THE UNIVERSITY OF WESTERN AUSTRALIA | A CENTURY OF ACHIEVEMENT

2nd McClelland Lecture

Analytical contributions to offshore geotechnical engineering

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The University of Western Australia

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ACHIEVE INTERNATIONAL EXCELLENCE

Bramlette McClelland (1921-2010)

- A giant of a man – pioneer of offshore foundation engineering
- Founder and President of McClelland Engineers
  - Headquartered in Houston
  - 14 offices around the world
- Awards included
  - 9th Terzaghi Lecturer (1972)
  - OTC Distinguished Achievement Award (1986)

What passes for "analytical" ?

"When I am working on a problem, I never think about beauty but when I have finished, if the solution is not beautiful, I know it is wrong."
Buckminster Fuller

Idealisation

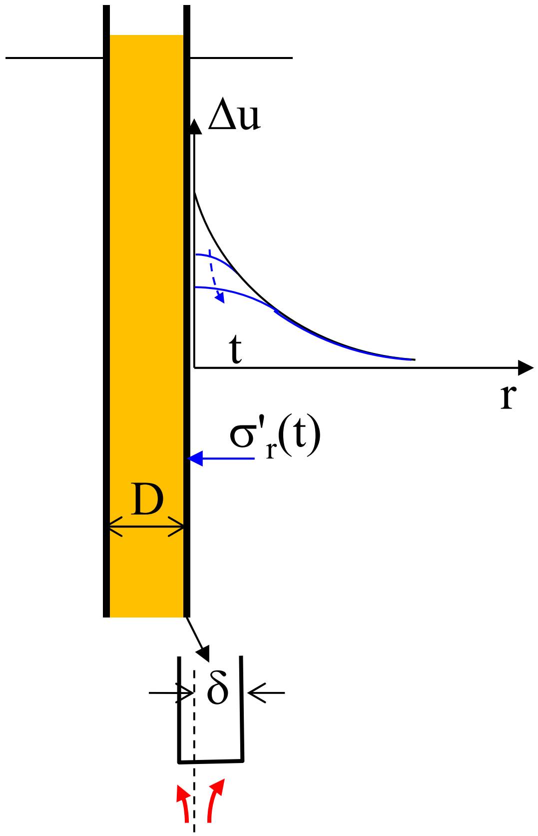
- True analytical solution (algebraic expression)
- Computable analytical formulation (design chart)
- Synthesis of numerical parametric study
  - Appropriate non-dimensional parameter groups
  - Algebraic or chart outcome

Realism ?

Overview

- Piled foundations
  - Consolidation after driving
  - Axial stiffness and cyclic loading
- Shallow foundations
  - Rectangular foundations for subsea systems
- Full-flow penetrometers
  - Resistance factors
  - Degree of consolidation during penetration
- Subsea pipelines
  - Embedment and axial resistance of deep water pipelines

Piled foundations - consolidation



Soil flow:

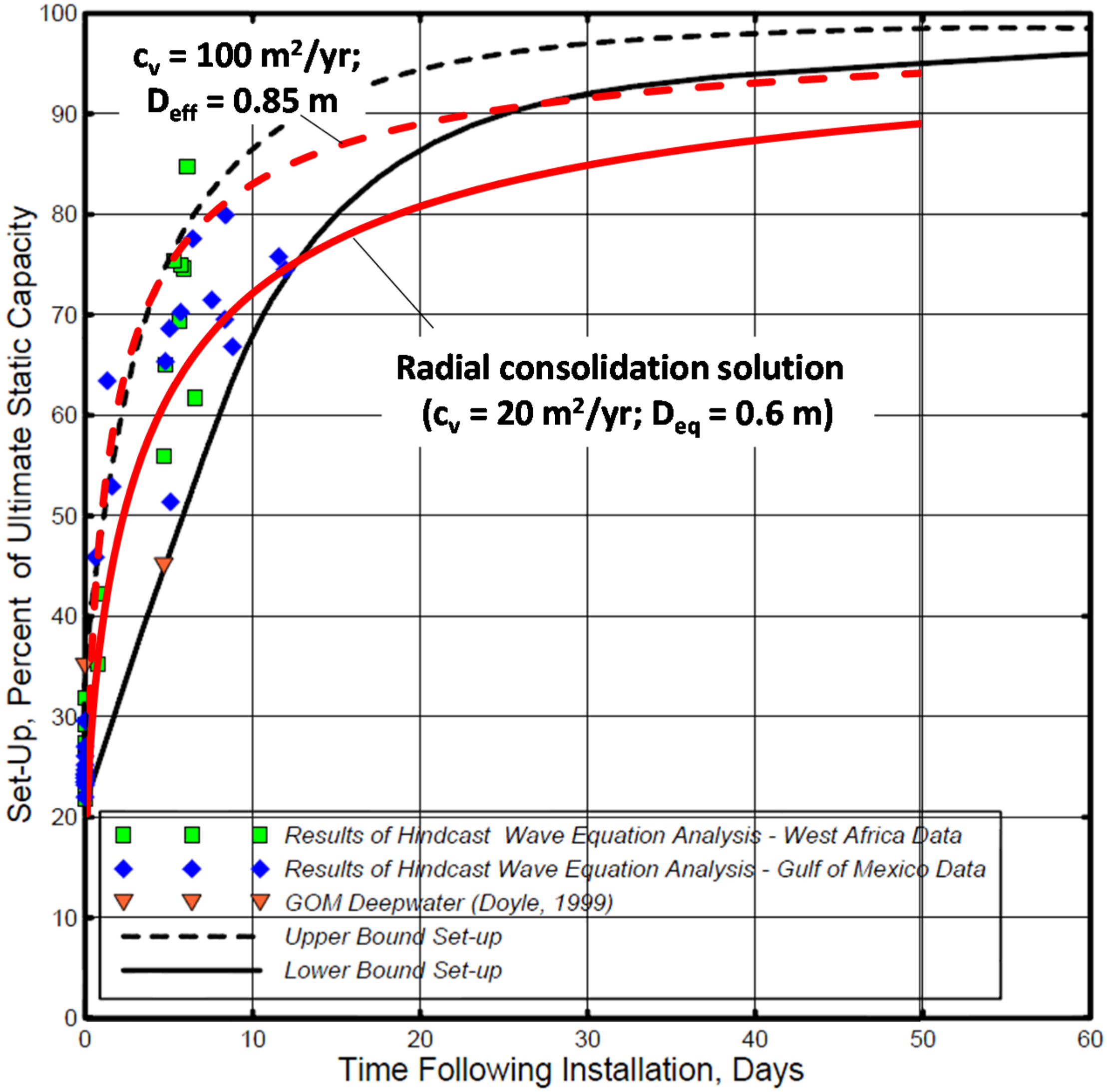
Piles: 0:100 D/δ ~ 40

Suction caissons ~ 50:50 D/δ > 300

- Radial consolidation solution
  - Refined through strain path method
- Non-dimensional time: $T = c_v t / D_{eq}^2$
  - c_v as for piezocone dissipation

    (horizontal flow; soil stiffness partly swelling)
  - D_{eq} reflecting outward flow of soil

Development of axial pile resistance



Consolidation index

$$CI \sim 1 - \frac{1}{1 + (T/T_{50})^{0.75}}$$

$T_{10} \sim T_{50}/20$: $t_{10} \sim$ 2 to 5 hours

$T_{50} \sim 0.6$: $t_{50} \sim$ 2 to 5 days

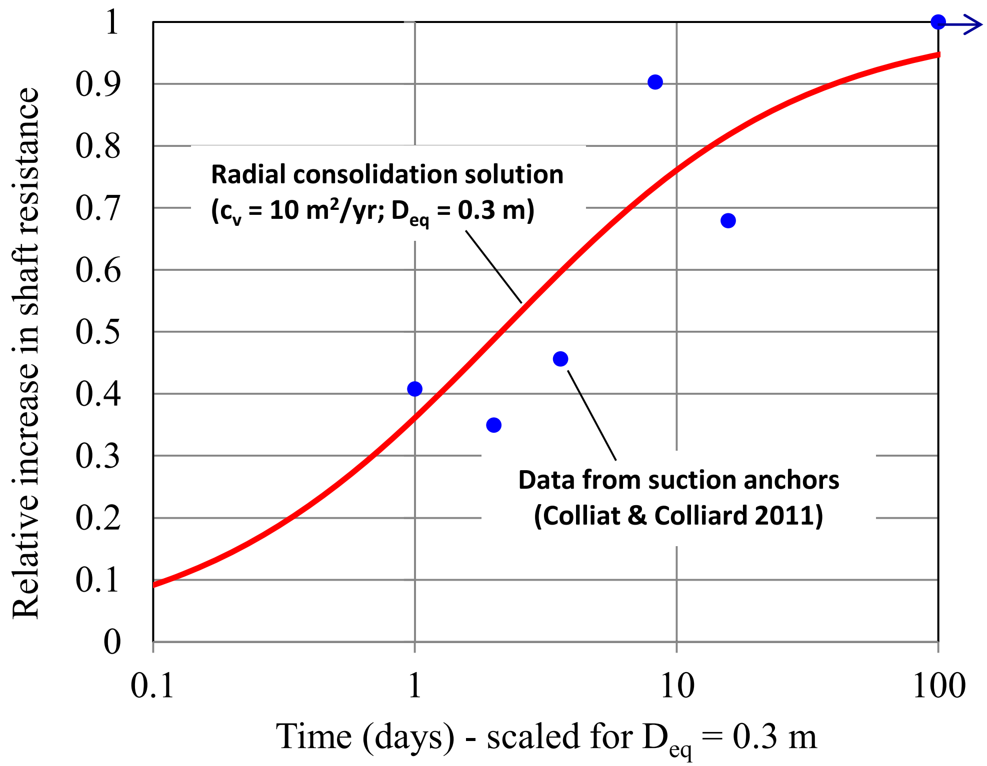
$T_{90} \sim 20T_{50}$: $t_{90} \sim$ 1 to 3 months

Consolidation around suction caissons

Colliat & Colliard (2011):

Diameters: 3.8 m to 8 m

D_{eq} ~ 0.28 to 0.45 m (extremely thin-walled)



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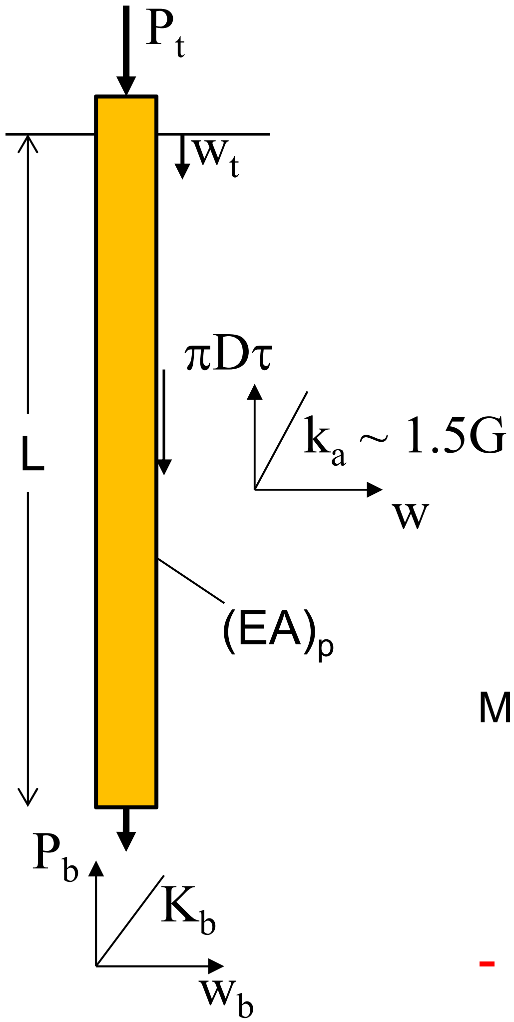
Consolidation - commentary

- Radial consolidation solution
  - Adequate fit to sparse data
  - Analytical framework: piles to caissons and different soil types
  - Consolidation coefficient: relevant c_v difficult to estimate

    field data (piezocone dissipation) a vital aid

Do we need the black magic of thixotropy for this problem?

