Foundation Optimisation for Ever Larger Offshore Wind Turbines: Geotechnical Perspective

Scott Whyte

OFFSHORE WIND OVERVIEW

Offshore Wind Industry

- Offshore wind power costs have dramatically dropped over last few years ≈£150/MWh (2015) to ≈ £58/MWh (2017)
- Exciting time for engineers within offshore renewable industry
- Foundation design optimisation significant component of price CAPEX reduction


The Telegraph
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Business
Cut-throat competition is slashing offshore wind costs to unthinkable levels
AMBROSE EVANS-PRITCHARD
2 OCTOBER 2016 • 7:30PM


Windpower ENGINEERING & DEVELOPMENT
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UK offshore wind reaches price parity with fossil fuels
September 15, 2017 Michelle Froese : 0 Comments
Three new wind farms are to be built in the UK as offshore wind prices reach their lowest levels ever. This f research published by Lloyd's Register in February 2017, revealing that the majority of industry experts we confident that renewable energy was reaching cost parity.
In the latest Contracts for Difference (CfD) round, DONG Energy, Innogy, and EDPR have been awarded licenses to build new wind farms in the UK– and the cost of offshore wind has fallen by 50% since 2015.
Wind farm developers submit bids to build new wind farms and the Government awards


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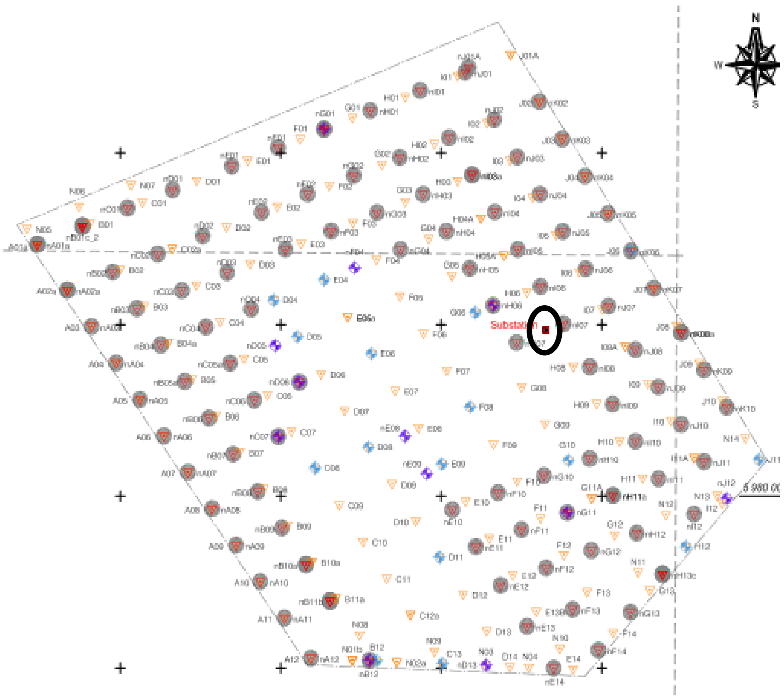
By Roger Harrabin
BBC environment analyst
11 September 2017

Challenge

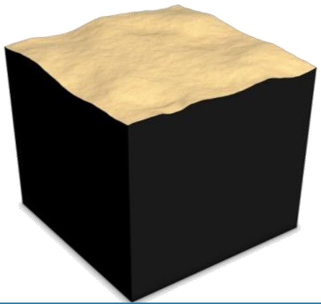


- Larger areas = potential of soil variability at turbine locations
- Different engineering considerations
- Significant pressure to reduce cost

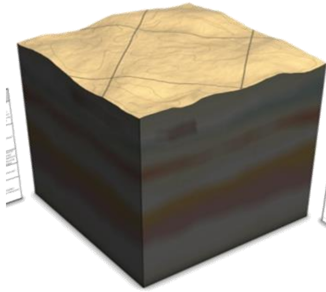
Overcome challenges - fully informed ground model coupled with innovative analysis design methods

Offshore Wind Site Characterisation and Ground Model Development

Marine Windfarm Life Cycle



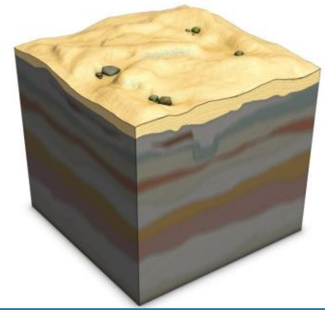
Project Identification



Desktop Study
(Creation of Ground Model)

Typical 3-6 months to evaluate geological, UXO, environmental and geotechnical constraints at the site

Risk based approach



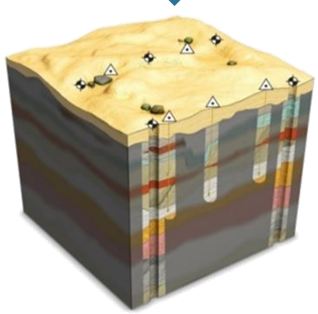
Preliminary Site Characterisation

Typical 1-2 Years, including Metocean, Environmental, Geotechnical and Geophysical Survey

Feasibility Study

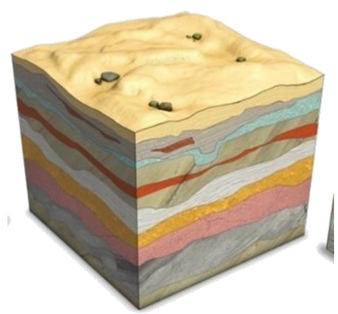
Typical 6 months, including date interpretation and foundation selection

Definition of Appropriate Technical Specification



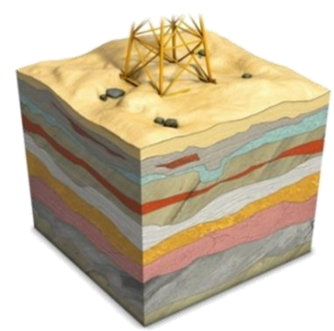
Detailed Geotechnical & Geophysical Investigation for Cable Route and Foundation

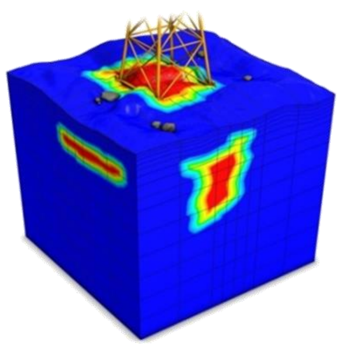
Typical 6 months



Data Interpretation & Upgrade Ground Model

Typical 3 months

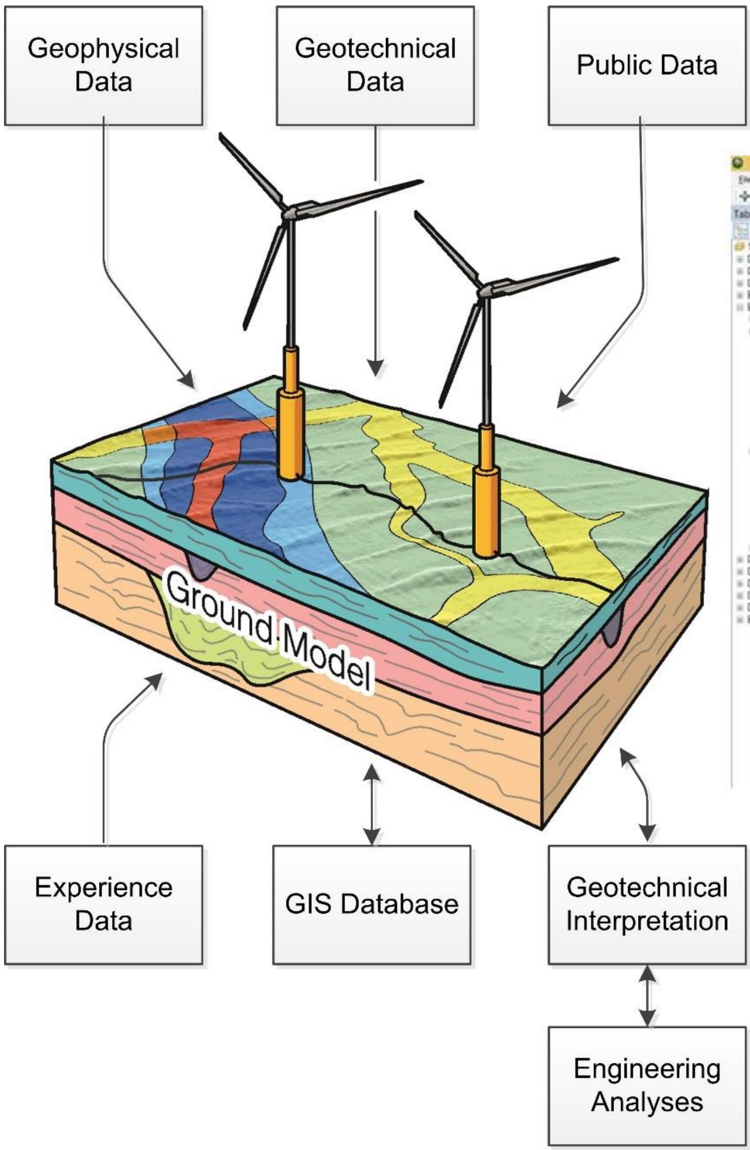


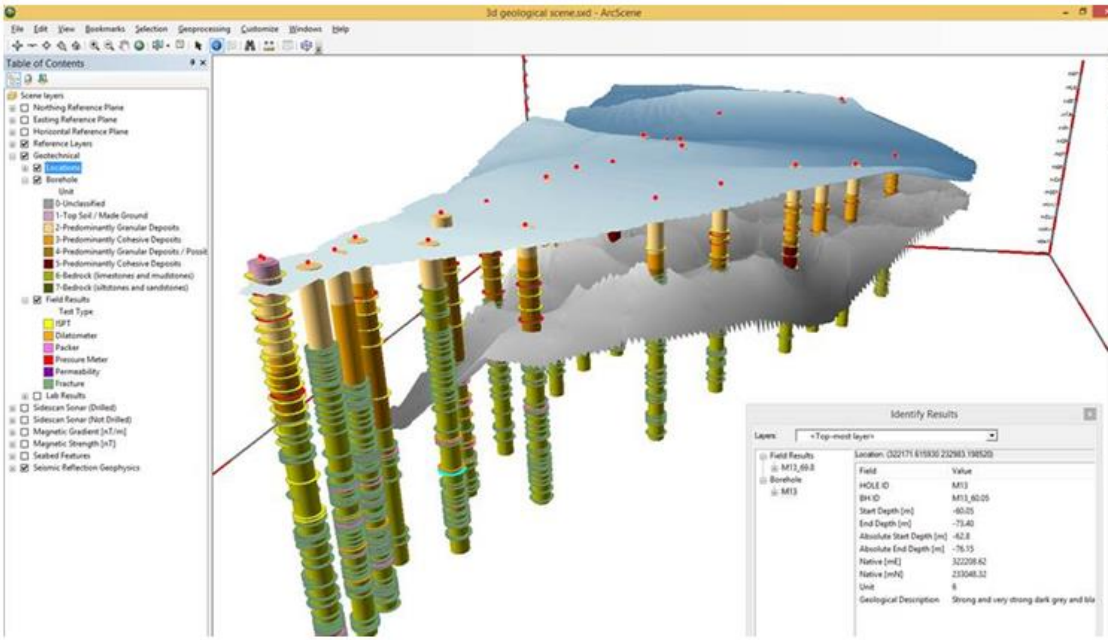


Detailed Engineering

Typical 4-6 months

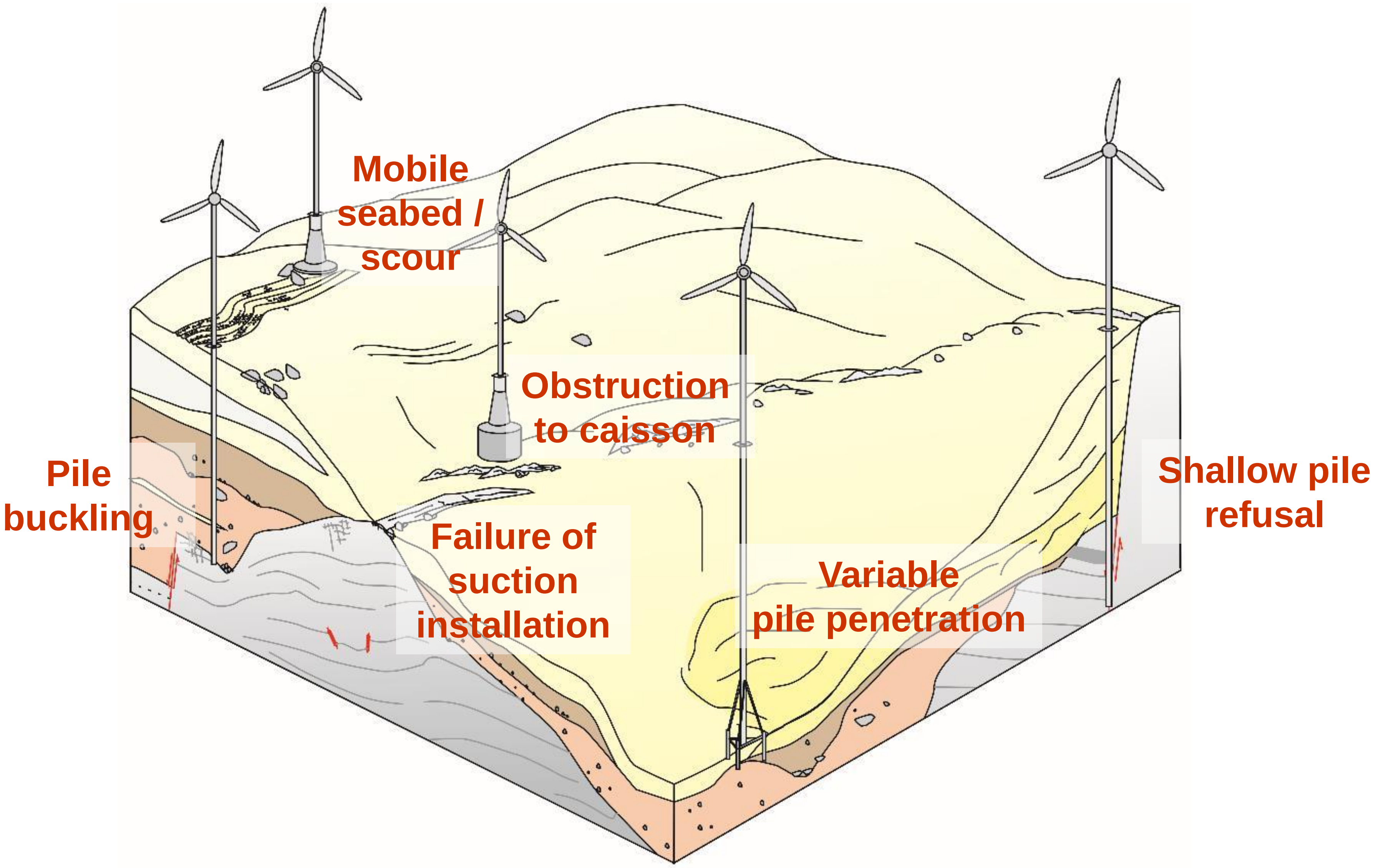
Integrated Ground Model





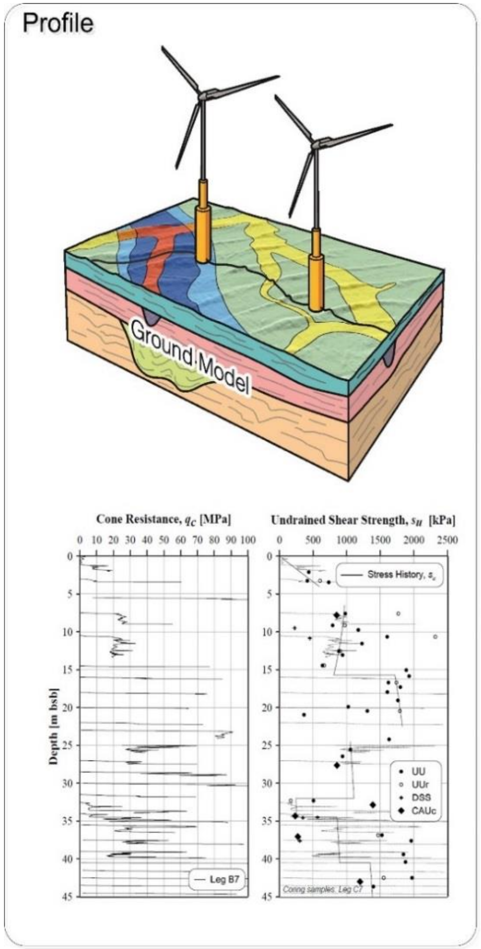
From Ground Model to Design

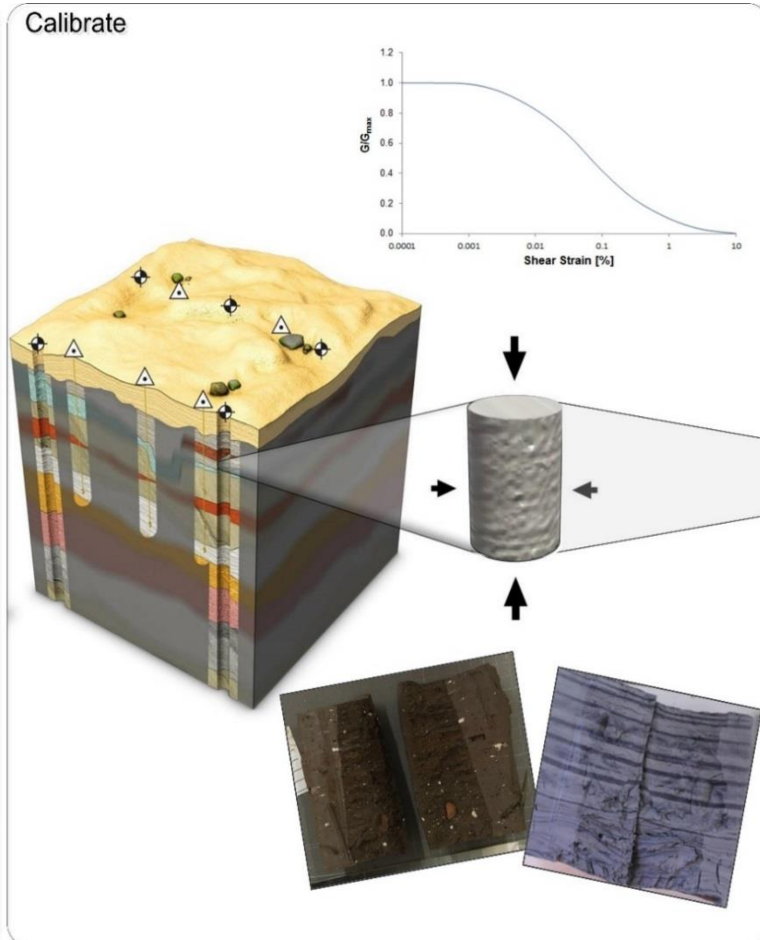
Foundation Constraints

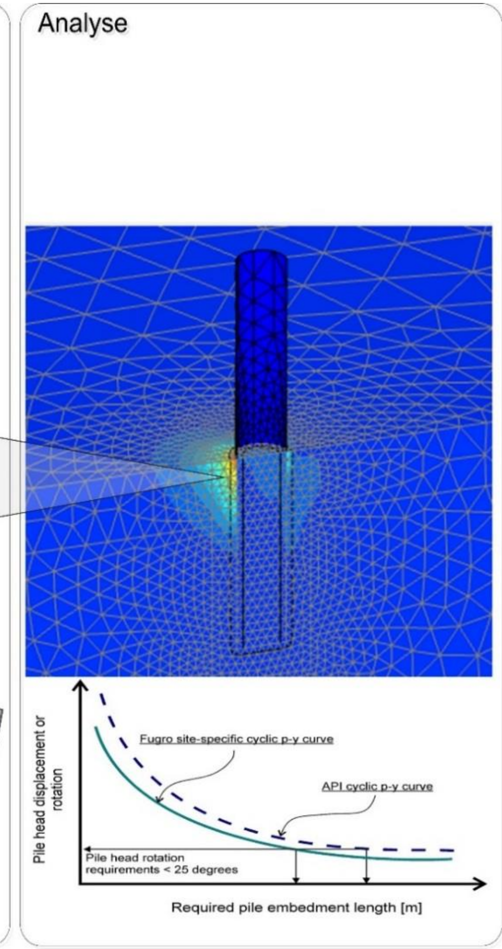


Geotechnical Design Process

Important that all stages performed together







- Site Investigation
- Laboratory Testing
- Ground Model Development

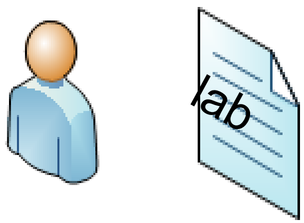
- Calibrate Suitable Models

Advanced Analysis

Optimisation

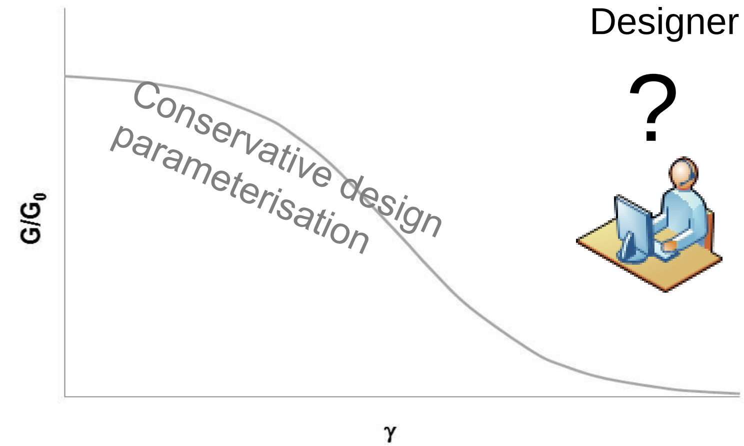
Pile Length/Diameter

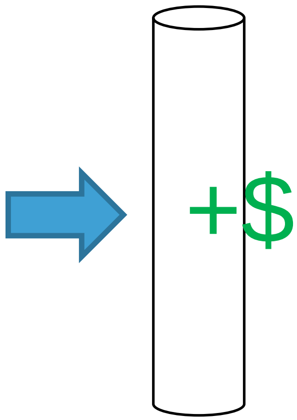
Contractor



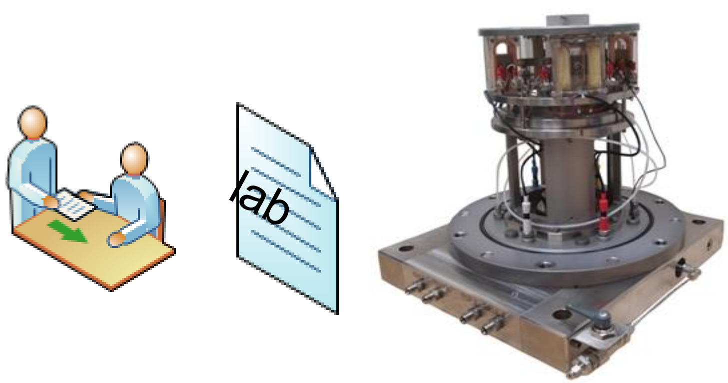
No small-strain lab testing

Designer

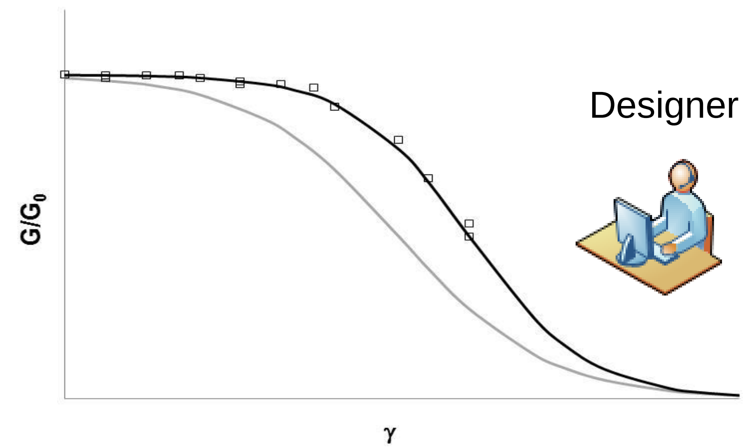


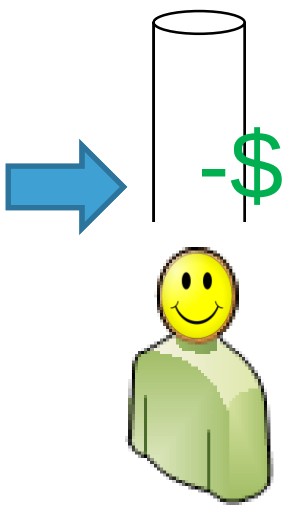


Contractor
& Designer



Designer





Geotechnical Modelling and Design

Important Note on Geotechnical Modelling!

