05 \leq q_{cyclic}/p'_0 \leq 0.5$

High resolution sensors: consistent strain & stiffness trends



Aghakouchak, Sim & Jardine 2015

HCA - simple shear cycling, Hollow Cylinder Apparatus



72mm OD sample HCA

Track changes in σ'_n matching pile conditions

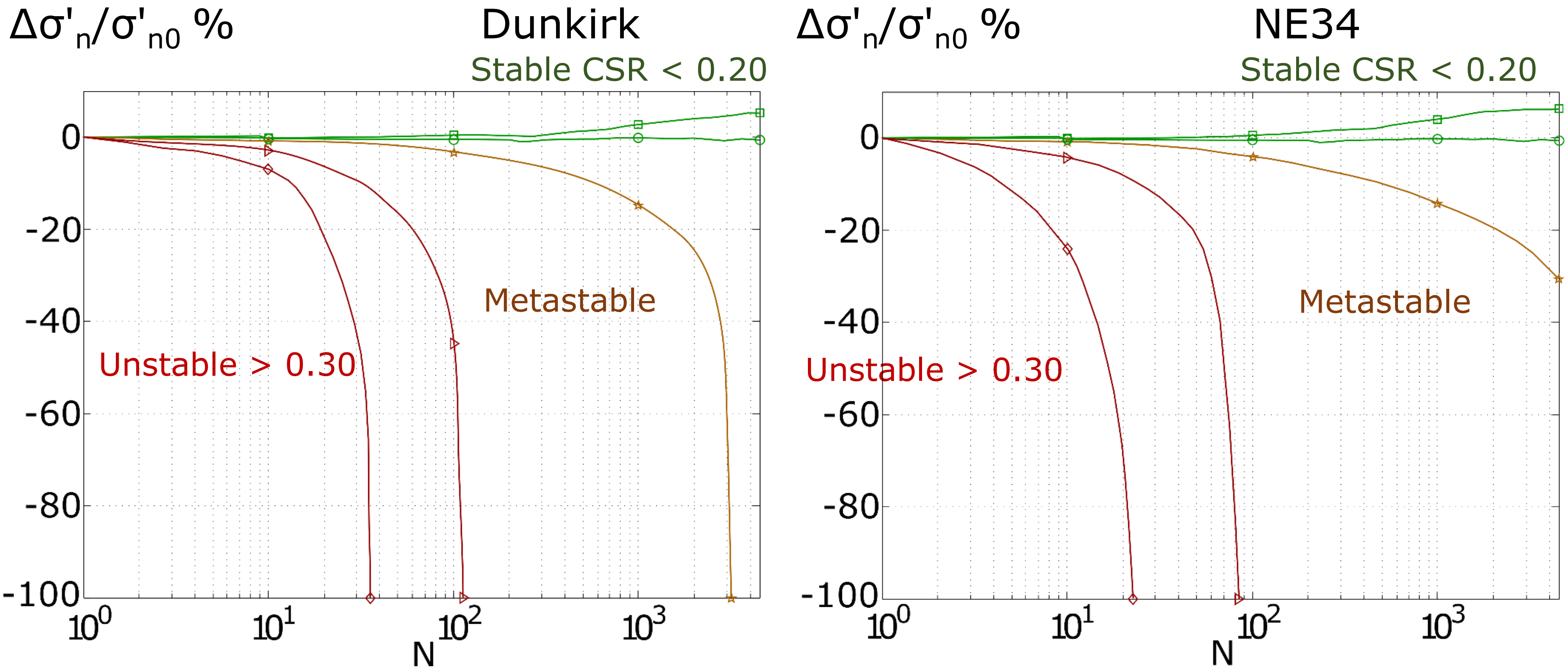
Measure σ'_1, σ'_2, σ'_3 & σ'_1 angle α

Nishimura 2006 Liu 2015

HCA simple shear: drifts in σ'_n over 4500 cycles

‘Driven pile’ cyclic HCA tests, five CSRs, $0.05 \leq \tau_{cyc}/p'_0 \leq 0.45$

Basis for predicting pile response

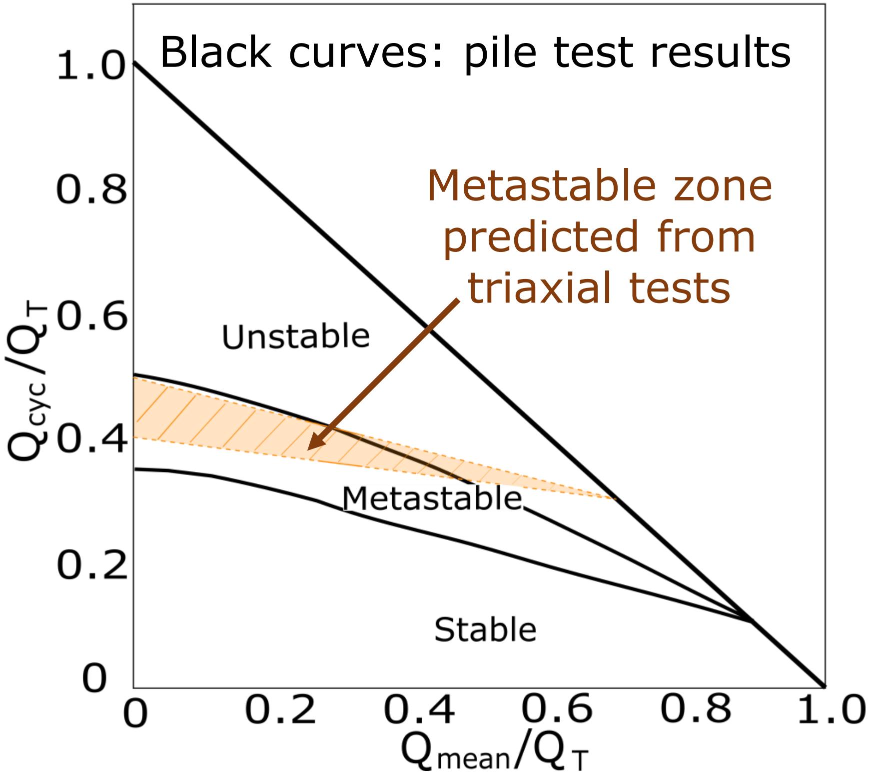


Aghakouchak 2015

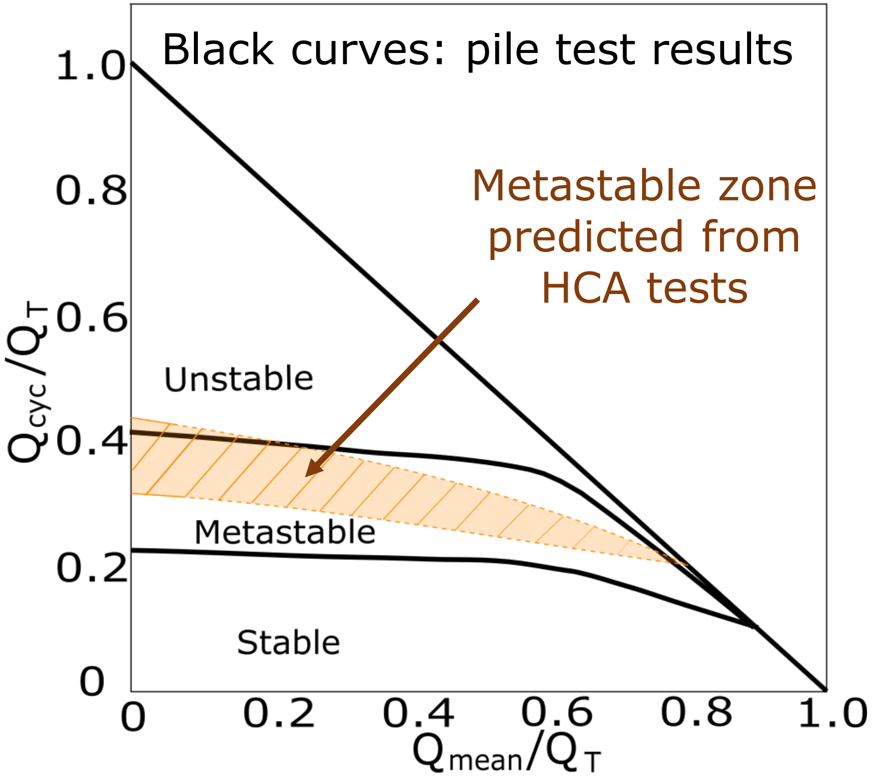
Analysis: projecting pile response zone limits

Aghakouchak 2015

Dunkirk field & triaxial predictions



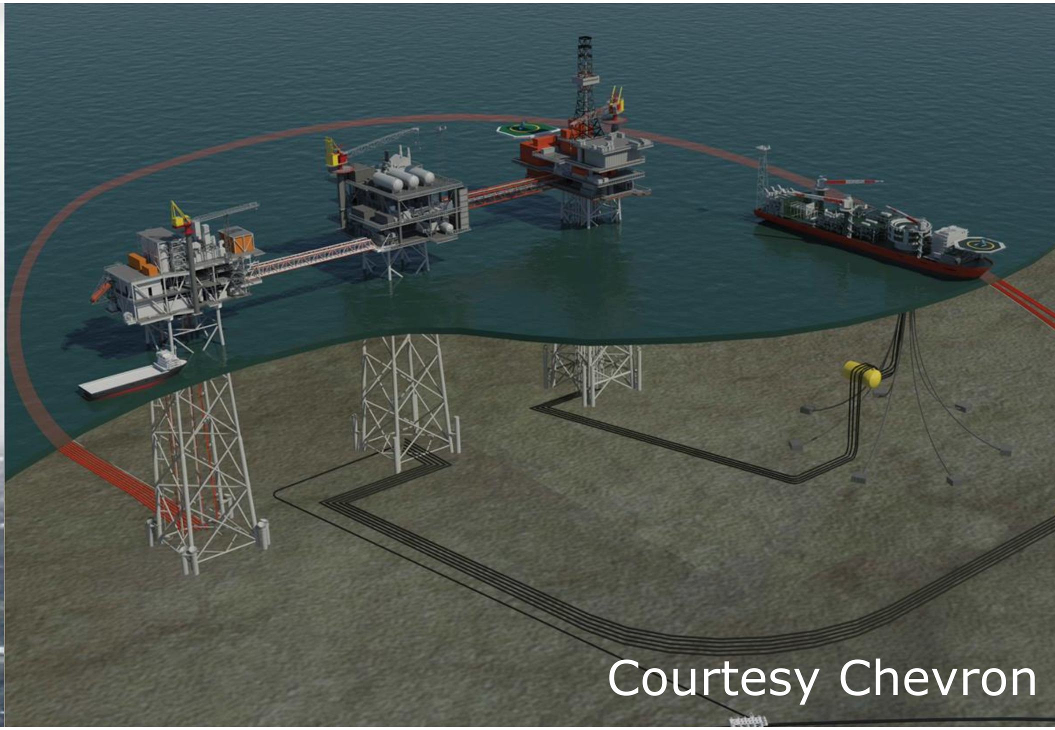
NE34 model & HCA predictions



Parallel laboratory work with clays

Jardine, Puech & Andersen 2012

Application in cyclic storm assessment



Clair & Clair Ridge Extreme West of Shetland storms; hard glacial tills: Hampson et al 2017

Captain: EOR project North Sea; new & reconfigured platforms; dense sand, tills & clays: Argiolas & Jardine 2017

Effective contributions on continental shelf

What about deepwater?