Axial stiffness of piles



$$K_{axial} = \frac{P_t}{w_t} = S\frac{K_b + S\tanh(\mu L)}{S + K_b \tanh(\mu L)} \longrightarrow S \quad (\text{for } \mu L > 2)$$

$$\mu L = \sqrt{\frac{k_a}{(EA)_p}}L \quad \text{and} \quad S = \frac{(EA)_p}{L}\mu L = \sqrt{(EA)_p k_a}$$

Pile shaft compliance

Mobilisation of shaft friction initiated near pile head:

$$\frac{P_{slip}}{Q_{shaft}} \sim \frac{1}{\mu L} = \frac{1}{L}\sqrt{\frac{(EA)_p}{k_a}}$$

- Consequences for progressive failure and cyclic stability

Cyclic stability diagram for axial loading of piles

Common form of 'global' stability diagram:

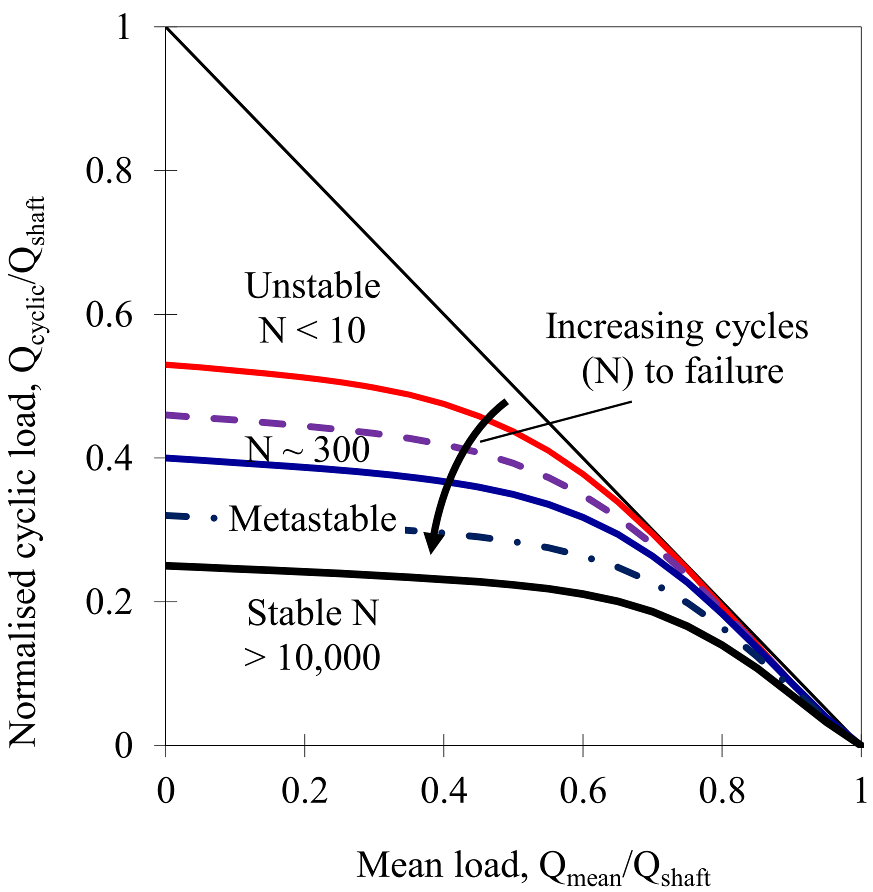
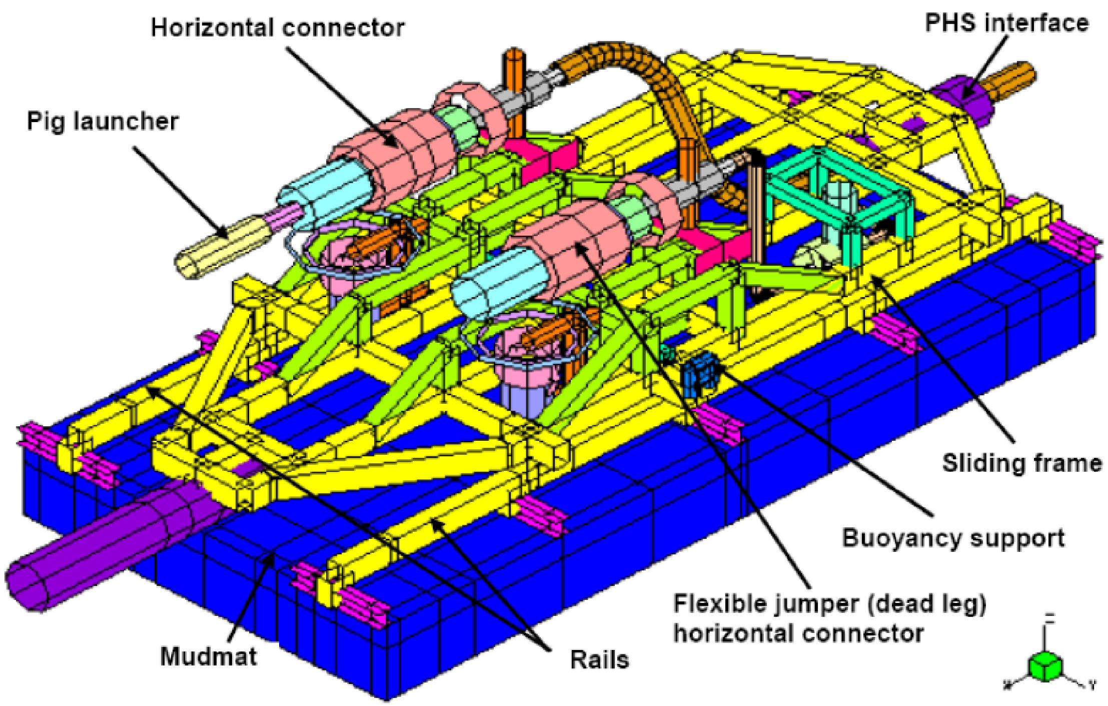


Diagram applies at element level - not globally

- Cyclic degradation progresses down pile from soil surface
- Pile shaft compliance important
- Model tests (low compliance) not directly applicable for design of more compliant piles used offshore

Shallow mat foundations

- Widespread use for subsea systems and pipeline terminations
- Generally rectangular: 50 to 200 m^2 in plan area
- Complex 6 degree of freedom loading



Pipeline end termination (PLET)

Production sled during lay

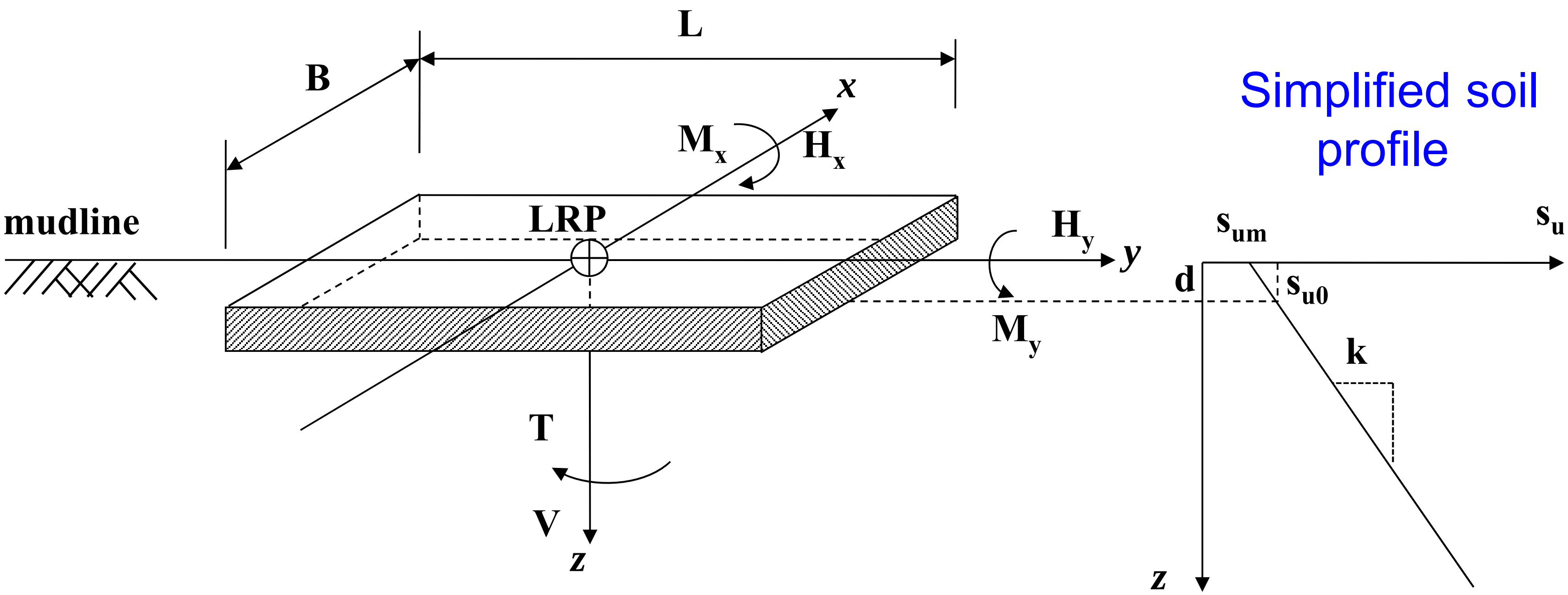
(photos *courtesy Subsea 7*)

Design considerations for small mat foundations

Holy grail: analytical failure envelope for general 3-D loading

- Industry design guidelines limited
  - Strip or circular geometries only
  - Oriented towards bearing capacity, with allowance for H, M
- Operational loads for subsea foundation systems
  - Vertical load (V) constant; low proportion of bearing capacity
  - Thermally induced variations of horizontal (H_x, H_y), moment (M_x, M_y) and torsion (T) from eccentric pipeline and spool connections
  - Critical failure mode: combined sliding and torsion

