DEPARTMENT OF ENGINEERING SCIENCE

UNIVERSITY OF OXFORD

Géotechnique Lecture 2011

Foundation Design for Offshore Wind Turbines

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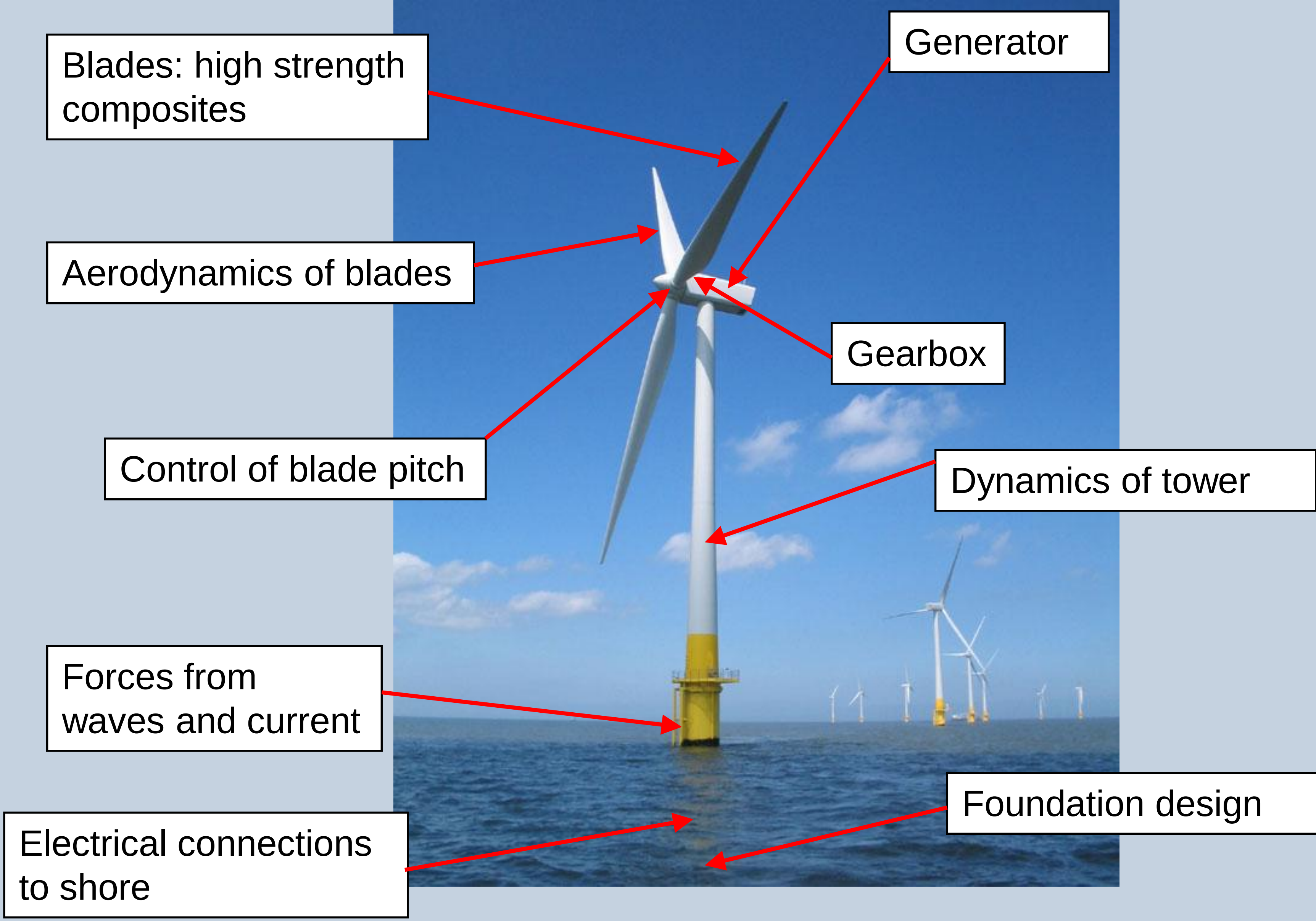
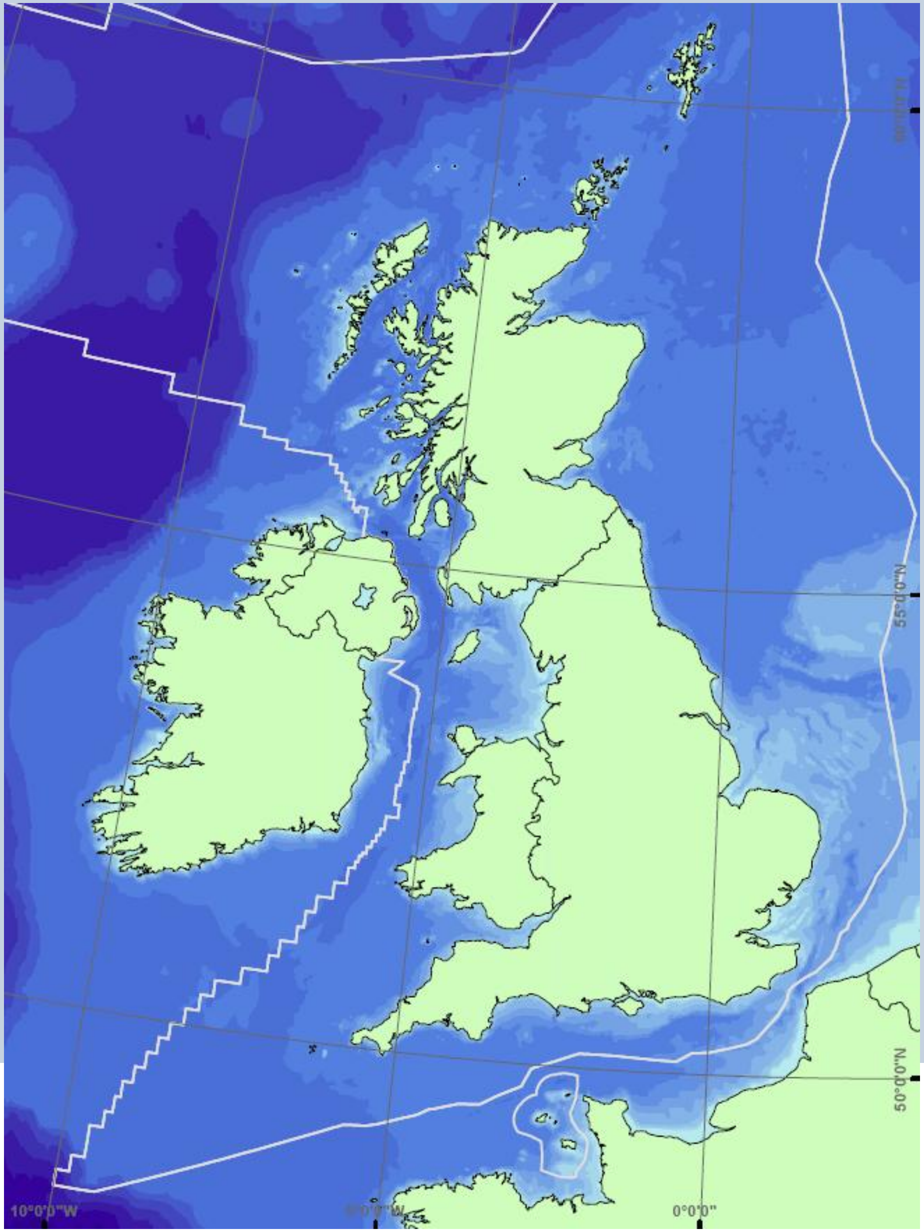
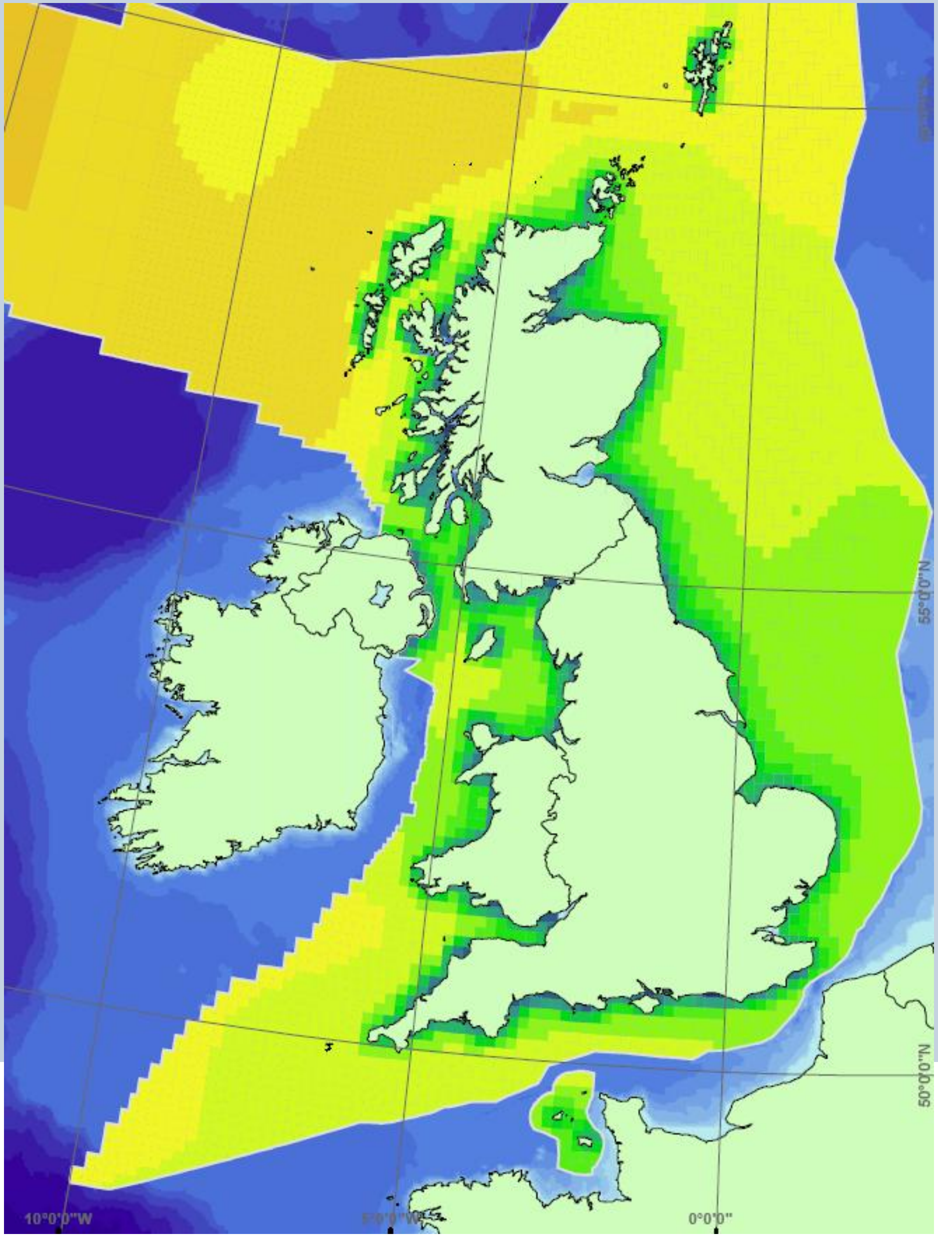
British Geotechnical Association
Institution of Civil Engineers
Wednesday 9th November 2011