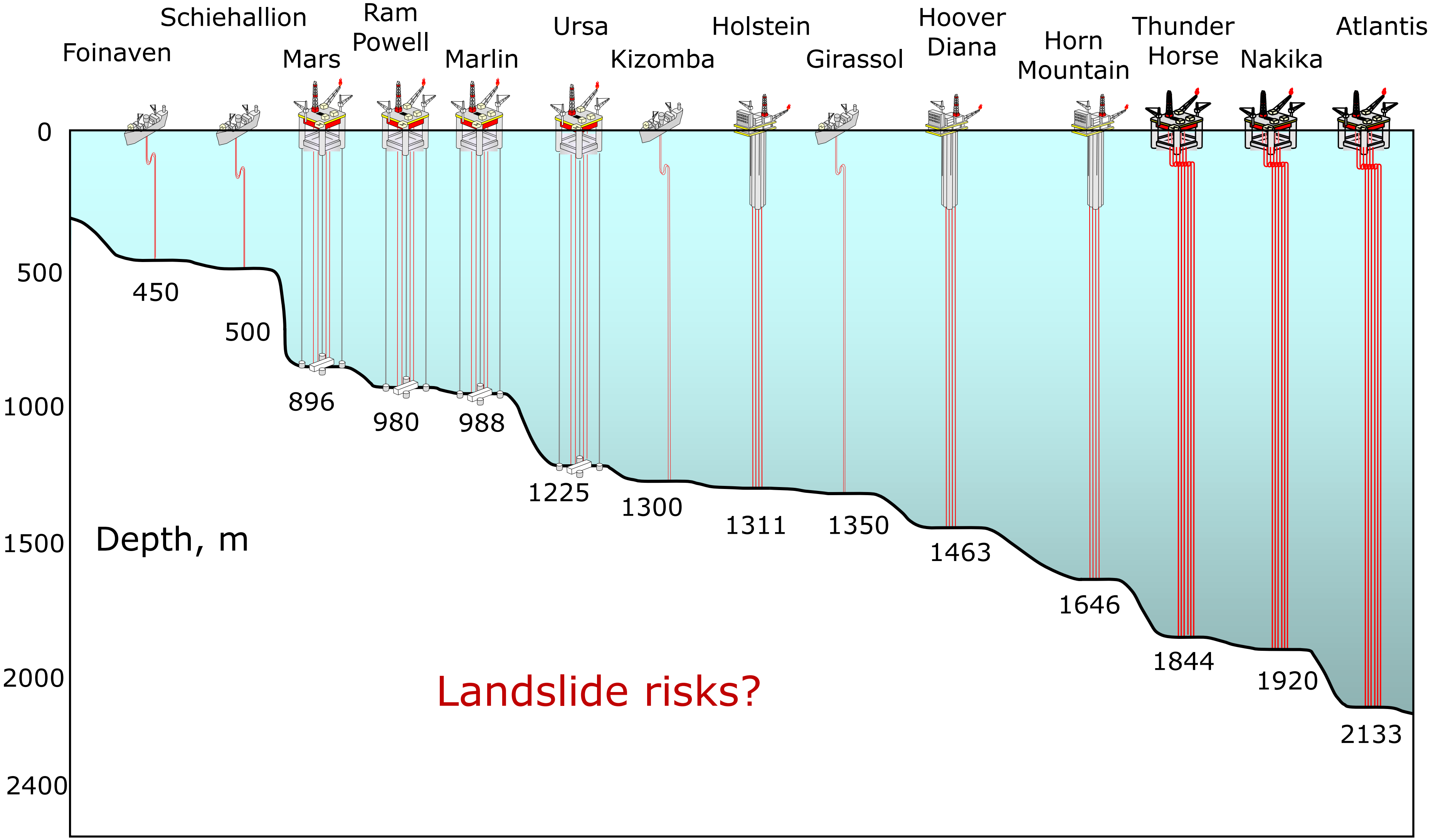
Deepwater

Off the continental shelf

Large offshore landslides

Gulf of Mexico example – Sigsbee Escarpment

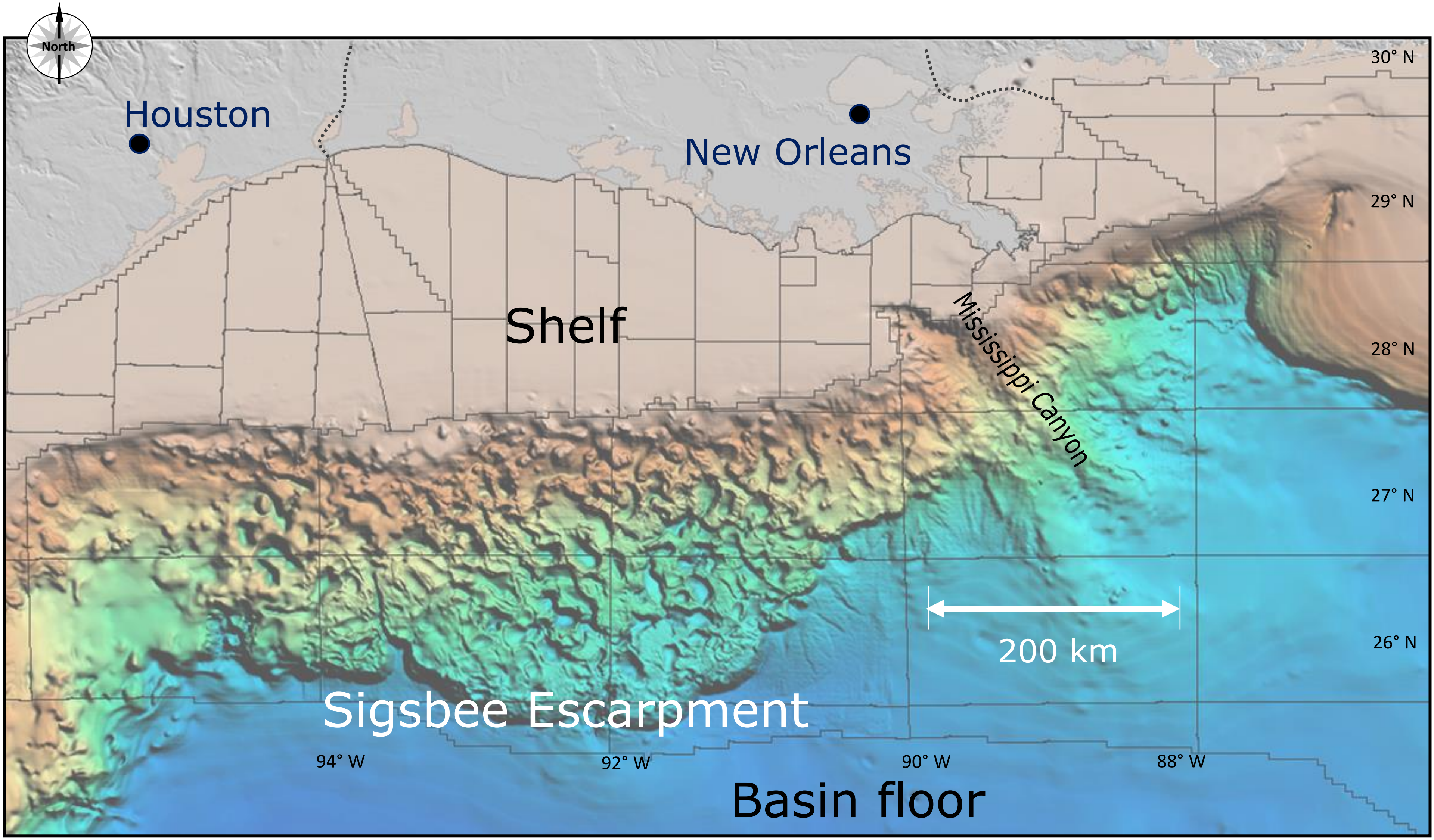
Pushing the envelope: 1997-2005, after Evans 2007



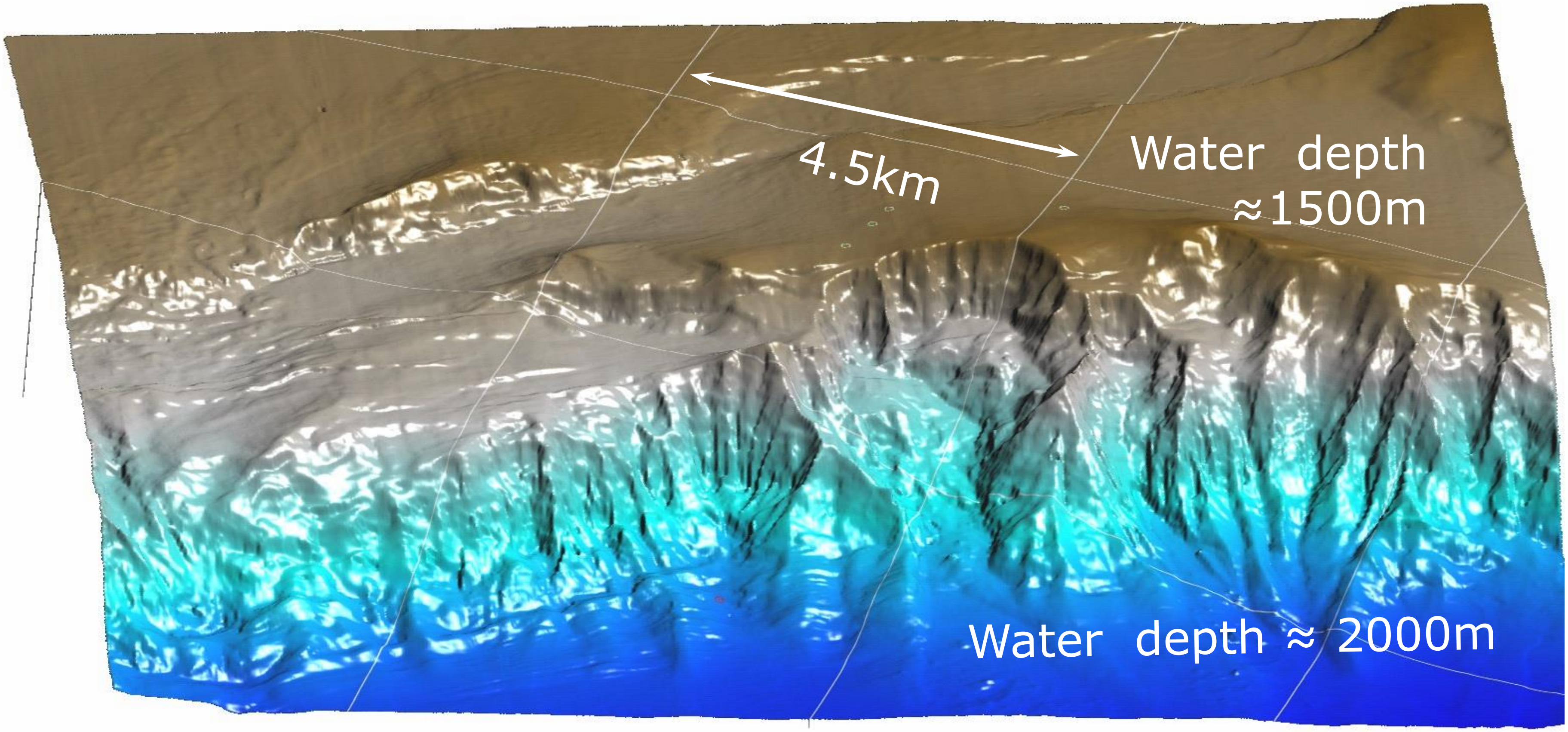
Landslide risks?

Sigsbee escarpment: Gulf of Mexico

Kovacevic, Jardine, Potts, Clukey, Brand & Spikula 2012



Sigsbee geomorphology

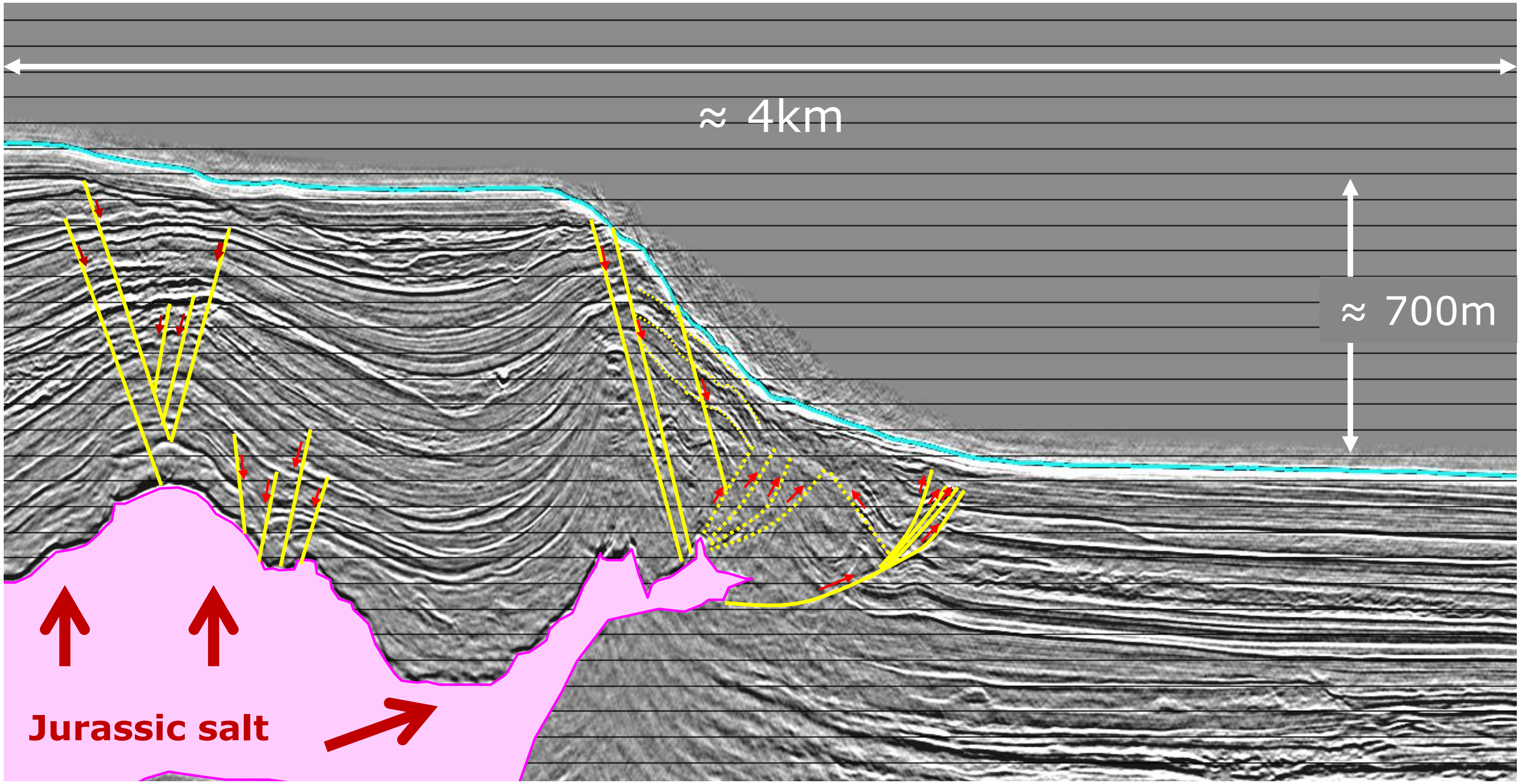


Developers' risk analysis: mechanisms & recurrence?

Controlled by active geology & sedimentation

Spreading, uplifting salt diapirs & thick Quaternary clay layers

Geology: geophysics & deep boreholes



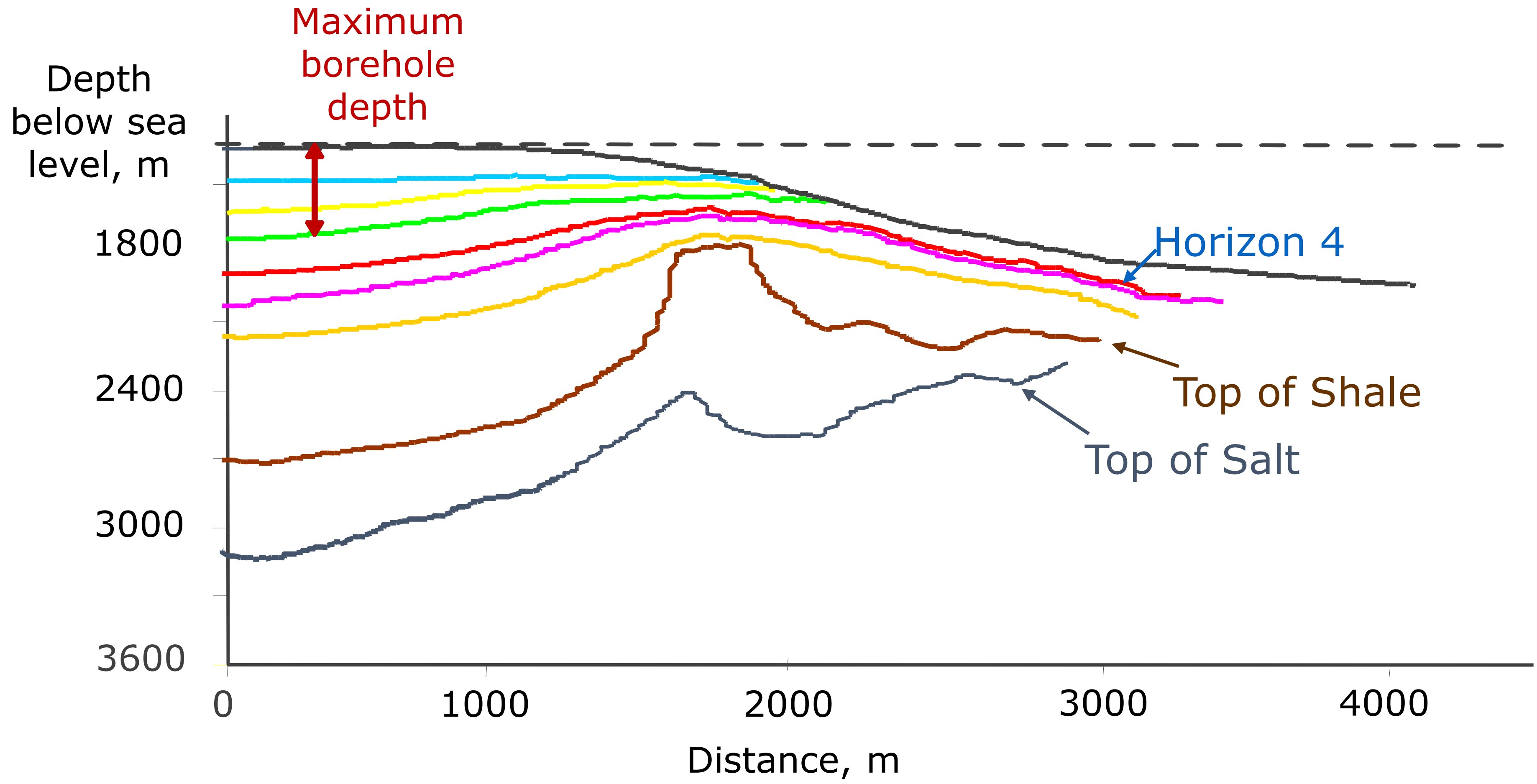
Lower continental shelf

Sigsbee Escarpment

Upper continental rise

Uplifting & spreading salt:
constrains & distorts Quaternary sediments

Ground modelling



Quaternary Horizons H6 to H0 include high I_p low residual φ' clay layers

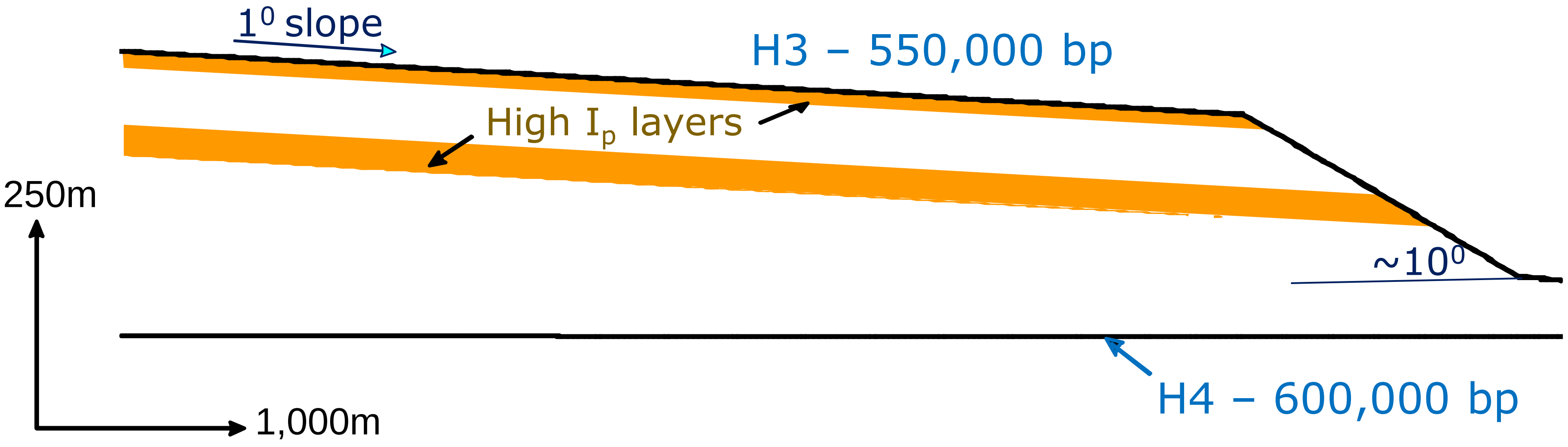
Routine stability analysis cannot model delayed progressive failure