Numerical analysis: parameterised solutions



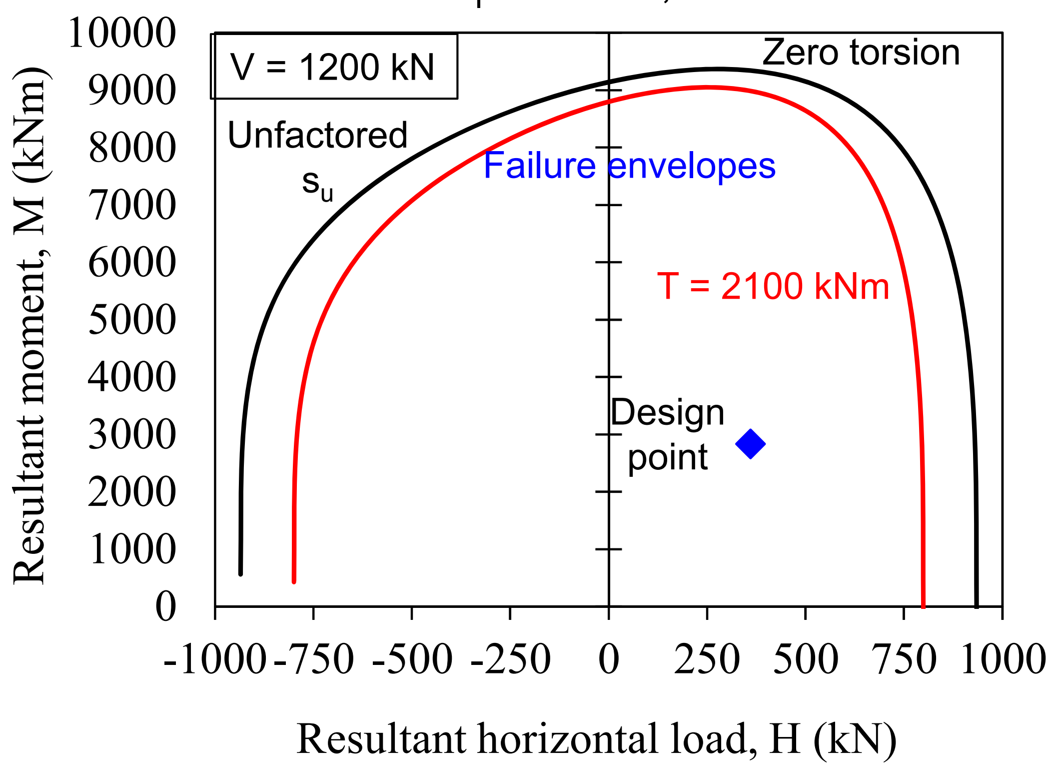
- Identify non-dimensional groups:

  B/L, d/B, kB/s_{u0}, H_x/H_y, M_y/M_x, V/As_{u0}, H_{res}/As_{u0} etc

- Evaluate ‘uniaxial’ ultimate capacities for each loading component
- Adjust ultimate horizontal and moment capacities for V/V_{ult}, T/T_{ult}
- ‘Collapse’ 6-dimensional failure envelope into 2 dimensions!

Design approach for small mat foundations

Parameter	Value	Units	Design loads	Value	Units	Mobilisation Ratios
Width, B	8	m	Vert. load, V	1200	kN	0.17
Length, L	16	m	Load, H_x	200	kN	0.21
Skirt, d	0.6	m	Load, H_y	300	kN	0.34
Strength, s_{um}	5	kPa	Moment, M_x	1500	kNm	0.07
s_u gradient, k	2	kPa/m	Moment, M_y	-2400	kNm	0.30
Skirt friction	0		Torsion, T	2100	kNm	0.45



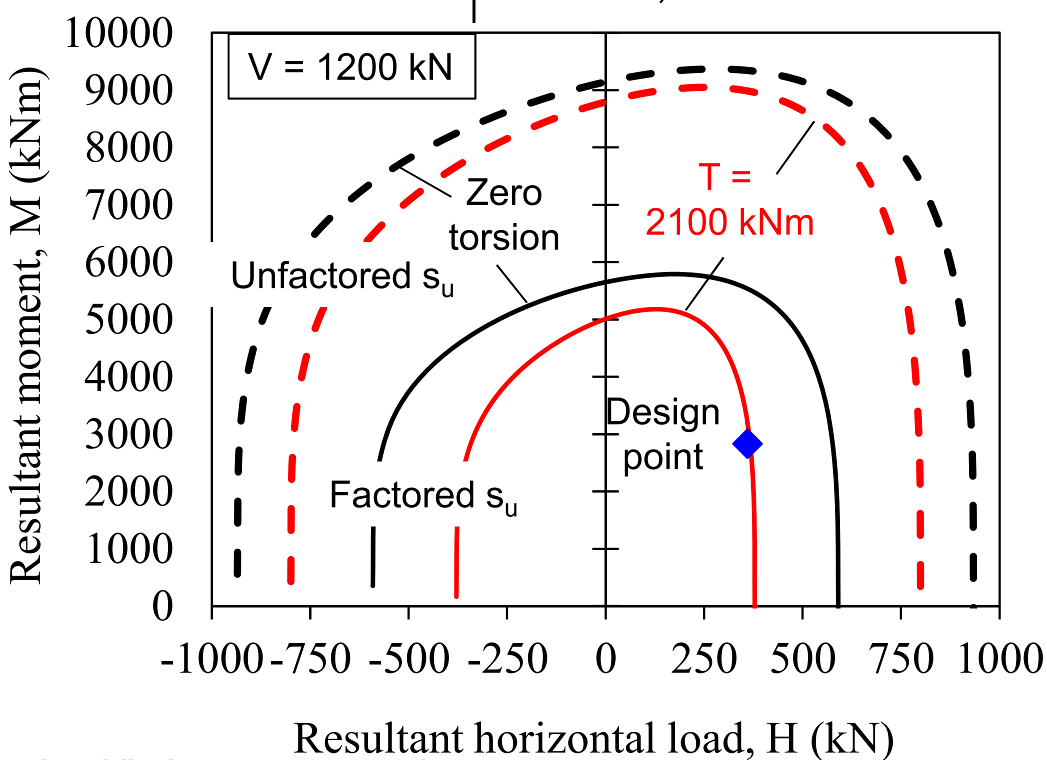
Failure envelopes

$$m_d^{\,q}\left(1-\alpha h+\beta h^2\right)+h^2=1$$

$$m_d=\frac{M+Hd}{M_f} \qquad h=\frac{H}{H_f}$$

Design approach for small mat foundations

Parameter	Value	Units	Design loads	Value	Units	Mobilisation Ratios	
Width, B	8	m	Vert. load, V	1200	kN	0.17	0.27
Length, L	16	m	Load, H_x	200	kN	0.21	0.33
Skirt, d	0.6	m	Load, H_y	300	kN	0.34	0.54
Strength, s_{um}	5	kPa	Moment, M_x	1500	kNm	0.07	0.11
s_u gradient, k	2	kPa/m	Moment, M_y	-2400	kNm	0.30	0.48
Skirt friction	0		Torsion, T	2100	kNm	0.45	0.72



Factored s_u (by 0.63)

Failure envelopes

$$m_d^{\,q}\left(1-\alpha h+\beta h^2\right)+h^2=1$$

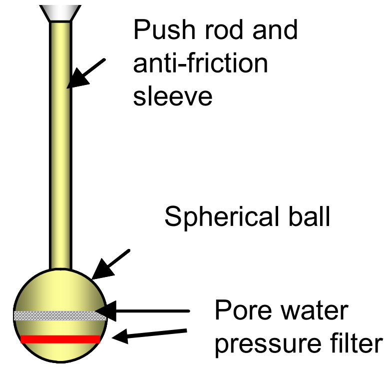
$$m_d=\frac{M+Hd}{M_f} \qquad h=\frac{H}{H_f}$$

Full flow penetrometers

Motivations for introduction, targeting soft soils

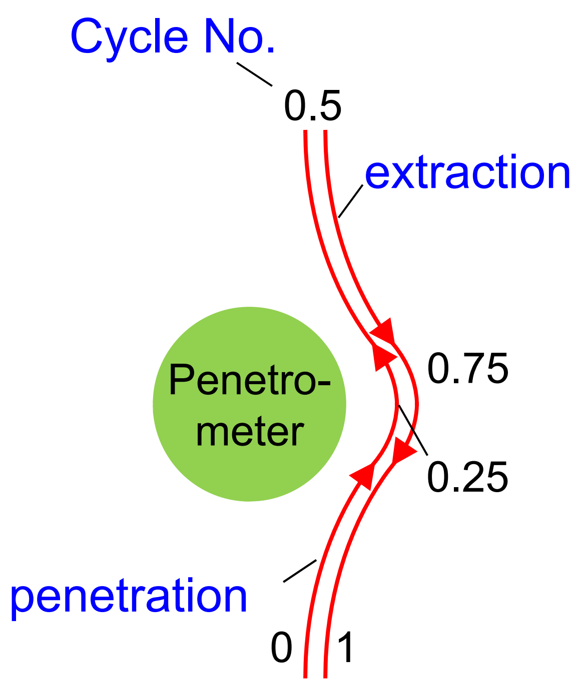
- Penetrometer shapes amenable to analysis
  - Resistance independent of soil stiffness or in situ stresses
- Sufficient projected area ratio for minimal correction for overburden stress
  - Shaft area < 15 % of projected area
- Soil sensitivity measured directly: cyclic testing
- Reduced reliance on ad hoc correlations for shear strength from penetration resistance
  - Variations in resistance factors arise from differences in sensitivity (and brittleness), and strain rate dependence