Computers and Geotechnics 93 (2018) 269–279

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Insights from a shallow foundation load-settlement prediction exercise

J.P. Doherty [a,*], S. Gourvenec [b], F.M. Gaone [b]

[a] School of Civil, Environmental and Mining Engineering, The University of Western Australia, 35 Stirling Hwy, Crawley, WA 6009, Australia
[b] Centre for Offshore Foundation Systems and the ARC Centre of Excellence for Geotechnical Science and Engineering, The University of Western Australia, Crawley, WA, Australia

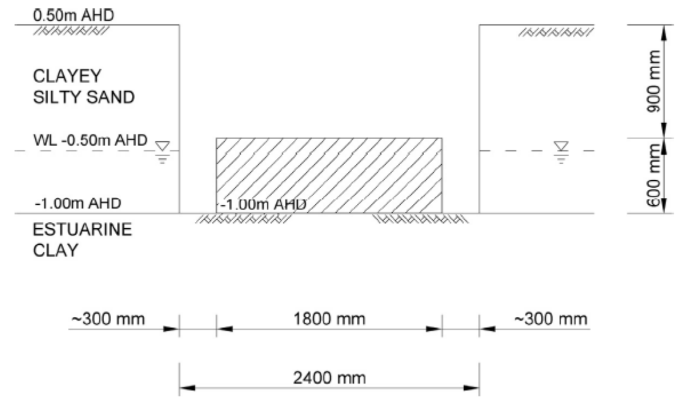
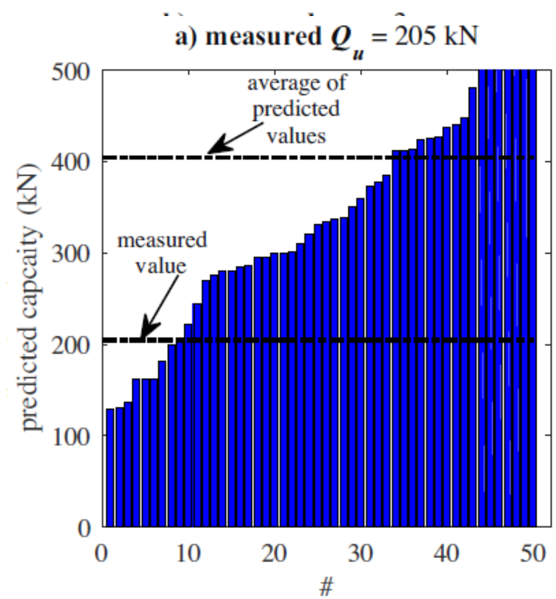


Fig. 4. Foundation geometry.

- *50 participants in recent shallow foundation prediction event (23 were from industry practitioners, 16 from academics and 11 from undergraduate students)*
- *All participants in prediction event given the same site investigation data (high quality lab test and in situ data provided);*
- *No correlation between calculation method/model used and accuracy of prediction*
- *Highlight importance of engineering judgement*



Offshore Wind Foundation Design

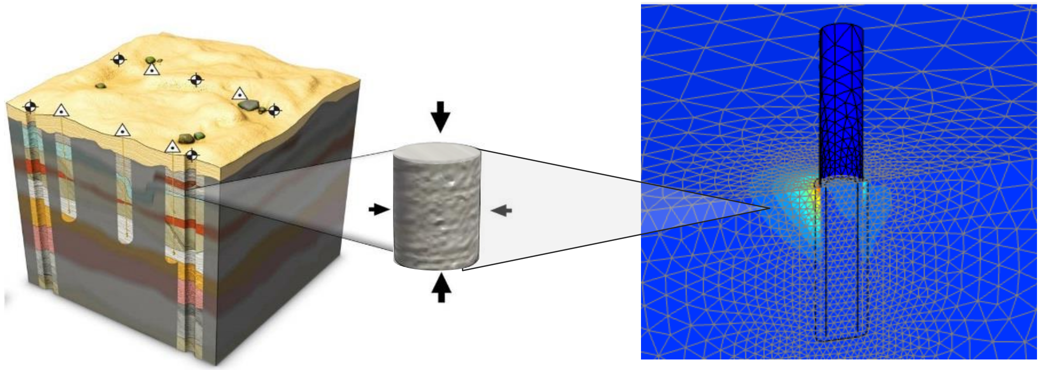
Jackets

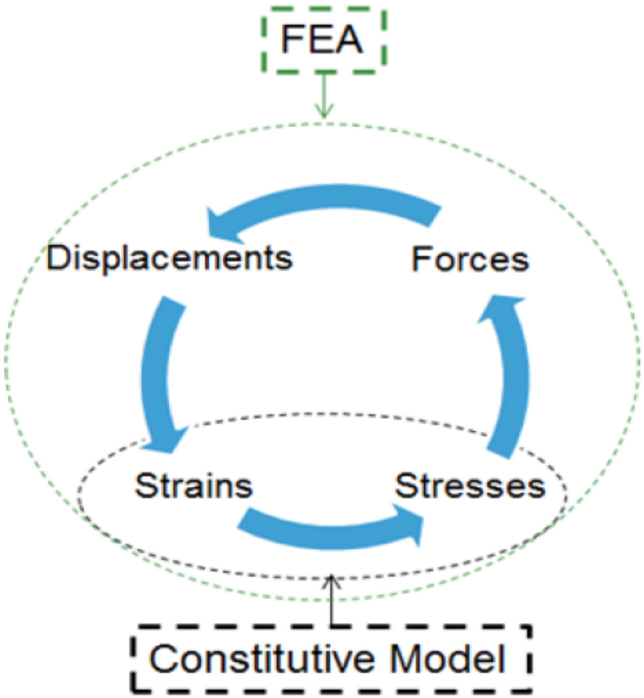
Gravity Base Foundations

Monopiles

Constitutive Modelling for FEA

- Finite Element Analysis (FEA) typically utilised for offshore wind turbine foundation design
- Constitutive model is a pivotal part of any FEA calculation





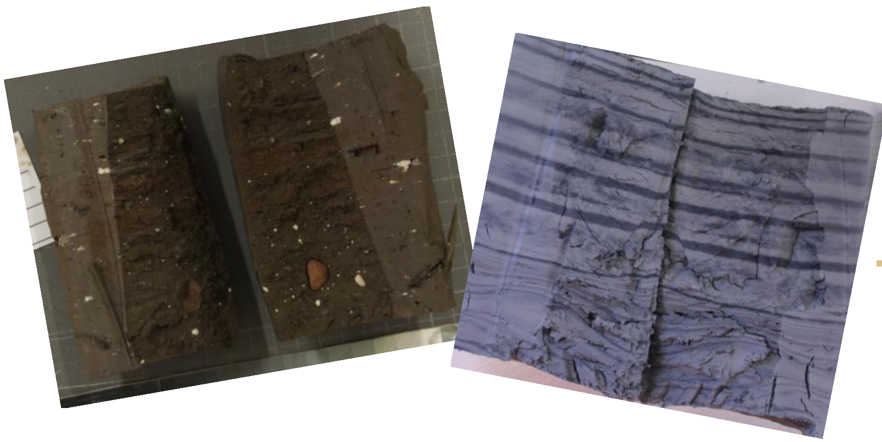
What is a constitutive model?

> *The constitutive model is a mathematical representation of the mechanical behaviour of the soil and is fundamental part of FEA of a geotechnical problem.*

The complexity of real soil behaviour

The in situ behaviour of real soil is very complex and governed by many factors such as:

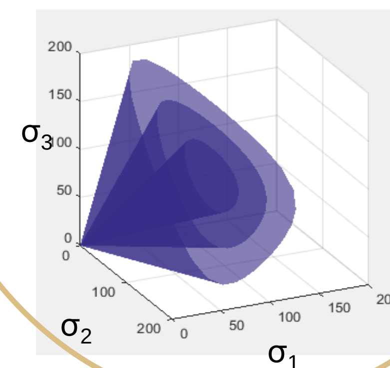
- Soil type;
- Stress history;
- Depositional environment.



$$\{\Delta\sigma\} = [D^{ep}]\{\Delta\varepsilon\}$$

$$[D^{ep}] = [D^{e}] - \frac{[D^{e}]\left\{\frac{\partial G}{\partial \sigma}\right\}\left\{\frac{\partial F}{\partial \sigma}\right\}^{T}[D^{e}]}{\left\{\frac{\partial F}{\partial \sigma}\right\}^{T}[D^{e}]\left\{\frac{\partial G}{\partial \sigma}\right\} + A}$$

$$A = -\frac{1}{\Lambda}\left\{\frac{\partial F}{\partial k}\right\}^{T}\Delta k$$



Given the complexity of real soil, a single all-encompassing constitutive model is not feasible.

Hence there is a need to highlight the salient features of the soil behaviour depending on the geotechnical problem and soil type

Constitutive Modelling for FEA

Google Scholar | constitutive model soil

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R Nova, DM Wood - **Soil** mechanics-transient and cyclic loading, 1982 - Wiley, New York
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Yield criterion and elasto-plastic damage **constitutive model** for frozen sandy **soil**
Y Lai, L Jin, X Chang - International Journal of Plasticity, 2009 - Elsevier
Abstract A series of triaxial compression tests was carried out on a frozen sandy **soil** under confining pressures of 0–18 MPa at− 6° C. The experimental results indicate that, the strength of frozen sandy **soil** increases versus the increase in the confining pressures when
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AJ Whittle - Geotechnique, 1993 - icevirtuallibrary.com
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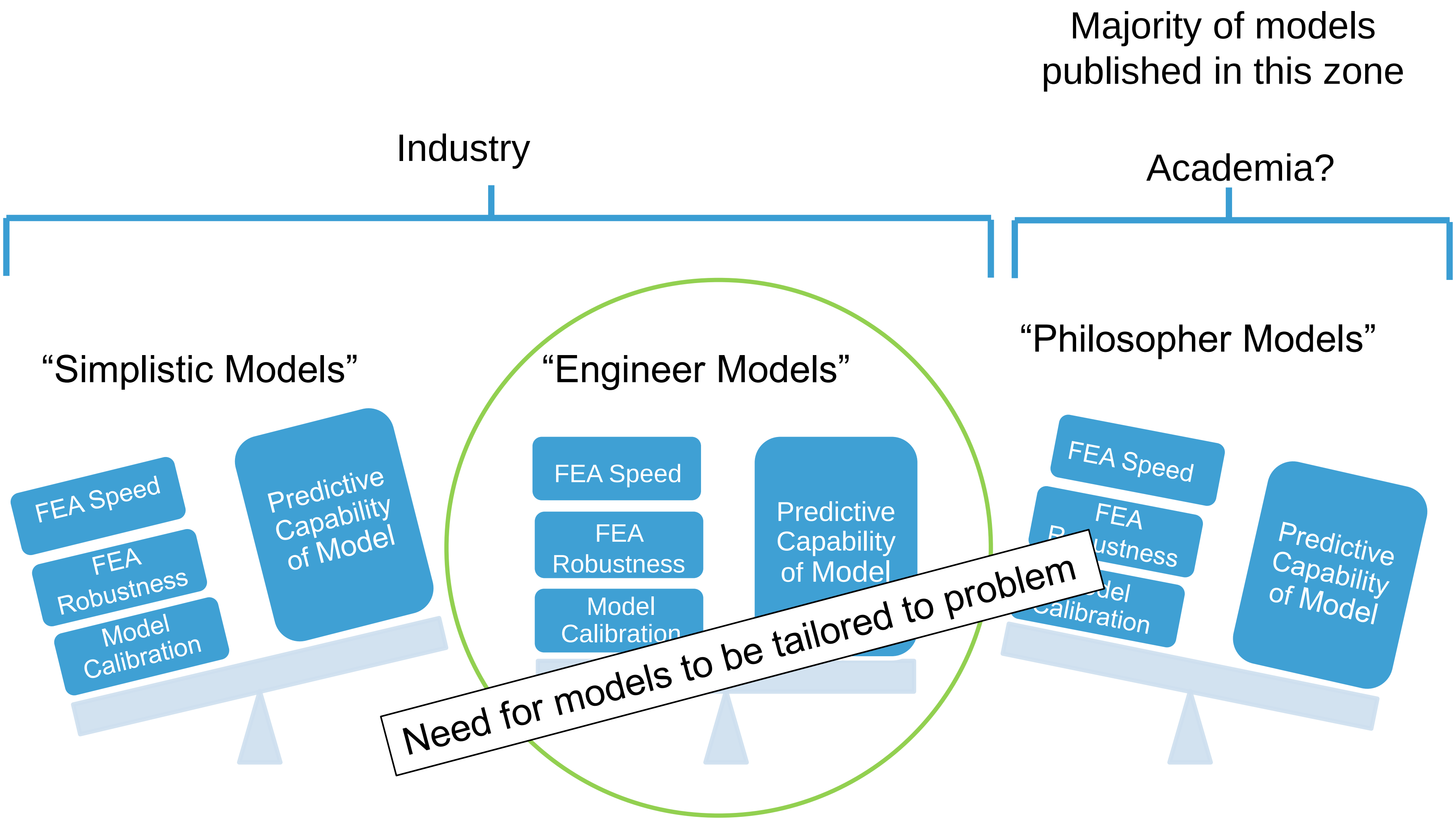
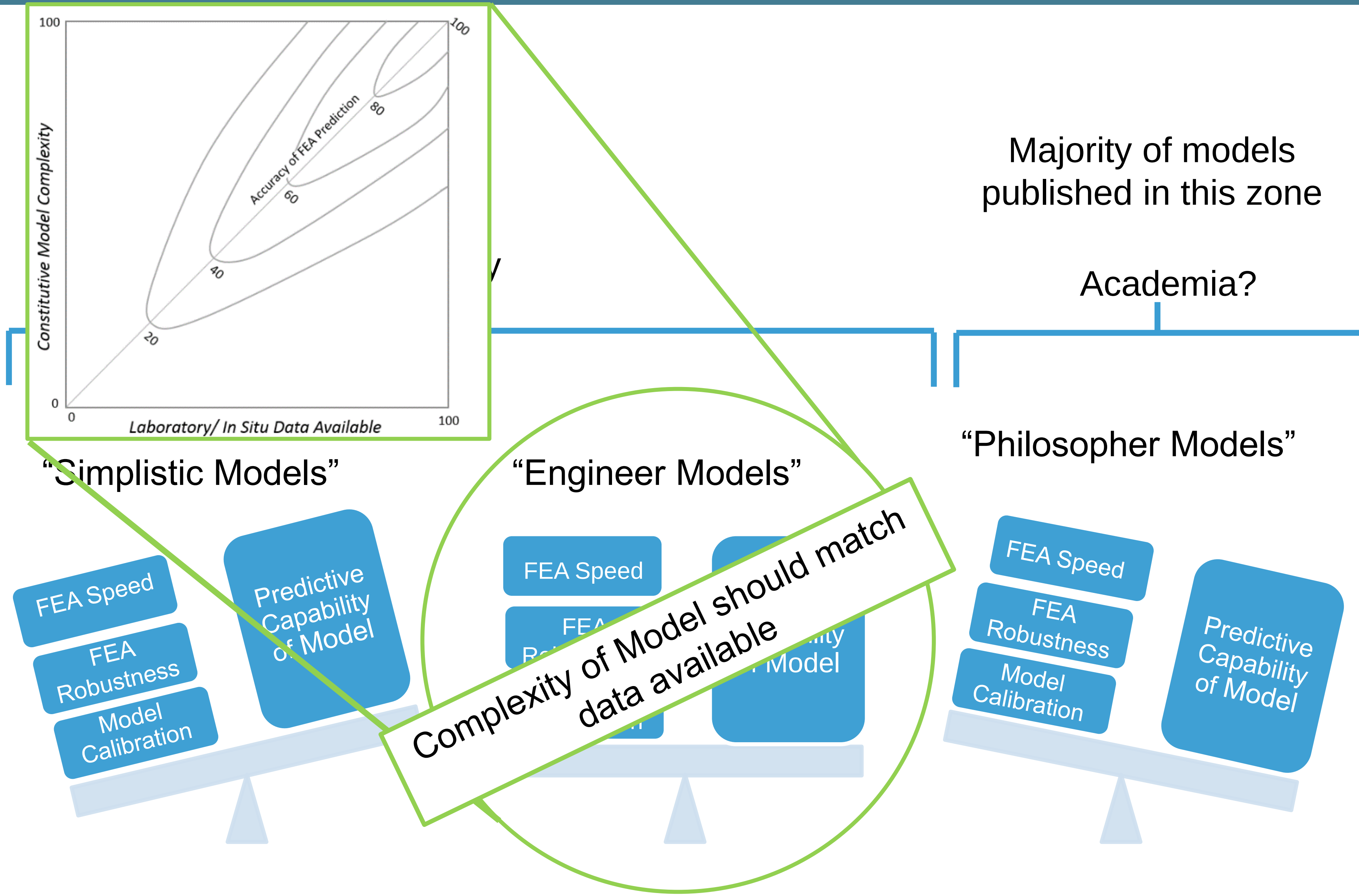
Constitutive Modelling for FEA

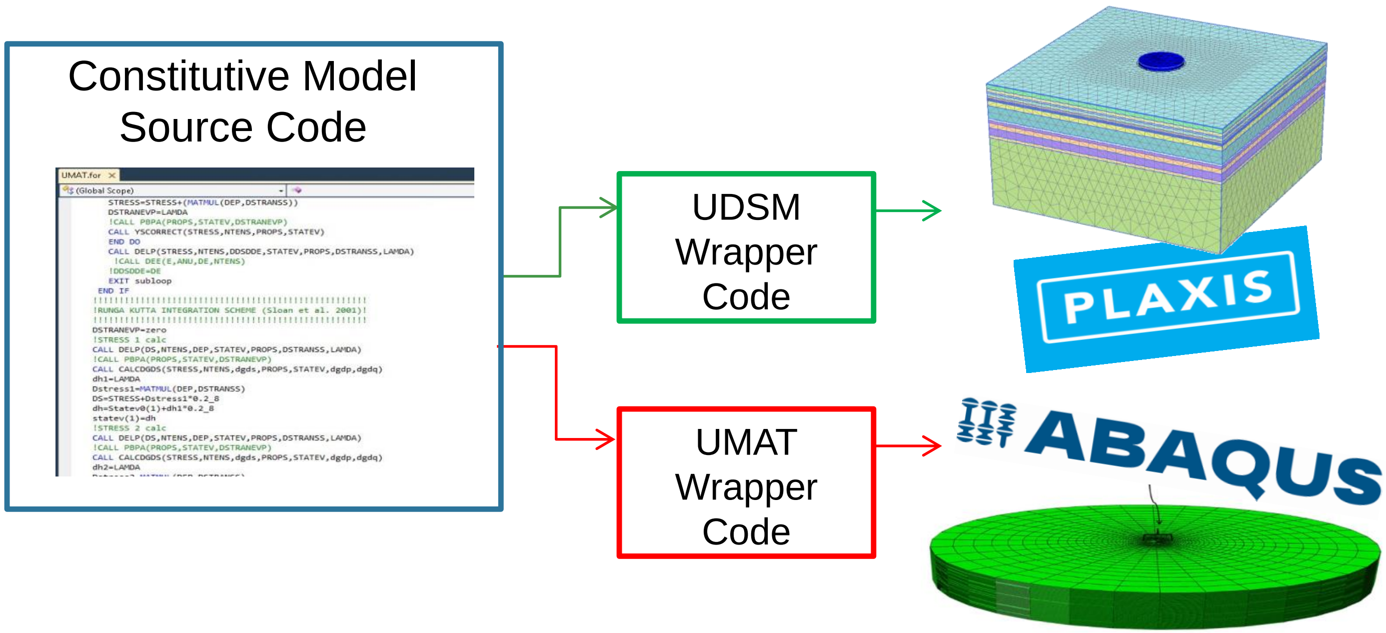


Constitutive Modelling for FEA



Implementation of Model

- Rigorous robust implementation of a bespoke constitutive model within commercial FEA packages is not a trivial task;
- Need to develop rigorous stress point algorithms (e.g. Sloan et al. 2001);

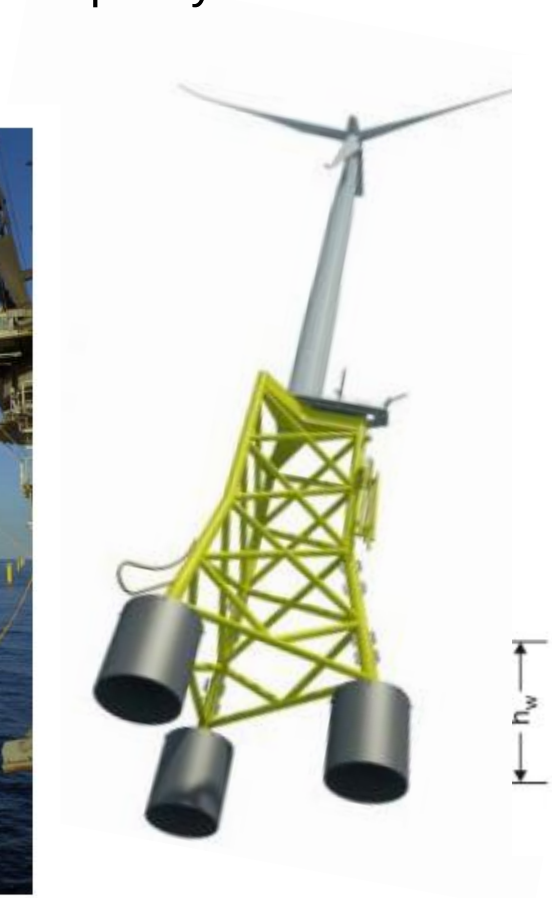


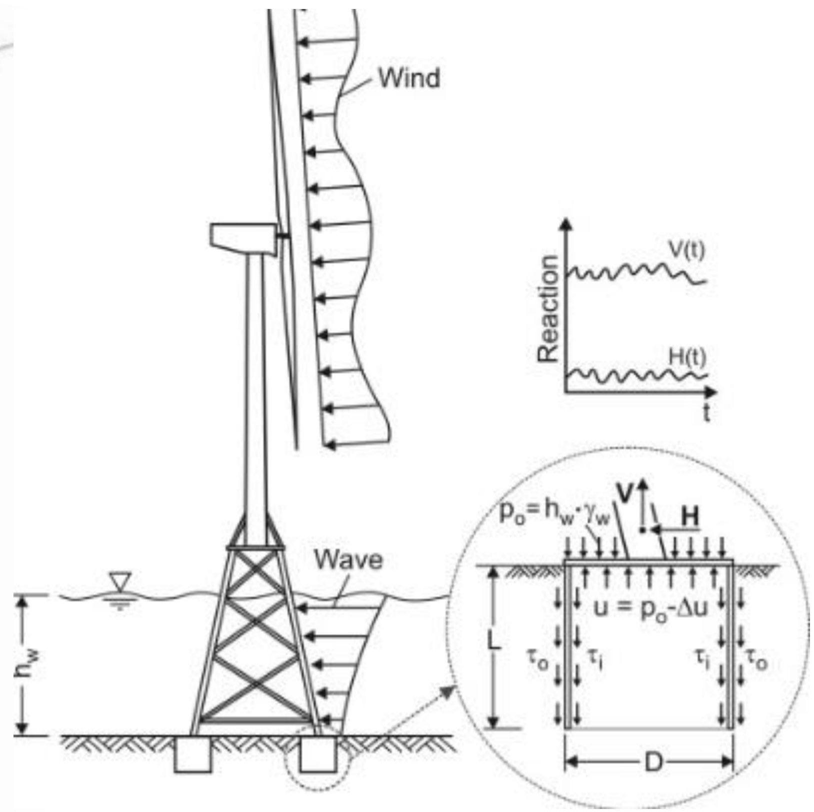
FEA of Suction Bucket in Sand Example

Suction Bucket under Tension Loading FEA

Multi-pod Suction Bucket Design

- Push-pull mechanism;
- Tension loading design considerations very important;
- How much tension capacity can be mobilised in sand?