Or predict historical and future slide recurrence periods

Numerical ICFEP ‘bottom-up’ modelling of last 600,000 years

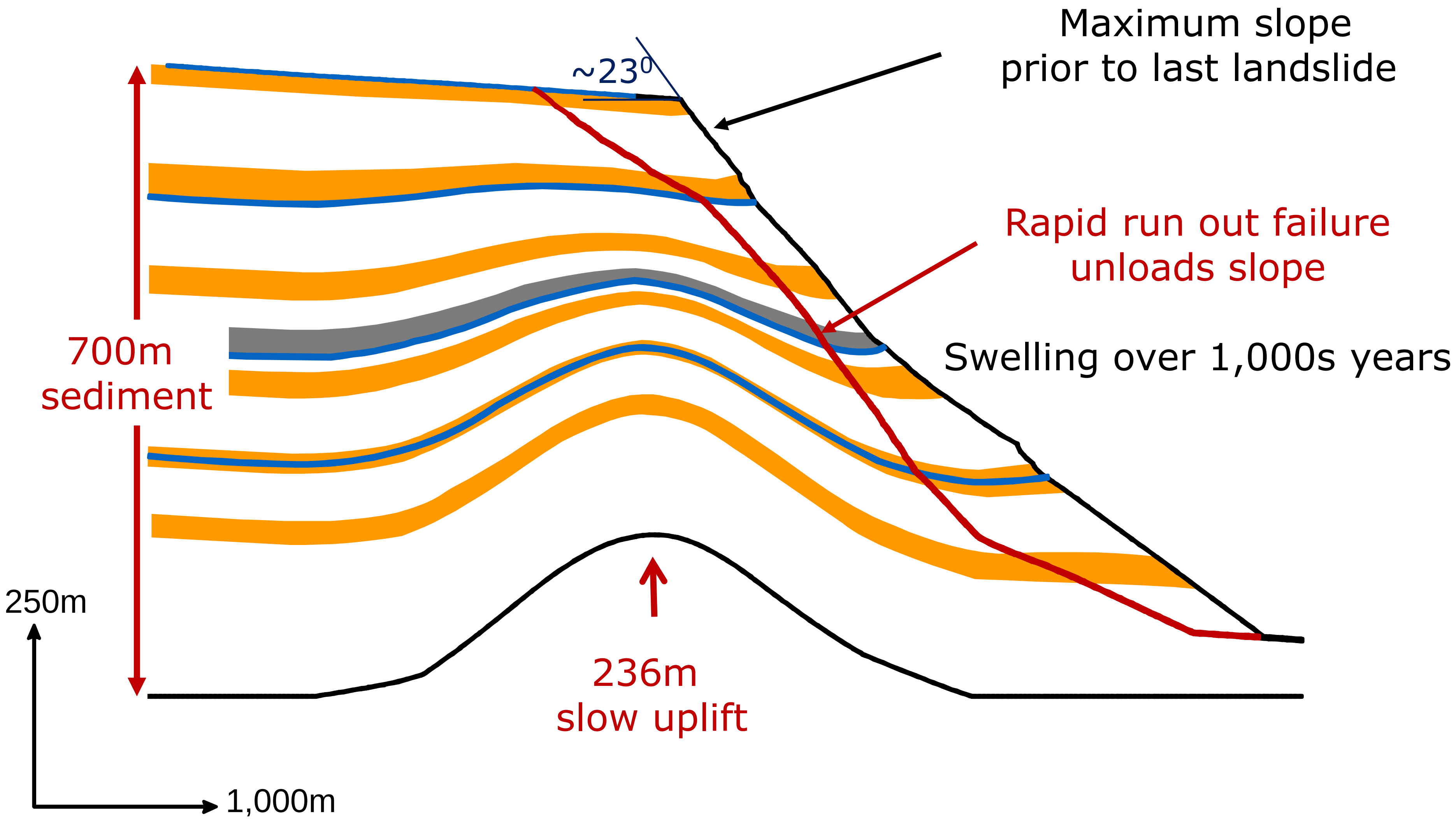
Alternating medium & high I_p layers added sequentially: Modified Cam Clay

Sedimentation on 1° slope towards initial 10° escarpment face



Parabolic basal uplift applied from H3 onwards

1st principles modelling: slope genesis & failure



Maximum slope prior to last landslide

Rapid run out failure unloads slope

Swelling over 1,000s years

Sets conditions for future stability

Analysis of slope since last slide

Long term swelling, overconsolidation, progressive failure

Coupled, strain softening Mohr Coulomb model
From triaxial & IC ring shear tests

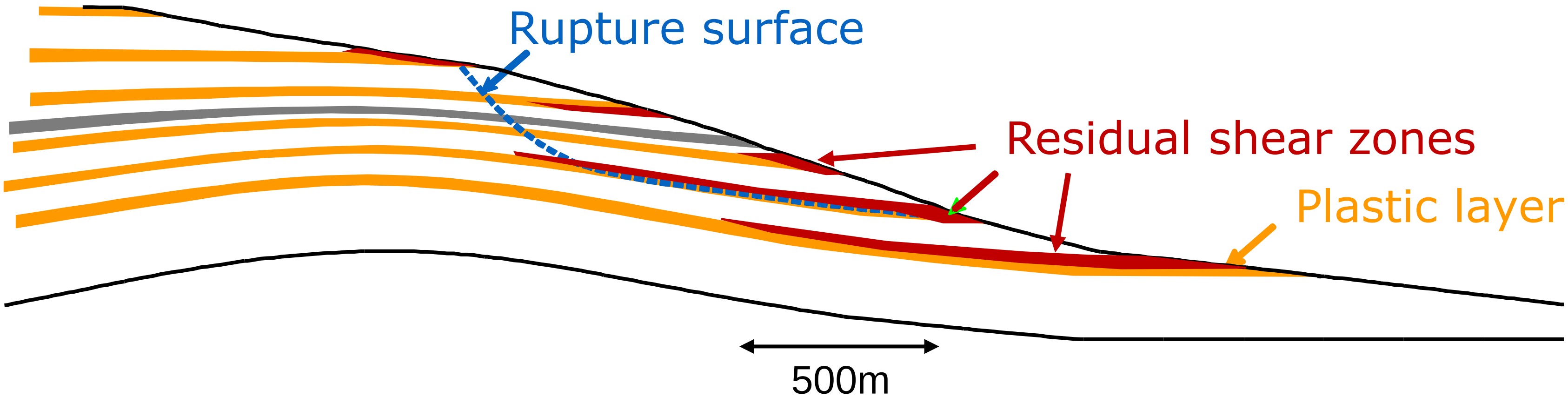
High I_p clay Peak $\varphi'_{peak} = 18^0$ $c'_{peak} = 10\text{kPa}$
Residual $\varphi'_{res} = 12^0$ $c'_{res} = 0$

Less plastic clays & sand: ductile $\varphi'_{crit} = 25^0$ & $\varphi' = 30^0$

Non-linear permeability & stiffness from lab tests

Predicting future risks

1.3km long failure likely, progressive & delayed mechanism



Recurrence interval: c. 5000 years

Critical to project risk assessment

Field verification? Local geomorphology & sediment dating

Part I – Maintaining oil & gas supplies

Contributions to continental shelf & deepwater field developments

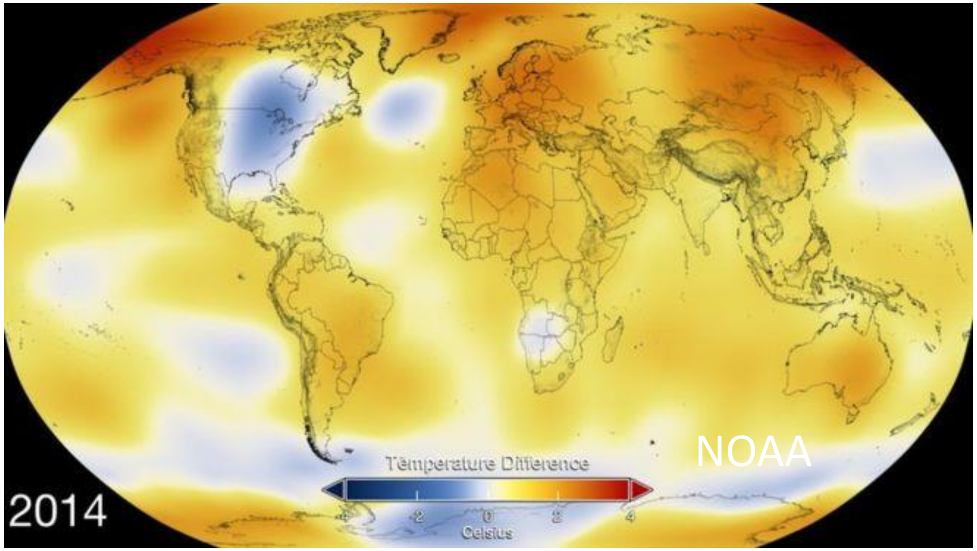
What about climate consequences & risks?

Intergovernmental Panel Climate Change, IPCC, model predictions

‘Business as usual’: 3-5.5°C mean warming by 2100

Mean +1^{o}C from 1750
non-uniform

Future trends?



Very likely: less Arctic sea ice & shallow permafrost

Likely: more frequent intense precipitation

Medium confidence: storm track shifts

Increasing flood risks

Part II – Addressing climate change

1st Modelling geotechnical response

Greatest impact: permafrost

Integrated approach, field verification

New design tools for adaptive engineering

2nd Practical adaptive engineering

Flood defence strengthening on difficult ground

Permafrost: depths up to 1km

North American permafrost

1^{o}C/decade N Alaskan permafrost warming, Romanovsky 2015

0.5 to 1^{o}C/decade air rise in Yukon

Thermal creeping landslides in sporadic permafrost

‘YT’ landslide, glacio-fluvial soils Little Salmon Lake, Yukon
Lyle et al 2014

NW Territories: thaw-slump features, up to 25m deep & 30ha
www.nwtgeoscience.ca/project/summary/permafrost-thaw-slumps

Predicting fate of Siberian permafrost

Imperial College project for BP

Climate: Global IPCC models & local adjustments

Imperial College Physics: Reifen & Toumi 2009

Local design tool: coupled Thermo-Hydro-Mechanical THM modelling tool with UPC Barcelona

Nishimura, Gens, Olivella & Jardine 2009

Regional: Depths & rates of change in permafrost state?

GIS, Engineering Geology & Thermal FE

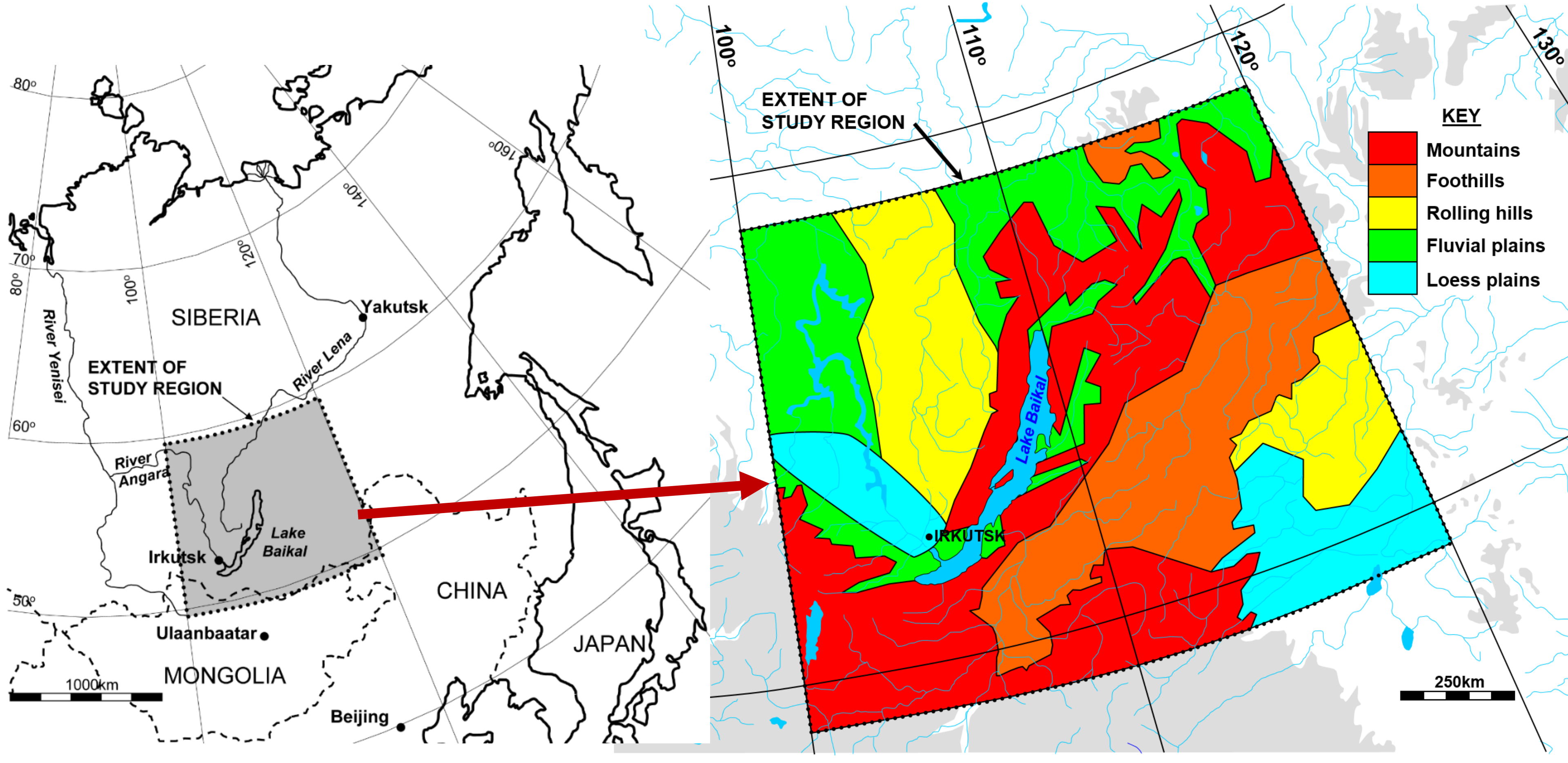
Nishimura, Martin, Jardine, & Fenton 2009