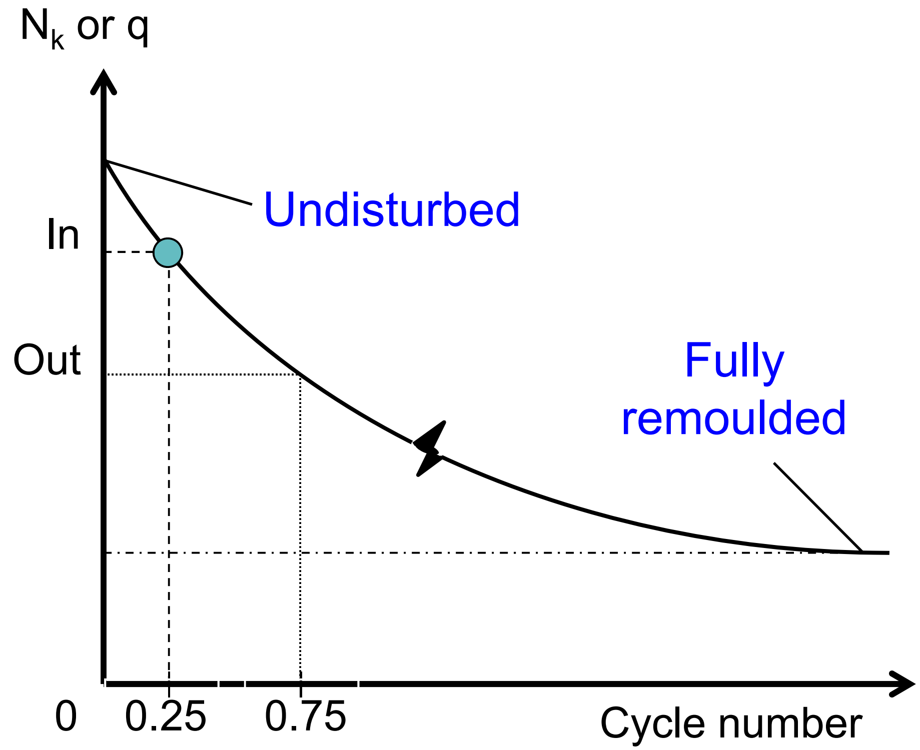
T-bar: 100 cm^2

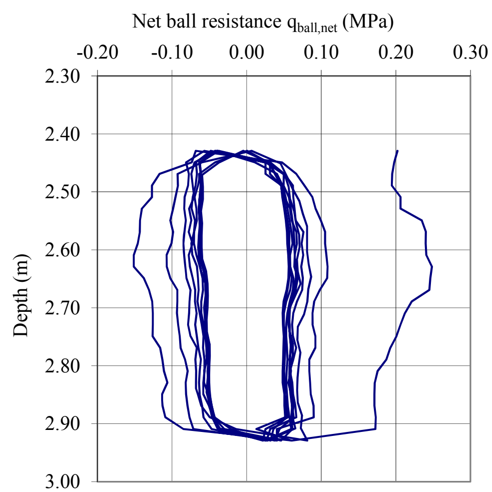


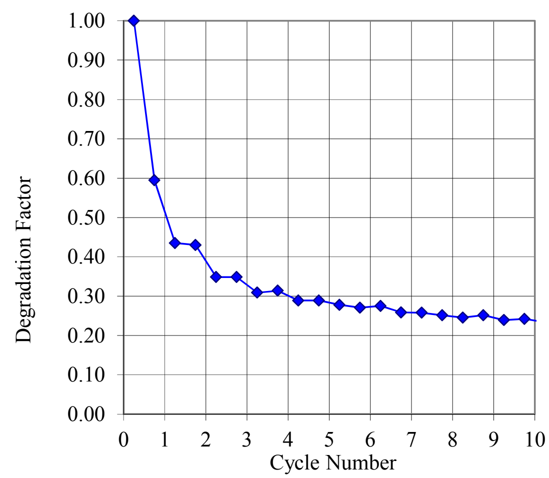
ball: 30 to 50 cm^2

Cyclic degradation of soil strength

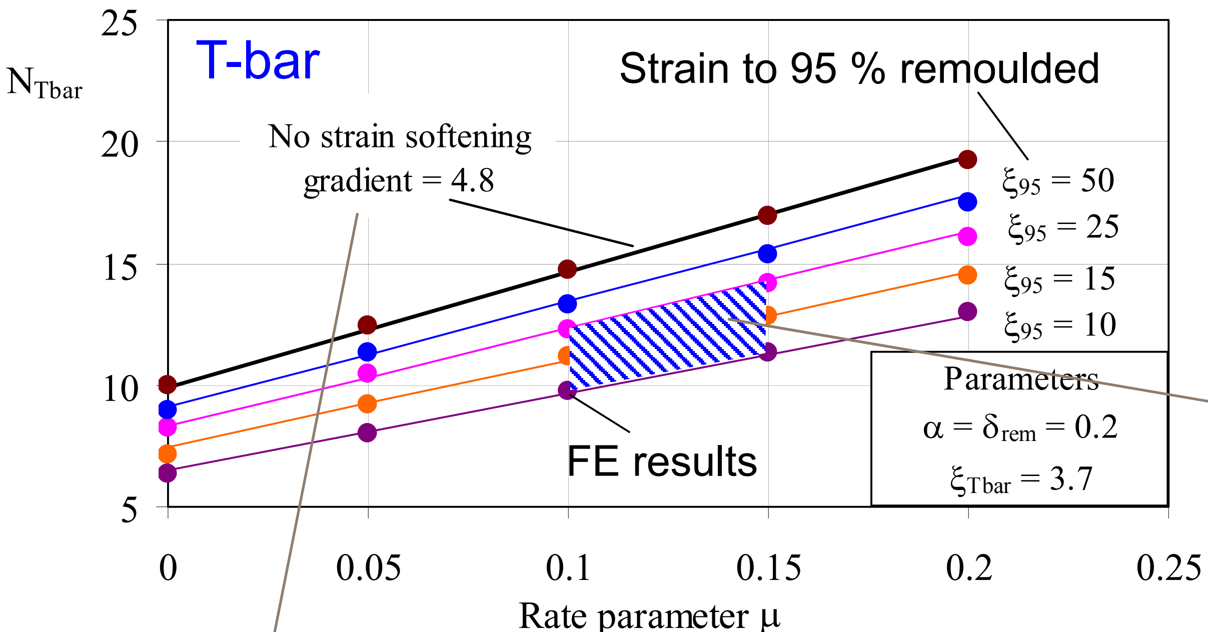








Theoretical resistance factors – rate dependence & softening



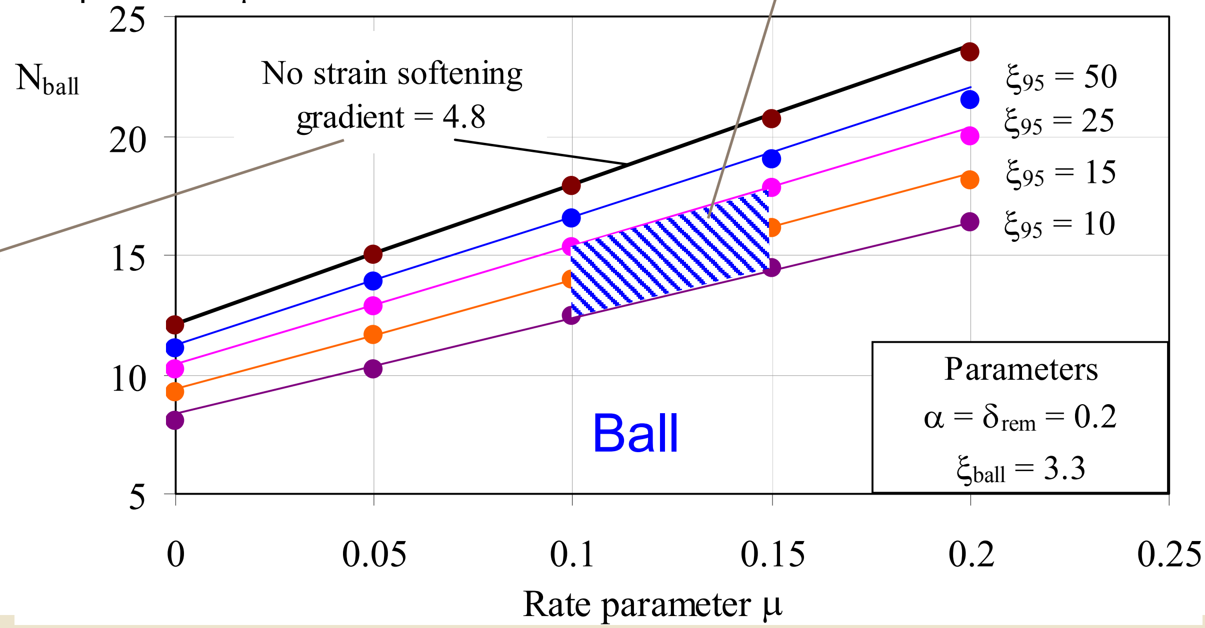
$$N_k = \frac{q_{net}}{s_u}$$

Typical parameters:

N_{Tbar} ~ 10 to 13

N_{ball} ~ 12 to 17

Gradient of 4.8 implies 'operative' shear strain rate of 20 %/s or approximately 0.5v/D



Consolidation around penetrometers

- In situ assessment of consolidation coefficient
  - Typically 3 to 10 times greater than from laboratory oedometer testing
  - Essential for estimating set-up times around piles, caissons etc
  - Pipeline-soil interaction (e.g. buckling, walking) sensitive to degree of consolidation during movement
- Penetrometer testing in intermediate soils (silt-sized)
  - Partial consolidation during penetration – how best to quantify?
  - Requires independent measurements – multiple pore pressure sensors?
  - *Or* varying penetration rate

Ideal: continuous sensing during penetration to detect *both* degree of consolidation and c_v

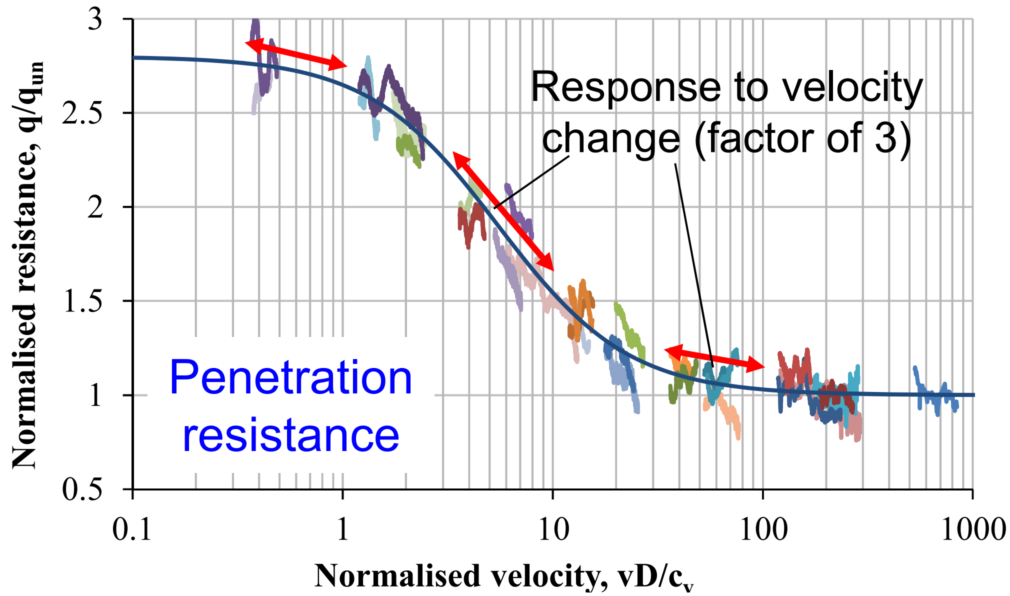
Partial consolidation effects – backbone curves

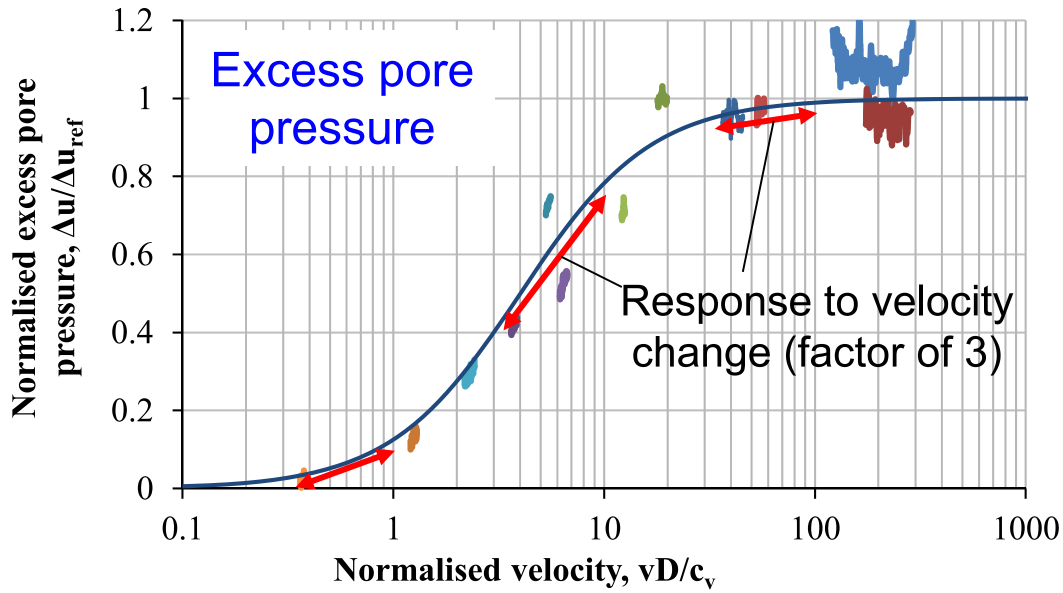
Effect on resistance, q, and excess pore pressure, Δu

- Function of relative velocity, vD/c_v
- Probe by changing penetration rate
- Ideally need prior knowledge of c_v - but at least measure it

Catch 22:

- What is effect of partial consolidation on subsequent dissipation test?