Blades: high strength composites
Generator
Aerodynamics of blades
Gearbox
Control of blade pitch
Dynamics of tower
Forces from waves and current
Foundation design
Electrical connections to shore

Water depth



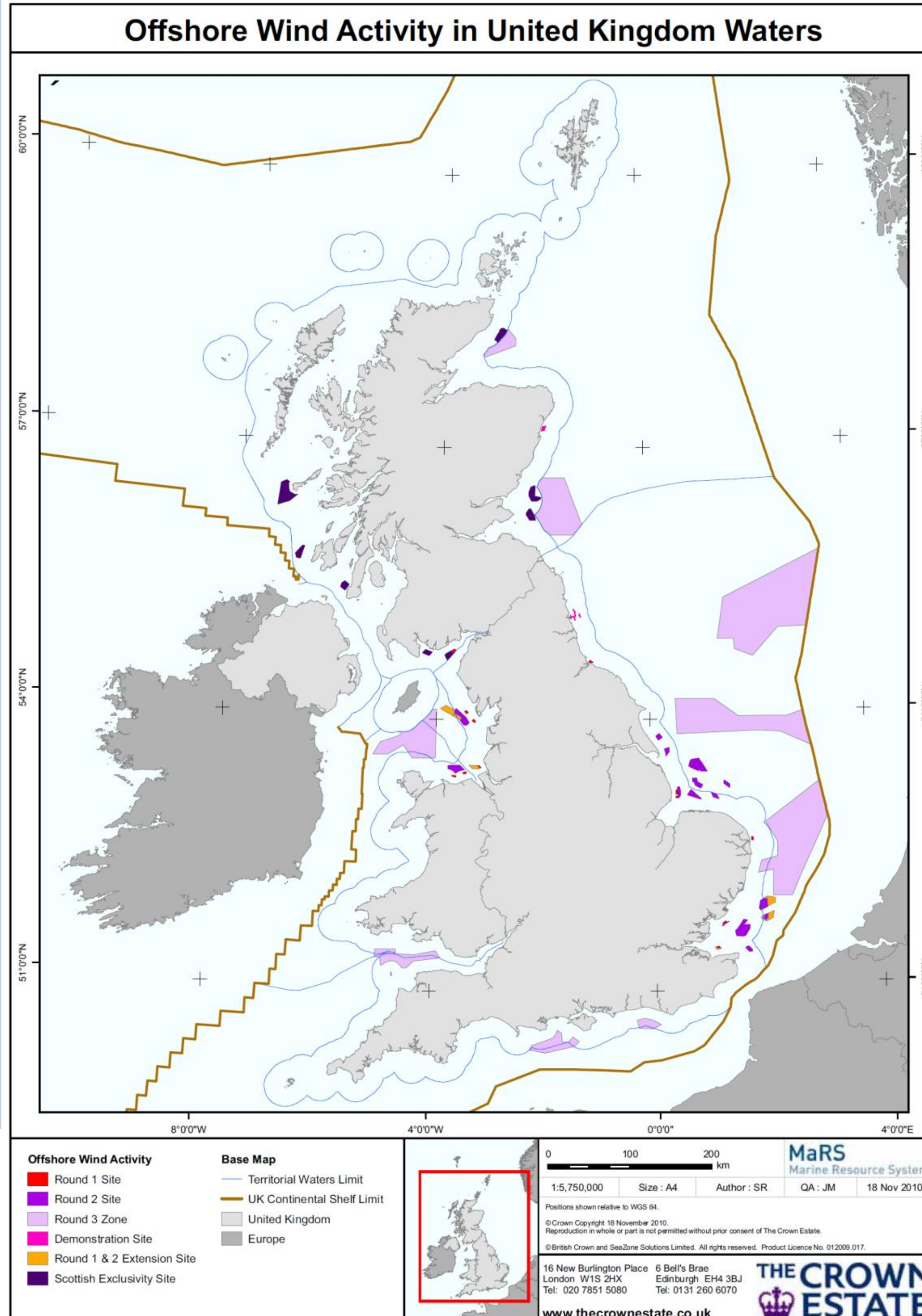
Average wind speed



Source: DTI Renewable Energy Atlas

Offshore sites

- Round 1 - 2001
  - ~ 1 GW
- Round 2 - 2003
  - ~ 7 GW
- Round 3 - 2010
  - ~ 32 GW



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UK Wind Overview

Status	Onshore Number	Onshore Power (GW)	Offshore Number	Offshore Power (GW)
Operational	296	4.2	14	1.5
Construction	32	1.5	6	2.0
Consent	232	3.6	5	1.6
Planning	314	7.3	4	2.0
Total	874	16.6	29	7.1
	96.8%	70%	3.2%	30%

- Figures are rated maximum power and not average delivered power
- Total UK installed generating capacity is approximately 91GW

Source: RenewableUK (bwea.com)

Offshore Wind – Challenges

- RenewableUK indicates plans for about 42GW of wind power to be installed, though no time scale indicated
- Government announcements : 33GW by 2020
  - 6600 5MW turbines

- Over 800 turbines per year to 2020!
- *Replacement rate about 300 turbines per year indefinitely*

- Nearly 500 turbines installed and operating since 2000

- Total investment in region of £80bn to £100bn
- Many (tens of) thousands of jobs in the supply chain

Cost Makeup

- 4%   Development and consent
- 33% Turbine
- 15% Electrical
- 22% Support structure
- 26% Production, integration and installation
  - Source: Carbon Trust

- Foundations and installation part of the last two categories
- Opportunity to reduce costs by using alternative foundation concepts and installation processes
- …as well as by improving design approaches

- Costs are of the order say £3m to £3.5m per MW installed
  - Source UK ERC report Sept 2010