1000 x 1000km region, Lake Baikal, Siberia

Maps, atlases & Google Earth

Digital Elevation Models & ground reconnaissance

Five ground model stereotypes



Rolling hills, taiga forest

Cambrian to Ordovician sedimentary rocks
Permafrost, from 60m thick to absent

Three geotechnical profiles

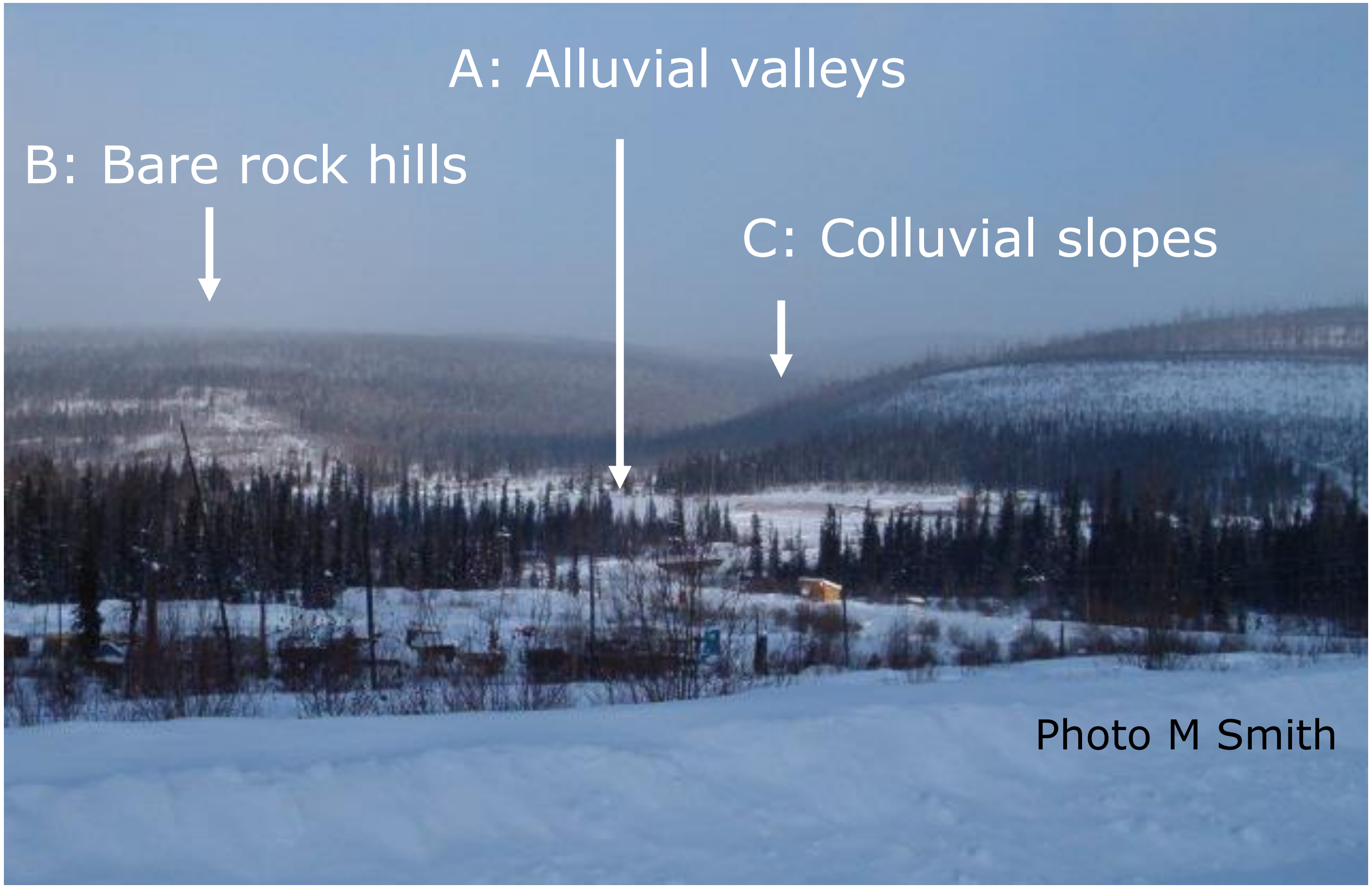


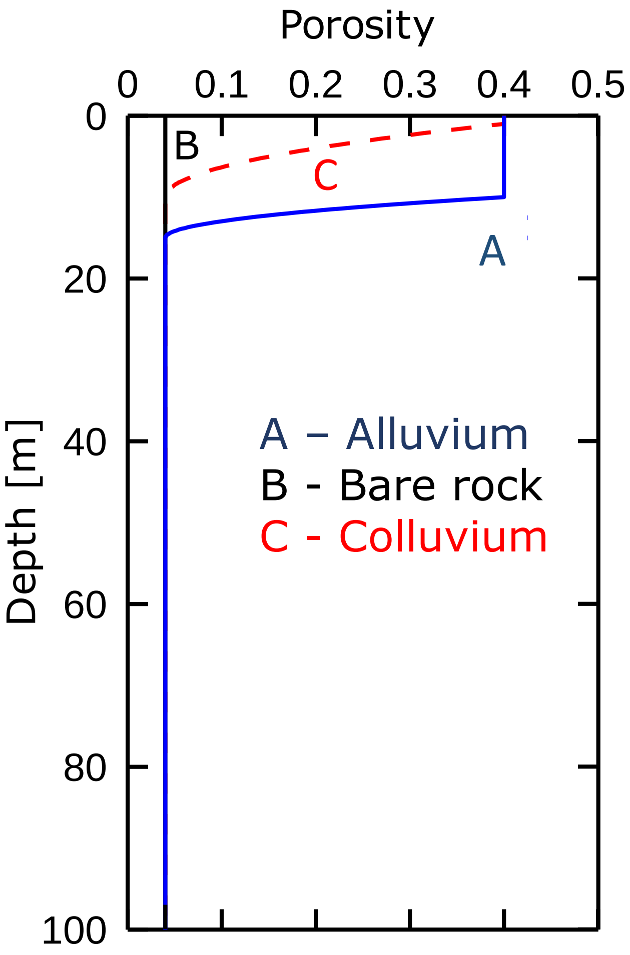
Photo M Smith

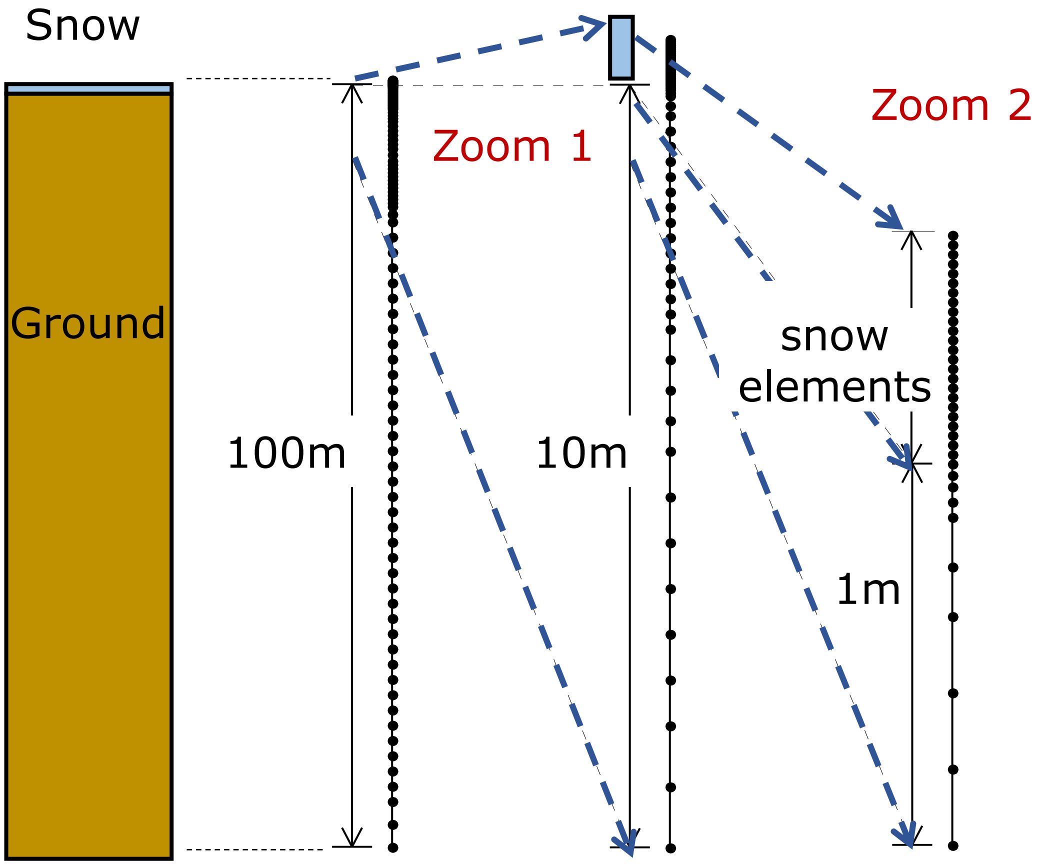
Detailed characterisation: Martin 2009

Geothermal FE Analysis: Nishimura, Martin, Jardine & Fenton 2009

Key ground properties:
Porosity & grading

Top boundary: air temperature
snow cover & surface transfer





Base boundary: regional flux

Analysis

Aim: predict temperature T variations with depth x & time t

1-D heat equation

$$\frac{\partial u(T)}{\partial t} - \frac{\partial}{\partial x}\left[\lambda(T)\frac{\partial T}{\partial x}\right] - q = 0$$

q = heat production/sink

u = specific internal energy

$$\frac{\partial u(T)}{\partial t} = \frac{\partial}{\partial t}\left[\{c_s \rho_s (1-\varphi) + c_l \rho_l S_l(T)\varphi + c_i \rho_i (1-S_l(T))\varphi\}T + l\rho_l S_l(T)\varphi\right]$$

c = specific heat

ρ = density

l = specific latent heat

s = solid

l = water

i = ice

S_l = degree of pore liquid-ice saturation

φ = porosity

λ = thermal conductivity

Analysis

Conductivity (λ) combines solid (s), liquid (l) & ice (i)

$$\lambda(S_l)=\lambda_s^{1-\varphi}\lambda_l^{S_l\varphi}\lambda_i^{(1-S_l)\varphi}$$

Freezing function: $S_l = f\,(T)$ depends on porosity & grading:

$$S_l=\frac{a\rho_s(1-\varphi)}{\rho_l\varphi}|T|^{-\beta}$$

α & β specified for Profiles A, B, C

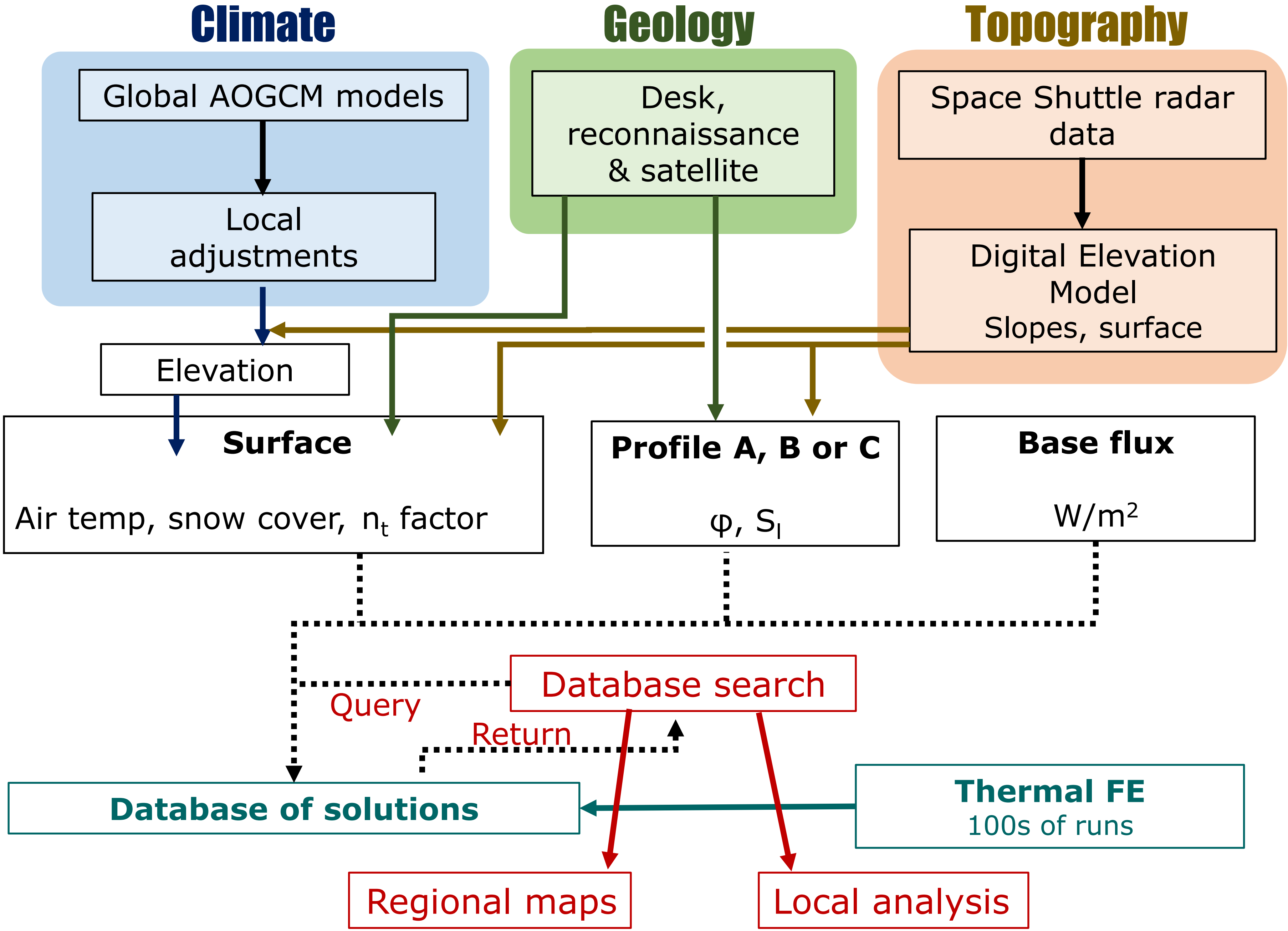
Batch-processing for FE database, hundreds of cases

Thermal maps: point-by-point `speed-dating' matching

Surface: Air temperature, snow & 'n_t' transfer factor, slope & aspect

Ground Profile: A, B or C

Base flux: 0.02 to 0.05 W/m²



Climate

Global AOGCM models

Local adjustments

Elevation

Geology

Desk, reconnaissance & satellite

Topography

Space Shuttle radar data

Digital Elevation Model Slopes, surface

Surface

Air temp, snow cover, n_t factor

Profile A, B or C

φ, S_l

Base flux

W/m^2

Database search

Query

Return

Database of solutions

Thermal FE

100s of runs

Regional maps

Local analysis

Results for one 60x80 km area

Permafrost top temperatures

1940 & 2000 predictions:
Validated against field survey

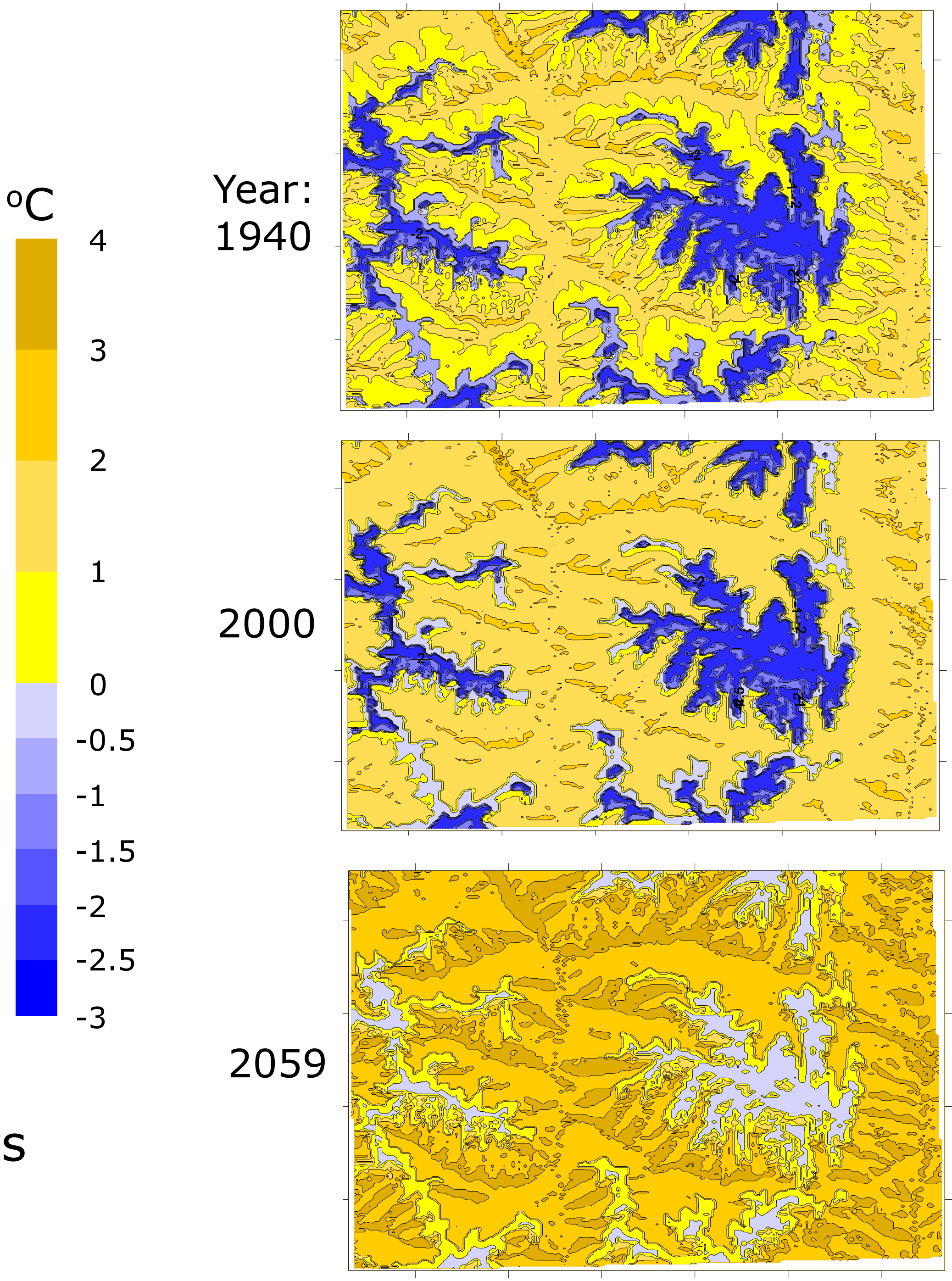
2059 climate: SRES A2 case

Melting landscape, CH_4 release

Slope & foundation failures

Infrastructure distress

Adaptive design
New THM analysis tool
Validated: Calgary pipeline tests
Naples metro ground-freezing



Climate change – 2nd topic

‘Nuts & bolts’ of practical geotechnical adaptive design

Strengthening flood dikes on weak peat foundations

In The Netherlands

With Deltares, Rijkswaterstaat & HHNK Water Authority

Zwanenburg & Jardine 2015

Uitdam, north of Amsterdam

30 km dike fails stability checks

Improve at minimum environmental & economic cost?