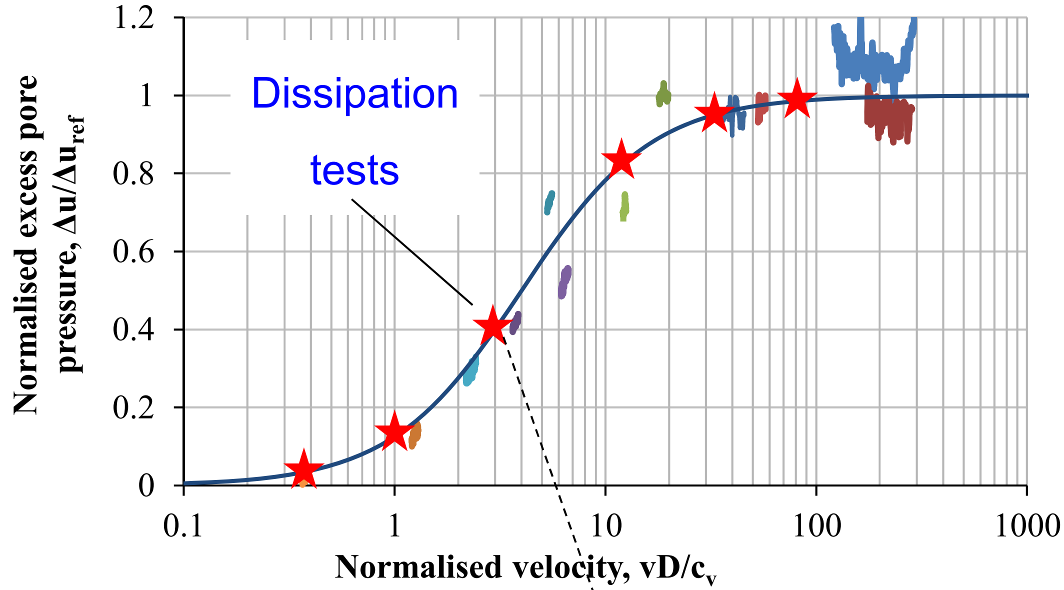
Partial consolidation effects – experimental study

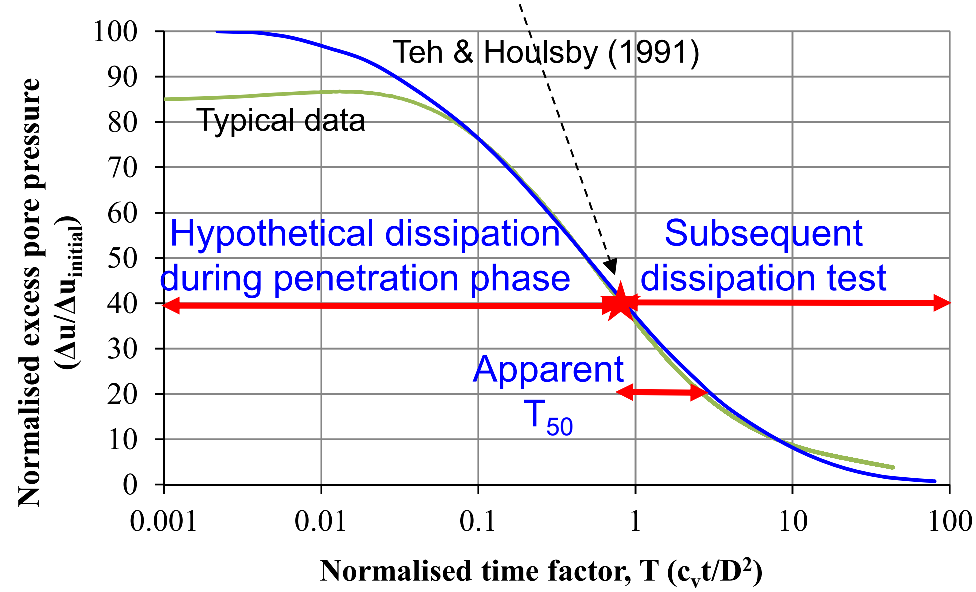
One soil type; varying velocity

- Dissipation testing after penetration phase at normalised velocity, vD/c_v
- Reduced initial excess pore pressure
- Gradual increase in t_{50} times

Simple analytical assumption

- Reduced excess pore pressure corresponds to initial phase of dissipation test
- Post-penetration dissipation leads to increased T_{50}
- Consequent under estimation of c_v





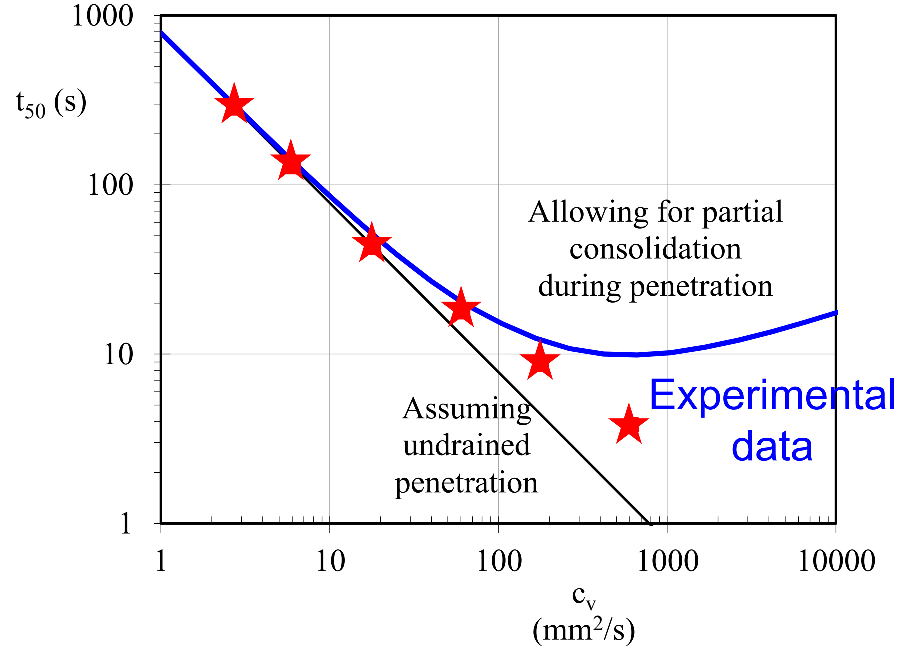
Partial consolidation effects – theory & experiment

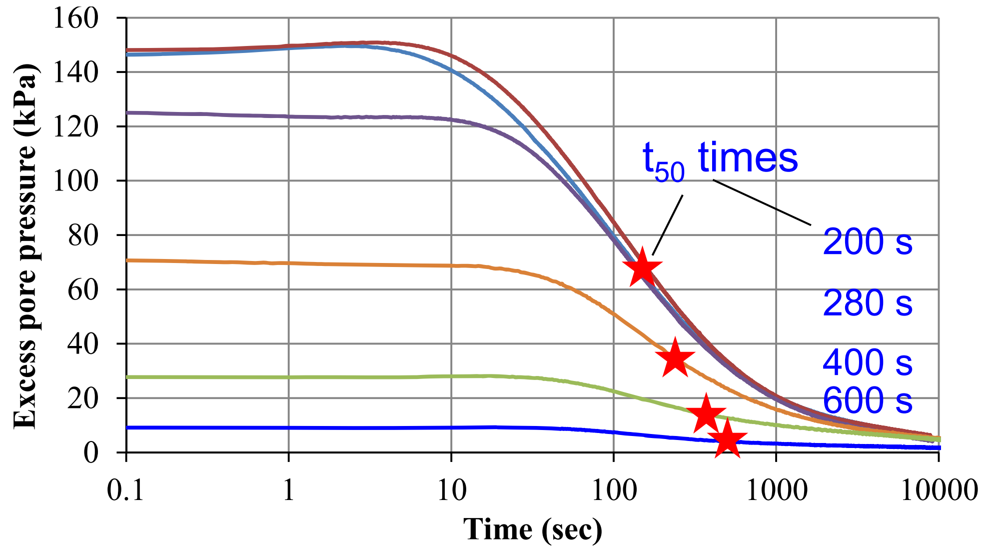
Theoretical approach

- Ignoring partial consolidation effects gives c_v inversely proportional to t_{50}
- Assuming all dissipation part of same theoretical curve gives apparent lower limit to t_{50}