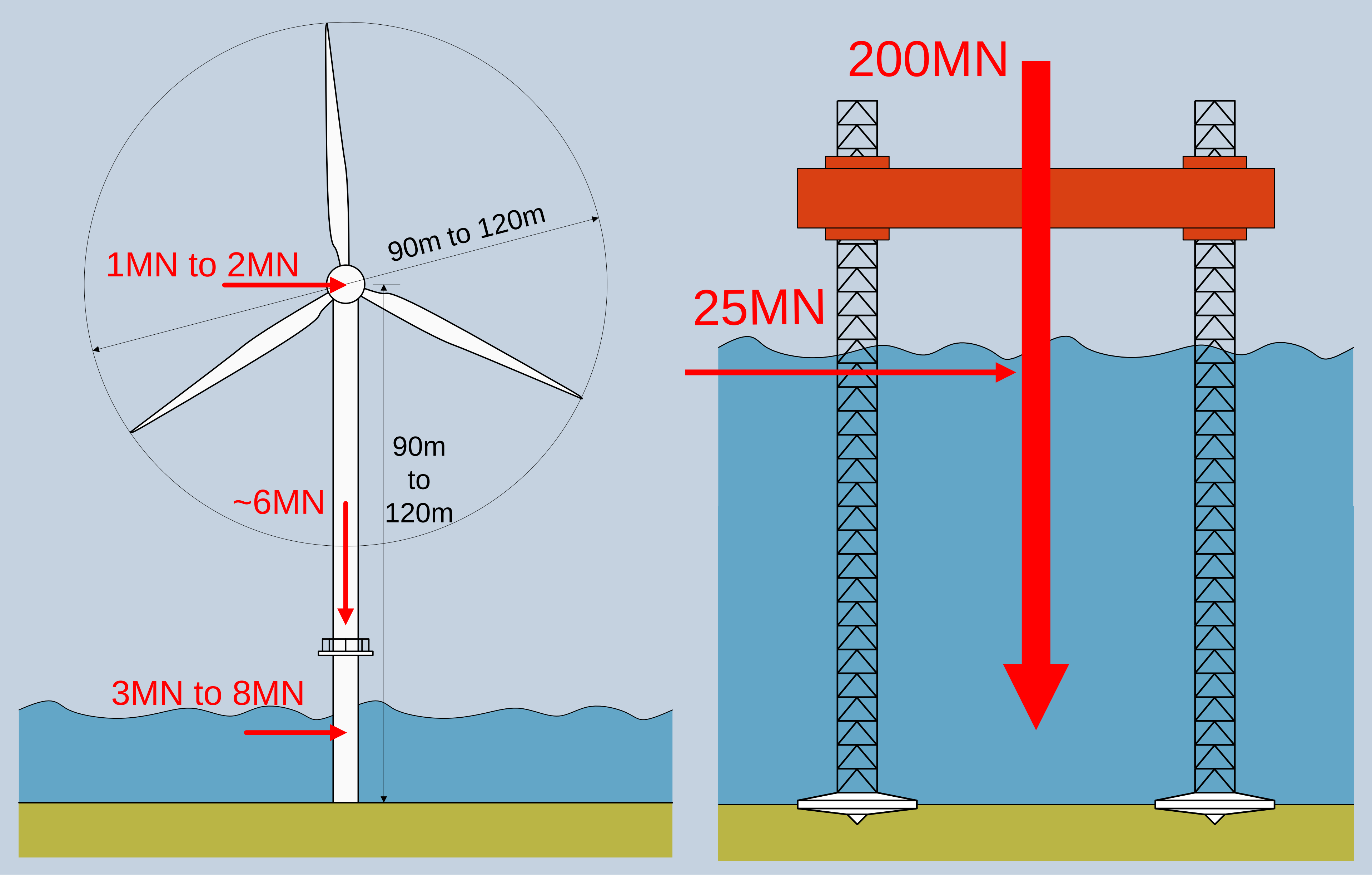
Geotechnical Issues

- A full range of geotechnical conditions can be found at the various sites - mobile sand banks, dense sand, stiff clays, layered materials, soft clays, rocky strata, boulder clay

- Can be considerable variability over a site (turbines are typically spaced more than 500m apart)

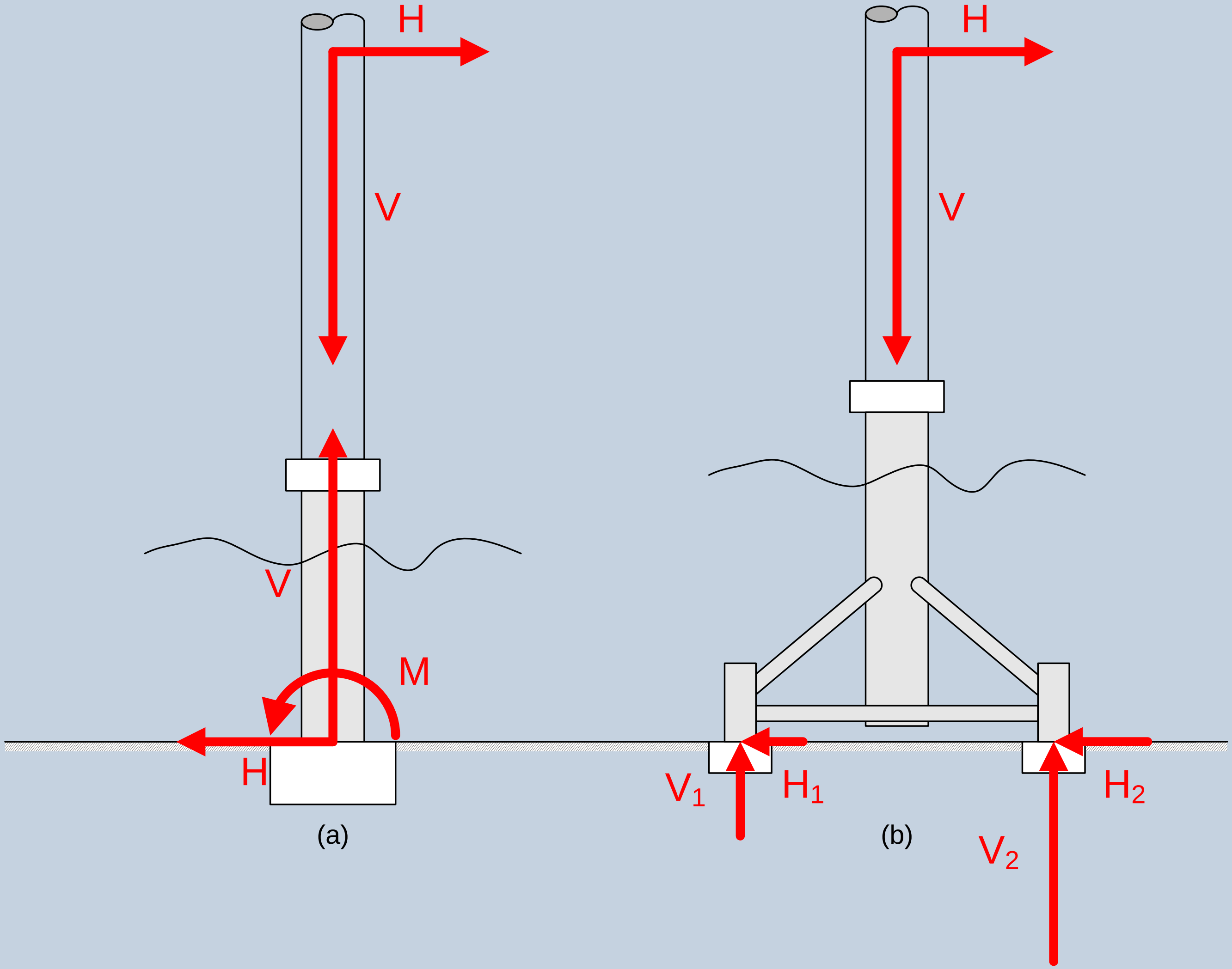
- A site investigation is important early in the design process and may involve CPTs, Boreholes, vane tests, geophysical surveys

- There may also be element testing using samples obtained from the site



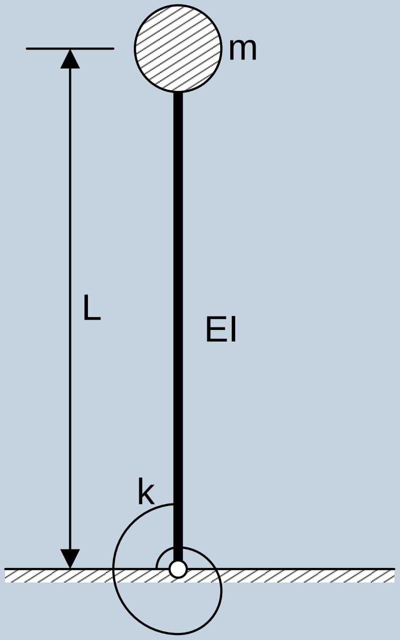
1MN to 2MN
90m to 120m
~6MN
90m
to
120m
3MN to 8MN
200MN
25MN