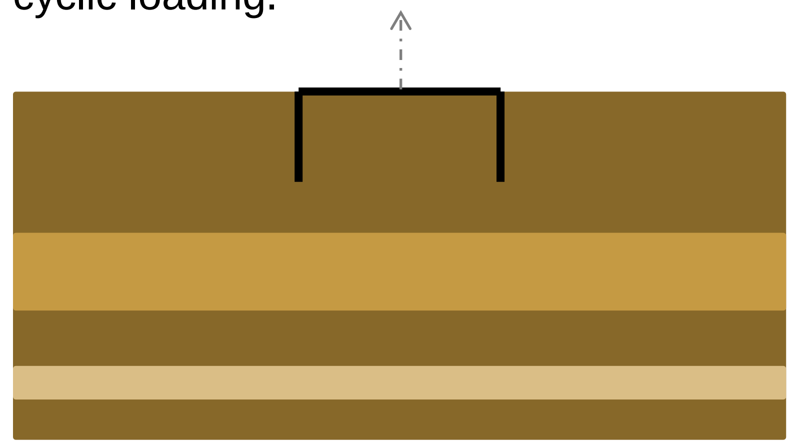




Thieken et al. (2014)

FEA and Development of Bespoke Consitutive Model Example

Scope of work: Investigate the bearing behaviour of a suction bucket foundation under tensile load and consider potential for upward ratcheting under cyclic loading.

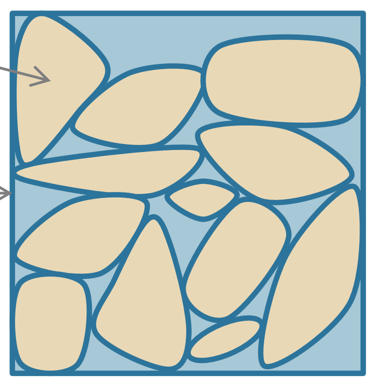


Important notes for constitutive model selection:

- Dense slightly silty fine SAND soil profile;
- soil is strongly dilatational during shearing;
- under storm loading rates the soil likely to behave undrained to partially-drained;
- effect of dilatancy manifesting as negative excess pore pressures pivotal

Soil particles

Pore pressure in voids



$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - u\boldsymbol{I}$$

$\boldsymbol{\sigma}$ = total stress tensor

u = pore pressure

$\boldsymbol{I}$ = unit matrix

During rapid loading the tendency for volumetric expansion is resisted by suctions generated due to the incompressible nature of water which results in a significant increase in the effective stress and in turn the mobilised strength.

FEA and Development of Bespoke Consitutive Model Example

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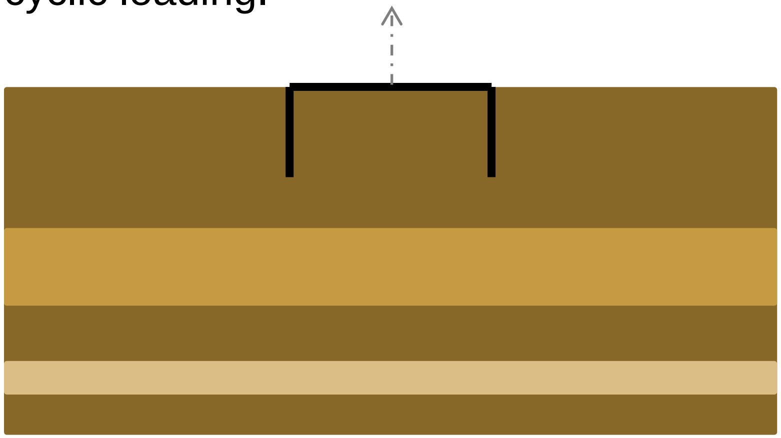

Important notes for constitutive model selection:

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- effect of dilatancy manifesting as negative excess pore pressures pivotal

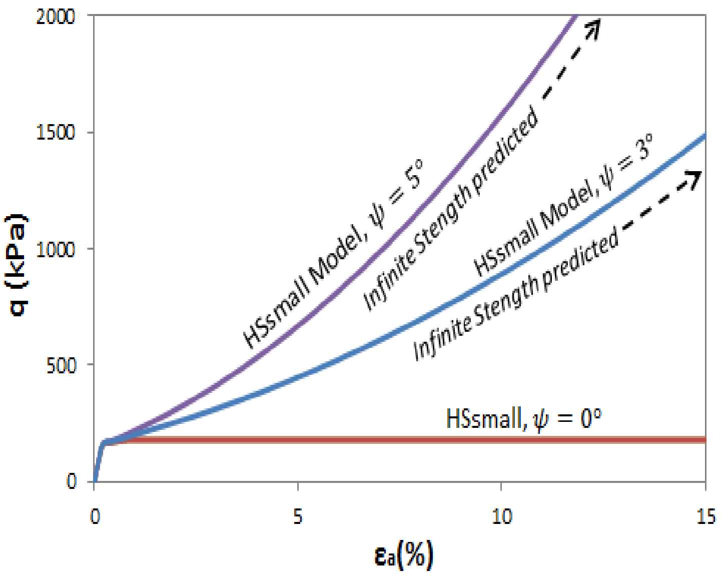
Therefore:

- Soil model used for analysis must capture a representative dilatational response!
- No built-in existing models could capture this behaviour.
- Must develop and implement bespoke model to perform reasonable analysis.

Suction Bucket under Tension Loading FEA

Typical models within commercial FEA packages considered for dense sand not suitable for problem in question:

- Mohr Coloumb model (Plaxis & Abaqus) *Not suitable*
- Hardening Soil (HS) or HSsmall models (Plaxis & Abaqus) *Not suitable*
- Modified Capped Drucker Prager Model (Abaqus) *Not suitable*



Although some offer reasonable prediction in drained element test conditions the prediction in undrained conditions is very poor for undrained conditions.

Suction Bucket under Tension Loading FEA

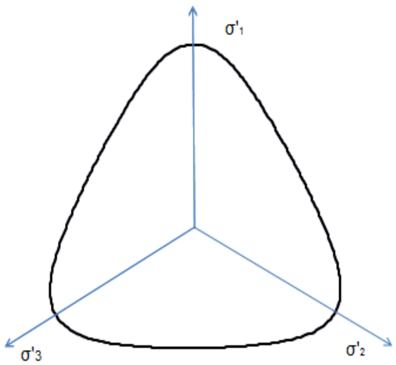
Elastic Law

- Non-linear stiffness as a power function of current stress
- Utilises Houlsby et al. (2005) hyperelastic formulation

$$D_{ijkl} = p_a \left(\frac{p_0}{p_a}\right)^n \left[\left(nk\frac{\sigma'_{ij}\sigma'_{kl}}{{p_0}^2}\right) + k(1-n)\delta_{ij}\delta_{kl} + 2g\left(\delta_{ik}\delta_{jl} - \frac{1}{3}\delta_{kl}\delta_{ij}\right)\right]$$

Yield Surface

- Wedge Type Pressure dependent Surface (Sheng et al. 2000)
- Can be approximated to Mohr Coulomb Model
- No Hardening or Softening
- Could use other surface



Model Components

Plastic Potential Function

- Stress and state dependent plastic potential function that could be added to any similar model (e.g. standard MC model)

$$G = \sqrt{\frac{1}{A\,p'_{cv}}\left(p'_{cv} - p'\right)^x + q^y}$$

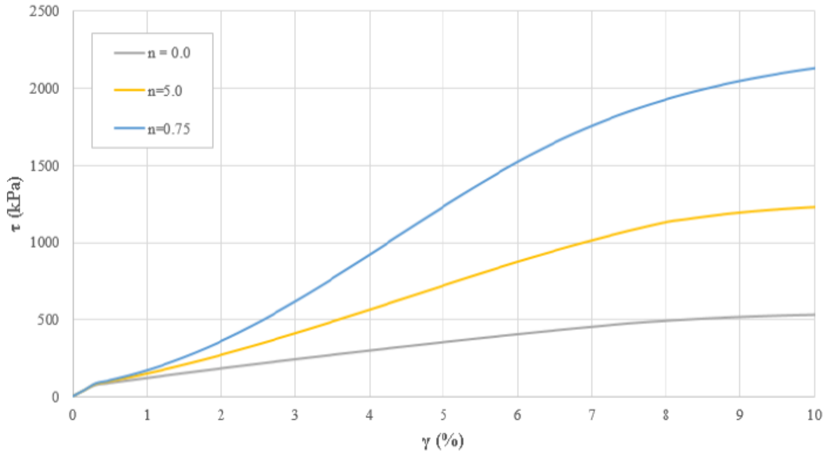
Critical for partially-drained to undrained conditions

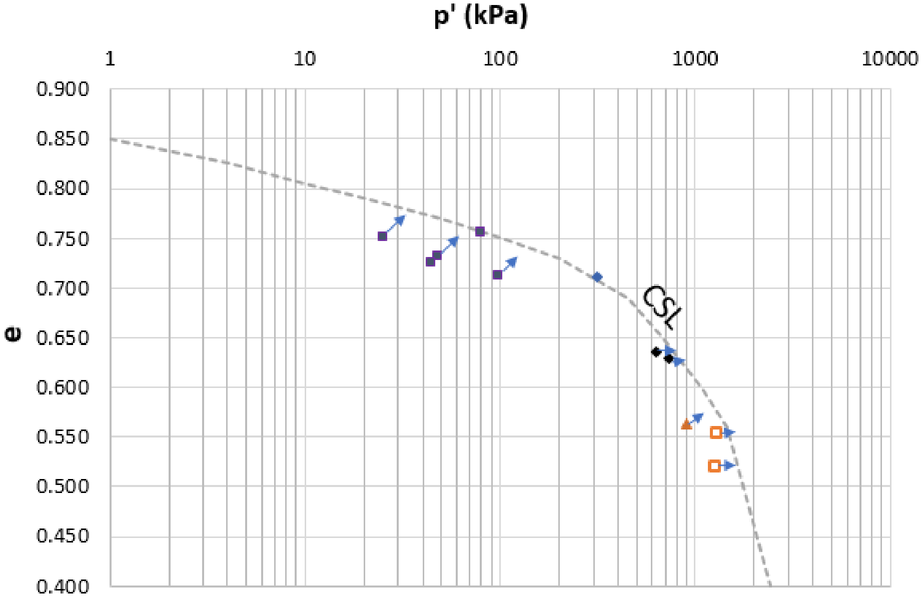
Fugro Reference:
Whyte, S. et al. (2017). Practical Constitutive Model for Dense Sand…SUT OSIG

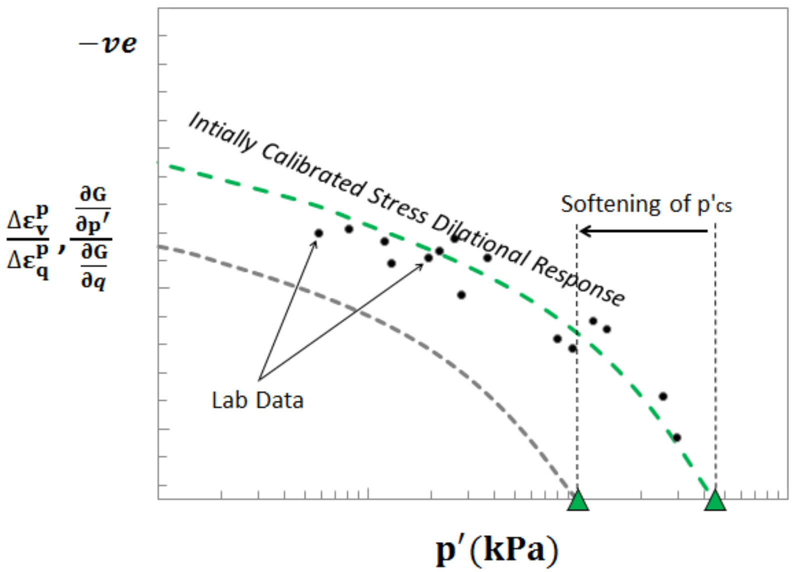
Model Calibration

Versatile stress-dilatancy relationship fit to data:

- Stress and state dependent
- p'_{cv} from CSL
- Results in family of state dependent plastic potential surfaces
- Bespoke model developed and lab testing programme tailored to calibrate model

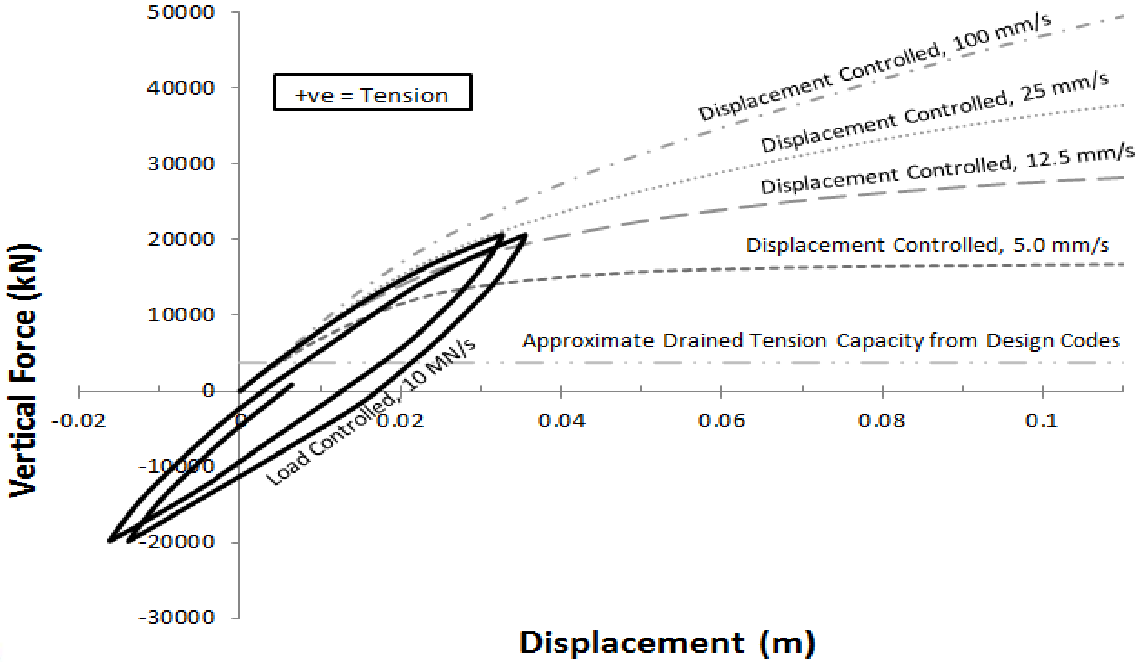


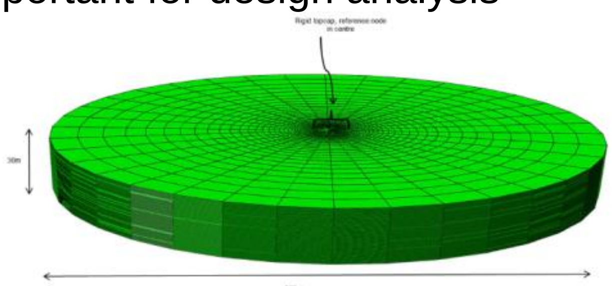




Suction Bucket in Dense Sand FEA Example

- Monotonic capacity significantly increases under rapid loading due to negative excess pore pressures
- Permeability and dilational parameters most pivotal for predicted response
- Realistic load history data very important
- Cavitation cut-off within FEA important for design analysis





Monopile Design
Monotonic to Cyclic
3D to 1D Models

Dynamic and Cyclic p-y Curves for Monopile Design

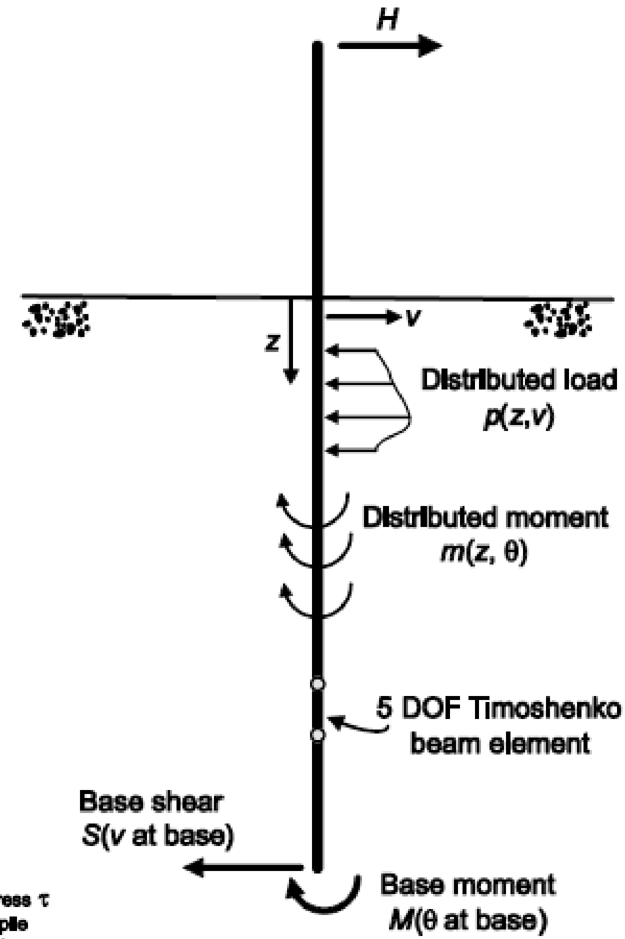
Monopile Foundation

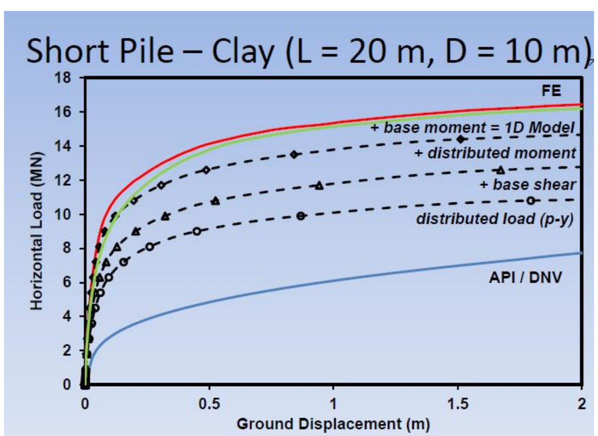
Monopile Design

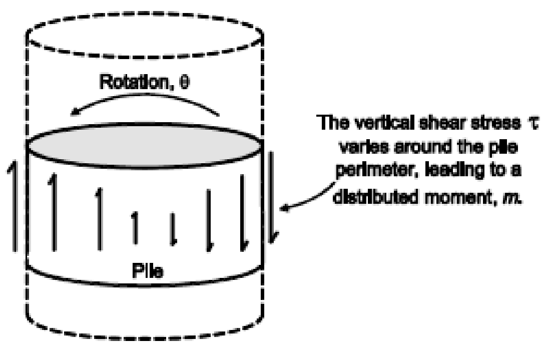
- Monopiles being utilised significantly beyond what was thought possible in terms of turbine size and water depth
- Using design methods typically employed for the foundations of jacket structures may not be appropriate
- New methods recently proposed (e.g PISA Method)

1D PISA Method Model (Byrne et al. 2017)

- **Distributed load curve** – distributed load *p* and lateral displacement *v*
- **Distributed moment curve** – distributed moment *m* and section rotation θ
- **Base shear curves** – base shear force *S* and lateral displacement *v*
- **Base moment curve** – base moment *M* and base rotation θ



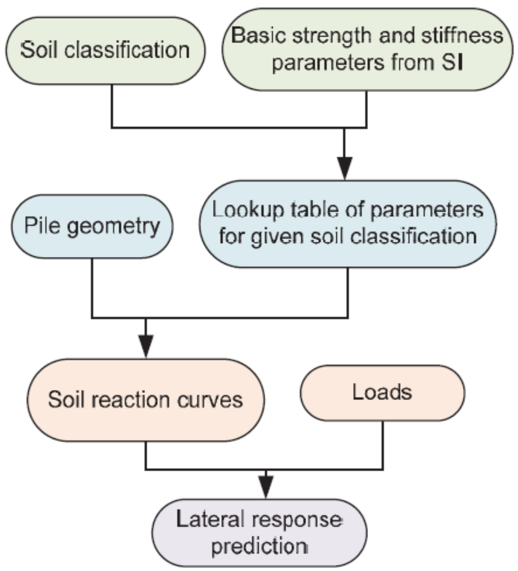




Monopile Design Process

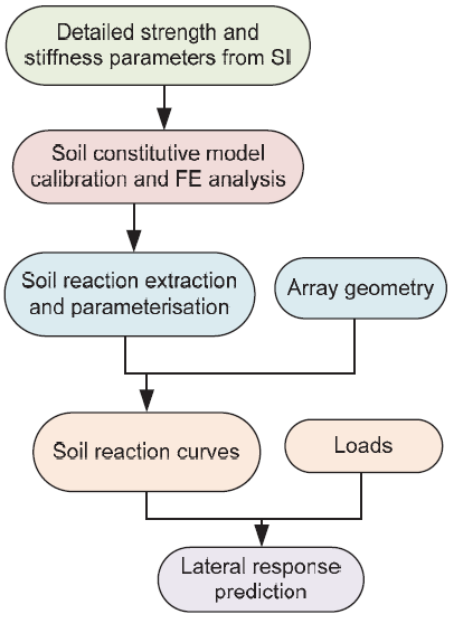
Proposed methods from PISA to determine soil reaction curves (Byrne et al. 2017)

Rule Based Method



Feasibility/Prelim Concept Design Stage

Numerical-based Method



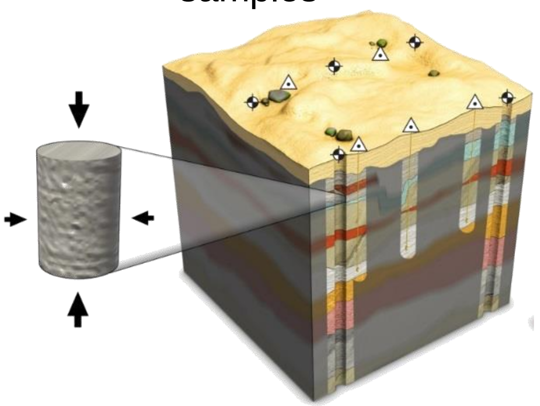
Detailed Concept Design

Similar to codified approach DNV (2014)
PISA includes additional reaction curves

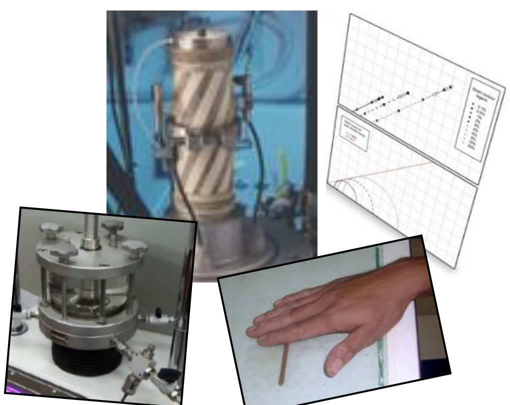
Approach of developing site specific reaction curves also presented by many authors before PISA (e.g. Erbrich (2014))