Geotechnical controversies:

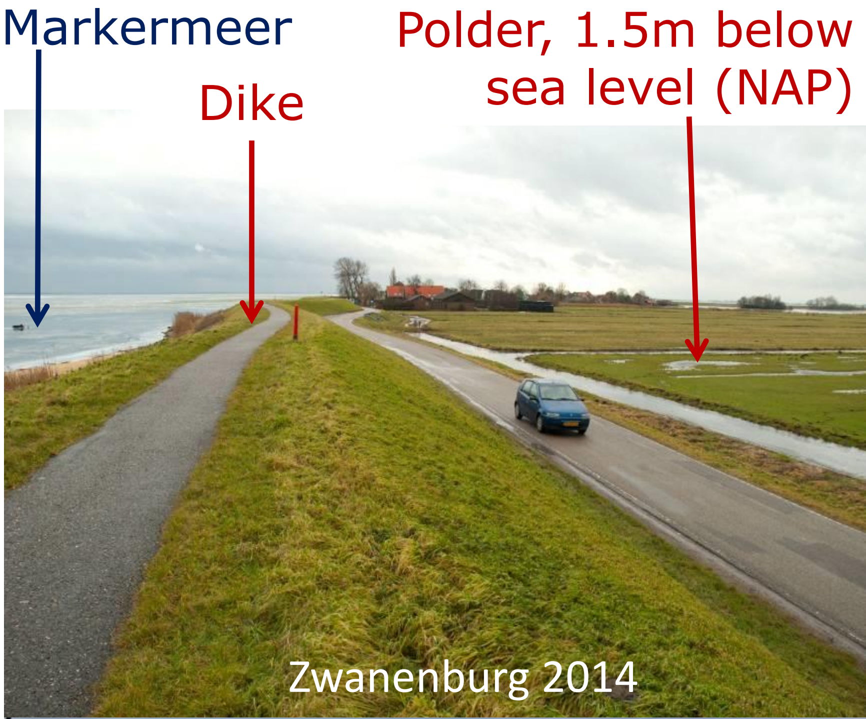
Models for peat?

Effects of past loading?

Failure mechanics?

Drained or undrained?

Resolve by field, lab & theoretical studies



Zwanenburg 2014

Google Earth 2014

Uitdam 1.6ha test site

18 boreholes, geological logging

in-situ profiling & lab testing

4.5m peat, H2 - H3 Von Post, over clay

85% organic, $750 < w < 1200\%$

Unit weight ≈ water, low σ'

Thin surface ‘crust’

Oedometer yield: $8 < \sigma'_{vy} < 14$ kPa

Triaxial & DSS: $5 < s_u < 10$ kPa

Load tests to failure

Six instrumented foundations

Range of different geometries

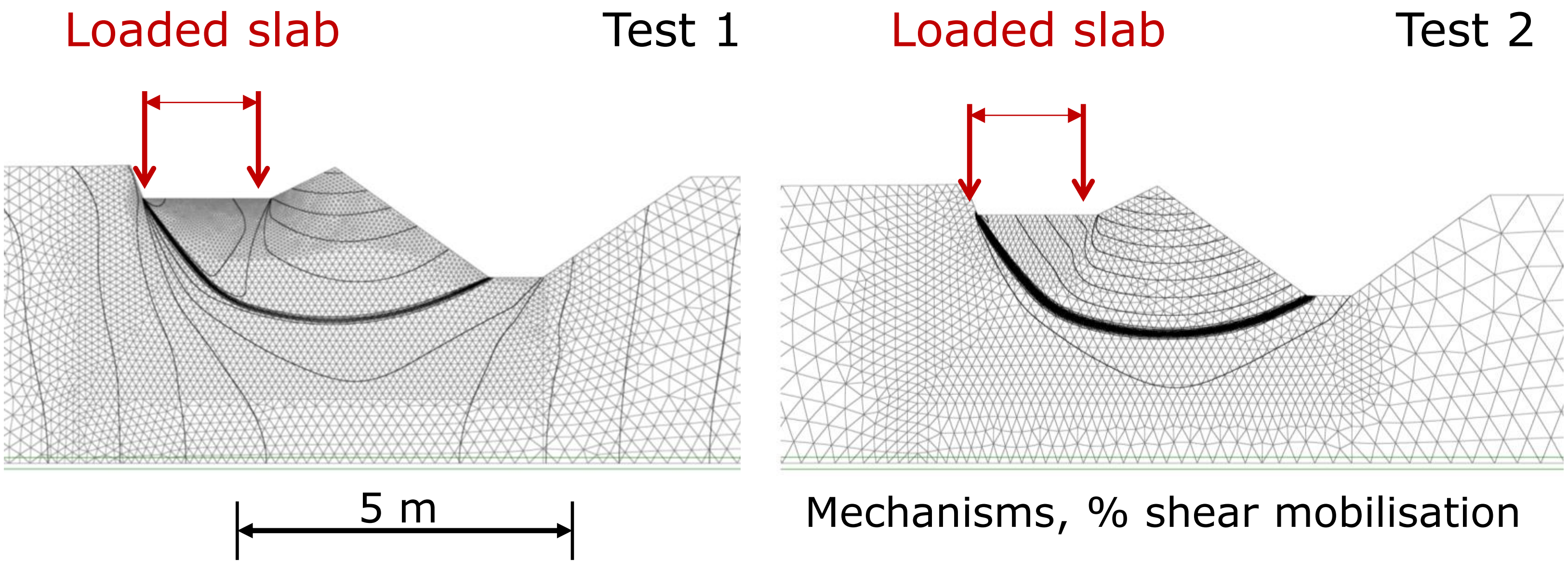
Controlled loading to failure

Short & long term,
Single & multi-stage tests

Highly compressible; 1.5m settlement in 6 months under 35 kPa

FE Analysis supported by lab & field testing

Analysis capturing details of undrained failures

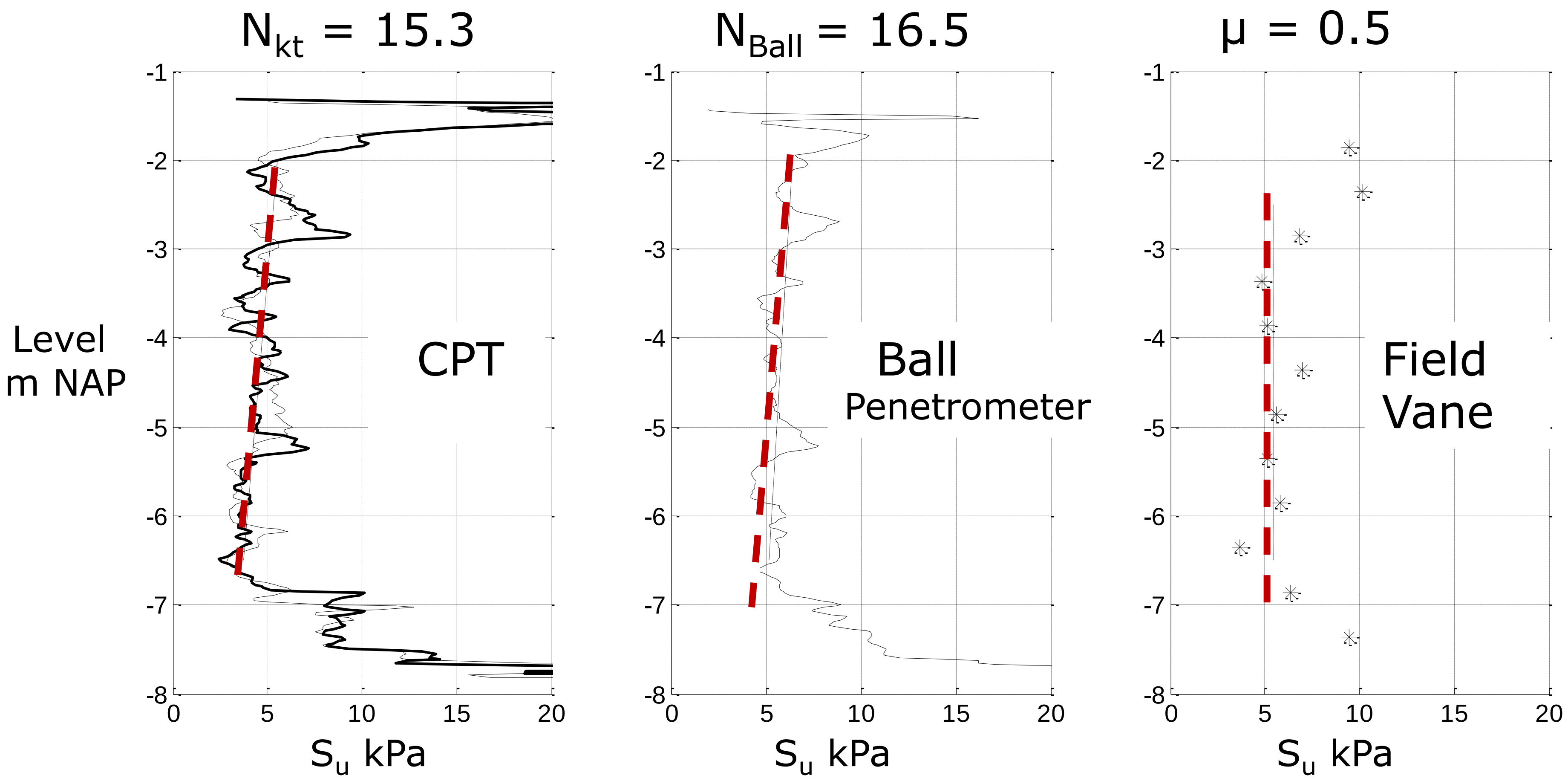


Calibrate laboratory & field tests to iterative back-analyses

Develop range of parameter selection routes

Apply in dike remedial works

In-situ s_u test calibrations



$N_{kt} = 15.3$

$N_{Ball} = 16.5$

$\mu = 0.5$

Test 6 Area: pre-loading

Apply to profile consolidation s_u gains for multi-stage cases

Three calibrated s_u selection routes for adaptive stability design

1. Factored in-situ tests: CPT, Ball Cone & Field Vane

2. ‘SHANSEP’ s_u/σ'_v – OCR function

3. Lab: interpretation scheme

Part II

Addressing climate change

Modelling ground response & developing adaptive design

Simple & complex methods for range of climates, verified in field

Could add many more layers of complexity

Internationally agreed scientific conclusion:

Modelling plus adaptation is not sufficient,
greenhouse emissions must fall

Part III
Supporting renewable energy

Aim: reduce offshore wind costs & enable deeper water projects

Foundations: up to 30% of capital cost, 22% on average

1st Deeper water sites

Apply oil & gas research

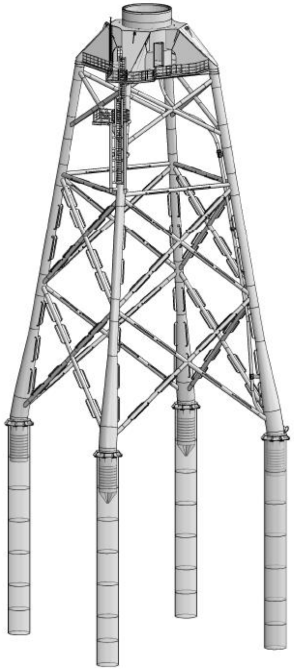
Address ‘problem’ geomaterial: Chalk

2nd Shallower monopile projects

Modernise design: PISA Joint Industry Project

With Industry, UK Innovate, Carbon Trust, PISA partners

1st - Multi-pile structures for deeper water



Jacket, tripod & floating support structures

Sand & clay sites

ICP from SI stage: East Anglia One

Small strain testing & analysis

102 three-leg platforms, Rattley et al 2017

Borkum West II

40 large tripods

New research for ‘Problem’ sites

Chalk: Wikinger, German Baltic

70 four-leg jackets

Borkum West II - German N Sea: Merritt et al 2012, Jardine et al 2015

40 tripods, 2.48m OD piles

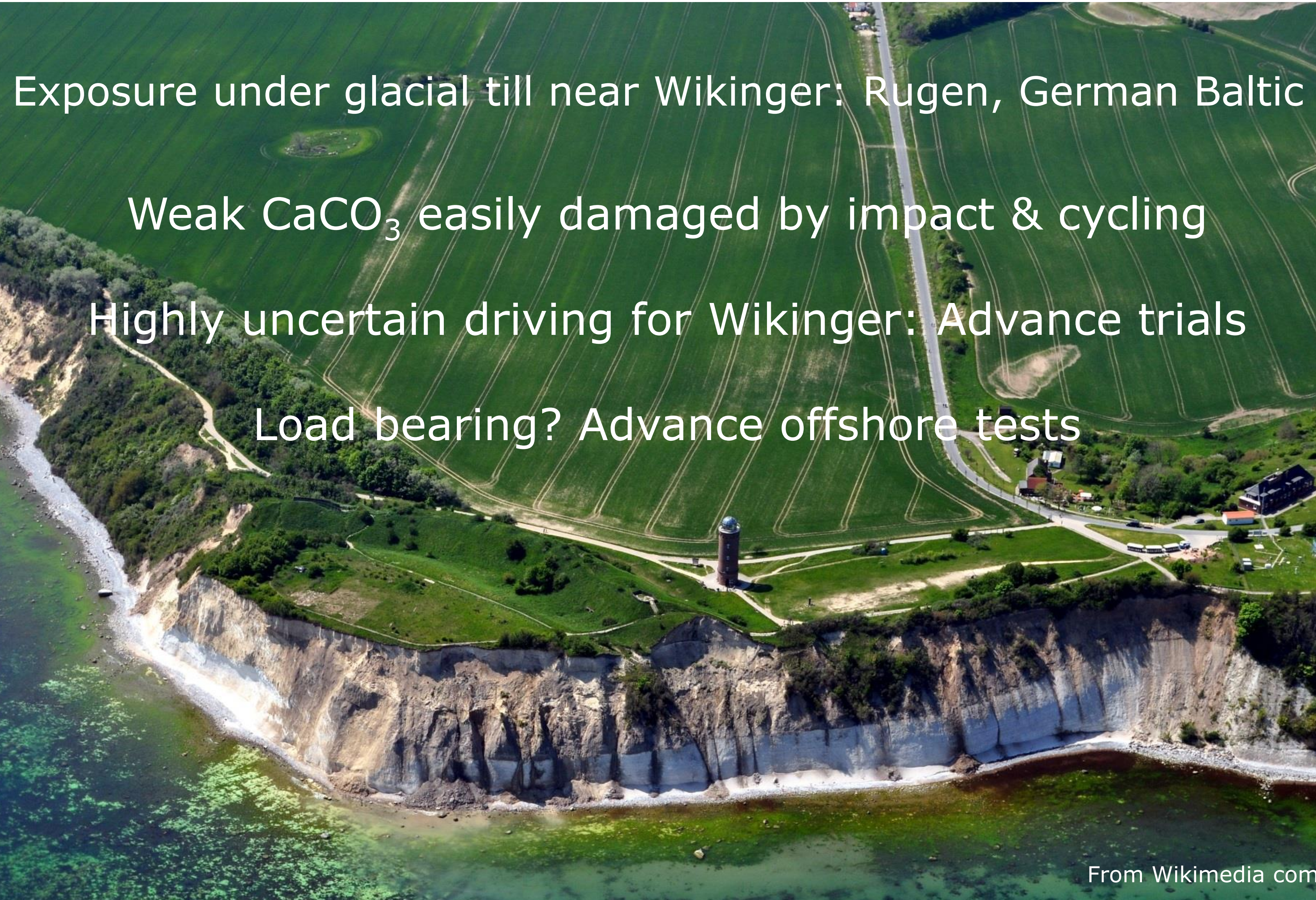
Dense sands & stiff clays

50 year storm cyclic loading

ICP: large cost reductions

Photos courtesy Trianel

Chalk sites: special problems for large driven piles



Exposure under glacial till near Wikinger: Rugen, German Baltic

Weak $CaCO_3$ easily damaged by impact & cycling

Highly uncertain driving for Wikinger: Advance trials

Load bearing? Advance offshore tests

From Wikimedia com

Tests on 1.38m OD piles for 70 jacket turbines in chalk: Wikinger

Barbosa, Geduhn, Jardine, Schroeder & Horn 2015

	Penetration	% chalk
WK38	16.2m	20
WK43	30.7m	66
WK70	31.0m	78

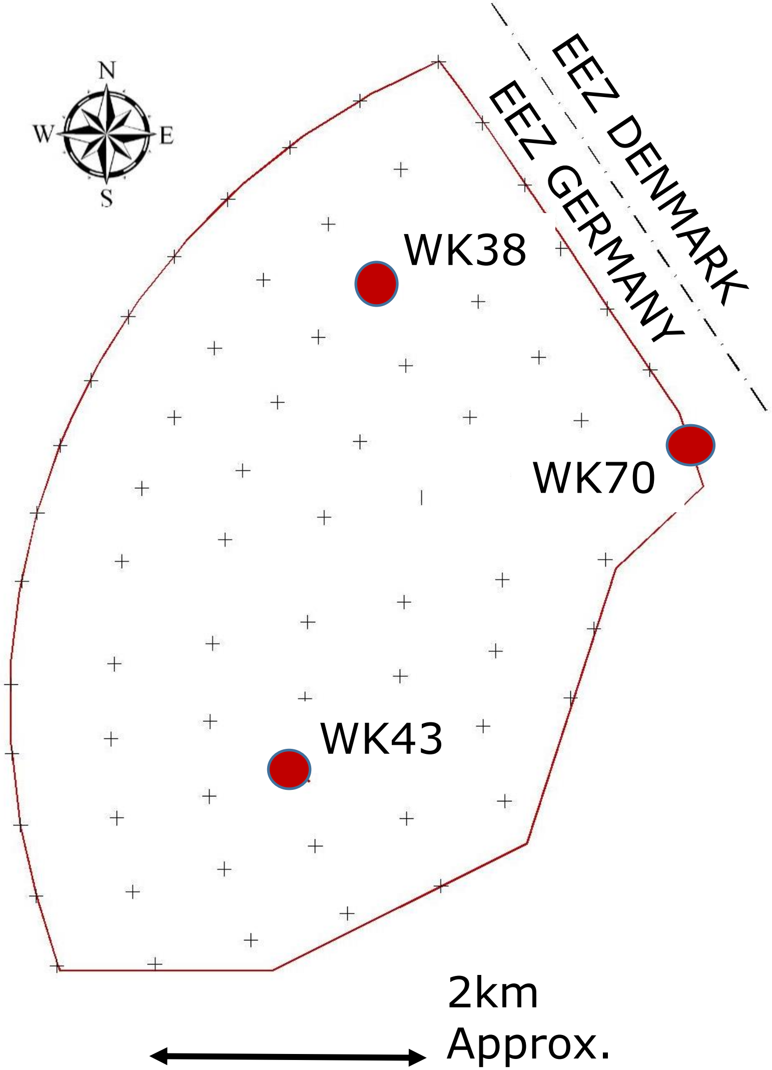
Three piles driven at each
Dynamic monitoring

↓

11 to 15 weeks’ set-up

↓

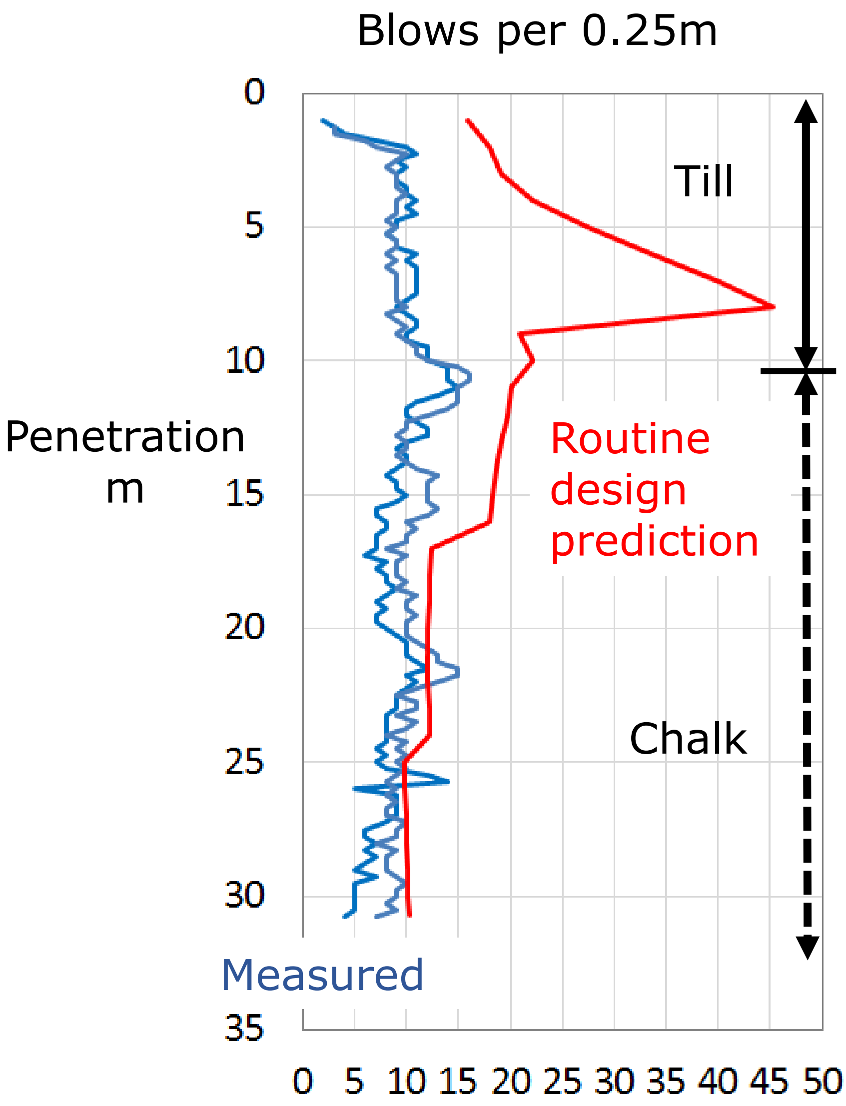
At each location
Static tension to failure
Instrumented restrike
Cyclic test at WK38

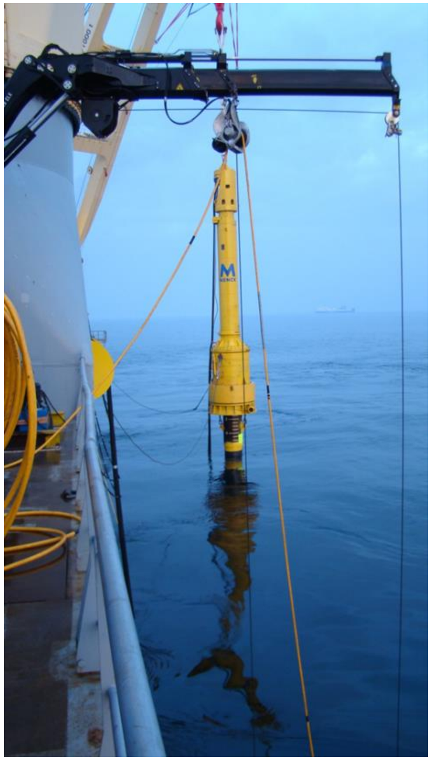


Test pile installation, October 2014: 17m Euro budget

First fully remote stage-loaded large scale seabed tests; 40m water

Driving response: WK43, 1.38m OD pile





Instrumented dynamic monitoring:

Signal matching analysis:
h/R* trends

Worrying low driving resistances?