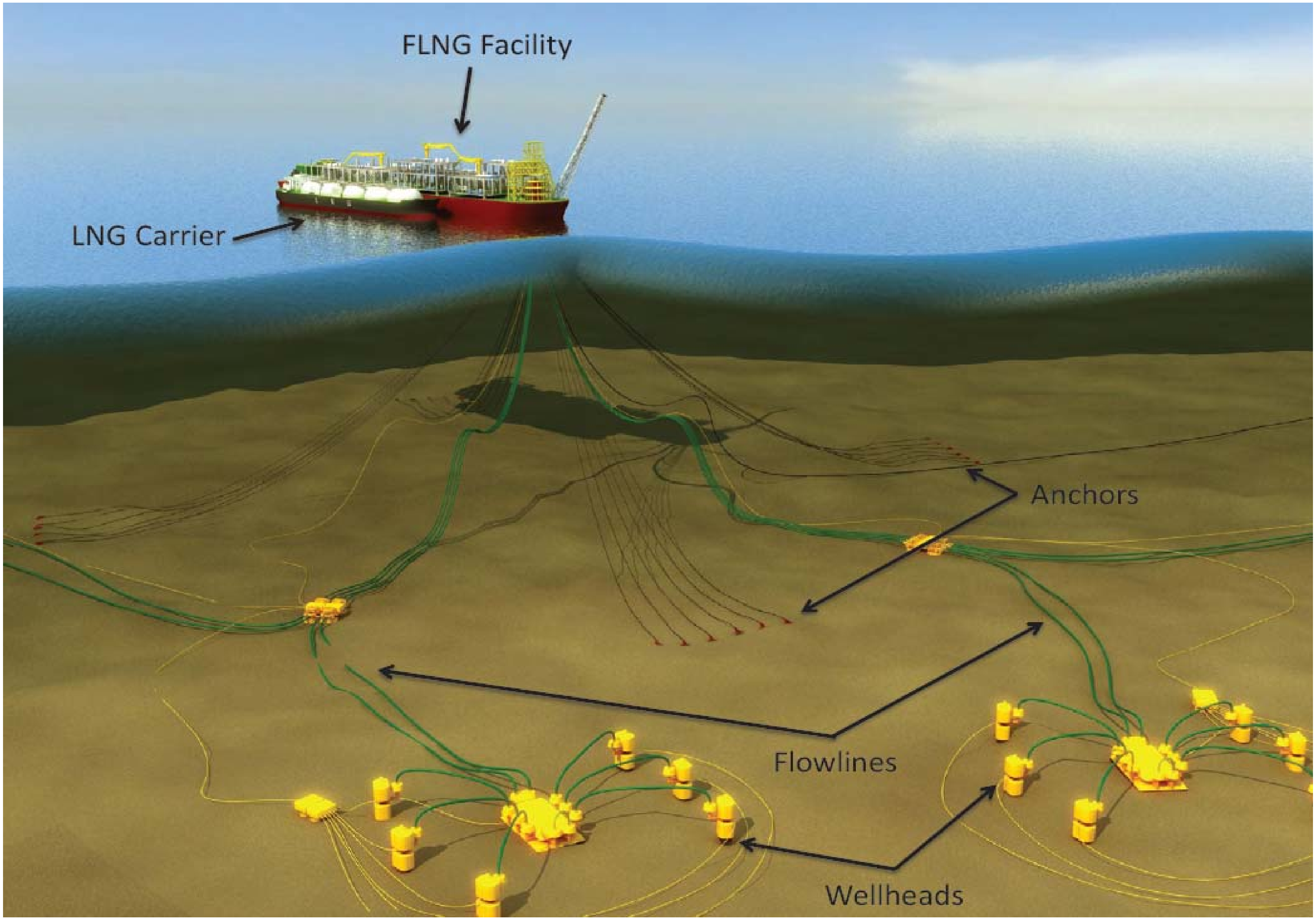
Experimental data

- Observed (up to) 3-fold increase in t_{50}
- Experimental data fall between above two assumptions
- Need revised theory!





Pipeline geotechnical engineering



Deep water pipeline geotechnical design issues

Infrastructure

- Pipeline: laid directly on seabed, possibly with concrete weight coating
- Pipeline initiation, anchoring and manifold systems

Embedment in seabed

- Pivotal for lateral stability, lateral buckling analysis, axial sliding
- Pipe lay dynamics has major impact on embedment
- Need combination of analytical solutions and empirical adjustments

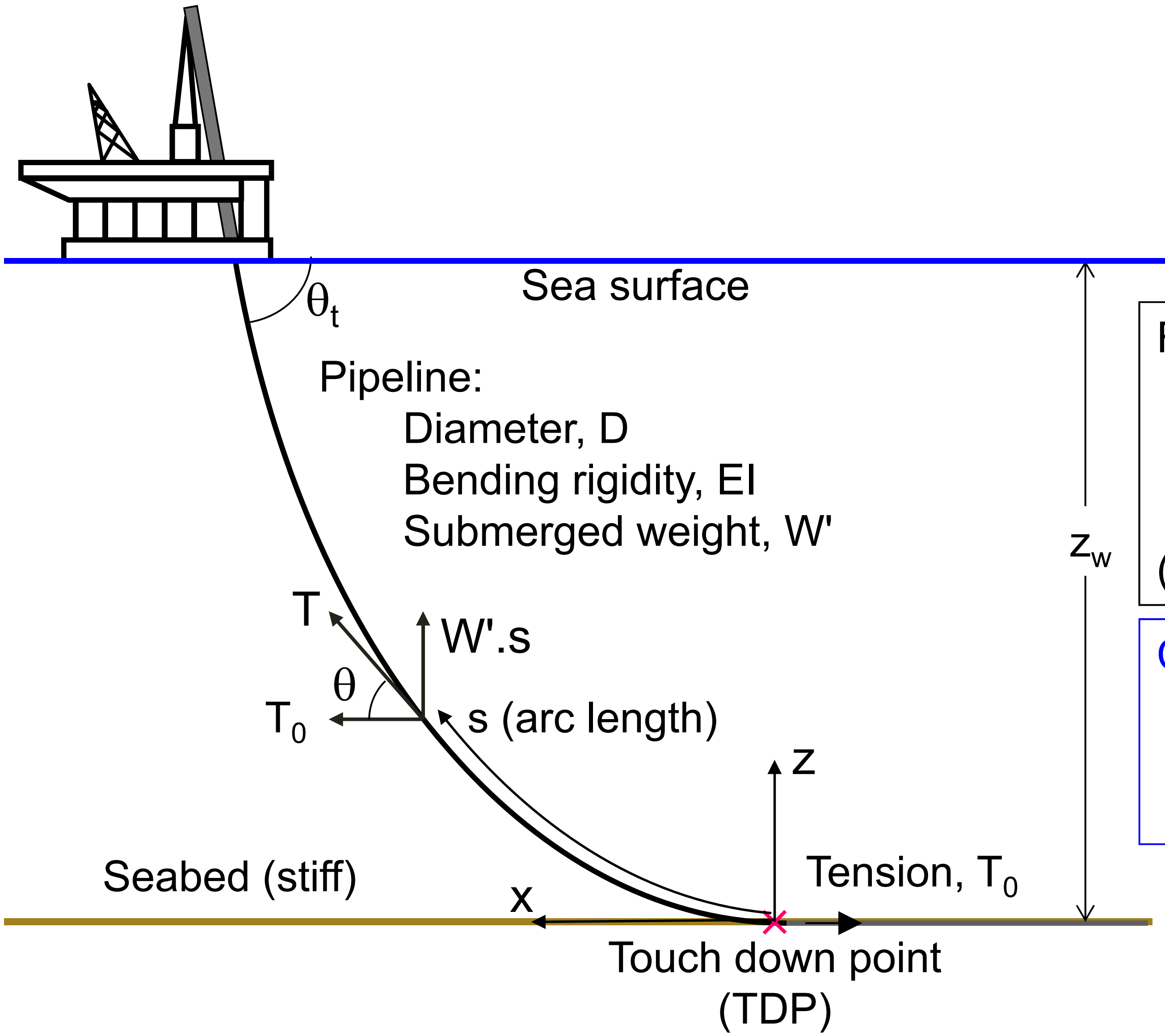
Lateral stability

- Breakout resistance, post-breakout residual resistance

Axial friction

- Large range depending on drainage conditions, hence velocity and time scale of movement

Pipeline geometry and key parameters



From equilibrium:

T_x constant (T_0)

T_z = W'.s

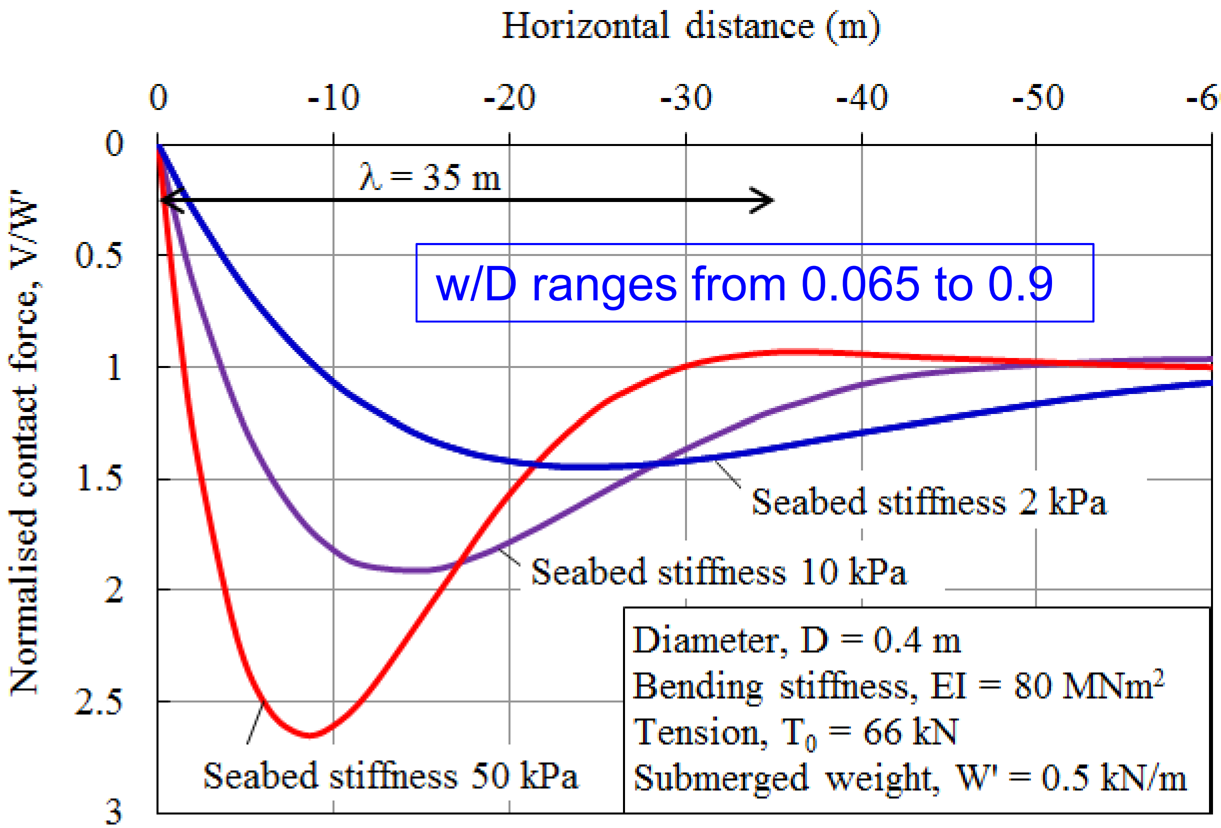
(cumulative pipe weight)

Characteristic length

$$\lambda = \sqrt{\frac{EI}{T_0}}$$

Pipeline embedment – quick estimate

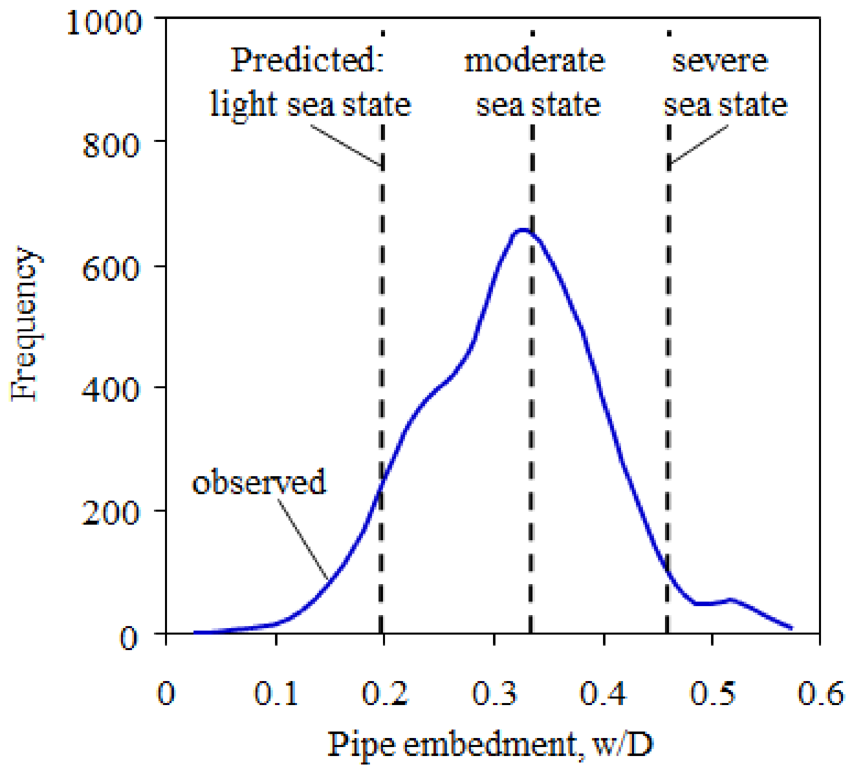
- Linear seabed strength gradient (upper 0.5 m): $s_u = \rho z$ kPa
  - Seabed plastic 'stiffness' (V/w): $k \sim 4\rho D$
  - Dynamic lay motions remould soil: need $\rho_{rem} = \rho / S_t$
  - Allowance for buoyancy effects as pipe embeds in soil (consider γ'/ρ_{rem})



Force concentration in touchdown zone: V/W' ~ 1.4 to 2.7

Pipeline embedment – refined approach (Westgate et al.)