Loads on an Offshore Turbine Foundation



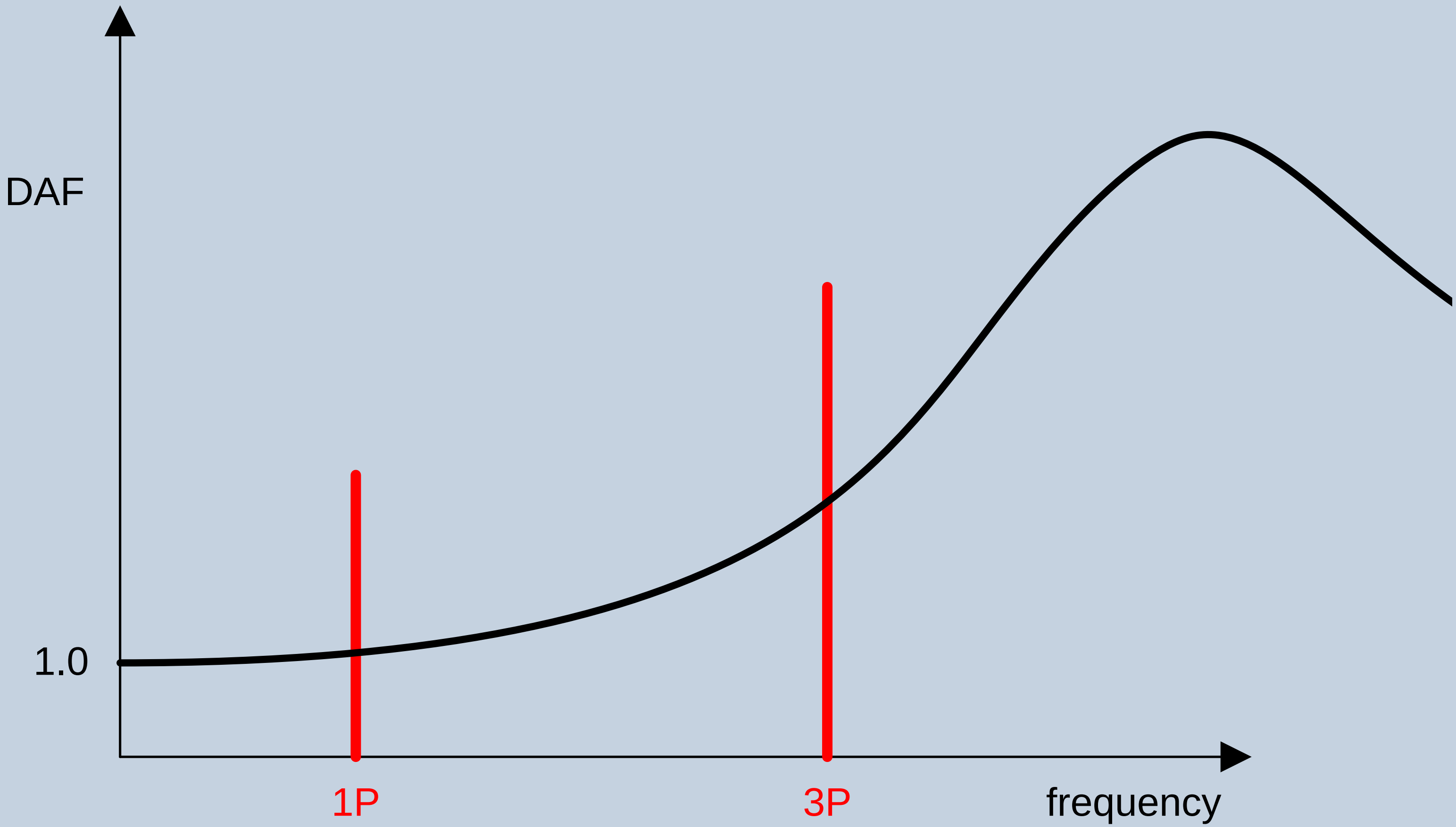
Foundation stiffness

- The main excitation frequencies are 1P (the rotational frequency) and 3P (the blade-passing frequency)
- These must be avoided
- The flexibility of the foundation reduces the natural frequency

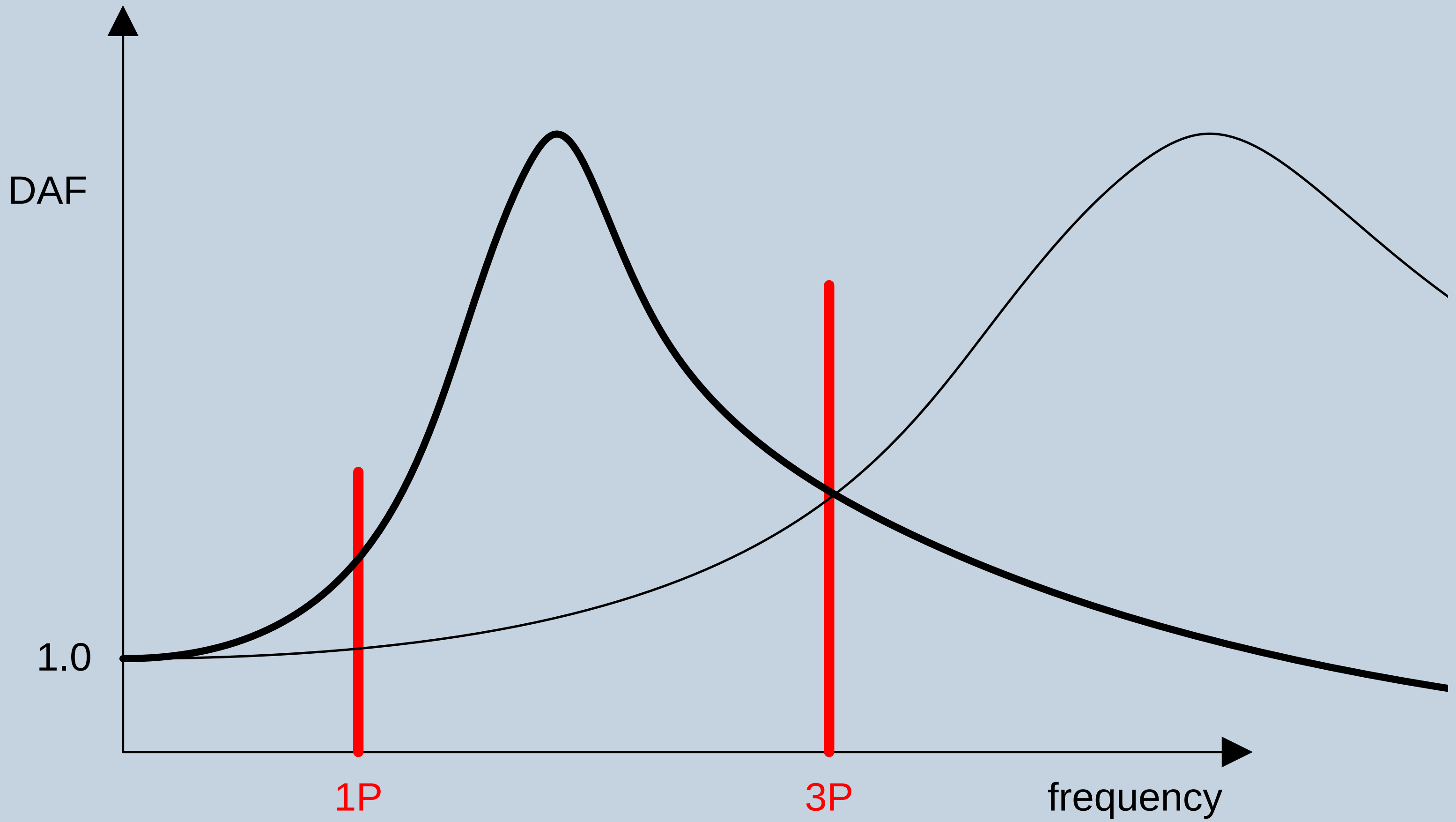


$$f_n = \frac{1}{2\pi}\sqrt{\frac{1}{m\left(\frac{L^3}{3EI} + \frac{L^2}{k}\right)}}$$