Monopile Design Process

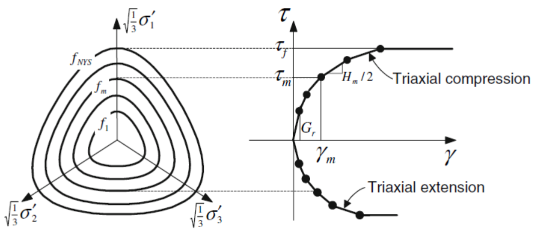
1. Extract high quality soil samples



2. Extensive testing of material



3. Calibrate suitable constitutive model



Deviatoric plane

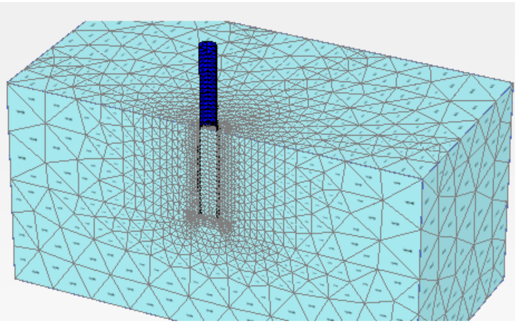
Octahedral shear stress-strain

$$\{\Delta\sigma\} = [D^{ep}]\{\Delta\varepsilon\}$$

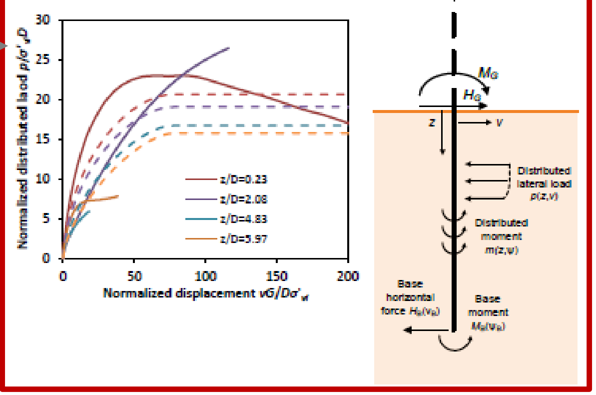
$$[D^{ep}] = [D^e] - \frac{[D^e]\left\{\frac{\partial G}{\partial \sigma}\right\}\left\{\frac{\partial F}{\partial \sigma}\right\}^T[D^e]}{\left\{\frac{\partial F}{\partial \sigma}\right\}^T[D^e]\left\{\frac{\partial G}{\partial \sigma}\right\} + A}$$

$$A = -\frac{1}{\Lambda}\left\{\frac{\partial F}{\partial k}\right\}^T \Delta k$$

4. 3D Finite element analysis



5. Extract reaction curves and normalise for 1D model



6. Optimise Pile lengths across site using 1D model and normalised reaction Curves

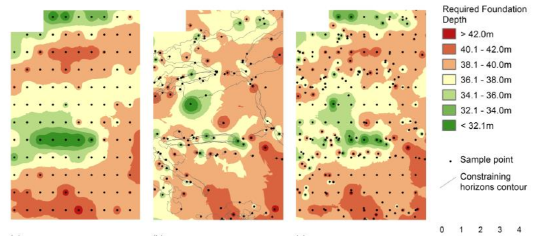


Figure 1: (a) Required foundation depth calculated from a regular point mesh, (b) optimised point mesh with contours of the main geological horizons in which the monopiles are founded and (c) final depth map of the combined results

Monopile Design Process

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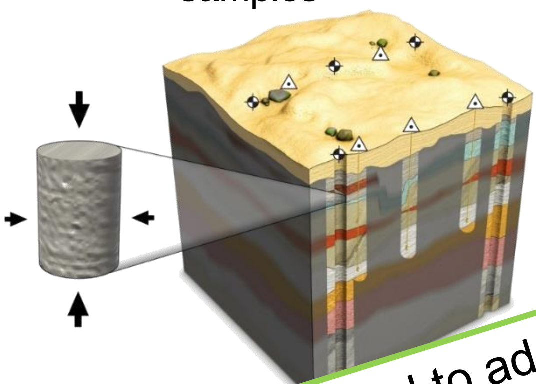

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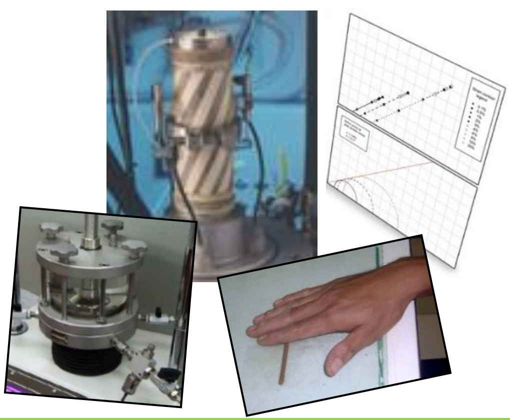

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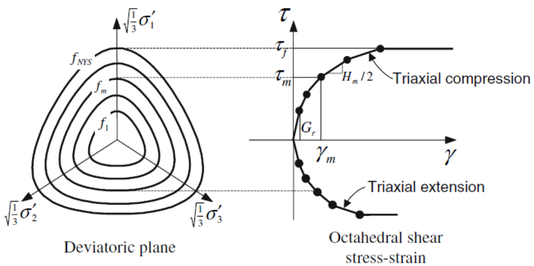

$$\{\Delta\sigma\} = [D^{ep}]\{\Delta\varepsilon\}$$

$$[D^{ep}] = [D^e] - \frac{[D^e]\left\{\frac{\partial G}{\partial \sigma}\right\}\left\{\frac{\partial F}{\partial \sigma}\right\}^T [D^e]}{\left\{\frac{\partial F}{\partial \sigma}\right\}^T [D^e]\left\{\frac{\partial G}{\partial \sigma}\right\} + A}$$

$$A = -\frac{1}{\Lambda}\left\{\frac{\partial F}{\partial k}\right\}^T \Delta k$$

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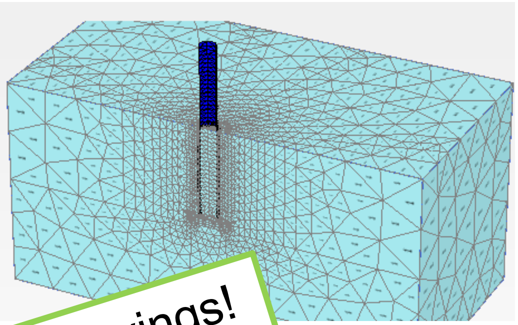
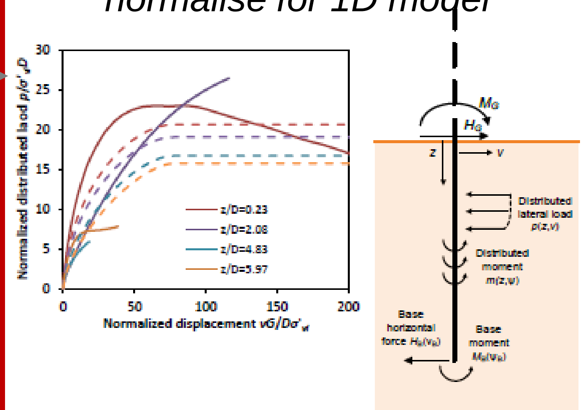


Potential to add largest savings!
Must all be considered together!

5. Extract reaction curves and normalise for 1D model



6. Optimise Pile lengths across site using 1D model and normalised reaction Curves

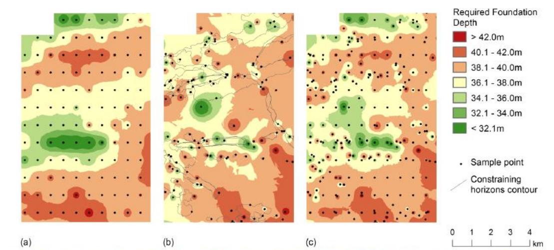


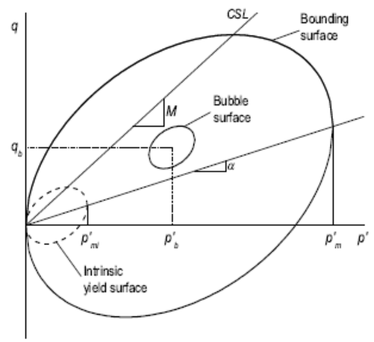
Figure 1: (a) Required foundation depth calculated from a regular point mesh, (b) optimised point mesh with contours of the main geological horizons in which the monopiles are founded and (c) final depth map of the combined results

Monopile Monotonic – Reaction Curve Extraction

OC CLAY

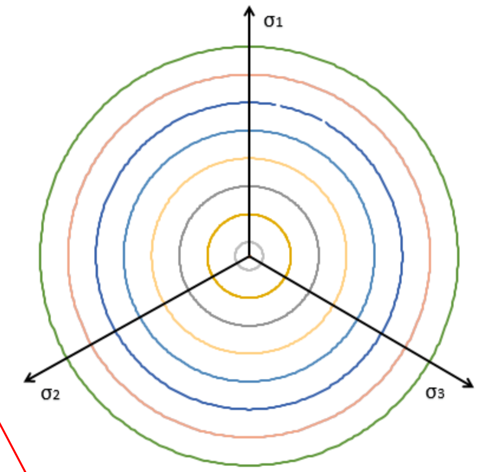
Modelling OC Clay with 3D FEA

- Effective Stress Model vs Total Stress Model

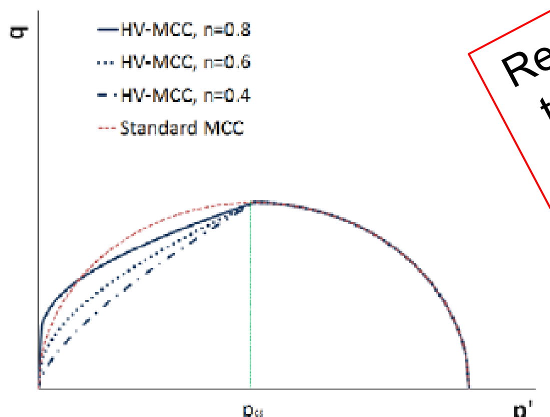


B-SCLAY1S model (Sivasithamparam & Karstunen 2012)

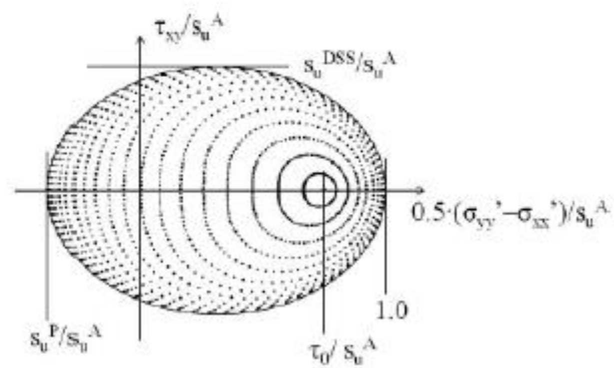
Regardless of model used it is important to understand the model and suitability to specific problem being modelled



Multi-surface total stress model



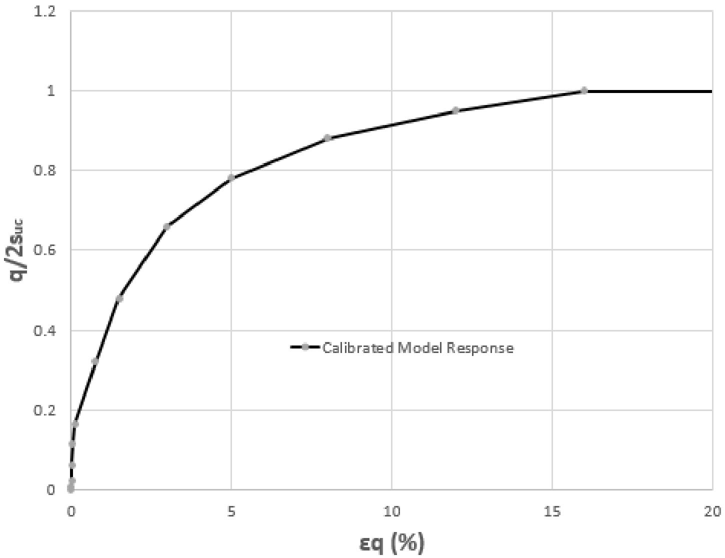
HV-MCC (After. Tsiampousi et al. (2013))

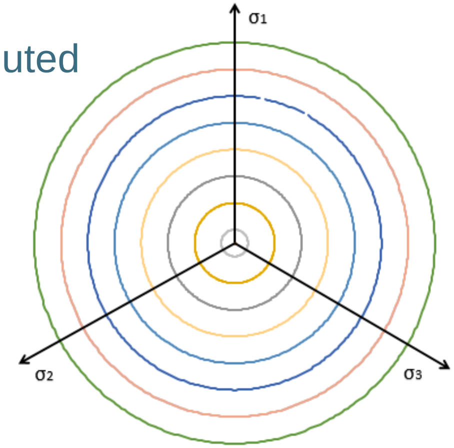


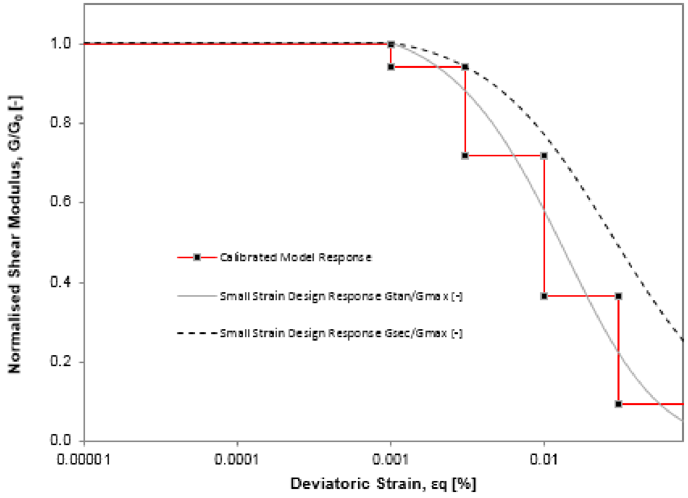
NGI ADP model (Grimstad et al. 2012)

Multi-surface Total Stress Model

- Some instances total stress model more appropriate e.g. monopile under short term loading in predominately clay profile;
- Calibration very easy and allows for exact match of stress strain backbone curve from lab data;
- If small strain stiffness of significant importance for modelling can have more surfaces in small strain range to give more resolution;
- Stress history captured within model;
- Implemented using distributed element approach

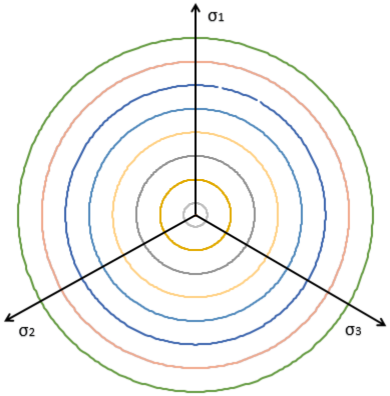


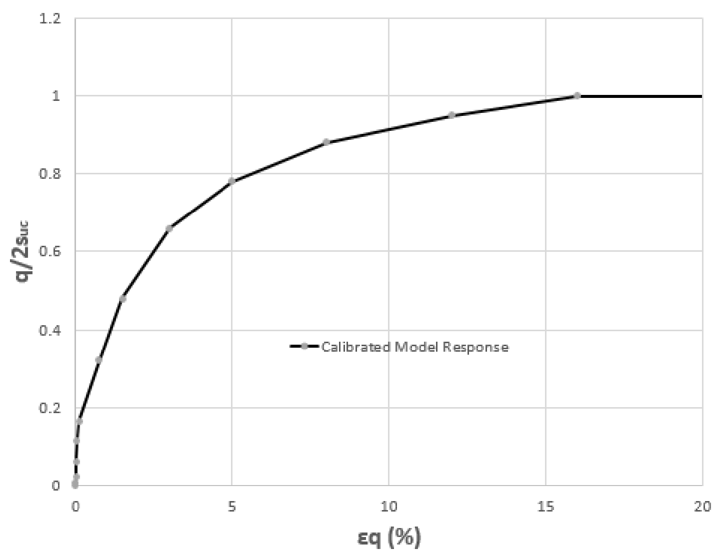




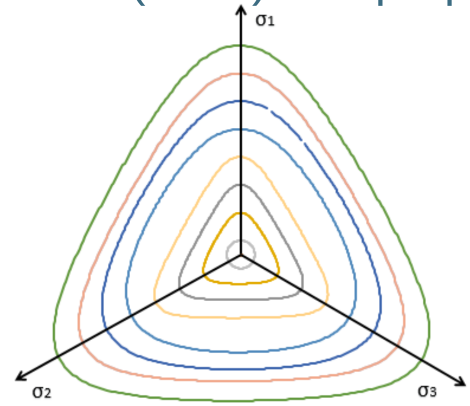
New Model Development

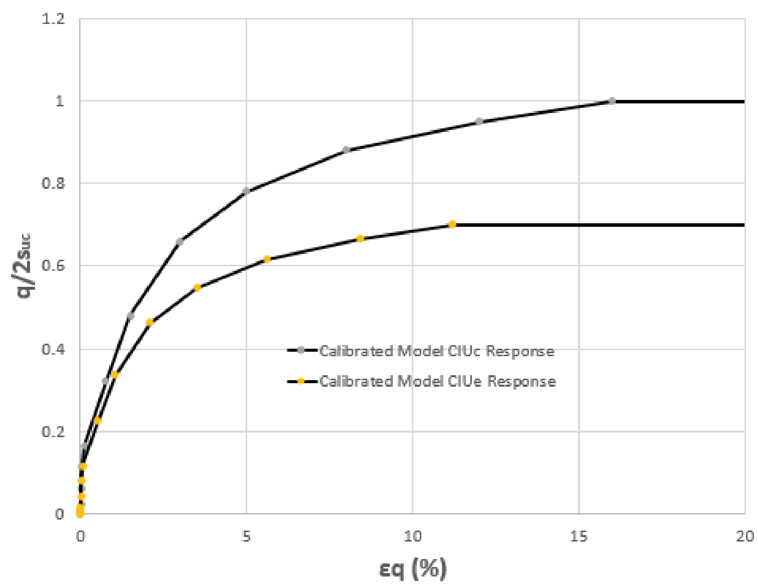
Multi-surface VM model
Houlsby (1999)





New Undrained M-Surf ACE model
Whyte et al. (2018) – In preparation

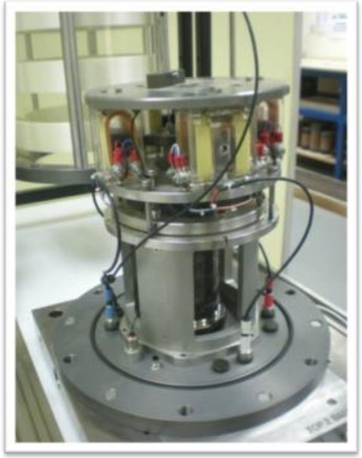


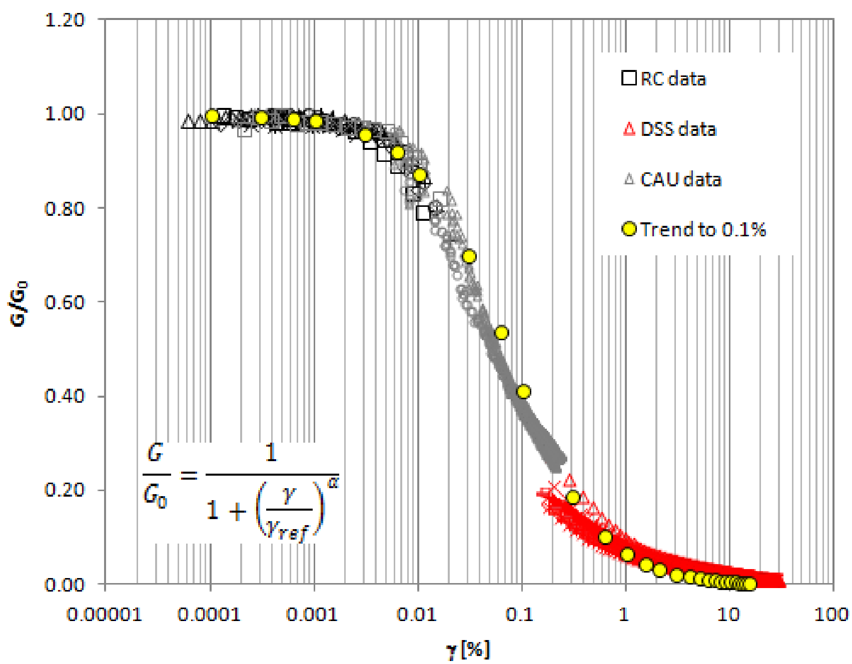


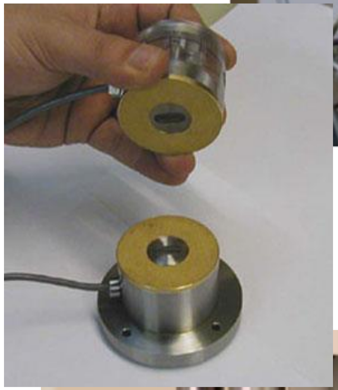
Total Stress Model Calibration

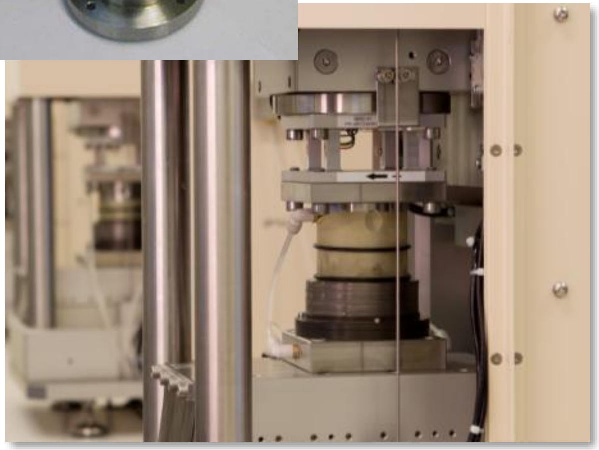
Testing Required For Calibration:

- Resonant column data used to define stiffness to 0.01%
- Bender Element test to define Gmax
- Triaxial with local strain gauges data used to blend the derived trend for 0.01% > γ < 0.1%
- Direct simple shear data and triaxial data used at γ > 0.1%