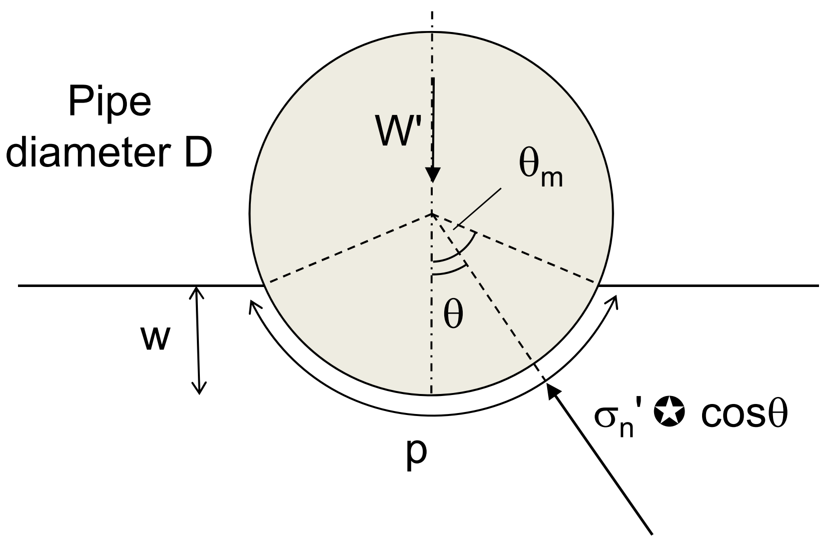
- Detailed assessment of lay-induced vertical and horizontal motions
  - Estimated lay rate, metocean conditions – hence number of exposure cycles
  - Pipeline configuration in touchdown zone (maximum dynamic vertical loads)
  - Cyclic soil degradation model from cumulative pipeline motions



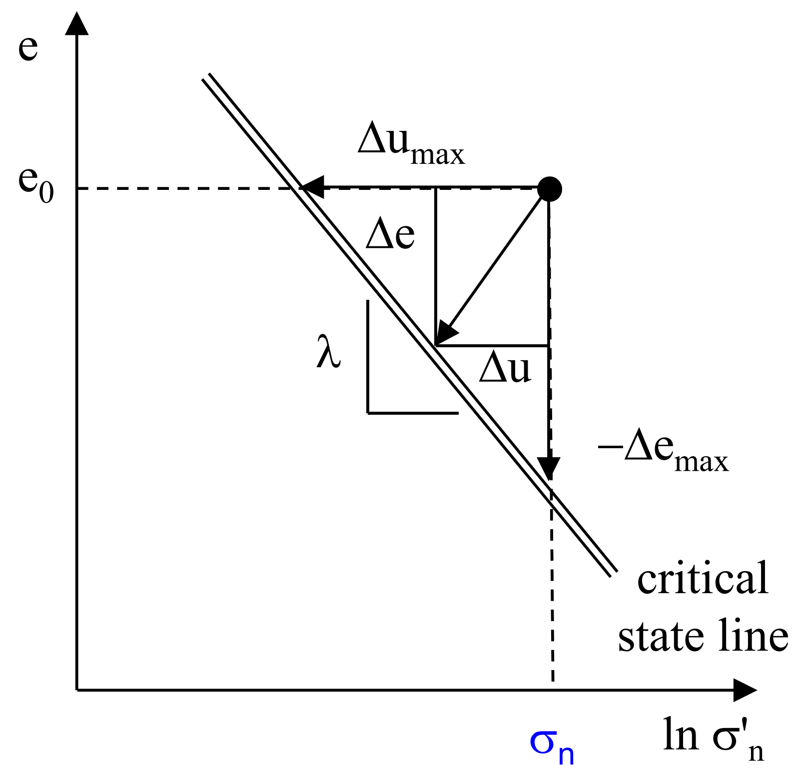
Non-deterministic estimates consistent with modern pipeline design approaches

Pipeline axial friction

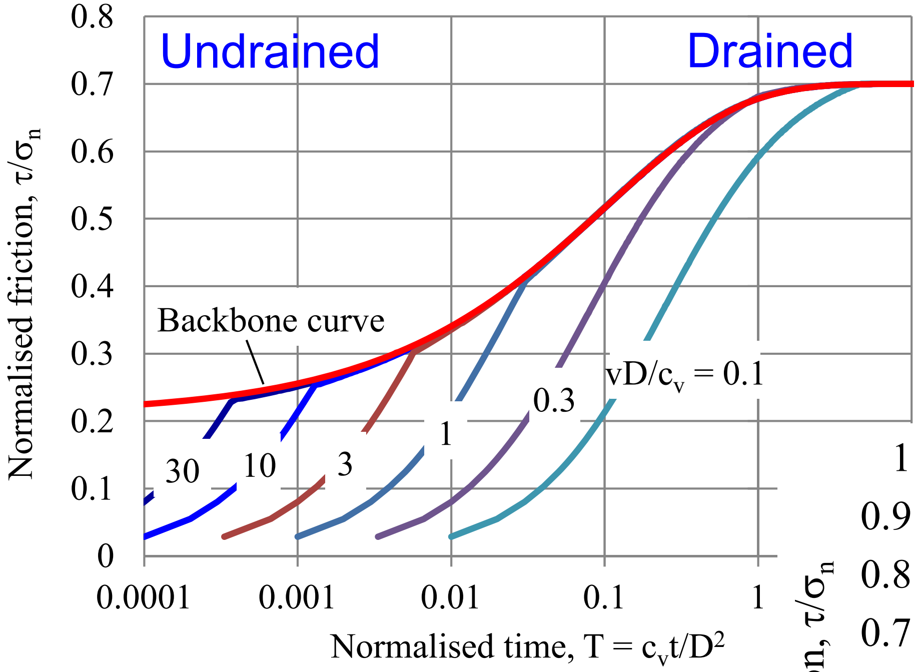
- Axial friction controlled by normal effective stress and pipe-soil roughness
  - Low effective stress level (< 5 kPa), so enhanced roughness coefficient
  - Rapid shearing results in excess pore pressures, reducing normal effective stress
  - Consolidation leads to hardening, and local reduction in soil water content



Average normal stress, σ_n, enhanced by wedging factor, $\zeta \leq 1.3$

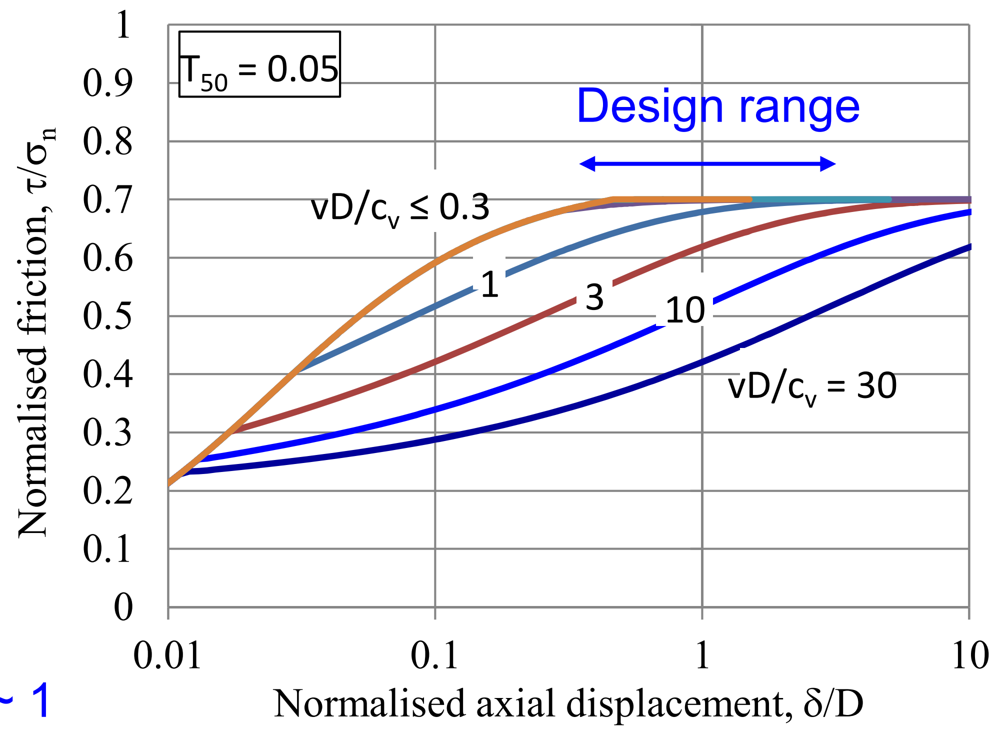


Time scale for consolidation during axial sliding



Critical state framework

- Rapid shearing leads to 'undrained' friction values
- Sustained sliding results in consolidation towards 'drained' friction



Initial excess pore pressure & friction

- Mobilisation time:

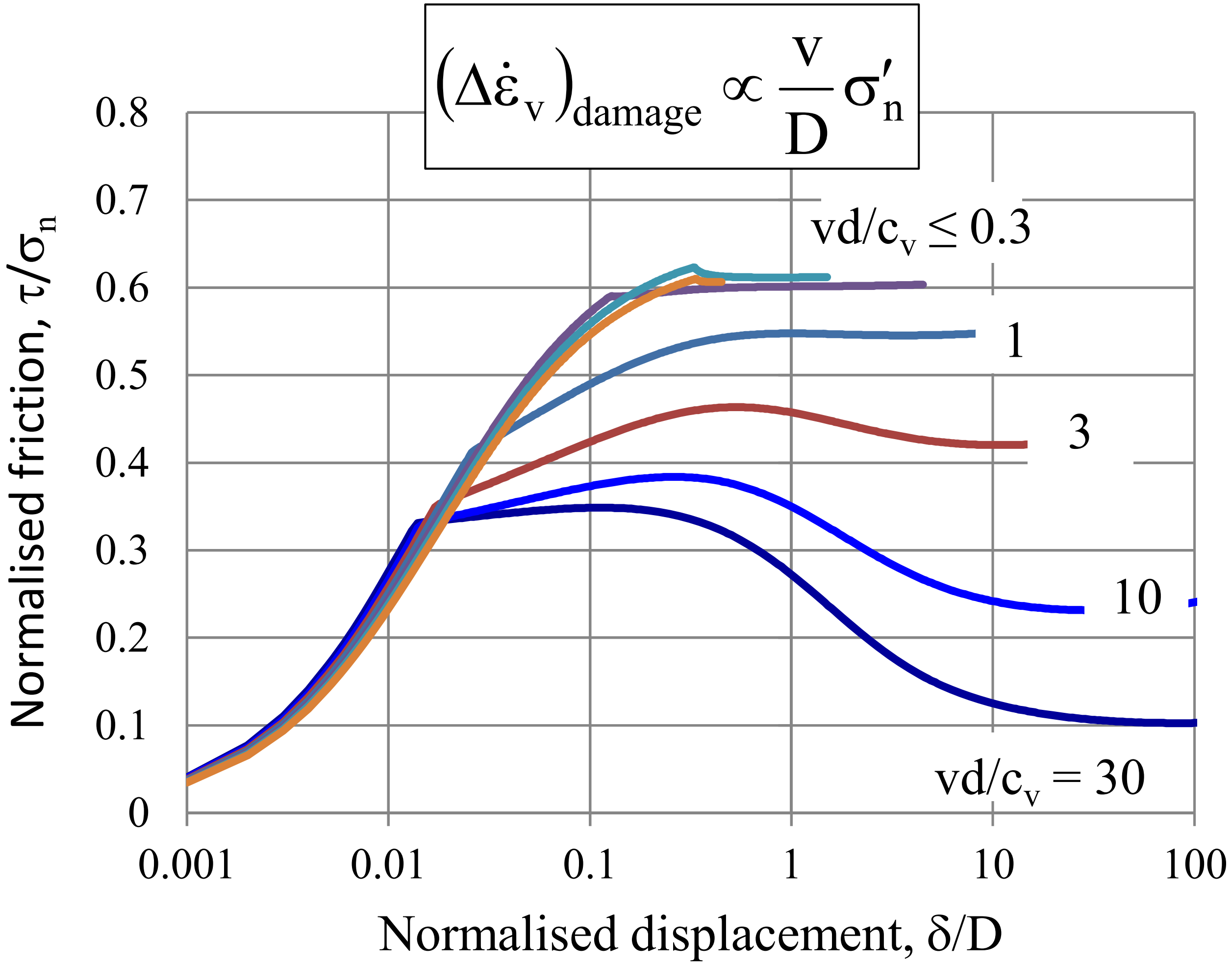
  δ_{slip}/v ✪ $c_v/vD \times \delta_{slip}/D$

- Consolidation time:

  $T_{10} \sim 0.001$; $T_{50} \sim 0.05$; $T_{90} \sim 1$

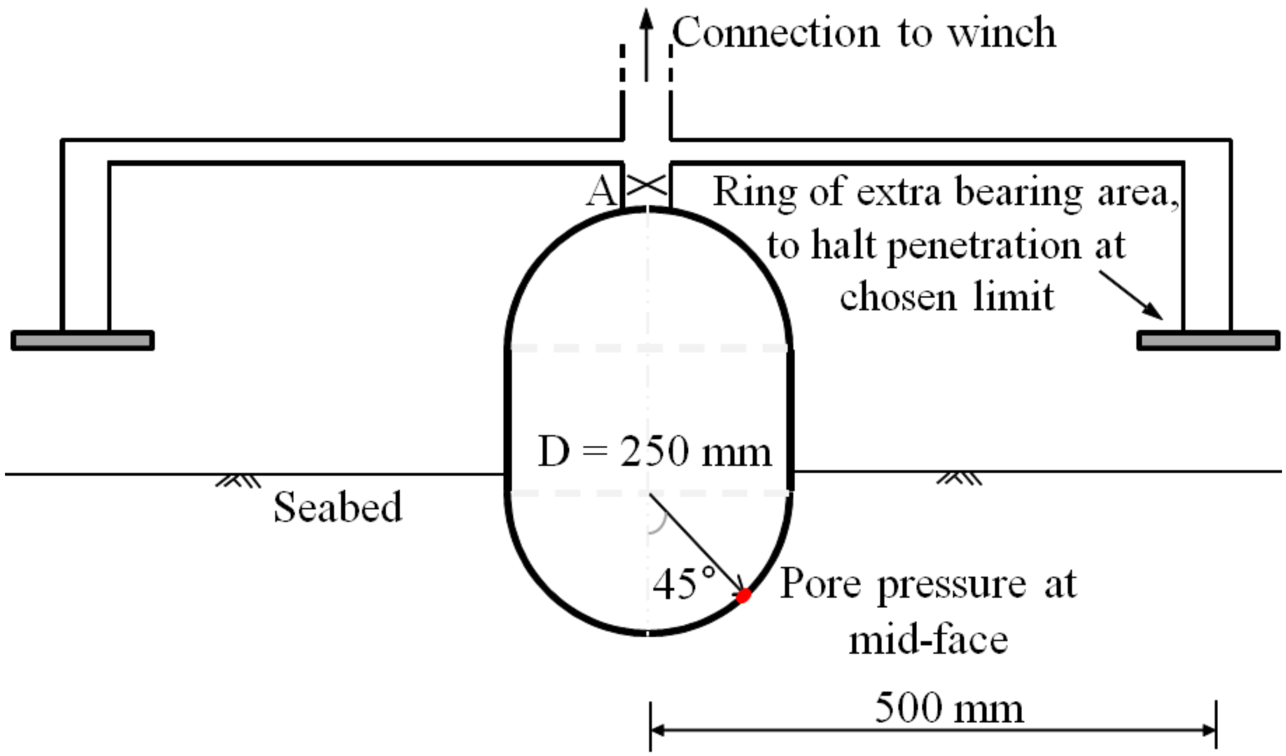
Additional effects during axial sliding

- High strain rates (v/D) enhance shearing resistance
- Sustained volumetric collapse of soil ('damage') – source of further Δu



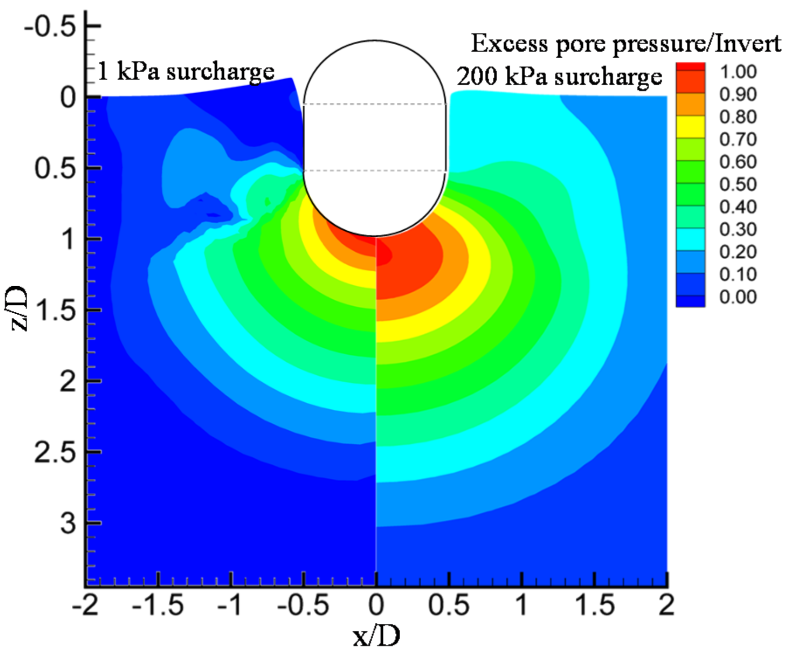
Consolidation properties at shallow depth

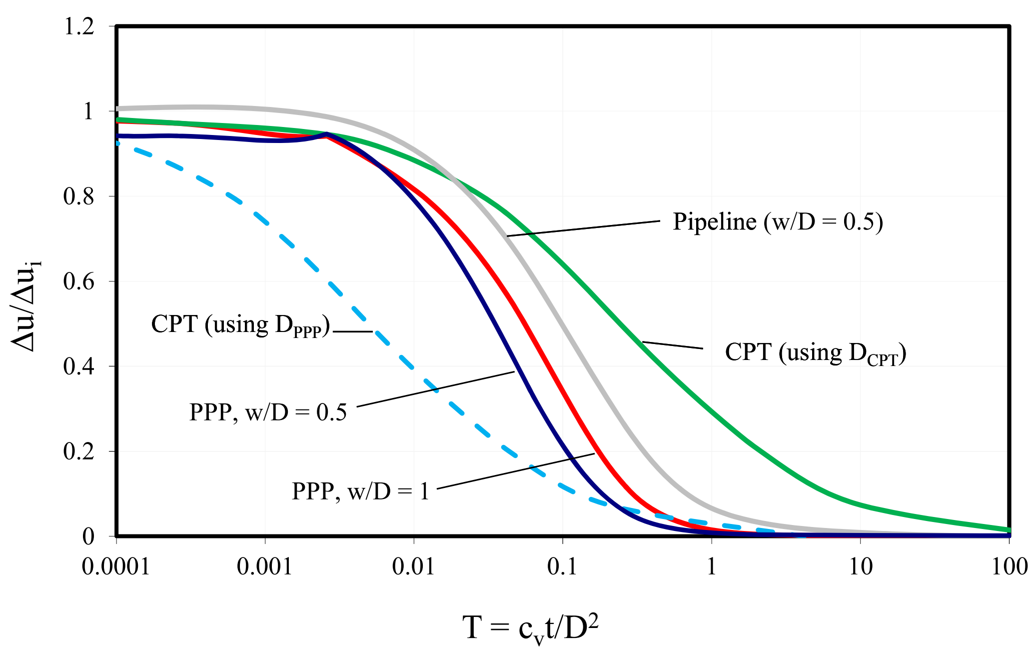
- Near surface measurement of consolidation coefficient
  - Piezocone no longer practical (shallow penetration; long dissipation times)
  - Introducing the 'parkable piezoprobe' (PPP) – offline dissipation data



LDFE analyses as basis for interpretation

- Couple Modified Cam clay large deformation FE analyses
  - Assessment of excess pore pressure field
  - Backbone consolidation curves





Concluding remarks

- Analysis underpins day to day design
  - Direct application of solutions
  - Planning of studies based on physical or numerical modelling
  - Empirical correlations: a challenge to capture analytically
- Simplicity a guiding light
  - Dimensional analysis
  - Idealisation of analytical models and input
  - Synthesis of outcomes – especially from numerical studies
  - Field and laboratory data vital: validation and adjustment of models

All is worthless without understanding!

Acknowledgements

- Colleagues and collaborators throughout the world, but particularly at
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  - Advanced Geomechanics
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- Mentors throughout my career