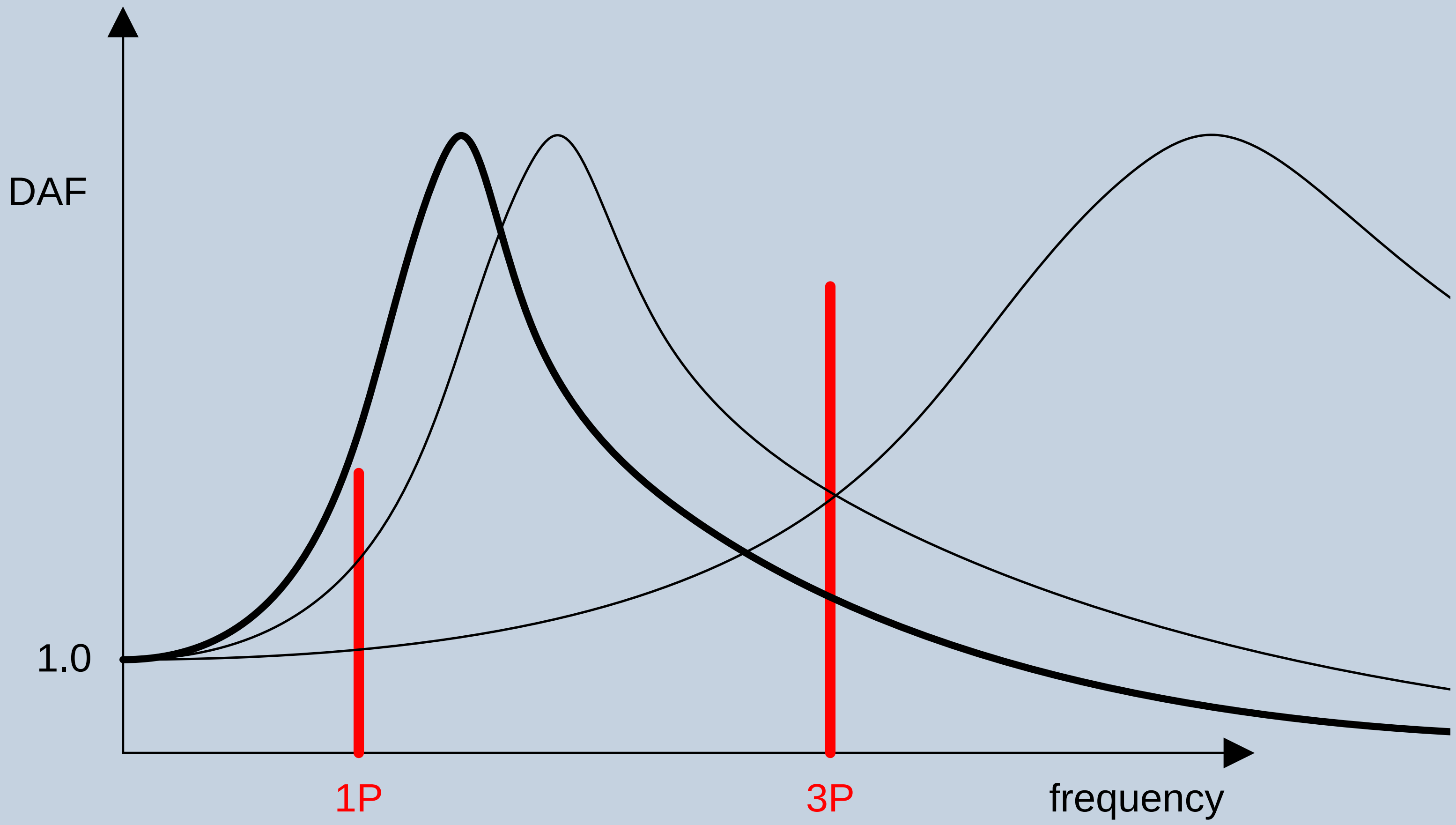
Stiff-Stiff Response



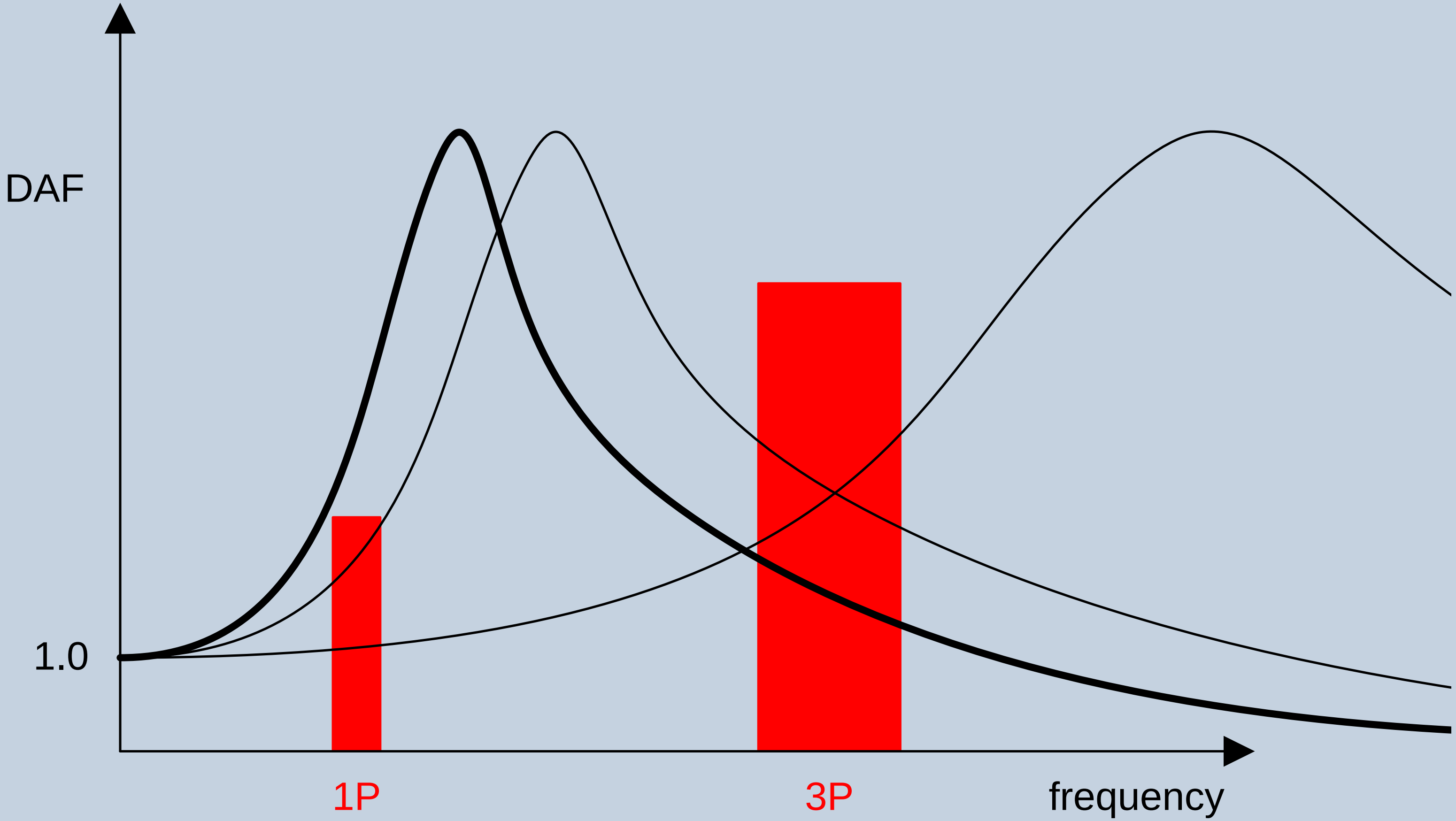
Soft-Stiff Response



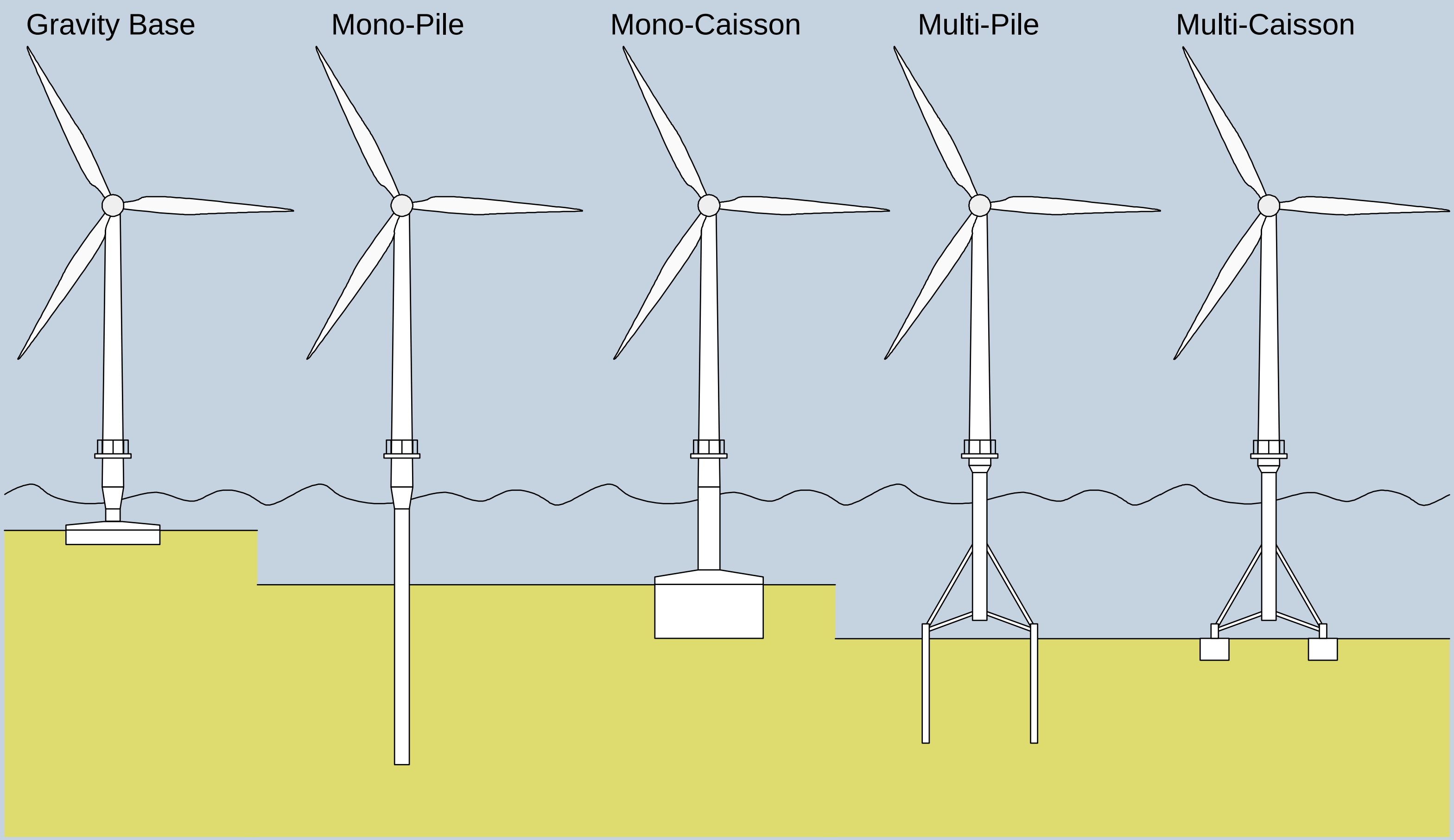
Effect of Foundation



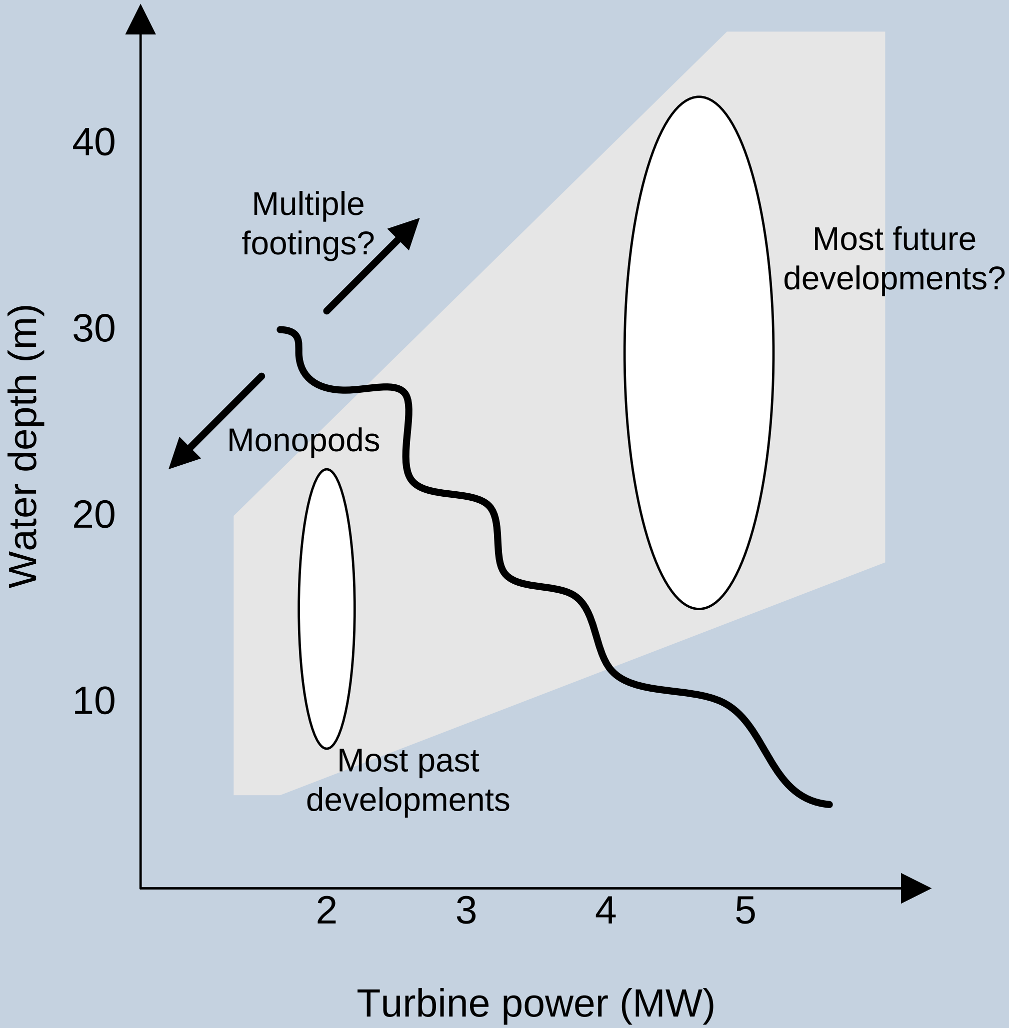
Range of Excitation Frequencies



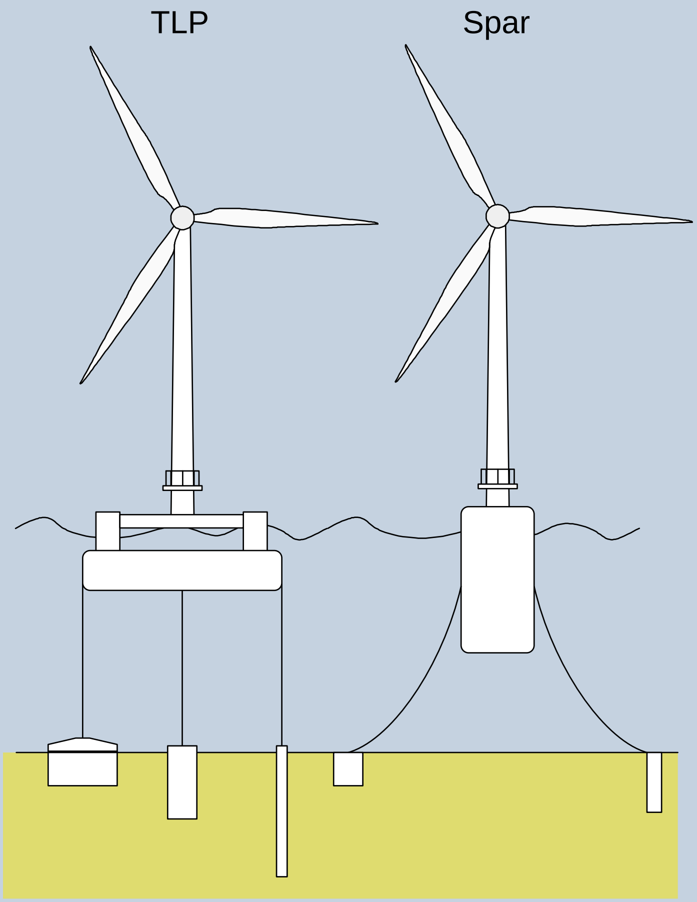
Options for Foundations



Size and Location of Developments



Other Designs / Possibilities



Experimental Work

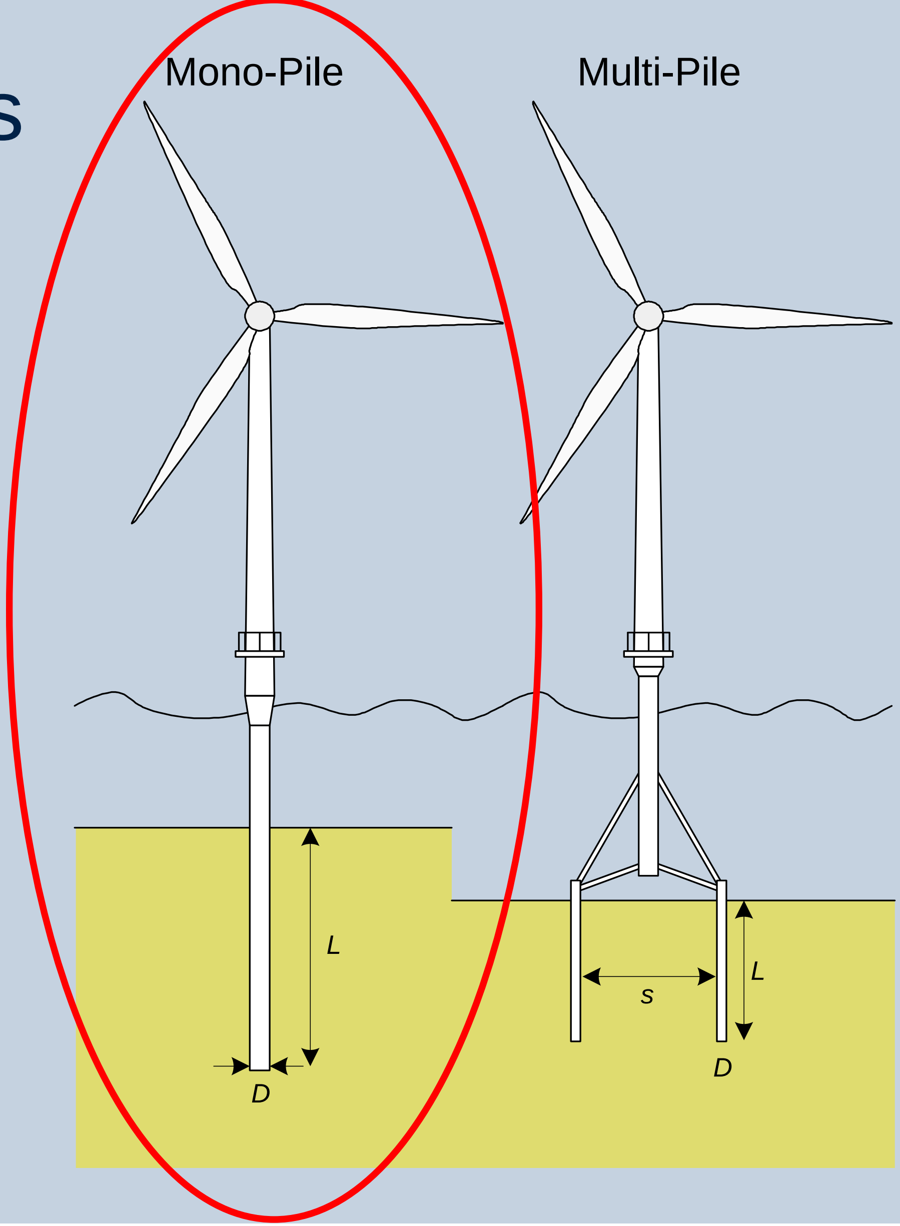
- Most of the work presented is based on small scale model tests in the laboratory
  - High quality sophisticated work carried out
  - Designed to build up a framework of response
- Careful consideration has been given to scaling of the results
  - Density of sands, strength of clays
- Dimensional analysis has yielded dimensionless groups relevant to each of the problems explored

CURRENT DESIGNS

PILE FOUNDATIONS

Mono-Pile Foundations

- A wind turbine monopile is at least 4m diameter and of the order of 25m long
- Driving is at the limits of offshore oil-and-gas experience which typically involves smaller diameter (~2m) and longer piles (~100m)
- Large diameter drilling is suitable in certain materials
- Options:
  - drive
  - drill and grout
  - composite e.g. drive-drill-drive