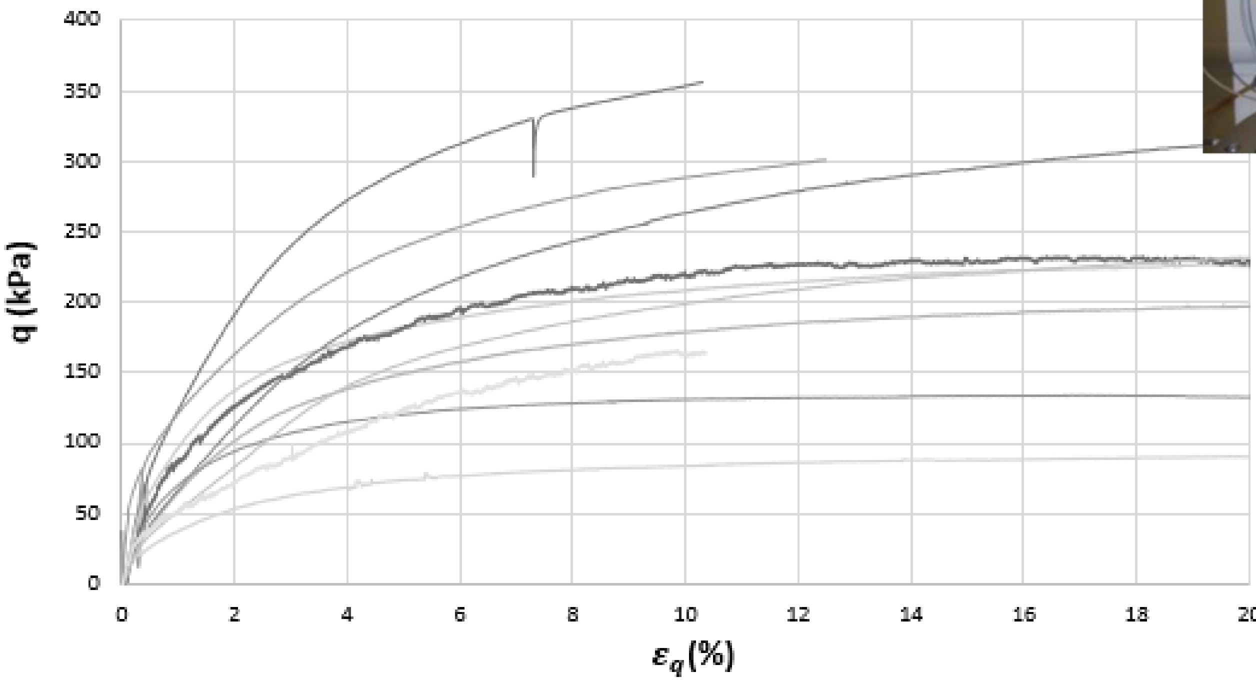






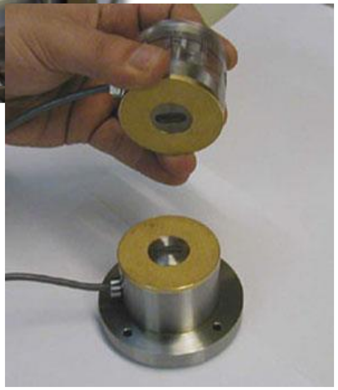
Monotonic Calibration

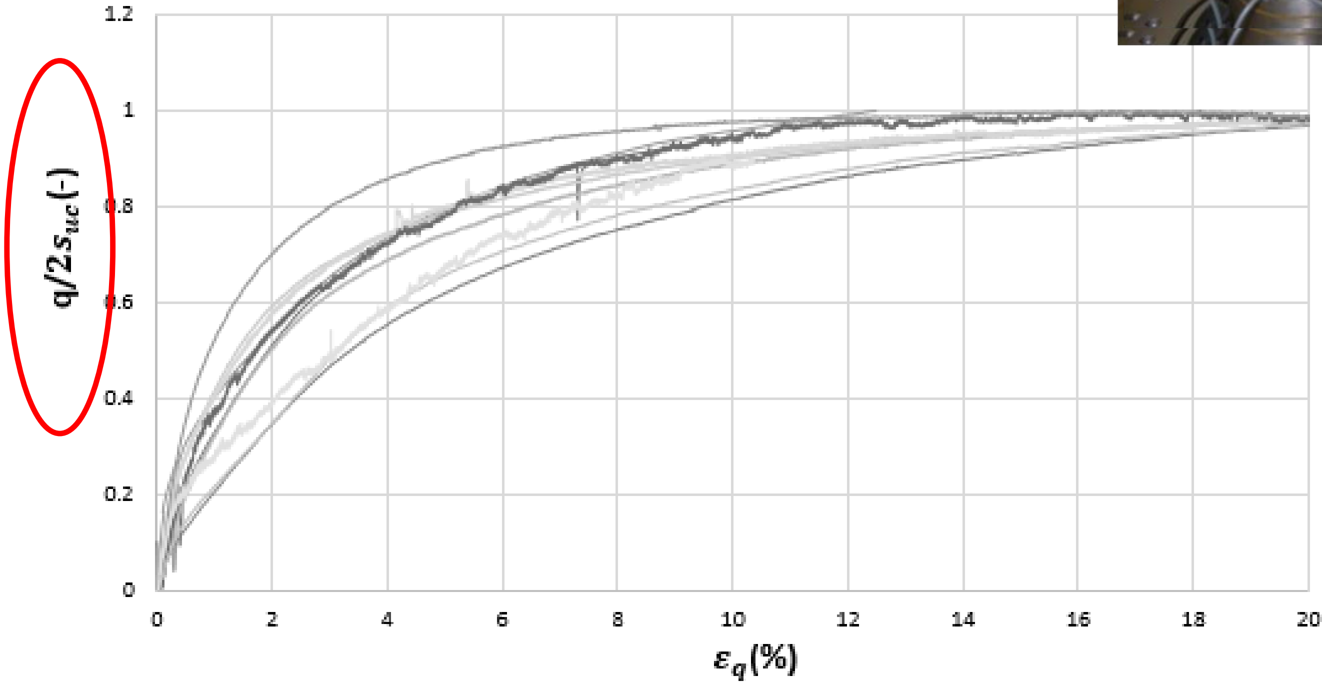
- Collection of triaxial compression tests from several samples from same OC Clay geological unit at several different North Sea Sites



Monotonic Calibration

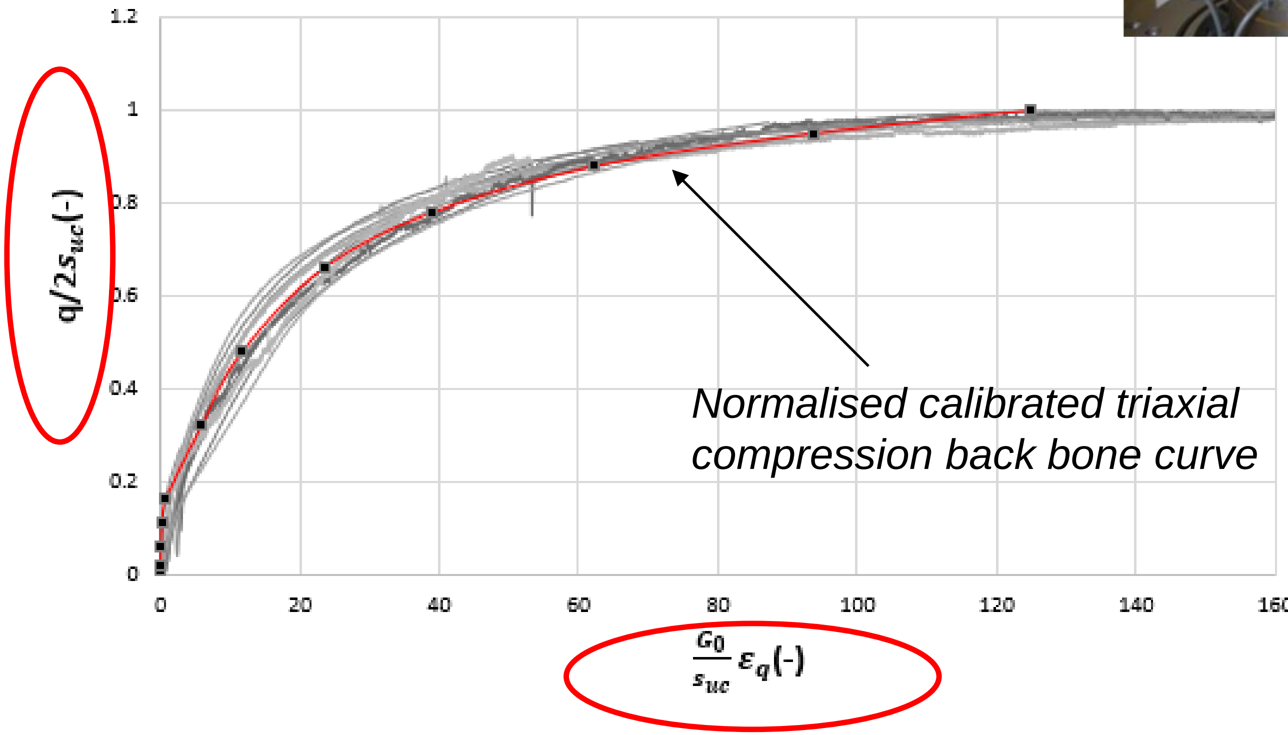
- Normalisation of backbone curve

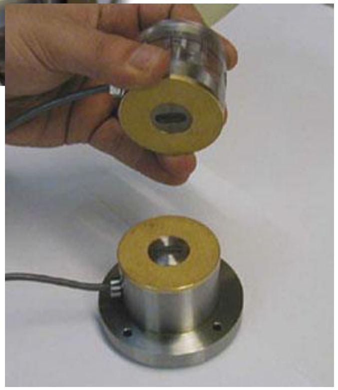




Monotonic Calibration

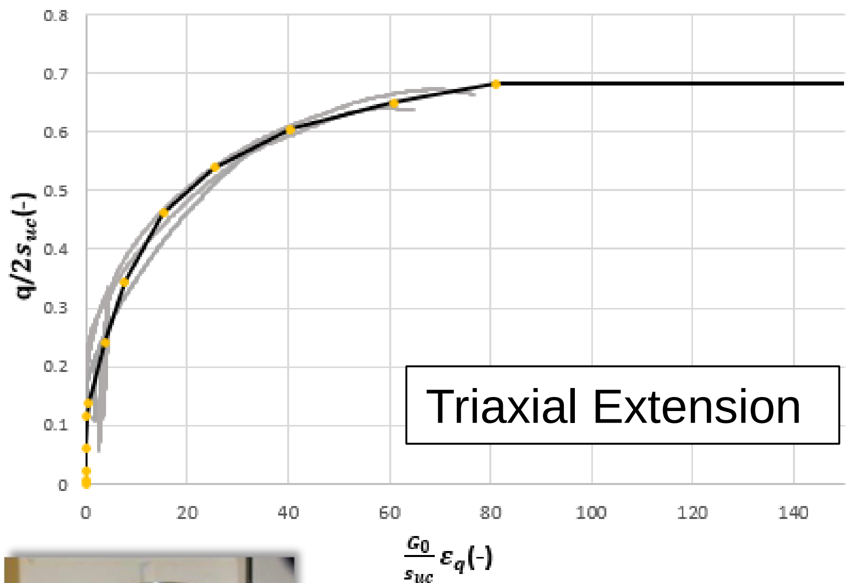
- Normalisation of backbone curve

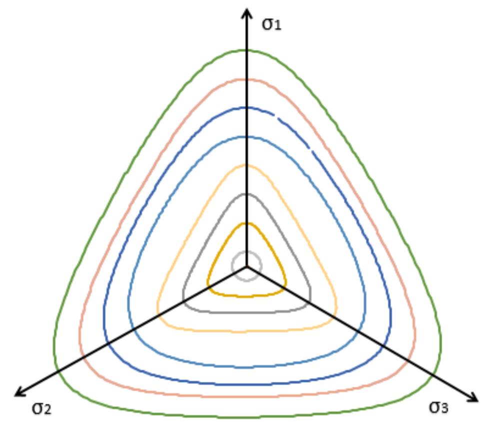


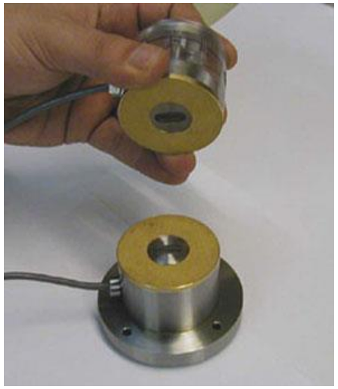


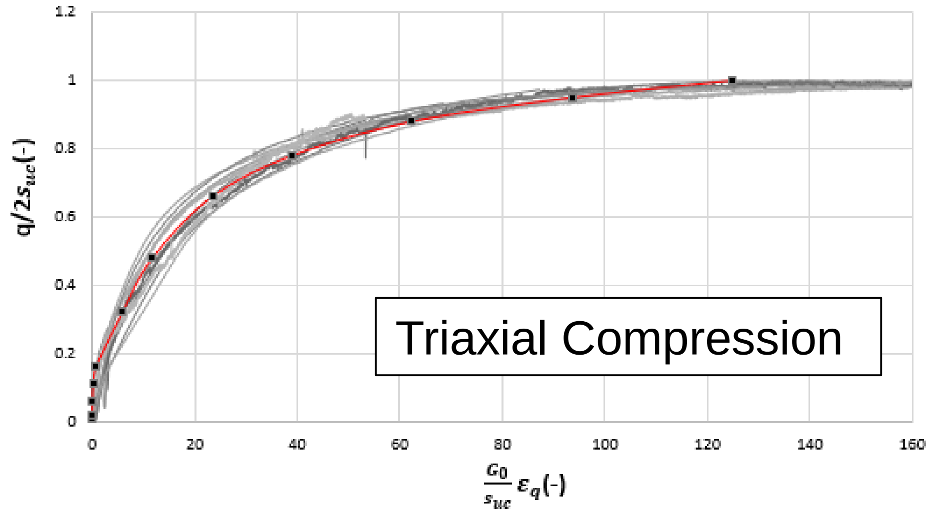
Monotonic Calibration

- Normalisation of backbone curve Triaxial extension and compression



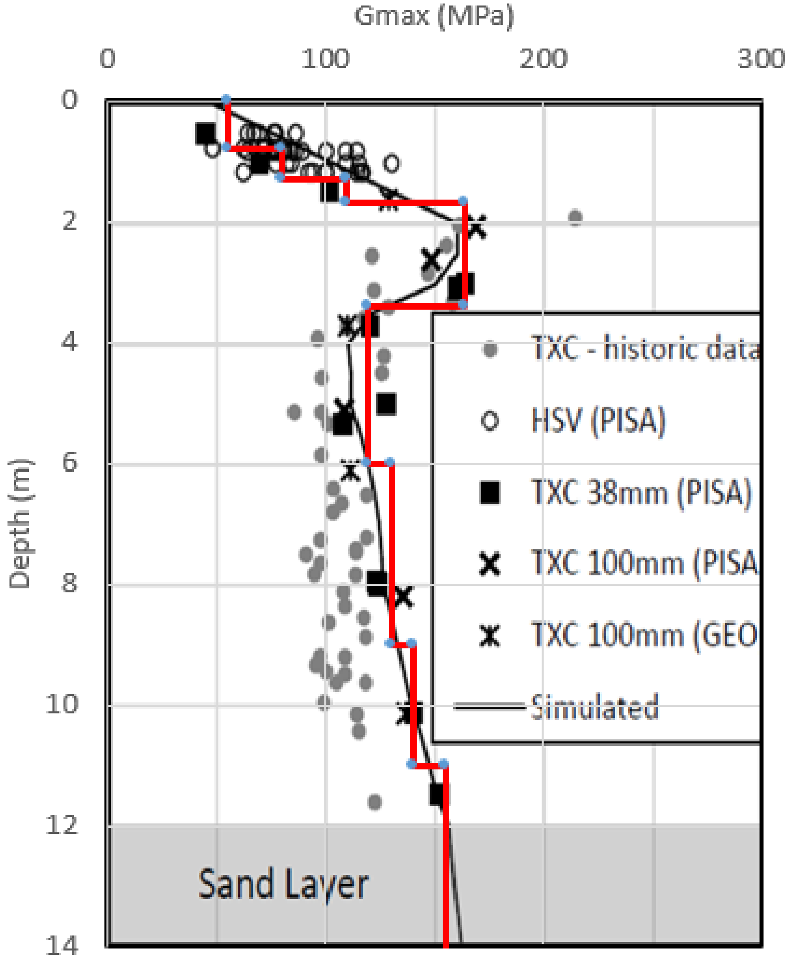


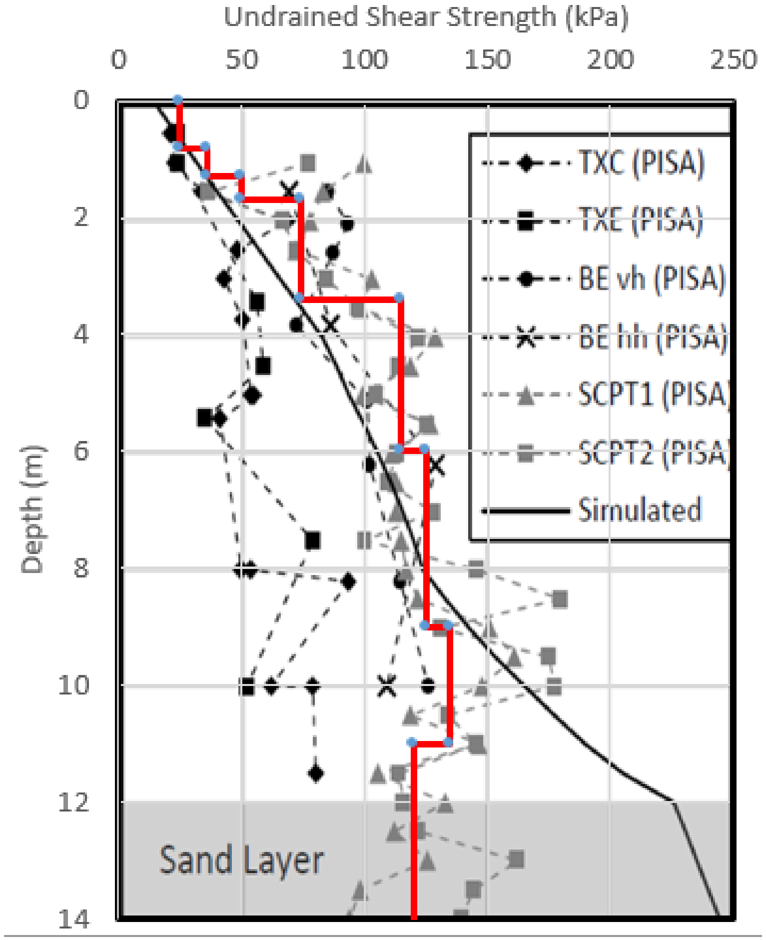




Site Profile – Cowden (PISA Site)

- Glacial till clay (assumed similar back bone curve)



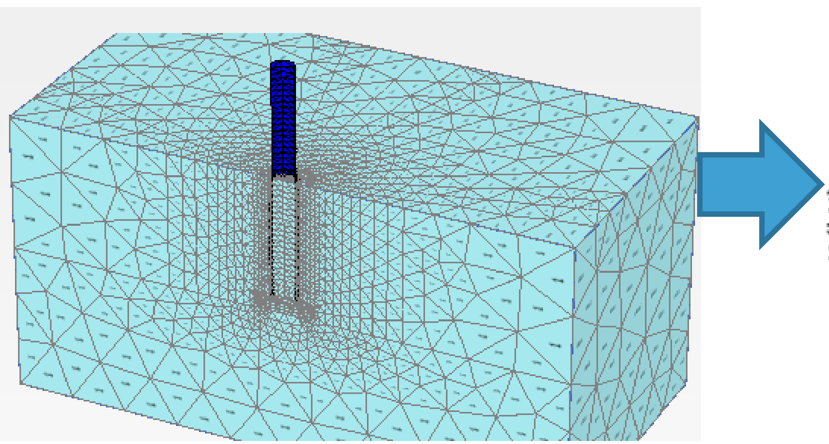


After. Byrne et al. (2017)

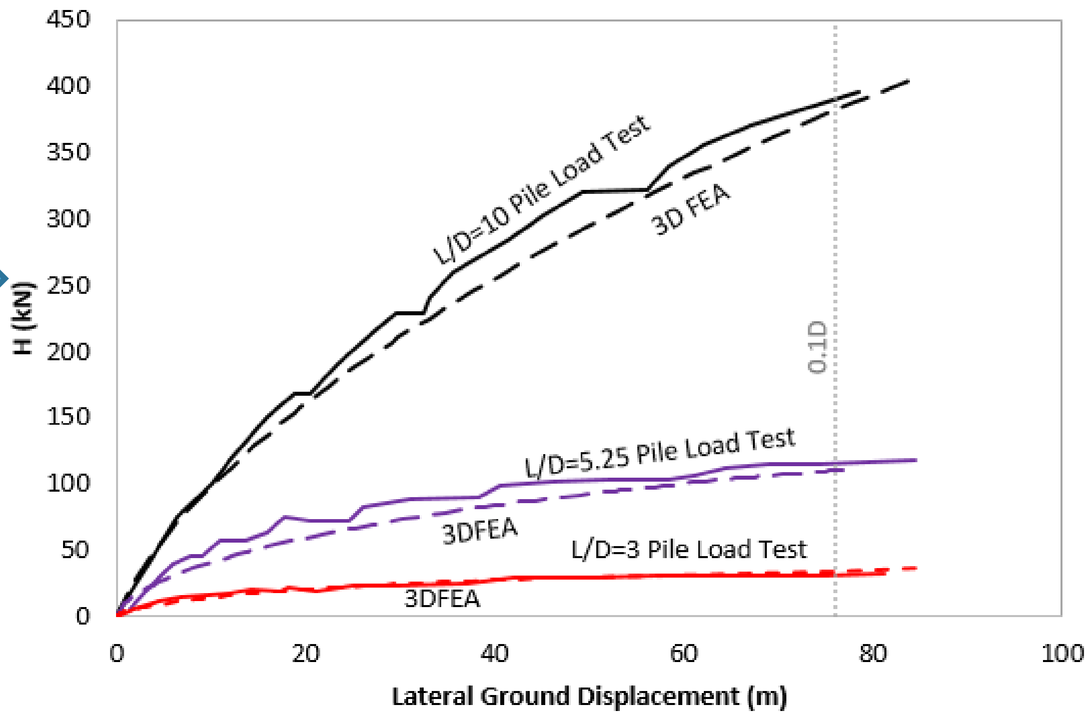
Comparison to PISA Cowden Pile Tests:

- Very good agreement between predicted response from 3D FEA and Pile Load tests;
- Run time less than 3 hours (approx. 20,000 elements);

3D FEA

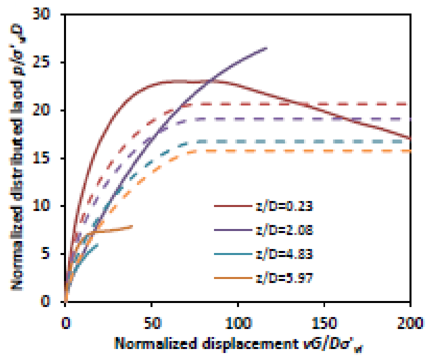


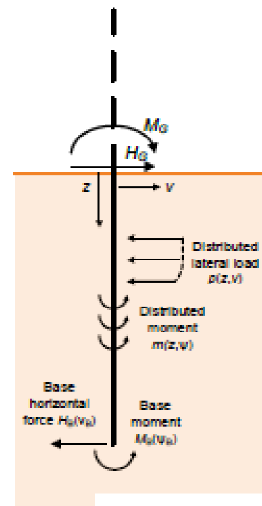
Comparison to Pile Load Test



Monopile Design Process

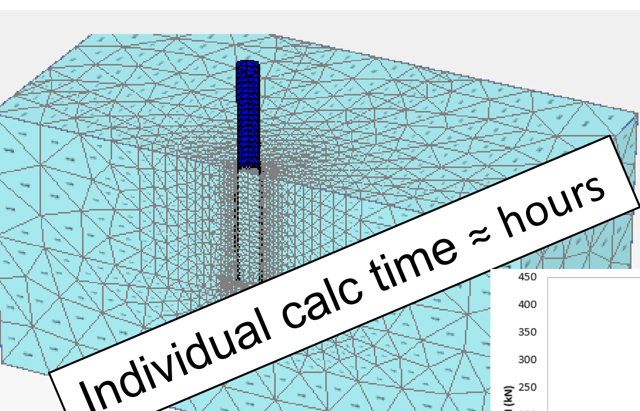
Extraction of site specific reaction curves