Re-drives show marked ageing

Linked to onshore ageing & cyclic: plain & ICP piles

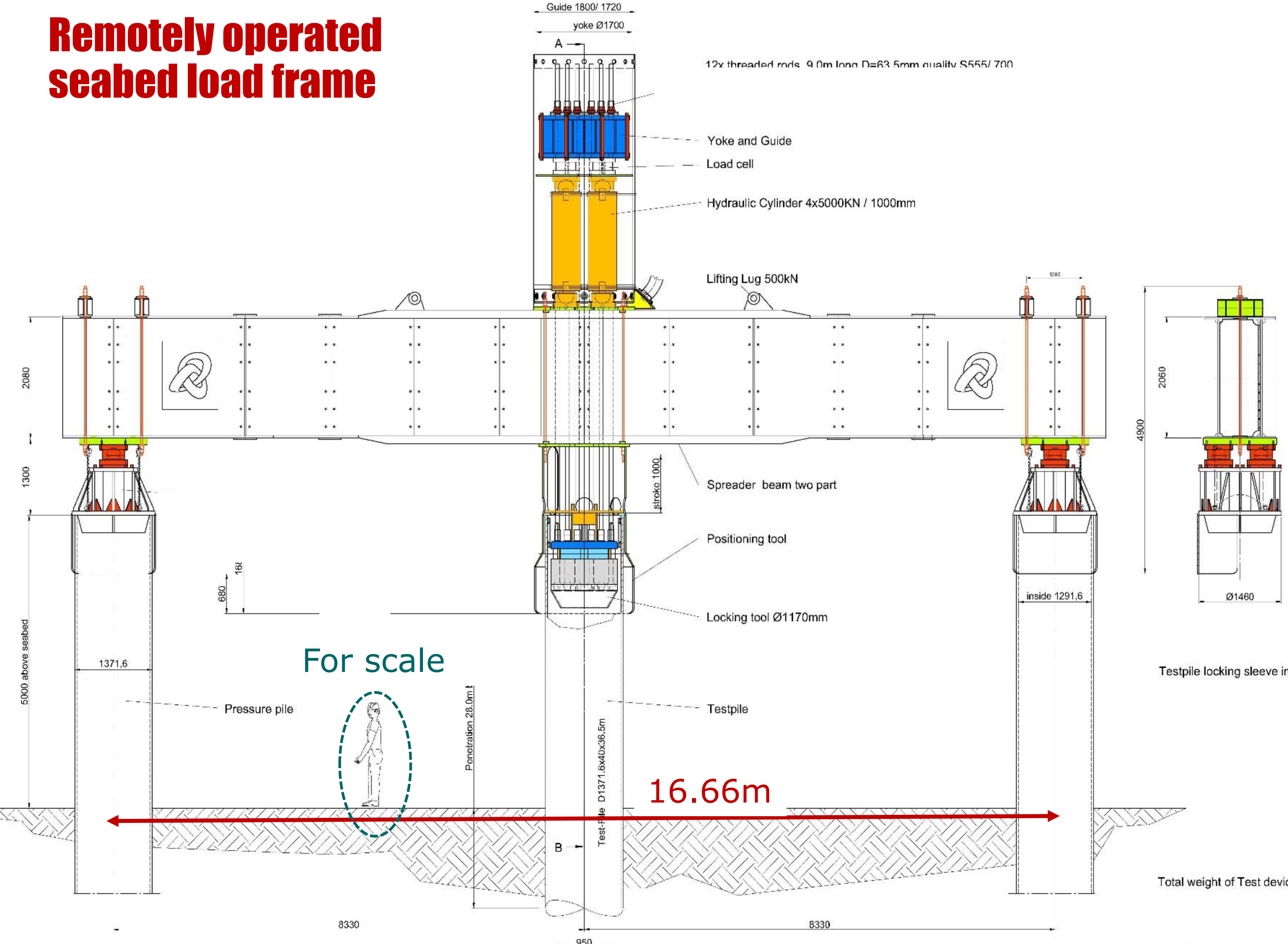
Barbosa et al 2017

Buckley et al 2017

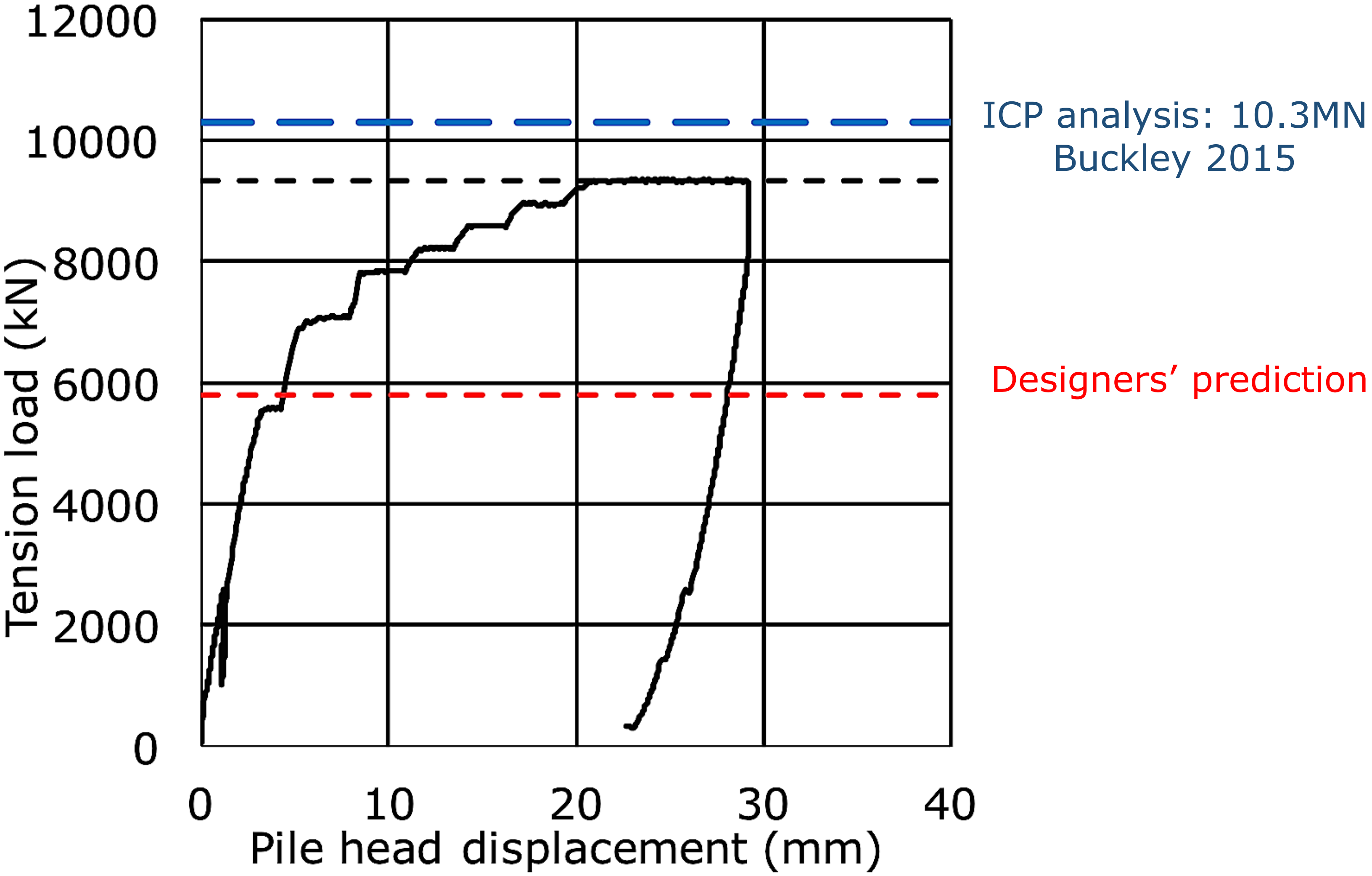
Deploying test frame: December 2014

Remotely controlled static and cyclic tension load tests

Remotely operated seabed load frame



WK38 turbine location test, 108 days after driving



Outcome: Wikinger foundations re-designed

Chalk: summary

Dynamic, static & cyclic offshore tests

Initial design proven conservative: good return on investment

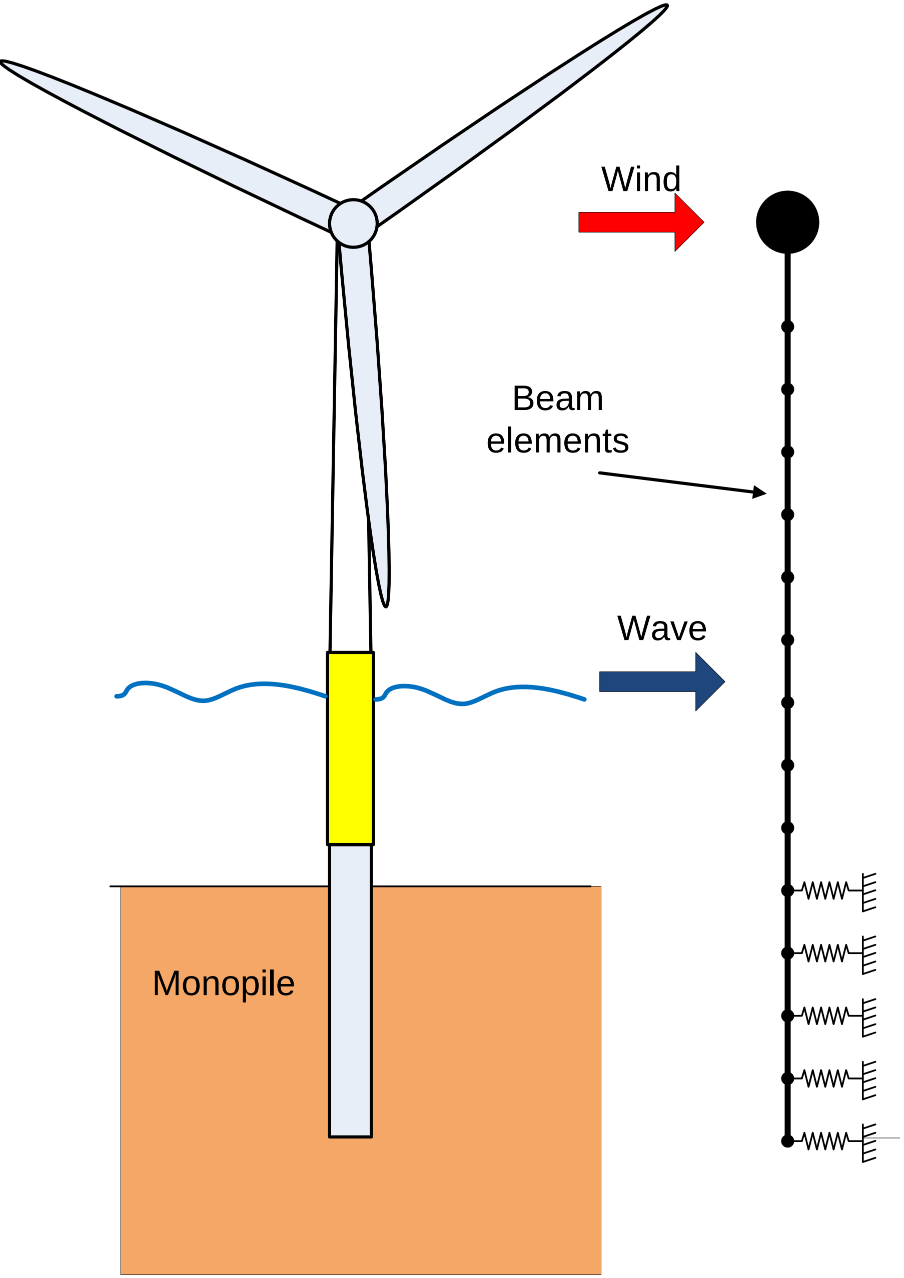
Research in progress

Production pile monitoring

Supporting ageing, cyclic & ICP chalk tests onshore in UK

Integrated with field studies on monopiles

PISA Joint Industry Monopile Project



With Oxford & UC Dublin

Cut costs, enable deeper water use in sands & clays

Analysis, laboratory & large field tests

Replace standard p-y methods

Low L/D: add extra components

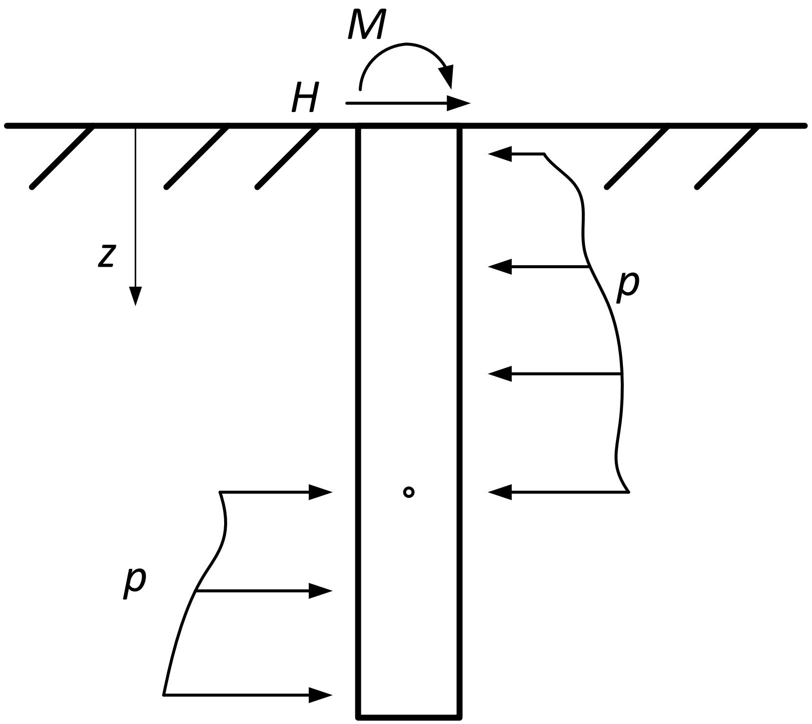
Calibrate: FE & stress path tests

Recognise: cyclic response

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

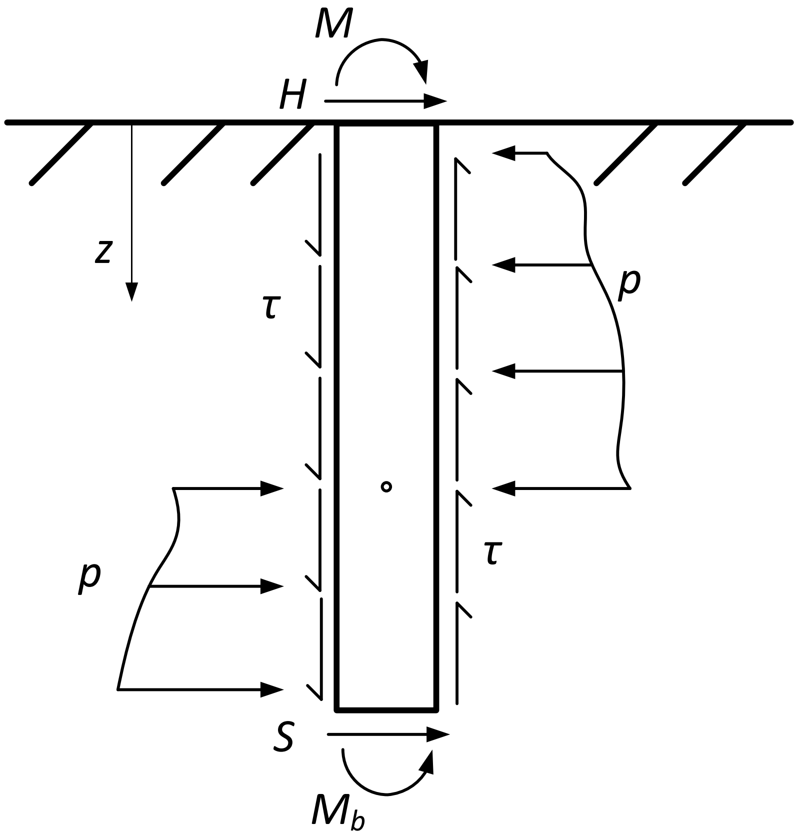
PISA design method: ‘Simple as possible, but no simpler’

Conventional



Only lateral p-y ‘springs’
Little scope to capture detailed
soil properties

PISA



Four sets of ‘springs’, check by
28 instrumented driven steel piles
Dunkirk & Cowden test sites

2m diameter piles under cyclic loading at Dunkirk

3-D ICFEP analysis calibrated to advanced lab tests

Dunkirk: dense marine sand

Two PhD testing programmes: stress path & HCA experiments

Cowden: Humberside

Sandy glacial till with stones & fissures

HCA ‘specimen sculpting’ aided by CT scanning

Research by Ushev & Liu

38 & 100mm D triaxial tests

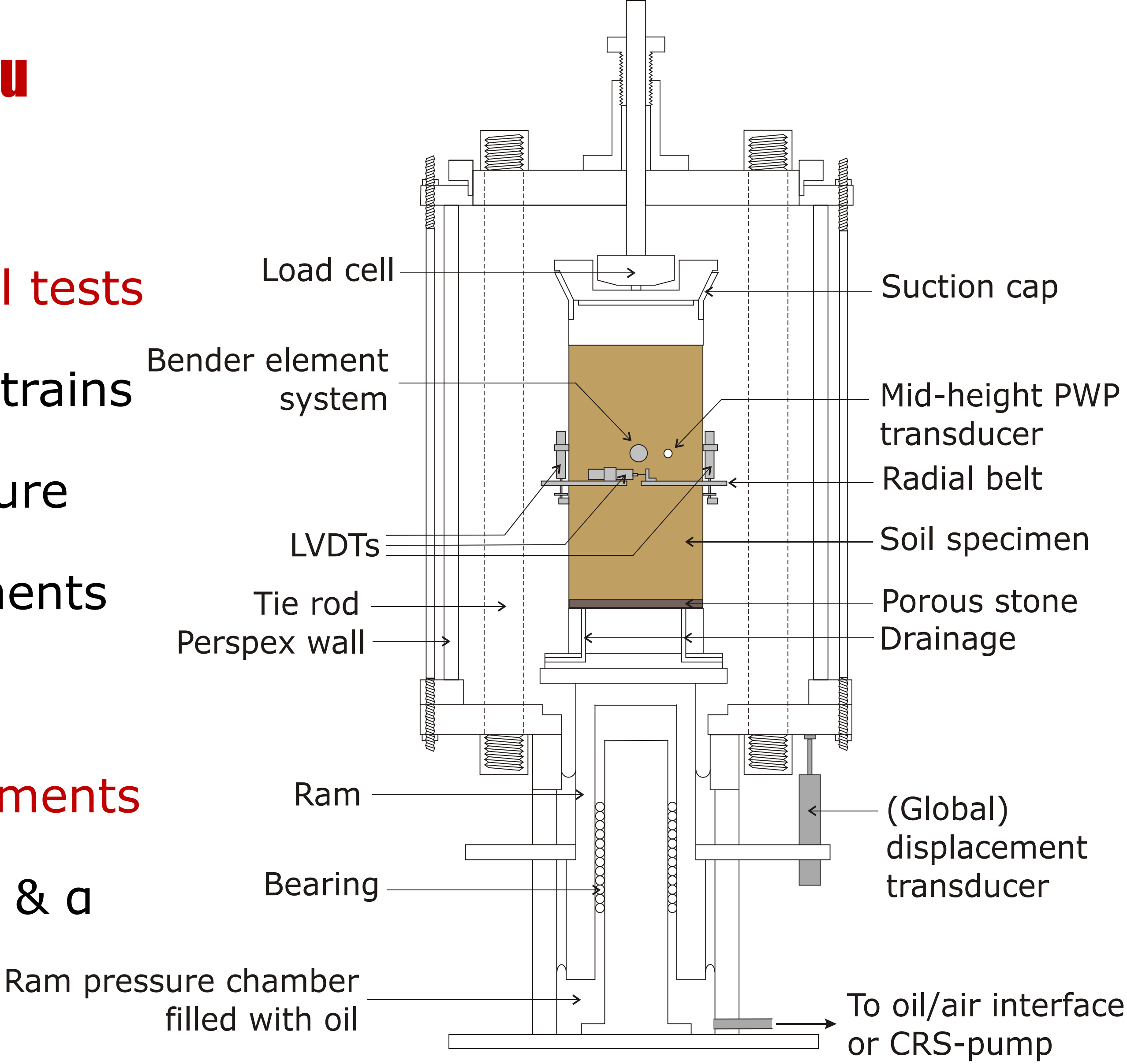
High-resolution local strains

Mid-height pore pressure

Dual-axis bender elements

72mm OD HCA experiments

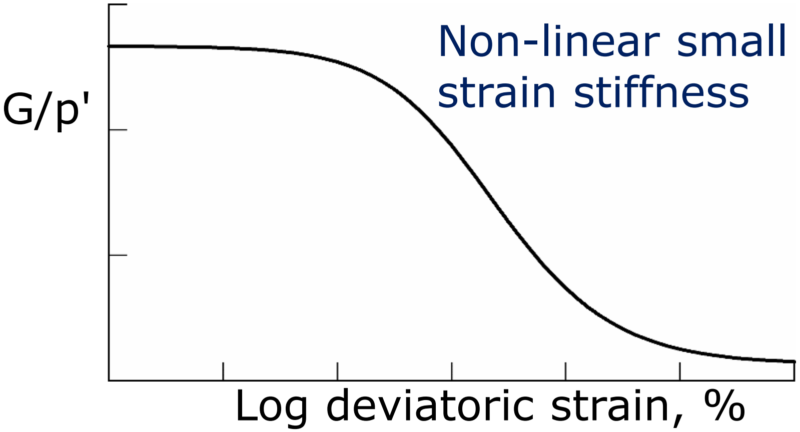
Control over σ_1, σ_2, σ_3 & α



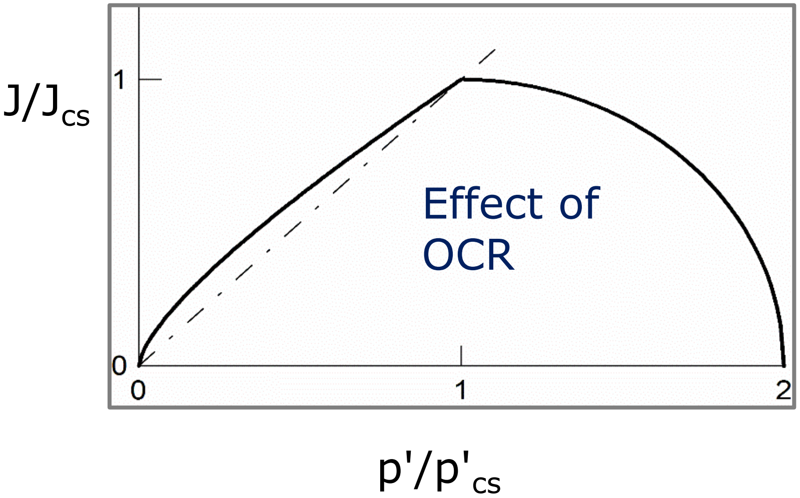
Compressibility, non-linear stiffness & shear strength
Anisotropy, strain rate & cyclic dependency