Mono-Pile Foundations

Average ~89 hours per pile at North Hoyle

Source http://www.rwe.com/web/cms/en/312104/rwe-innogy/sites/wind-offshore/in-operation/north-hoyle/construction-diary/wind-turbine-foundations/

Walney Wind Farm

Photos from Dong Energy: Christian LeBlanc Thilsted and Dan Kallehave

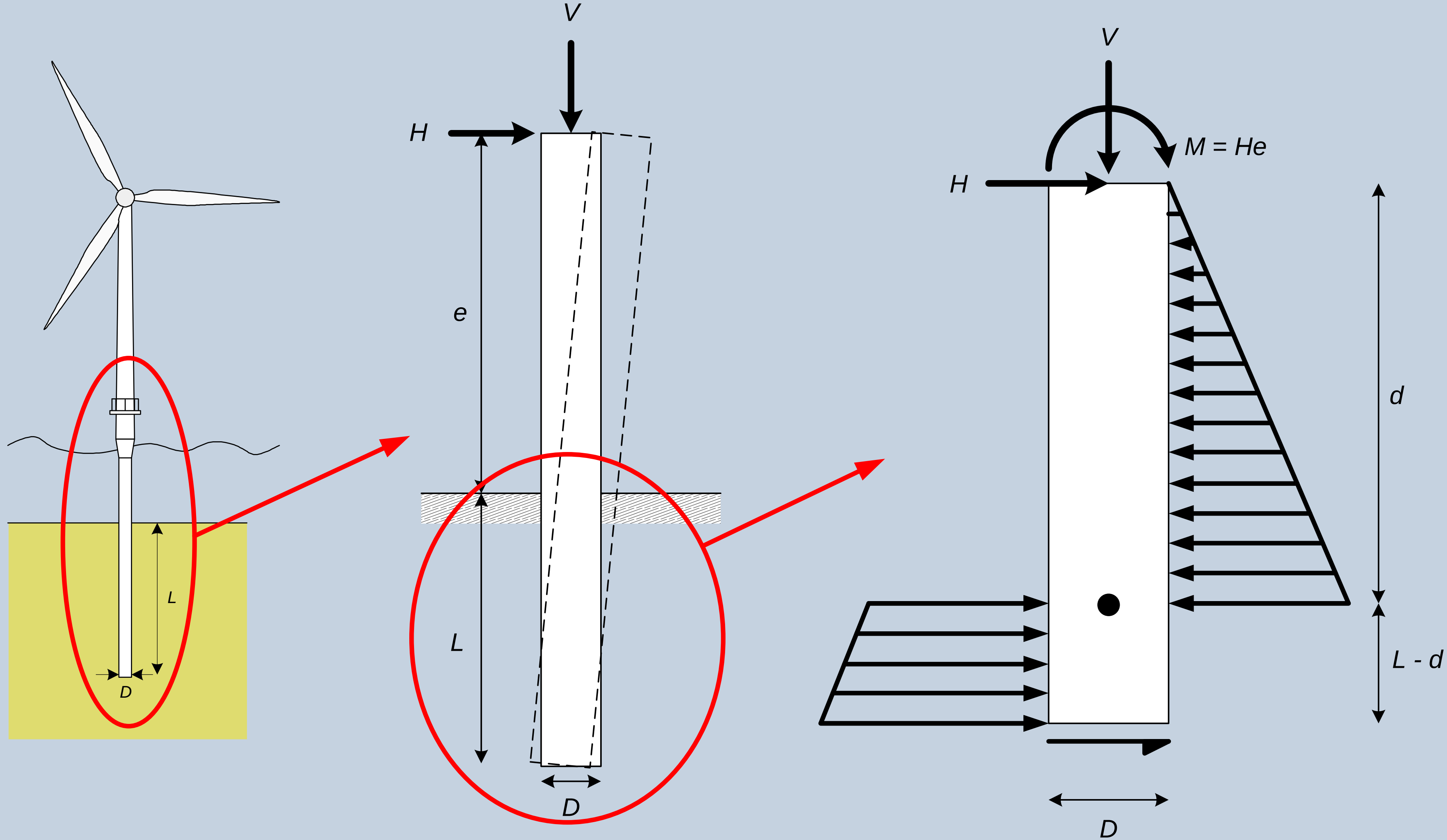
Pile Design Issues – Wind Turbine

- Stiffness is a key design criterion in addition to capacity.
- Various offshore design approaches are based on much more flexible piles and are more concerned with lateral capacity than stiffness.
- Typical offshore pile say L/D ~ 30 – 50 or more whilst wind-farm pile L/D ~ 4 - 8.
- Are the usual design approaches still appropriate?
- Performance under cyclic loading is important but there is very limited guidance for designers (if any at all…)
    - Accumulated rotations? Stiffness response?