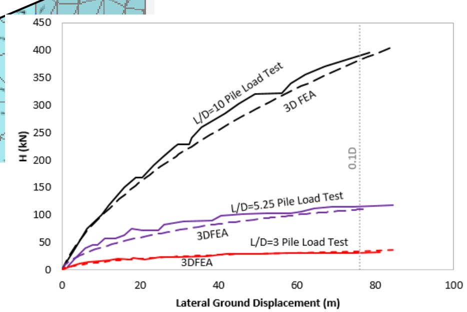


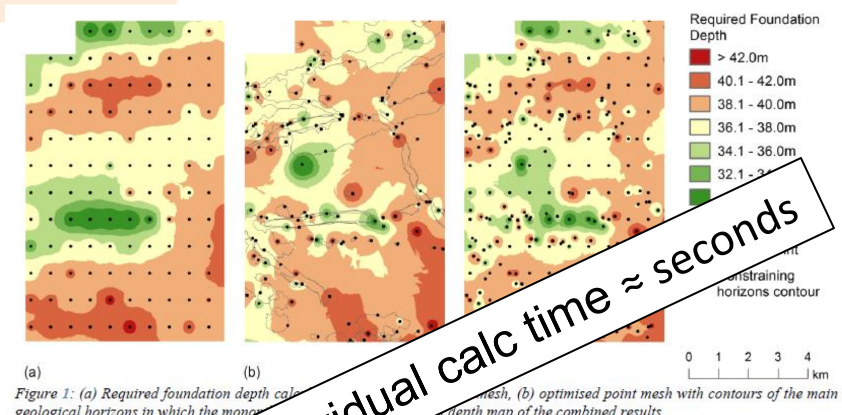
1000's of calculations across site using 1D model

3D FEA



Individual calc time ≈ hours





Individual calc time ≈ seconds

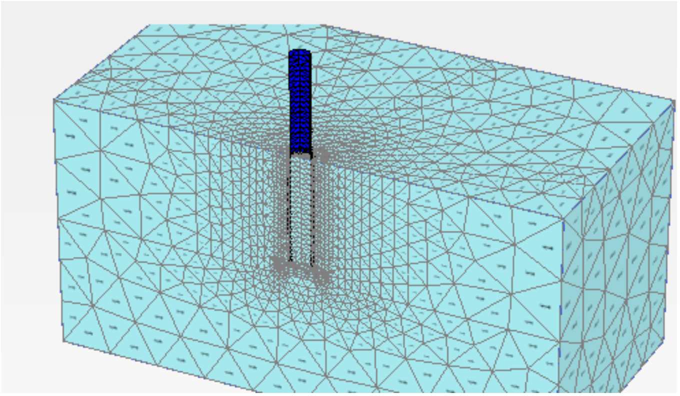
Monopile Monotonic – Reaction Curve Extraction

DENSE SAND

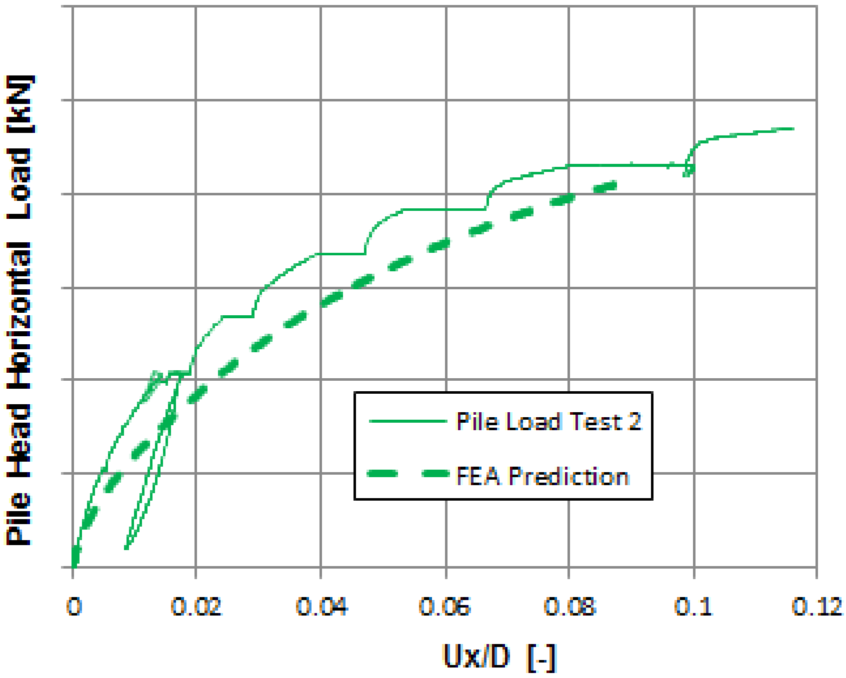
Monopile Design Sand Discussion

Comparison with pile load tests from 3D FEA:

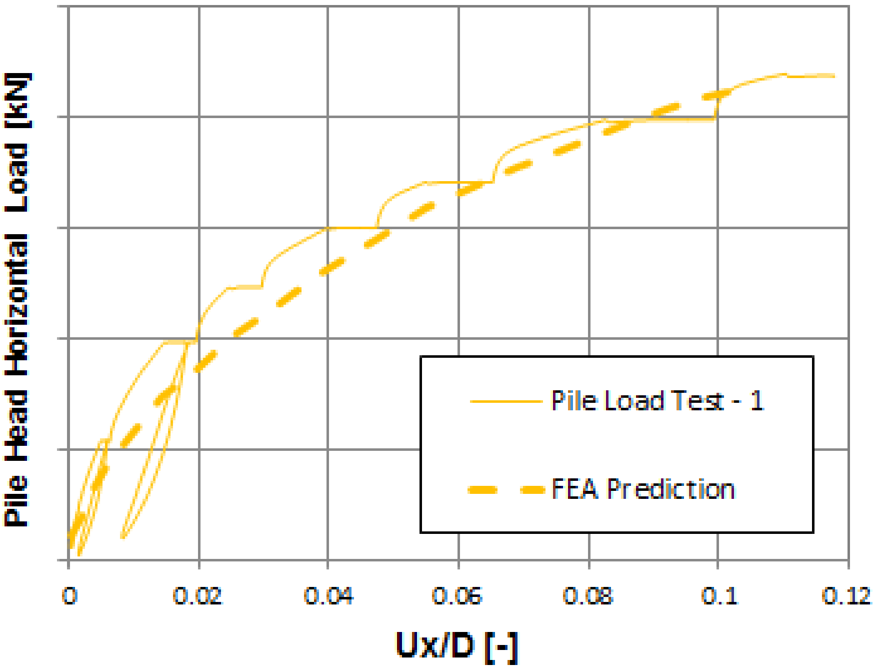
- User-defined soil model implemented and utilised for FEA
- Comparison to pile load tests shows good agreement



Medium Diameter Pile

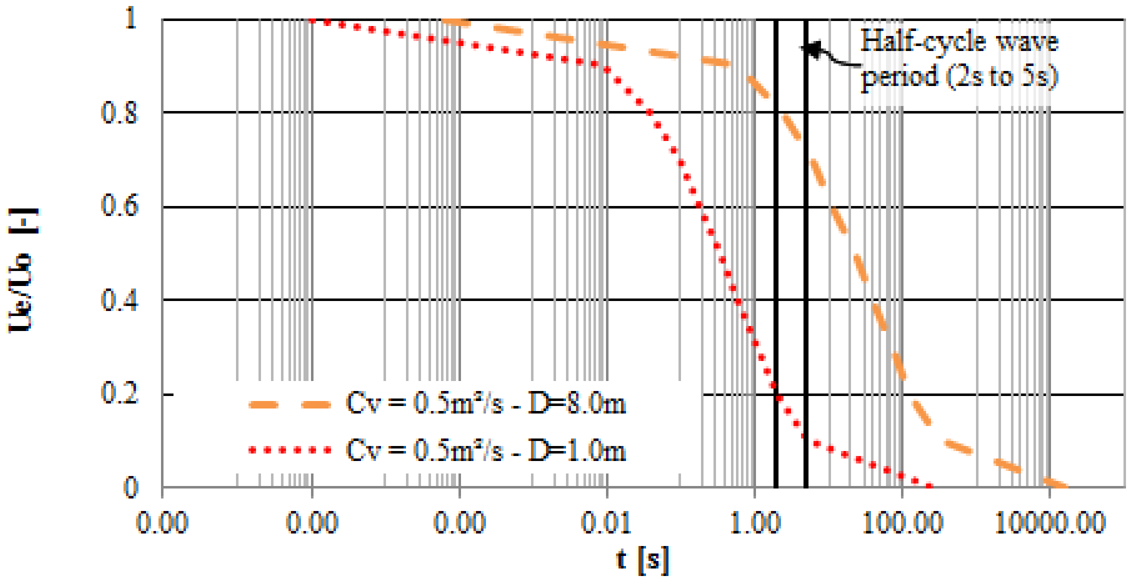


Large Diameter Pile



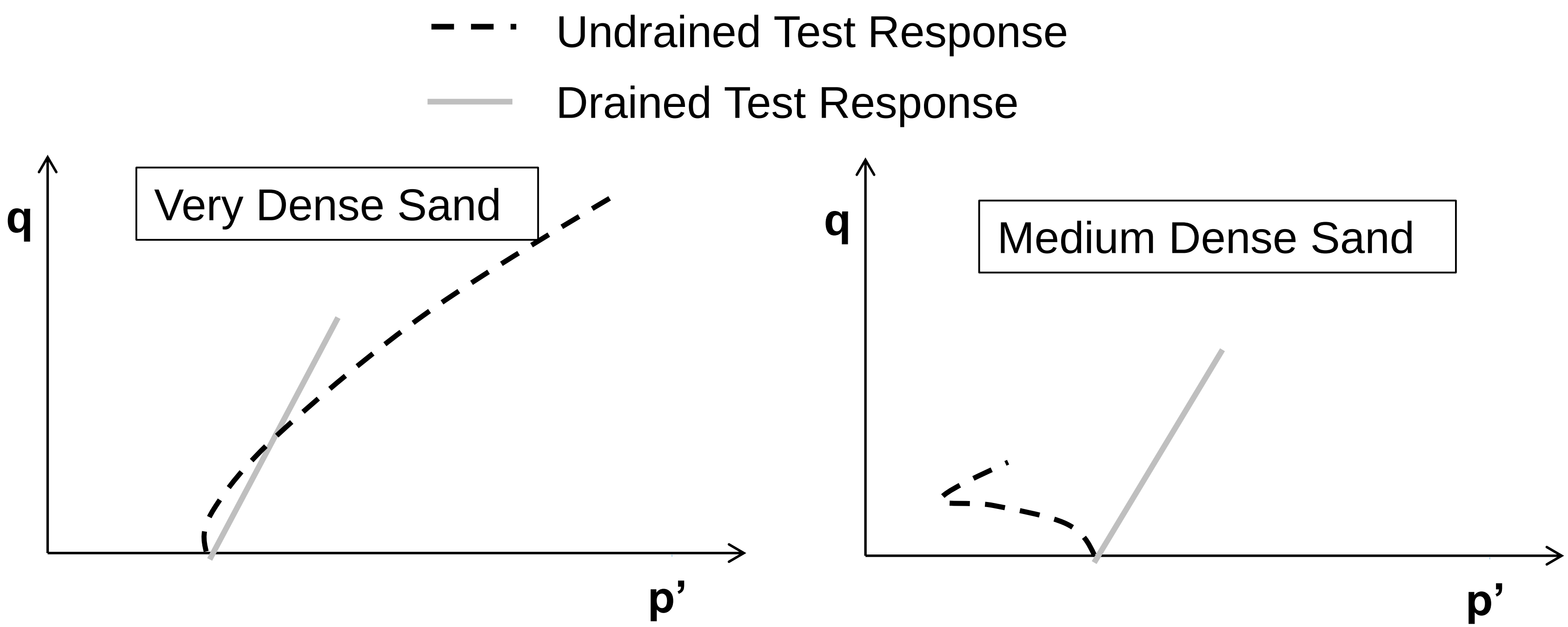
Lateral Loading of a large diameter monopile in Dense Sand…Drained or Undrained?

- Current design methods (i.e. API) assume lateral response in sand is fully drained;
- For slender piles indeed this is most probably the case;
- Most model & centrifuge testing on monopiles in sand have been under drained conditions;
- However, for large diameter monopiles this is unlikely to be the case under storm loading conditions



Implications for design:

- Monopile design in very dense sand designer can potentially allow for additional mobilised capacity in peak storm loading conditions
- However, it may be non-conservative to design for drained conditions in medium dense or lower sands.



Monopile **Cyclic** – Reaction Curve Extraction

1D Modelling Approach

pCyCOS Algorithm (Fugro In-House Software)

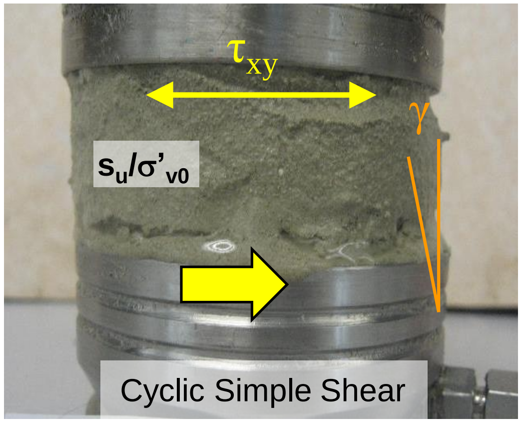
Fugro References:

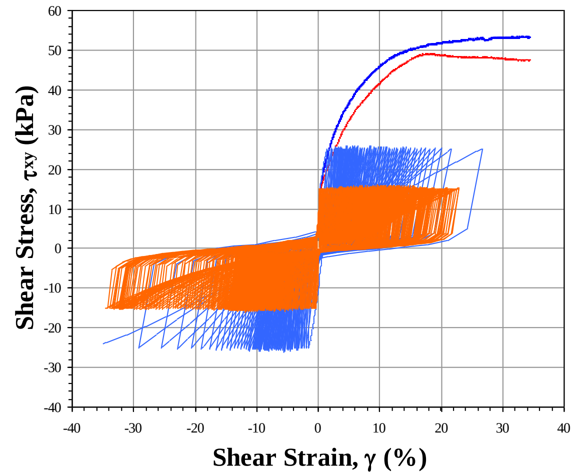
Erbrich, C. et al. (2010). Axial and Lateral Pile Design…ISFOG

Peralta, P., Ballard, J.C., Rattley, M., & Erbrich C. (2017). Dynamic and Cyclic Pile-Soil Response Curves for Monopile Design, SUT OSIG

Advanced Soil Response Characterisation

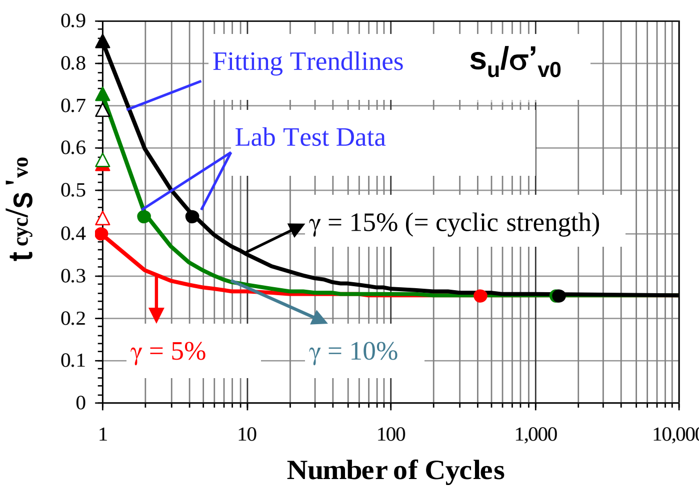
1) Perform cyclic laboratory testing of soil





2) Interpret and derive cyclic stress-strain curves

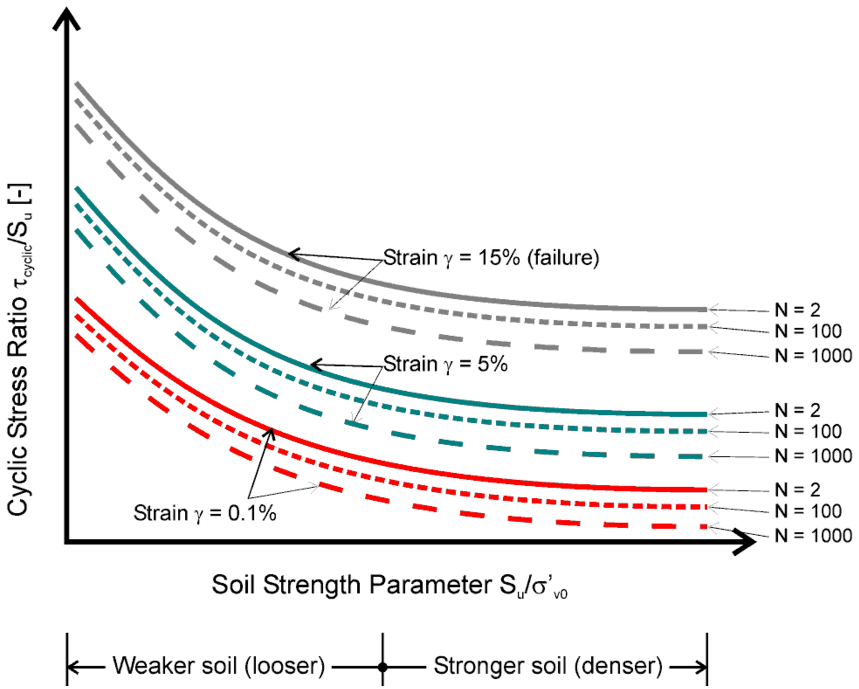
S-N Plots
(for various cyclic strains)



- ❑ Ensure sufficient number of cyclic tests for every soil type (sand, clay, silt, chalk)
- ❑ Ensure correct cyclic test performance and interpretation, <u>in line with design methodology</u>

Advanced Soil Response Characterisation

Illustration of Soil Cyclic Model



Based on Fugro database of soil cyclic strength and stiffness for SAND and CLAY, 1-WAY and 2-WAY cyclic loading

Interpolation function gives soil strength and strain for any given CSR, number of cycles, and soil density for sand or consistency for clay

Fugro Soil Cyclic Database

North Sea CLAY (2-way cyclic loading)

$$\mathrm{CSR} = \frac{\tau_{cyc}}{S_u} = a \cdot exp\left(b \cdot \frac{S_u}{\sigma'_{v0}}\right) + c \leq 1.0$$

a, b, and c – empirical parameters, function of N and γ_{cyc} (cyclic strain)

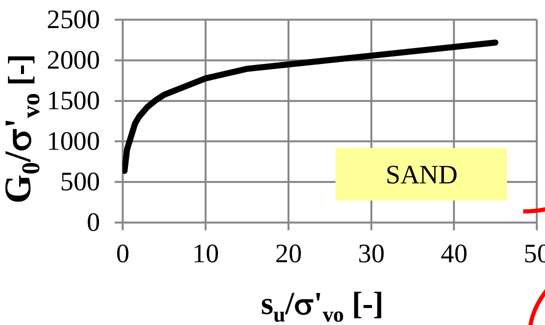
North Sea SAND (2-way cyclic loading)

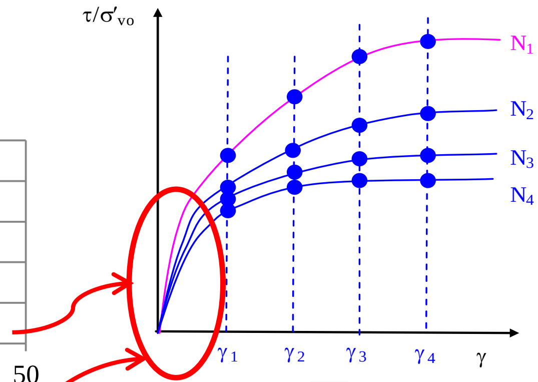
$$\mathrm{CSR} = \frac{\tau_{cyc}}{S_u} = A \cdot \left(\frac{S_u}{\sigma'_{v0}} + B\right)^{C}$$

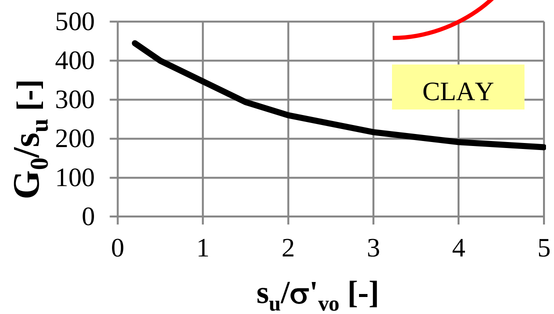
A, B, and C – empirical parameters, function of N and γ_{cyc} (cyclic strain)

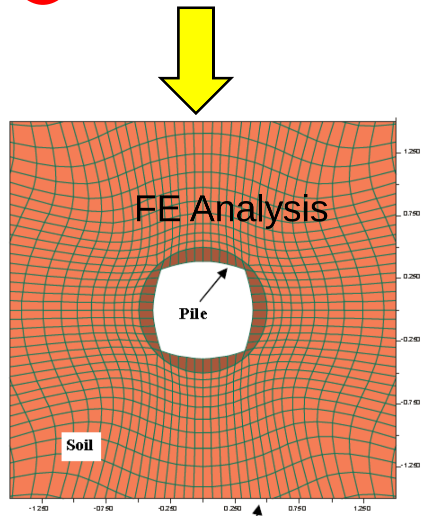
Dynamic and Cyclic p-y Curves for Monopile Design

1) Implement cyclic stress-strain curves in Finite Element model

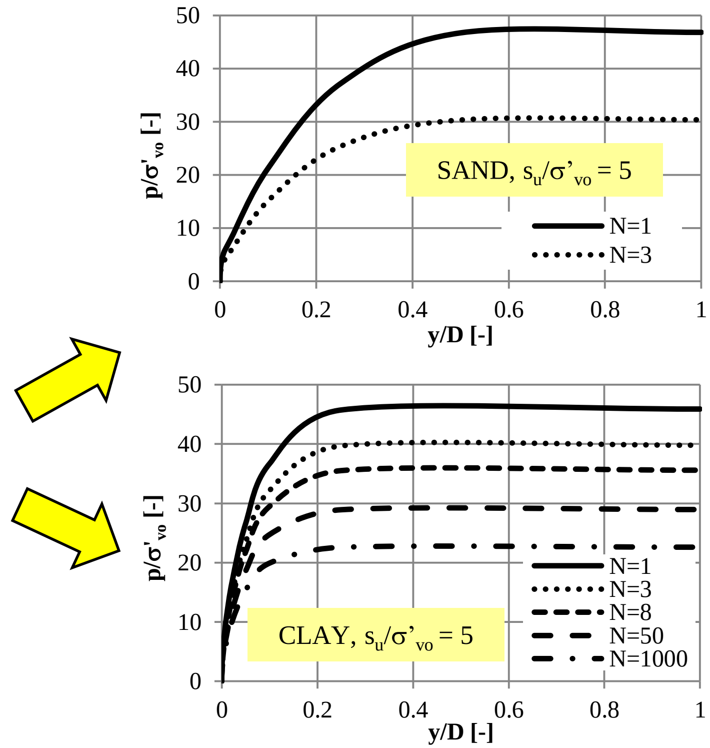






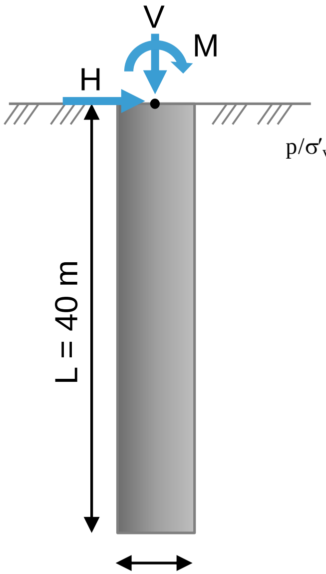


2) Extract envelope p-y curves (load-controlled)