3-D ICFEP soil models
Calibrated to laboratory & in-situ tests

Cowden: expanded Mod. Cam Clay

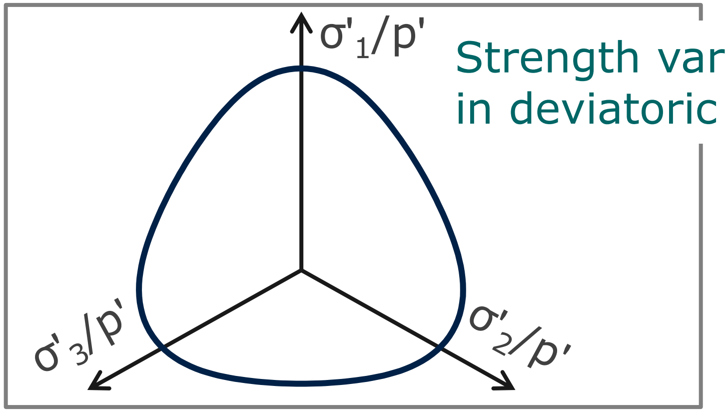


Non-linear small strain stiffness

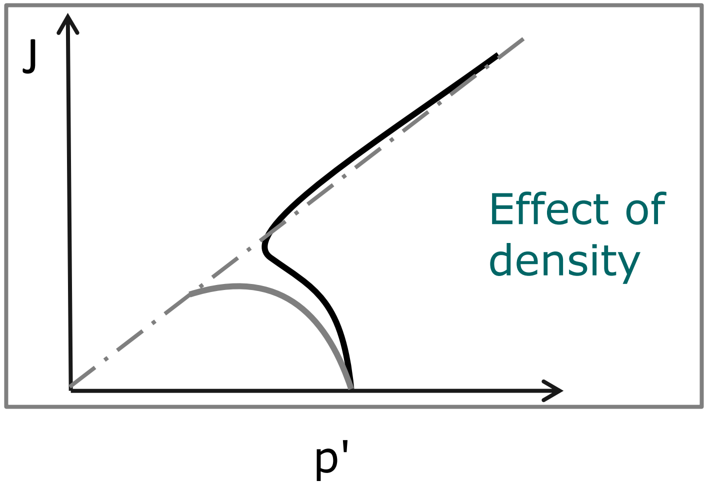


Effect of OCR

Dunkirk: Bounding Surface Plasticity



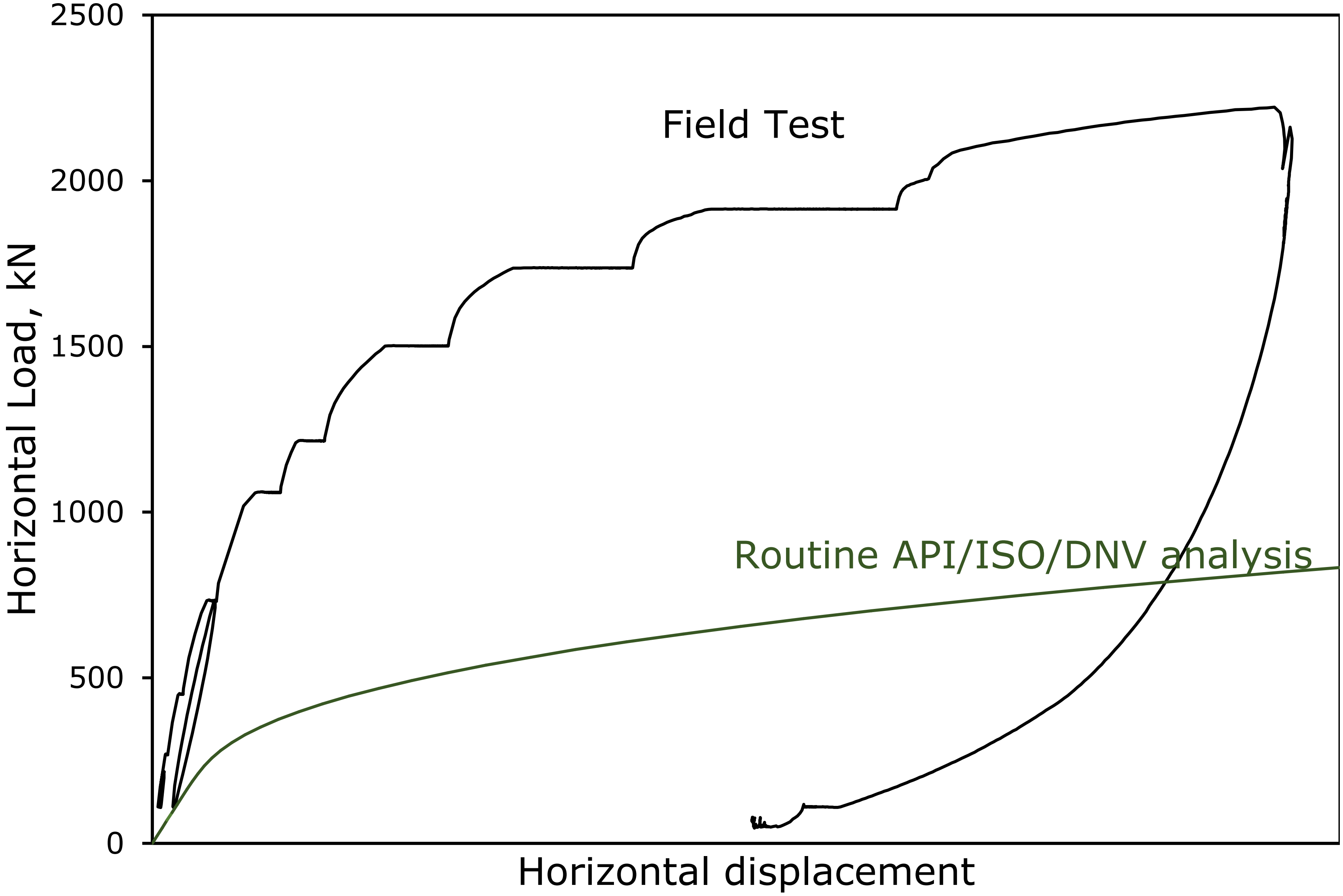
Strength variation in deviatoric plane



Effect of density

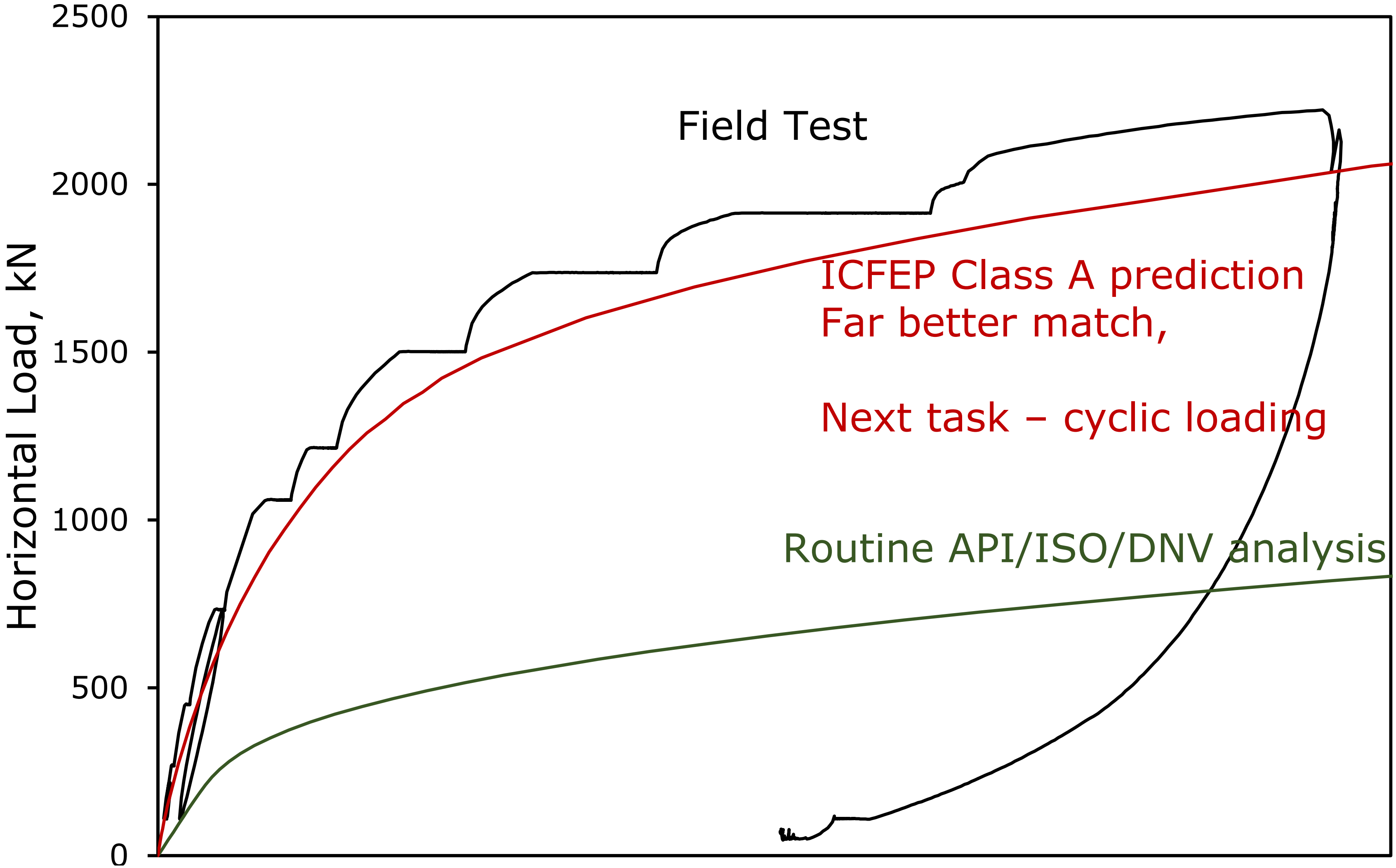
Zdravković, Taborda, Potts, Jardine, Sideri, Schroeder, Byrne, McAdam, Burd, Houlsby, Martin, Gavin, Doherty, Igoe, Muir Wood, Kallehave & Skov Gretlund 2015

Modelling 2m OD, 10.5m deep, Cowden piles



Routine analysis: far softer than field

Modelling 2m OD, 10.5m deep, Cowden piles



Equally applicable to onshore foundations & caissons

One of our ‘broader themes’; the other three?

First, integrated approach

Geology, experiments, analysis & full scale field behaviour

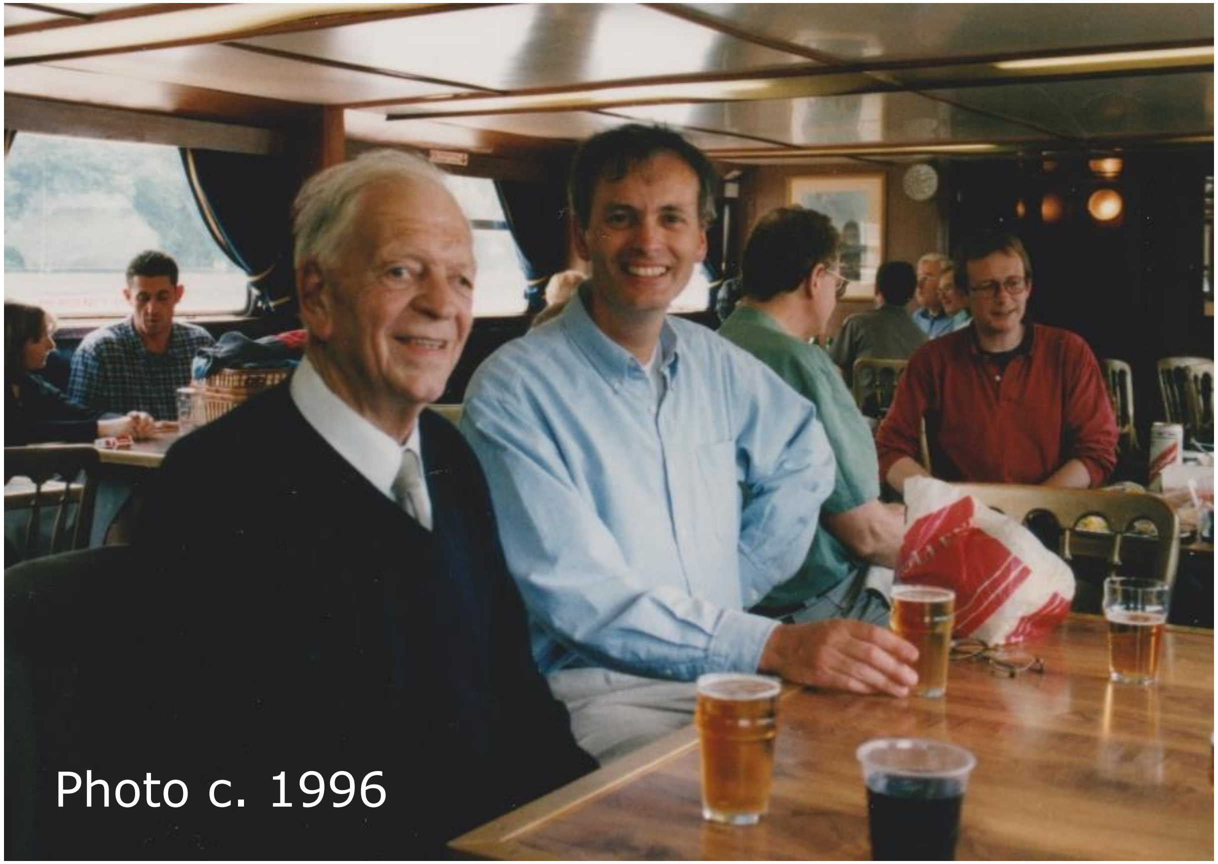


Photo c. 1996

4th Rankine Lecturer, Professor Sir Alec Skempton 1914-2001

Next, broad collaboration

- Atkins
- BP Cambridge In-situ
- Chevron
- Conoco Phillips
- Deltares
- DONG Energy
- EPSRC
- ESG, formerly PMC
- Fugro
- Geotechnical Consulting Group, GCG
- Grenoble Tech, Laboratoire 3S-R
- Health & Safety Executive, HSE
- Iberdrola, Scottish Power Renewables
- Innovate UK
- Lankelma UK
- Offshore Wind Consultants, OWC
- Oxford University
- Royal Haskoning DHV
- Shell UK
- UPC Barcelona
- University College Dublin
- University of Western Australia
- Zhejiang University

Steve Ackerley
Amin Aghakouchak
Ricardo Argiolas
Pedro Barbosa
Alan Bolsher
Andrew Bond
Róisín Buckley
John Burland
Byron Byrne
Fiona Chow
Jim Clarke
Clive Dalton
Bethan Davies
Itai Einav
Trevor Evans
Pierre Foray
Clark Fenton
Liana Gasparre
Antonio Gens
Joanna Haigh
David Hight
Michael Hotze
Rupert Hunt
Graham Keefe
Stavroula Kontoe
Barry Lehane
Tingfa Liu
Christopher Martin
Ross McAdam

Andrew Merritt
Michael Mygind
Rory Mortimore
David Nethercot
Satoshi Nishimura
Robert Overy
Eric Parker
Duncan Parker
David Potts
Mark Randolph
Michael Rattley
Siya Rimoy
Way Way Sim
Carlos Santamarina
Felix Schroeder
Matias Silva
Philip Smith
Jamie Standing
David Taborda
Ralf Toumi
Christian Le Blanc Thilstead
Cristina Tsuha
Emil Ushev
Robert Whittle
Zhongxuan Yang
Lidija Zdravkovic
Bitang Zhu
Cor Zwanenburg

Finally

Fit for purpose practical tools

“As simple as possible, but no simpler”

Wide spectrum of complexity considered

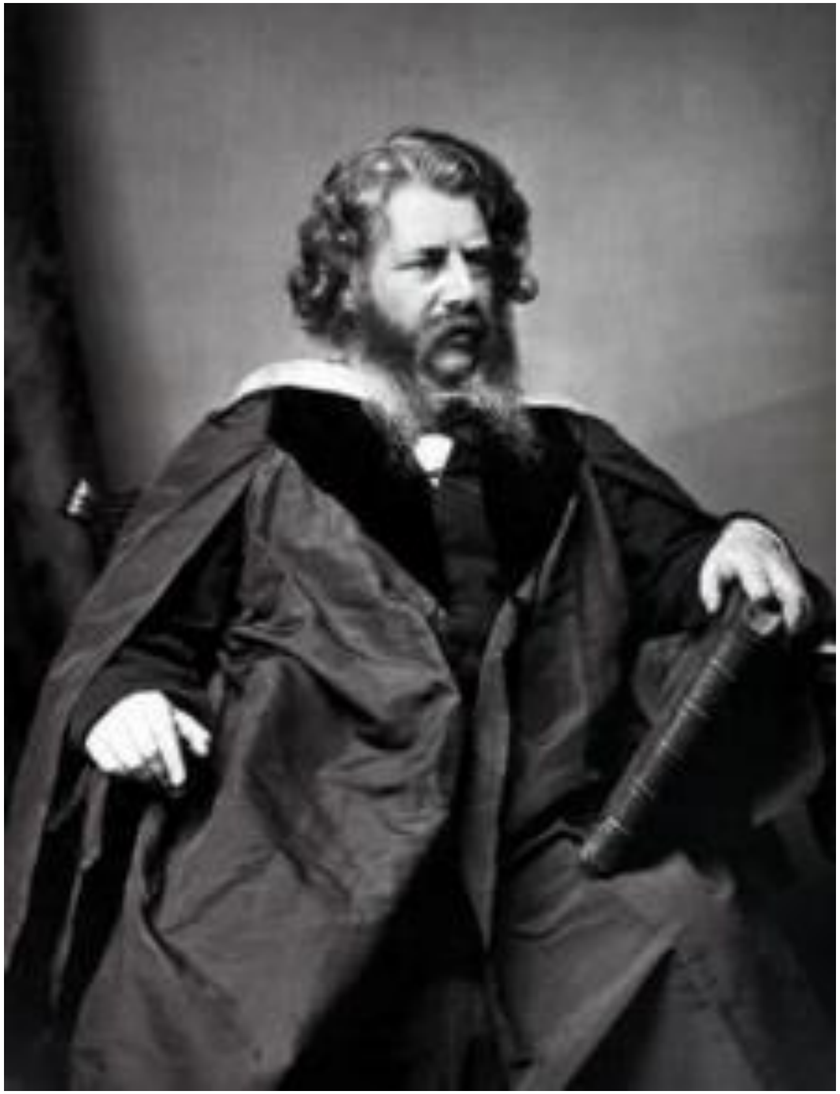
Future challenges, one example per main part

I – Stress regime inside & around open driven piles?

II – Creeping thermal landslides?

III – Cyclic loading of monopiles & caissons?

Geotechnical progress towards resolving the energy conundrum?



Maintaining safe & efficient offshore oil & gas supplies

Addressing climate impact & developing effective adaptation tools

Tackling problem at source: improving renewable energy economics

Thank you

for your patient attention