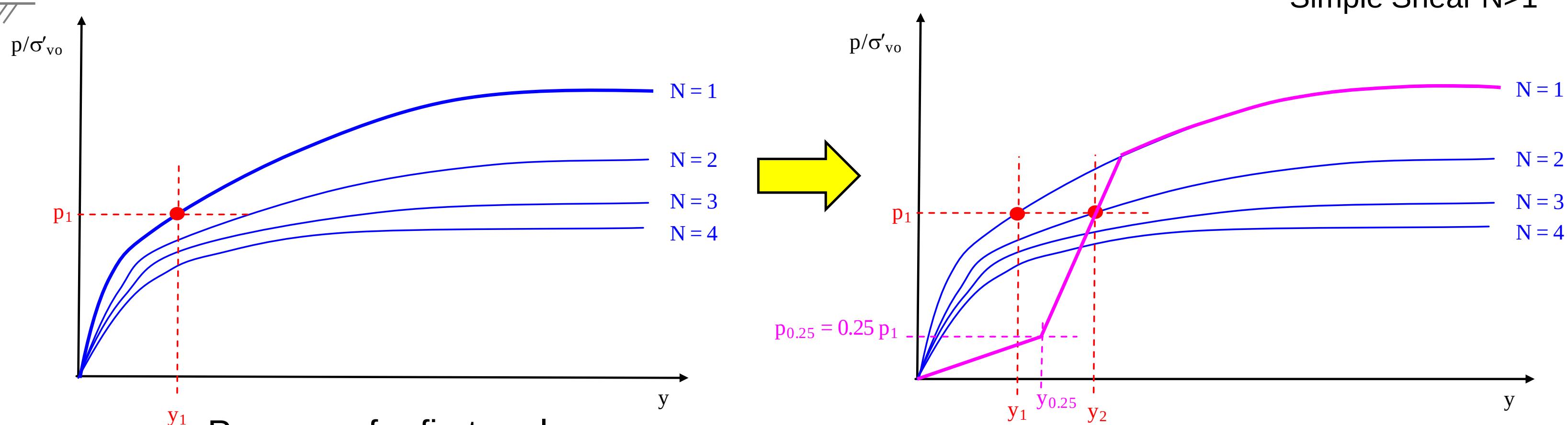
Monopile Cyclic Loading

pCyCOS Algorithm (Fugro In-House Software)



D = 7 m

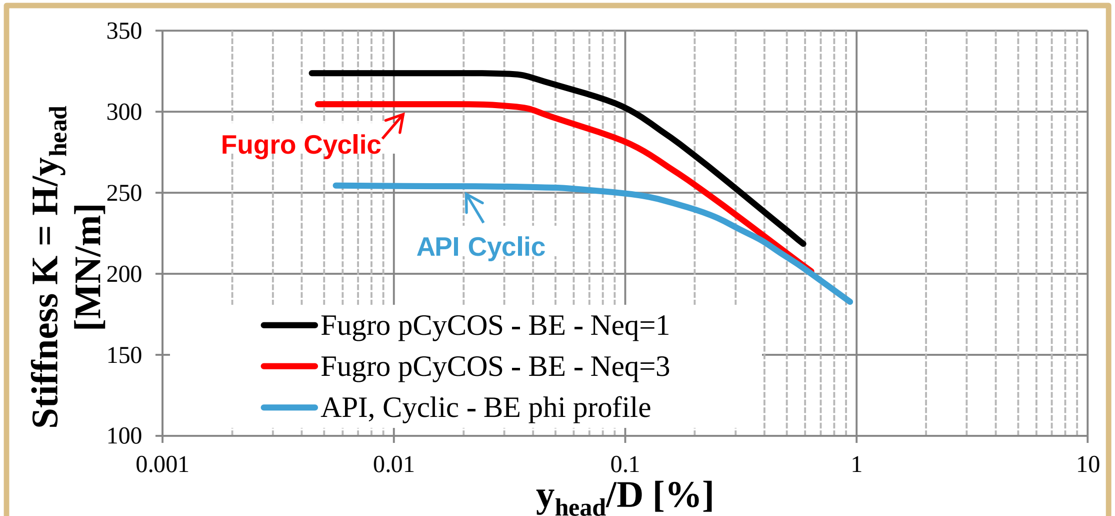
Simple Shear N>1



P-y curve for first cycle (from envelope p-y @N=1)

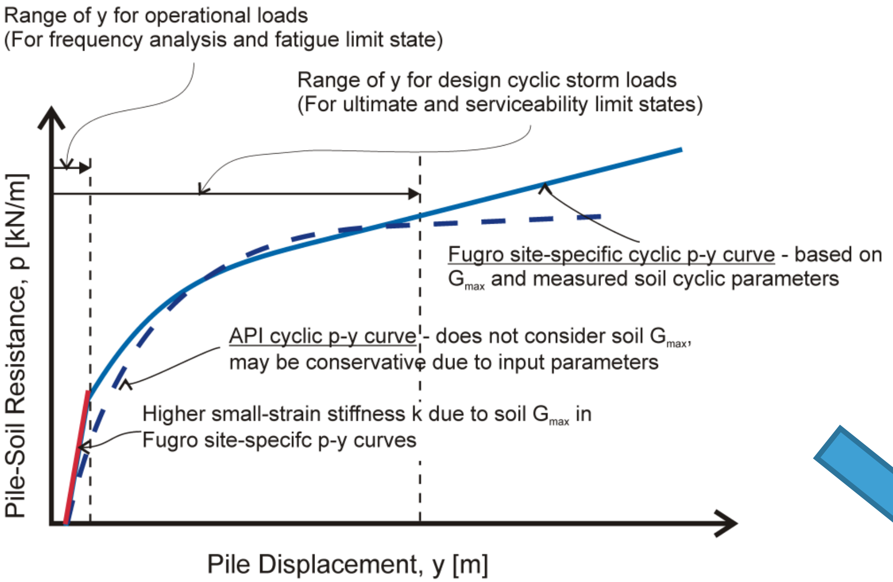
P-y curve for second cycle

- **Full non-linear soil and pile response** from very small elastic displacements to large cyclic displacements
- **Design optimisation** due to higher pile-soil stiffness in particular for operational load case (at small pile head displacements)



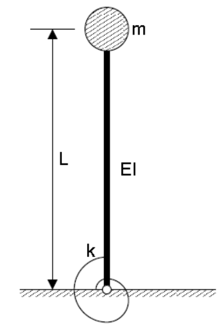
Comparison of Pile Head Load-Displacement Stiffness

Comparison with Standard Method for Silica Sands and Clays



Natural Frequency Analysis

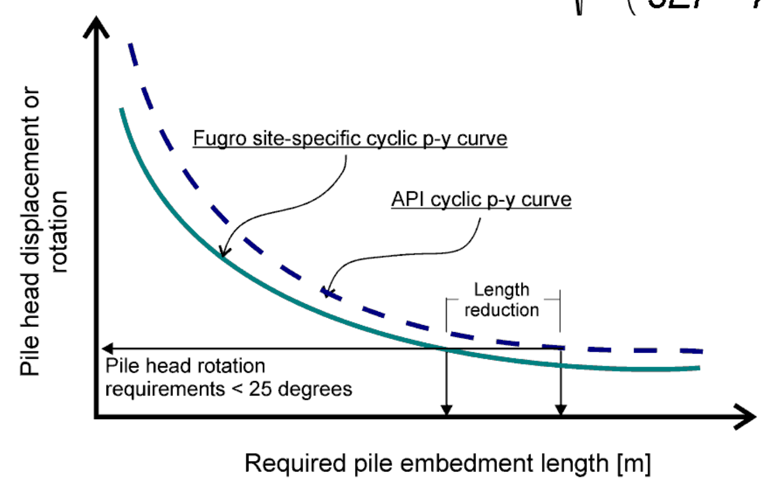
Higher stiffness k for small-strains leads to lower EI and lower use of steel



$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{m\left(\frac{L^3}{3EI}+\frac{L^2}{k}\right)}}$$

ULS and SLS

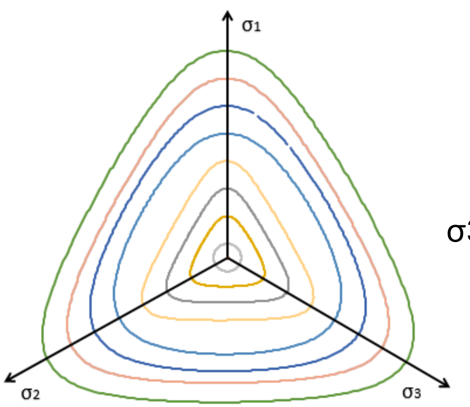
Lower cyclic displacements from Fugro p-y curves (calibrated from cyclic lab testing) lead to lower required pile length and lower use of steel

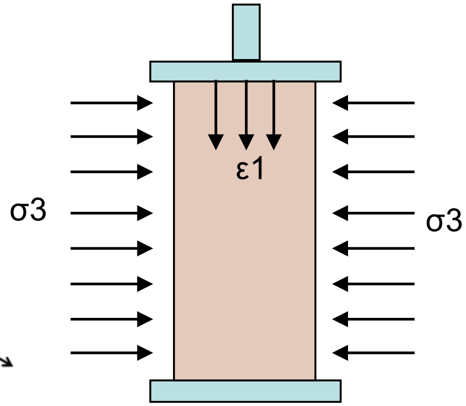


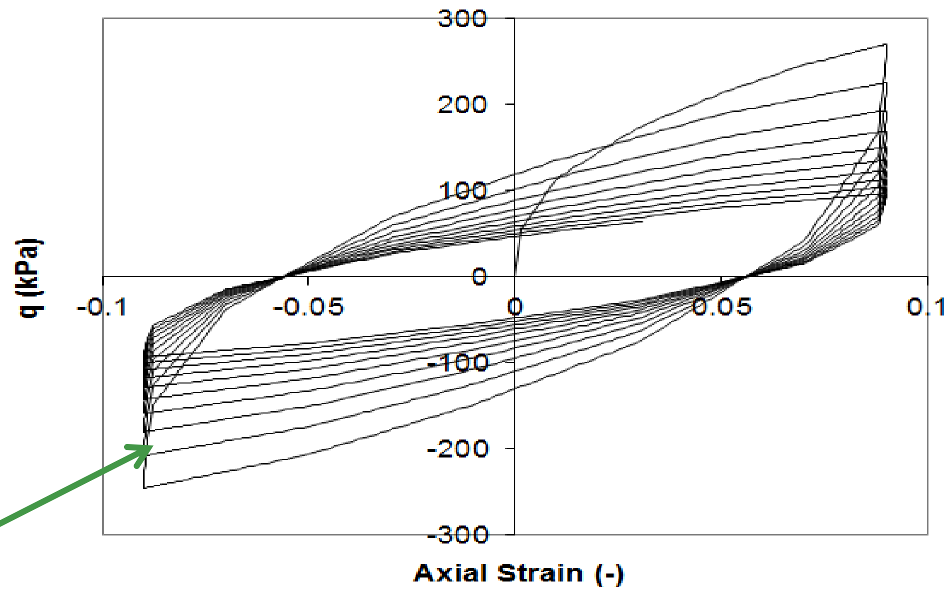
3D Cyclic Modelling Approach

New Constitutive Model Development (Undrained M-Surf ACE)

- Semi-empirical cyclic degradation extension to model:
    - Memory surface tracked as state variable to define if cyclic loading and degradation occurring;
    - New approach implemented which results in higher weighting of strain being added to single “broken spring” component during cyclic loading as a function of the accumulated plastic deviatoric strain (similar approach to Iwan & Cifuentes, (1986).



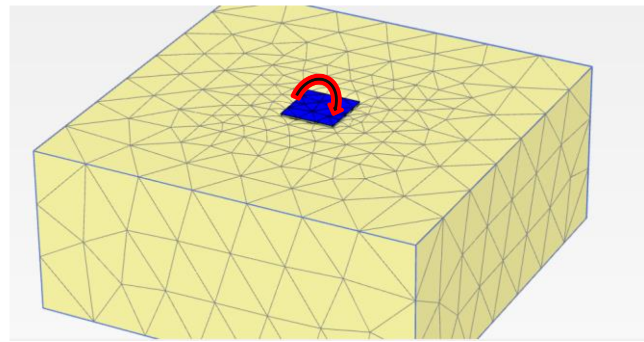




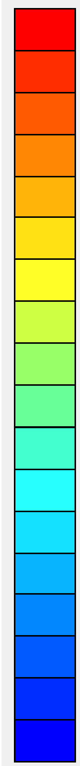
Result of new model cyclic degradation model from cyclic triaxial simulation

Undrained M-Surf ACE Model Simple Cyclic Example

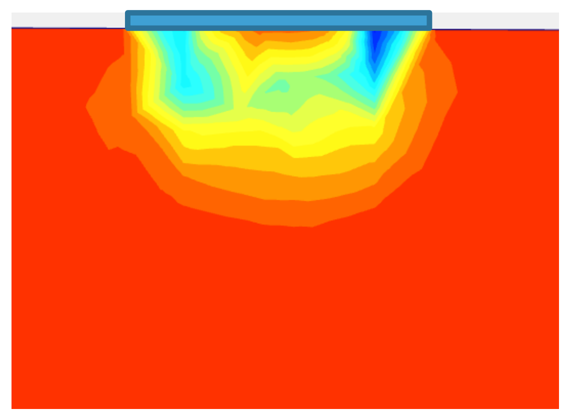
- Model implemented in Plaxis and Abaqus;
- State variable at each stress point in mesh with store cyclic degradation index;
- Rate effects being added to model



Degradation Index



Number of cycles = 3

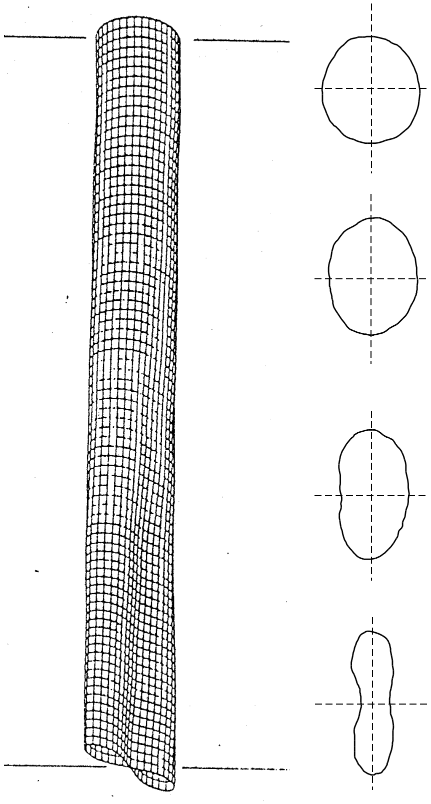


Number of cycles = 20

Extrusion of an Initial Deformed Pile

Problem Definition

Goodwyn A
(1992)



from Barbour & Erbrich, 1994

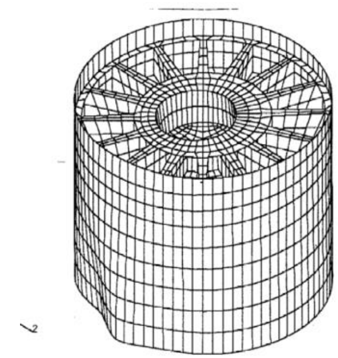
Valhall IP Platform
(2004)

Something very similar happened…..

from Alm, et al., 2004

How do we solve this problem?

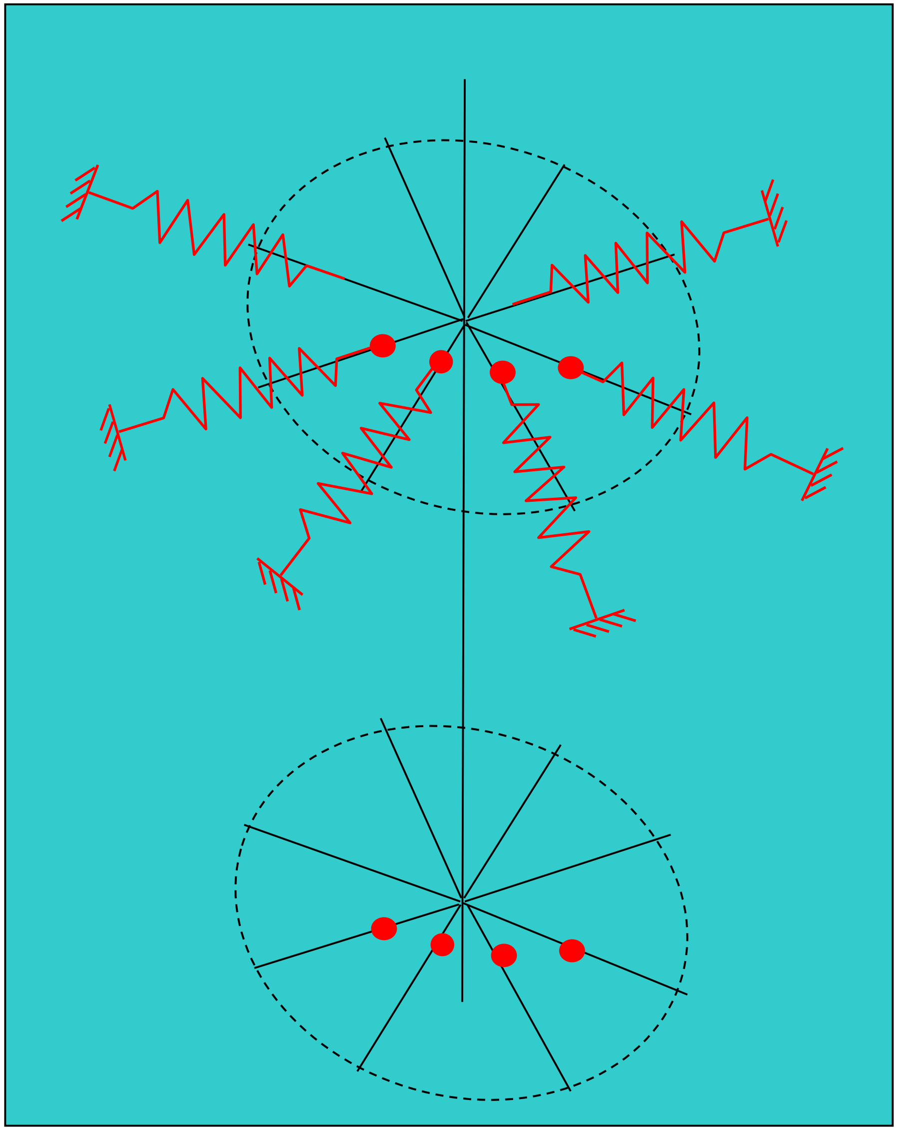
BASIL model
Developed for assessing extrusion of thin walled skirts in soil



from Barbour & Erbrich, 1995

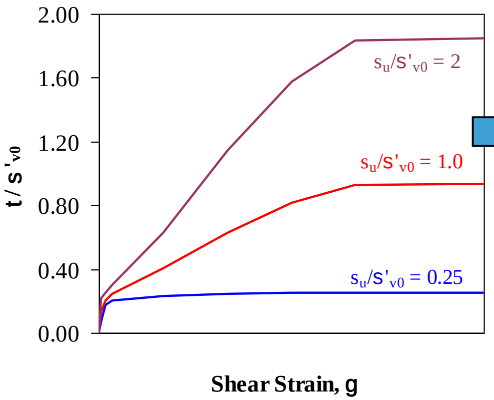
BASIL Model

- A ‘brush’ of ‘hairs’ radiating from pile centre line
- Pile ‘penetrates’ to first row of ‘hairs’
- Intersection of skirt tip with ‘hairs’ defines spring origin
- Pile ‘penetrates’ to next row of ‘hairs’
    - Springs from first row are loaded if any radial displacement
    - Pile deflects as required
- Intersection of skirt tip with next row of ‘hairs’
- And so on …..

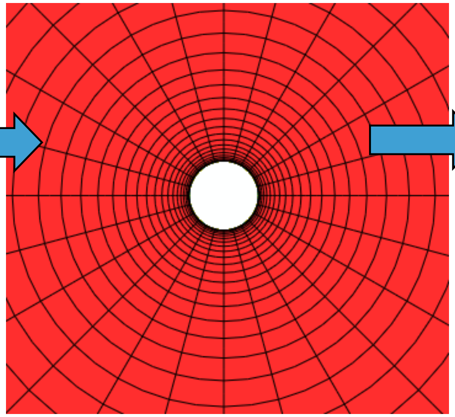


Soil Modelling

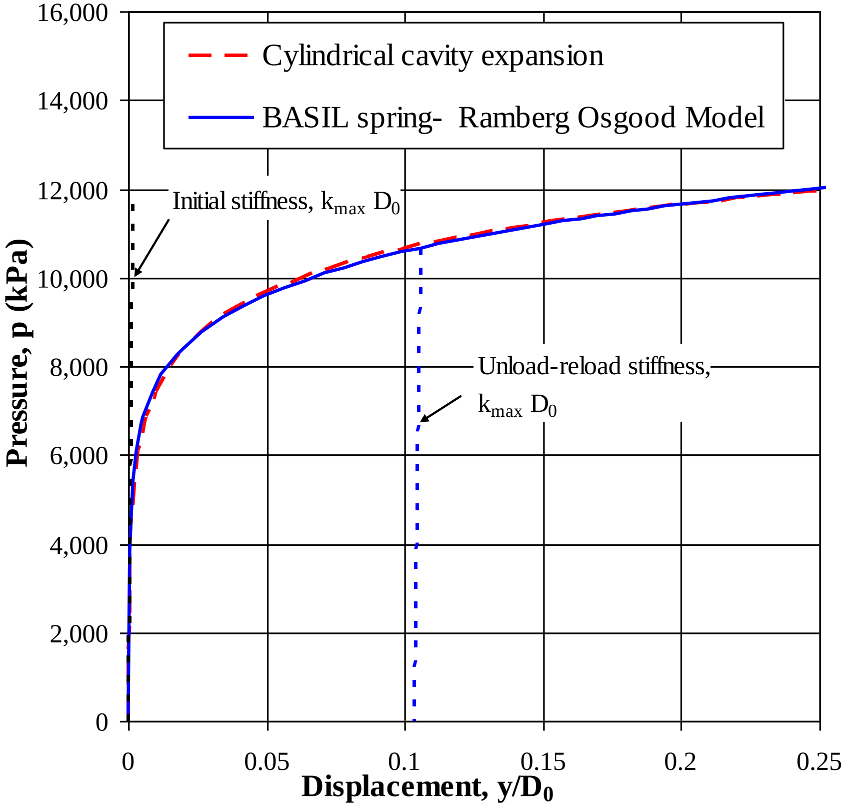
Stress-strain curves



FE Analyses

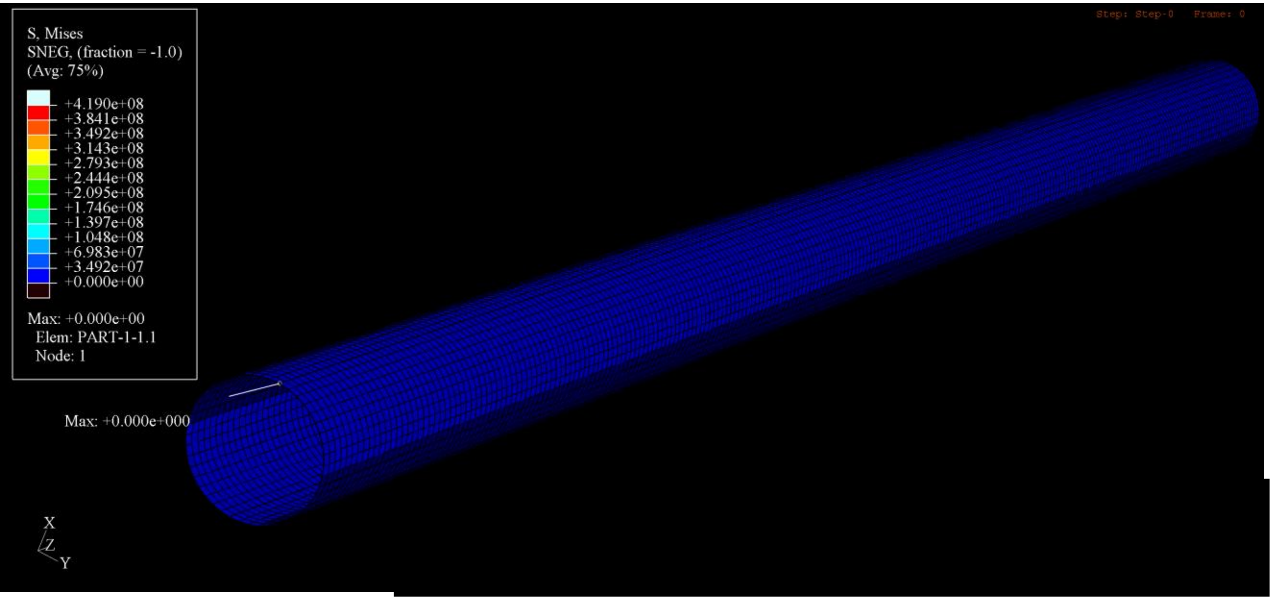


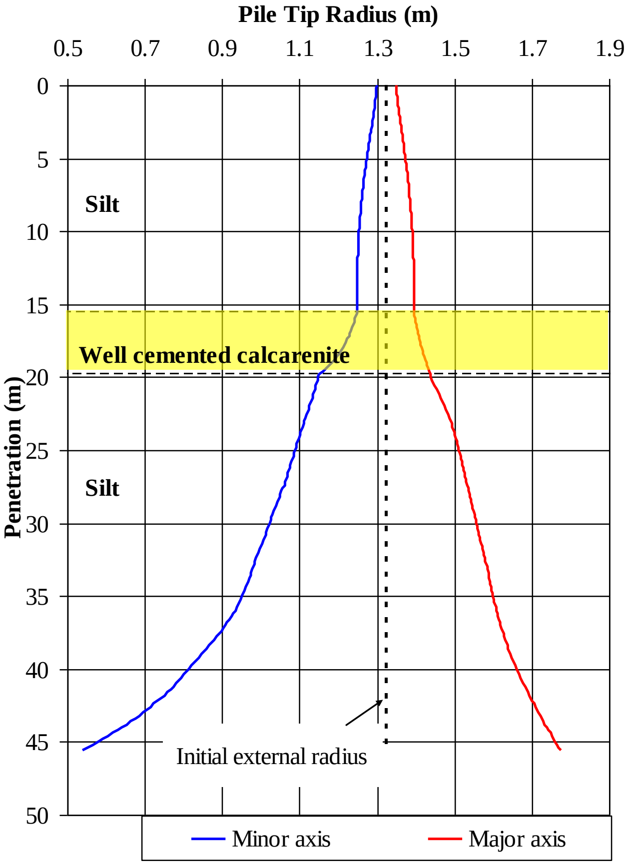
BASIL Spring



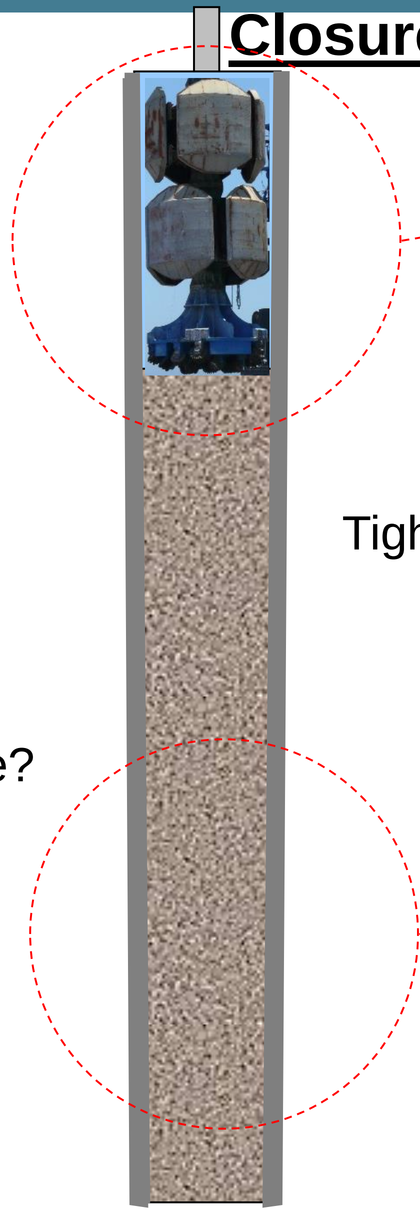
Example Analysis

Interlayered silt – with well cemented calcarenite layer





Closure



Not just an ‘extreme’ Goodwyn A or Valhall collapse to worry about…..

Clearance all round BHA

Remember:

Tight tolerances + small imperfections + the ‘wrong sort of soil’

MAY MEAN TROUBLE!

What about this…..
Not much wrong with this pile?

YOU HAVE BEEN WARNED…..

Hm… seems a bit stuck now!

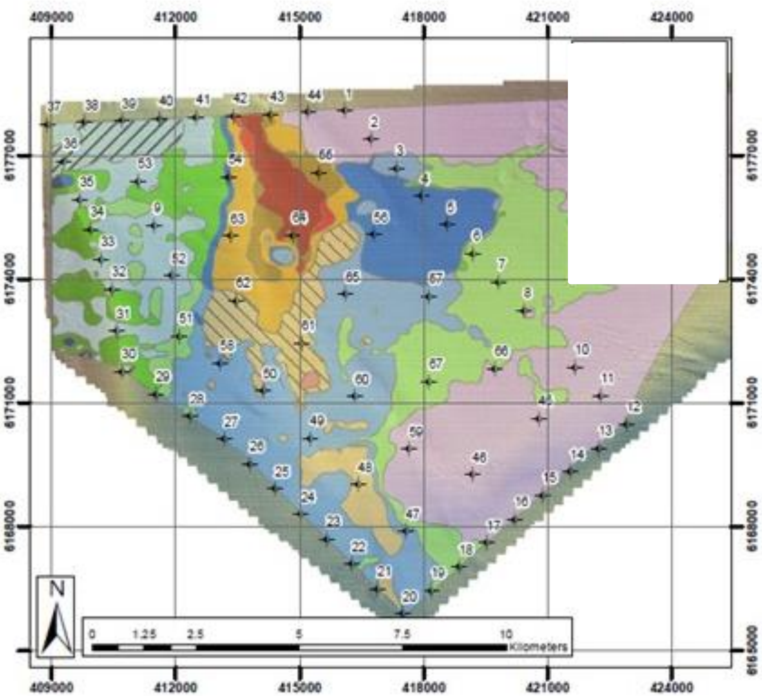
GEOSPATIAL ANALYSIS FOR OFFSHORE GEOTECHNICAL DESIGN

GIS Spatial Foundation Mapping

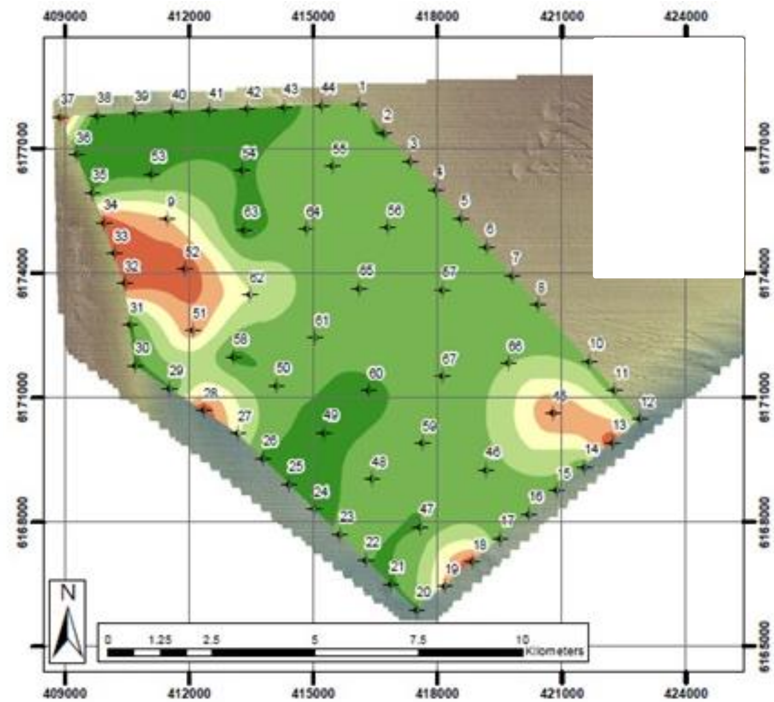
GIS-based geotechnical analysis tools to produce a foundation map for an OWF

- Any geotechnical analysis could be performed using this approach
- Allows for holistic design approach
- Potentially couple with other OWF spatial drivers (e.g. wake turbulence models and cable connection least cost maps) to allow for most economic layout

GIS-hosted Ground Model

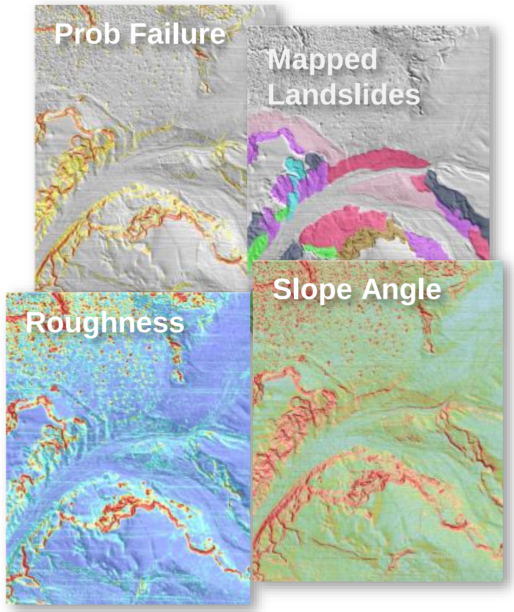


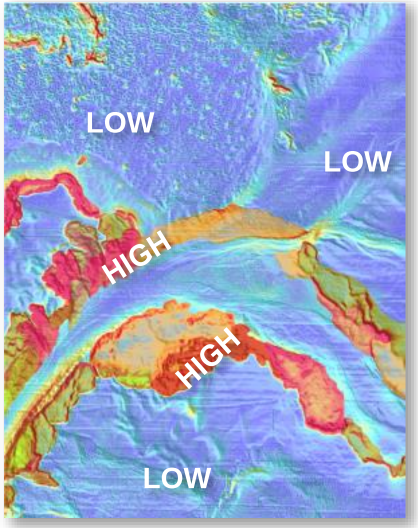
Required Pile Length Map



GIS Least Cost Routing – Geo-Cost Maps

Component Geo-Cost Maps





Composite Geo-Cost Map

5	6	5
1	3	8
6	8	9

Component Geocost Map 1

+

1	8	7
7	7	8
6	2	5

Component Geocost Map 2

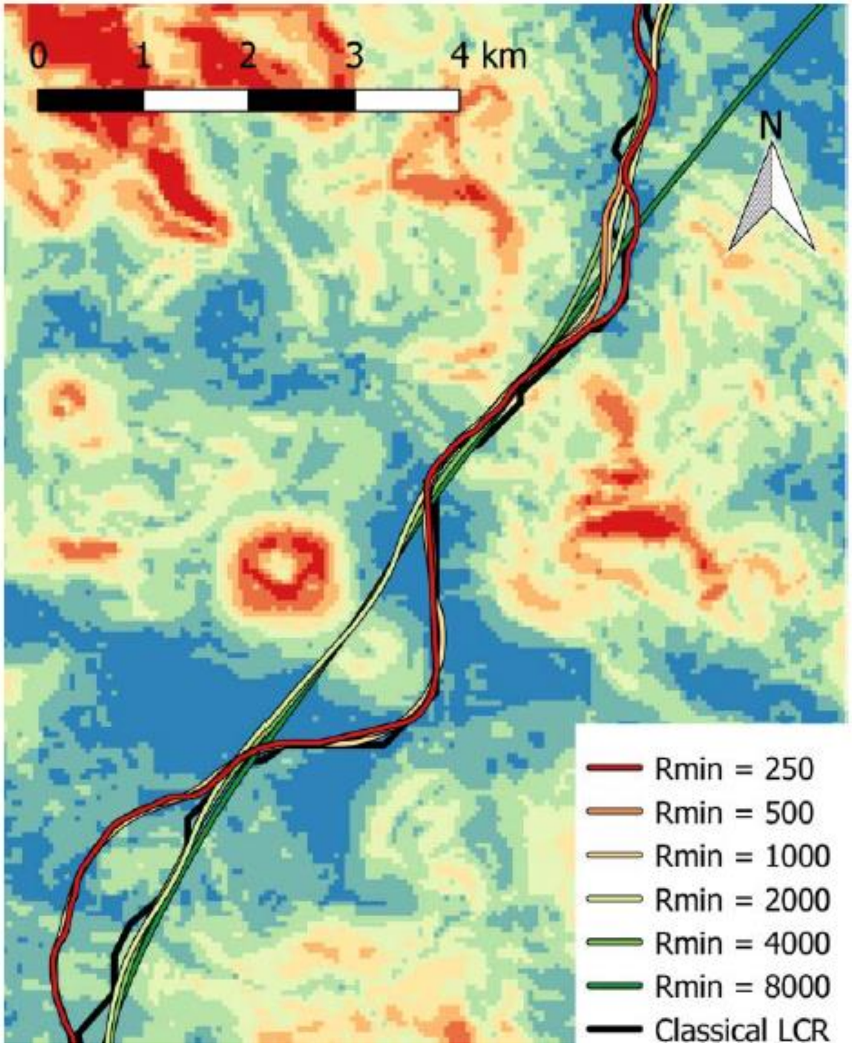
=

3	7	6
4	5	8
6	5	7

Composite Geocost Map

Least Cost Routing

- Classical routing optimisation methods produce many small radius deviations
- Traditionally significant post-processing required
- Fugro developed proprietary least cost routing method with curvature constrained incorporated
- Problem is solved efficiently by distributing the computing load on parallel processors, as well graphical processing units



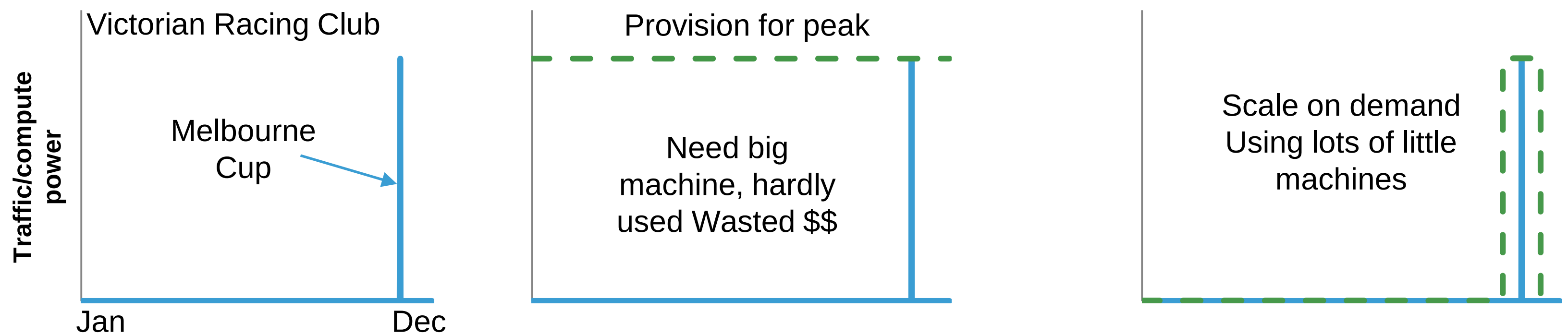
Pipeline Routing Example

Development of Cloud Based Applications

What is the Cloud?

Somewhere at the other end of your internet connection – a place where you can access apps and services, and where your data can be stored securely. The cloud is a big deal for three reasons:

- No effort on your part to maintain or manage it.
- You can access cloud-based applications and services from anywhere – all you need is a device with an Internet connection.
- It's effectively infinite in size, so you don't need to worry about it running out of capacity and scales on demand so you only pay for what you use.



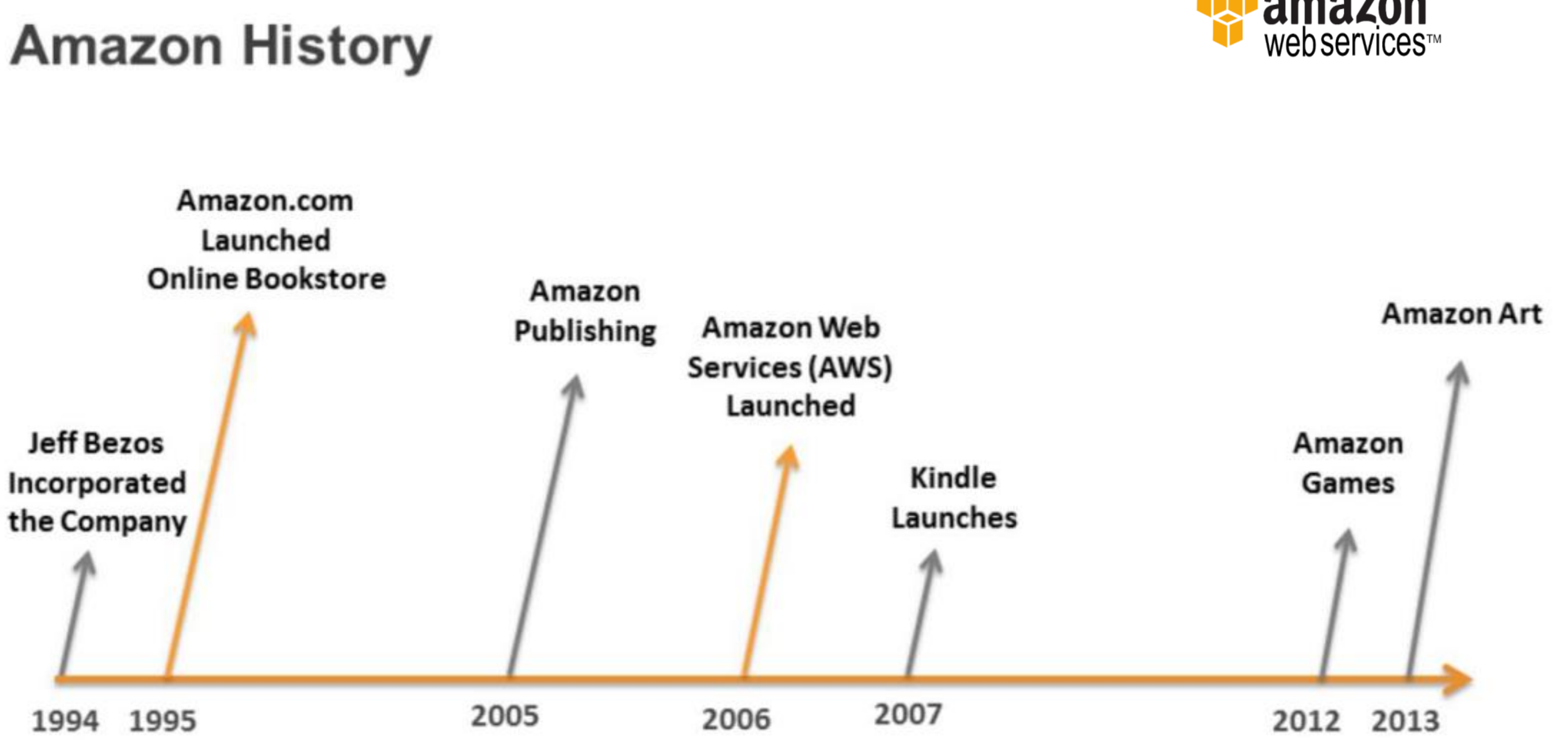
amazon web services™

Microsoft Azure

Google Compute Engine

rackspace® the open cloud company

Every day, AWS adds enough new server capacity to support all of Amazon’s global infrastructure when it was a $7B retailer



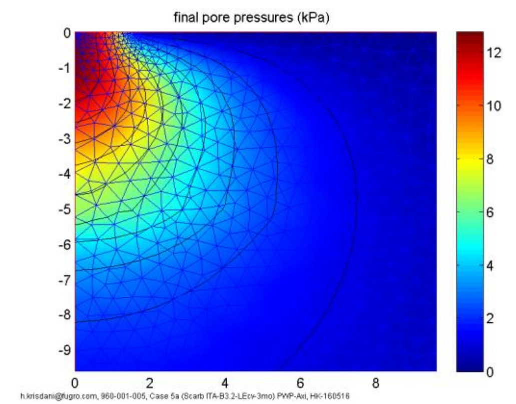
Web Based Calculation Tools (Web Apps): Overview

Description

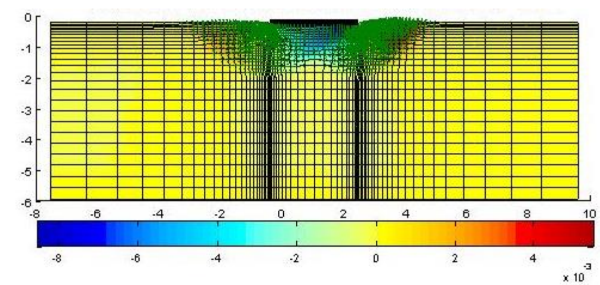
- Running Fugro in-house foundation analysis software in the cloud via a user-friendly web-based interface.

Benefits

- ***Quicker.*** Improve analysis speed (in some cases, reduced from hours to seconds) and accuracy by accessing virtually unlimited computing power using scalable numbers of cloud servers. Reduces man-hour requirements for design calculations and allows better optimisation of foundation designs – unlocks ability to perform statistical analyses.
- ***Consistent.*** Standardises software version and ensures analysis consistency.
- ***Easily accessed***. Can access the App from anywhere in the world.
- ***Secure.*** Secures intellectual property and data.



Quantifying consolidation strength gains under a shallow foundation



Calculating resulting foundation capacity

Web Based Calculation Tools (Web Apps): Overview

- Combining with scaling capability of cloud based computing allows for large volumes of foundation design calculations to be conducted

- This will allow a range of design options to be explored, resulting in optimised foundation solutions.

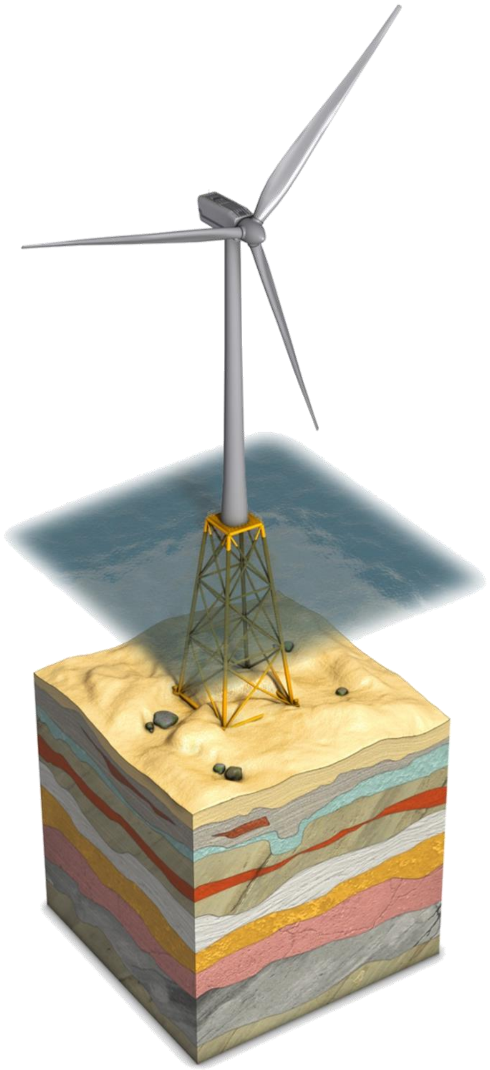
pCyCOS	CHIPPER	BearCon	CYCLOPS
SpudCone	App - 6	App - 7	App - 8
App - 9	App - 10	App - 11	App - 12

No.	Name	Function
1	pCyCOS	Assessment of **lateral** response of piles in **uncemented** soils subject to undrained monotonic and/or cyclic loading.
2	CHIPPER	Assessment of **lateral** response of piles in **cemented** soils subject to undrained monotonic and/or cyclic loading.
3	BearCon	Assessment of bearing capacity of shallow (skirted) foundation under combined loading (monotonic and cyclic).
4	CYCLOPS	Assessment of **axial** response of piles in **uncemented** soils subject to undrained monotonic and/or cyclic loading.
5	SpudCone	Assessment of spudcan penetration based on CPT data.
6	AGSPANC (under development)	Assessment of caisson foundation capacity.

Summary

Summary

- Significant need bespoke analysis methods developed on individual projects
- Integrated Geotechnical and geoscience needed to fully understand site and develop ground model
- Geotechnical designer/modeller should be involved in lab testing schedule and site investigation
- Advanced laboratory testing needed in conjunction with suitable constitutive models



Thank You!