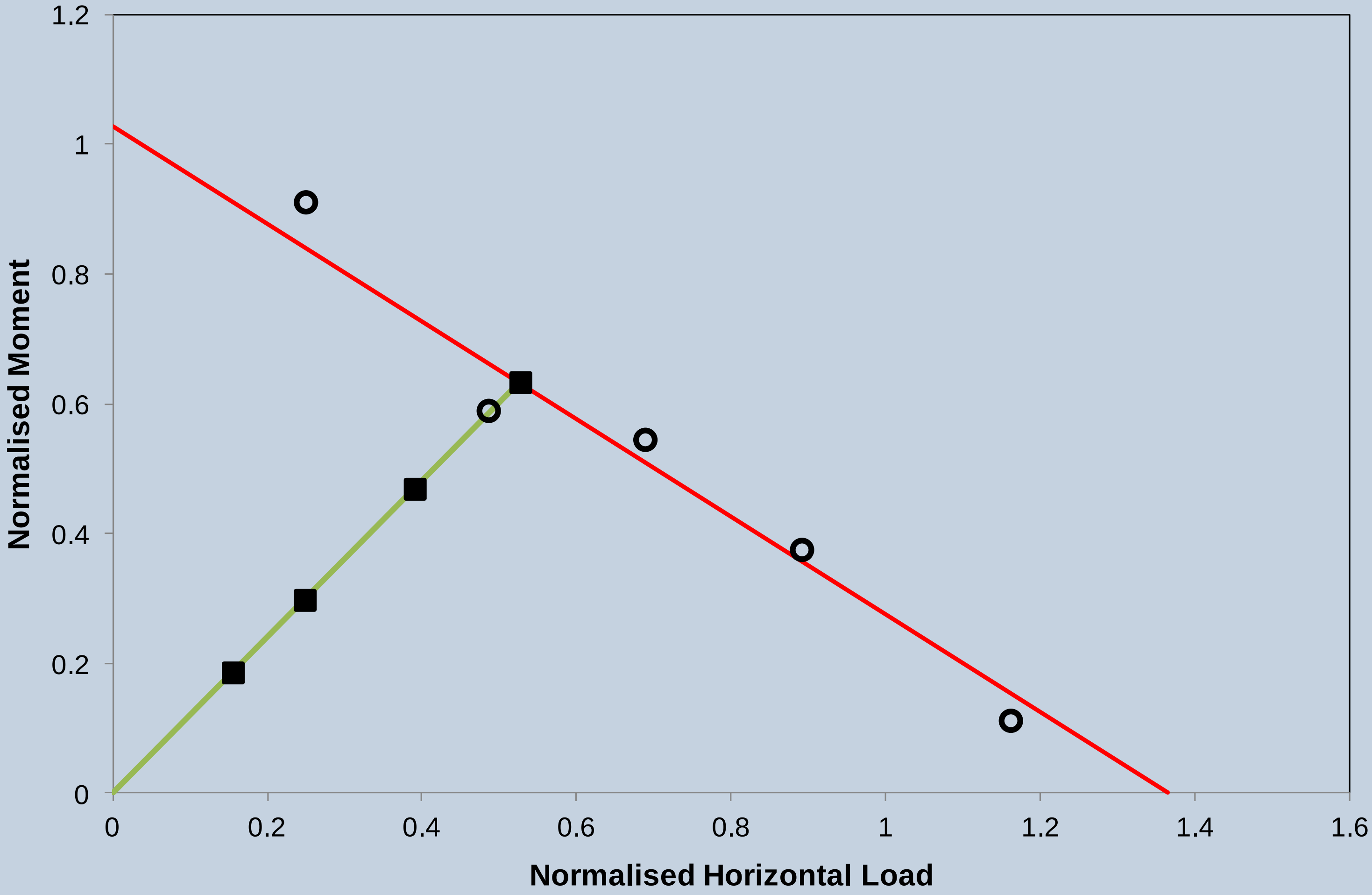
Structural configuration

Idealisation of applied forces

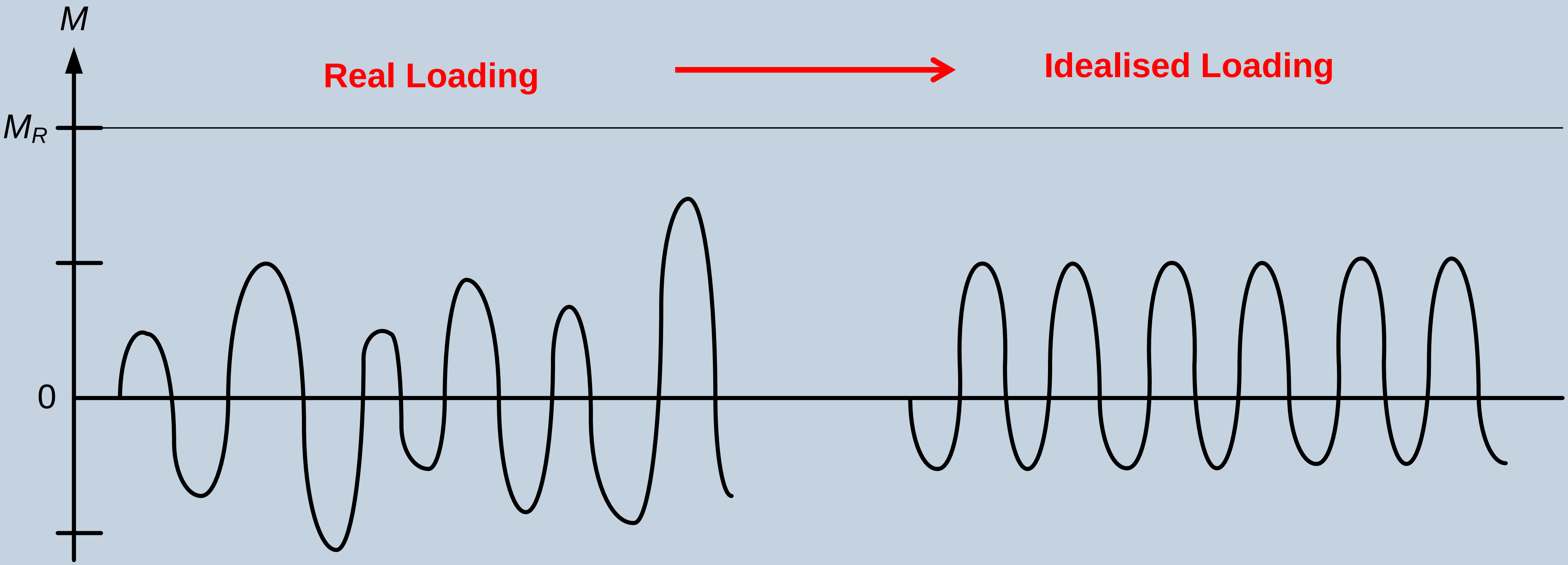
Soil reactions



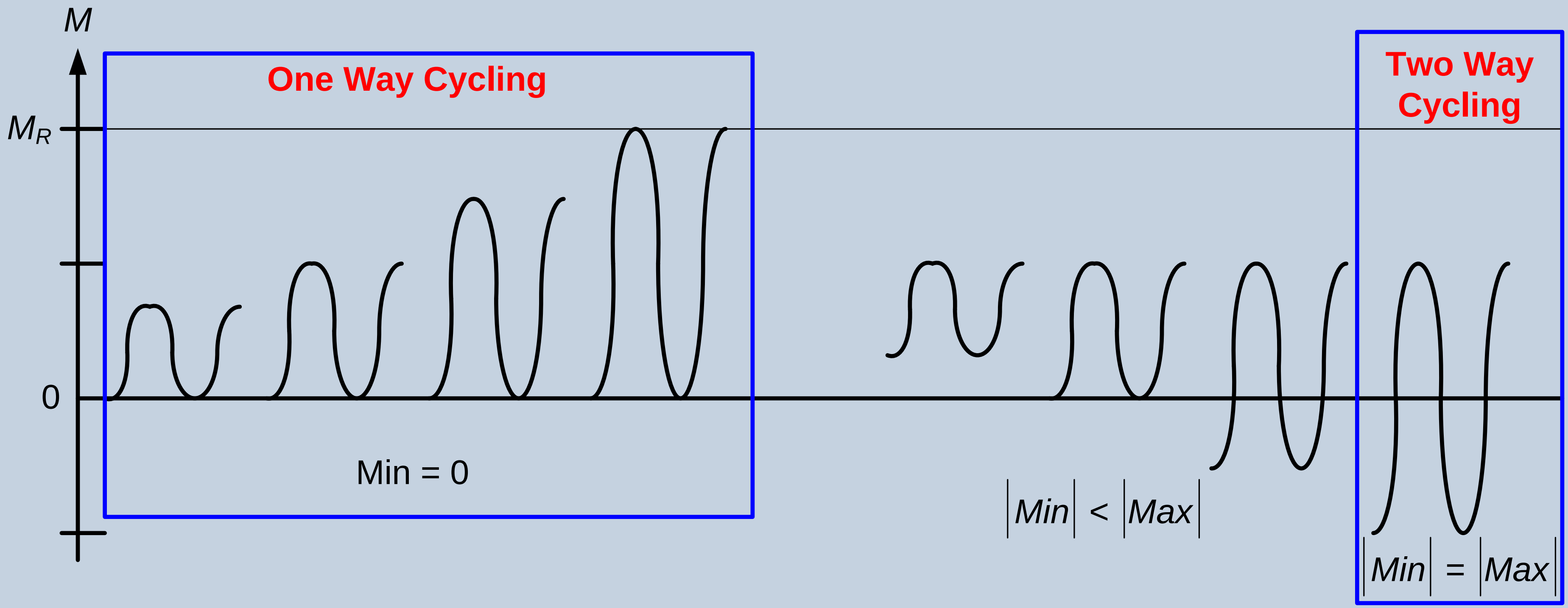
Static Tests

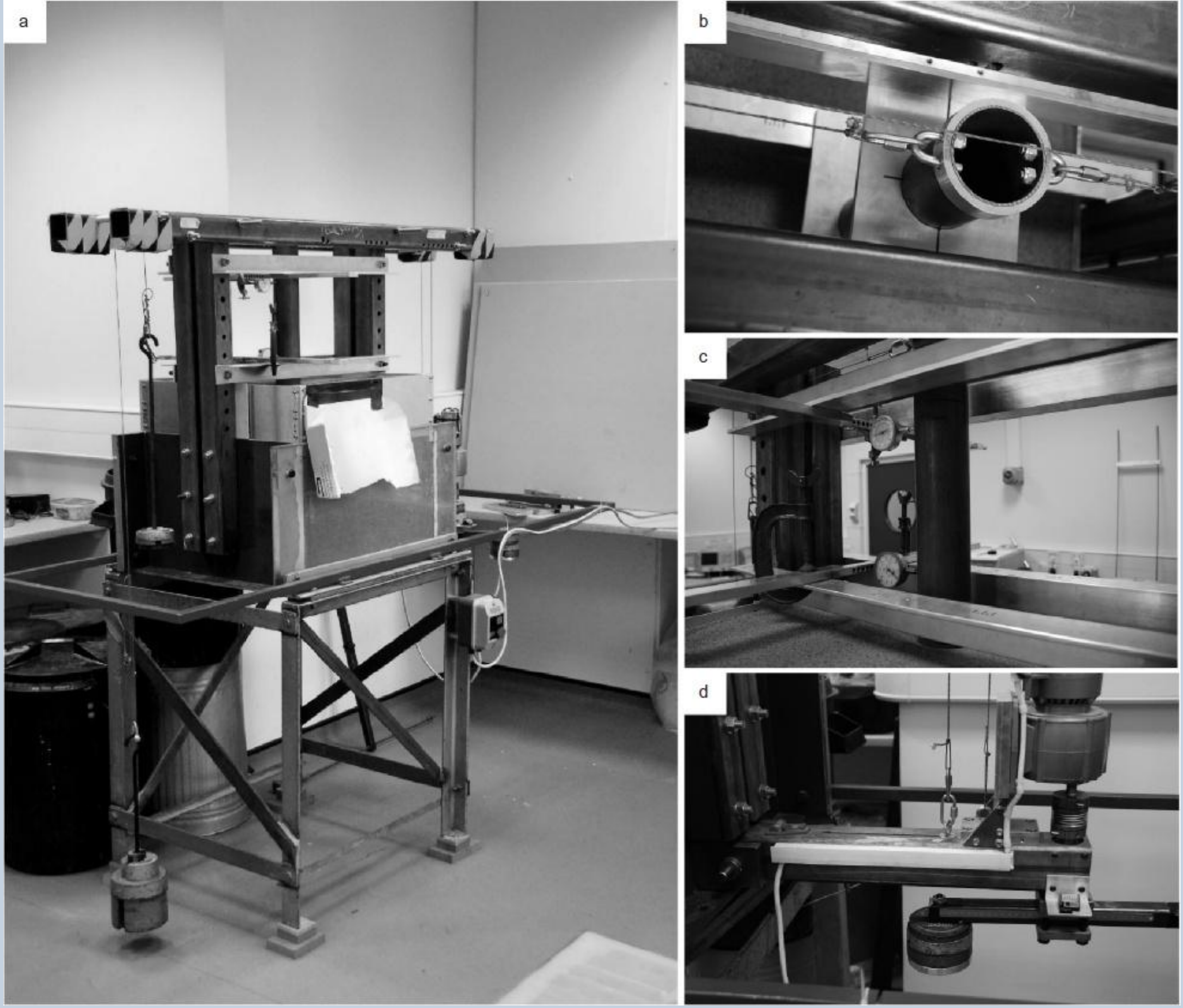


Cyclic loading

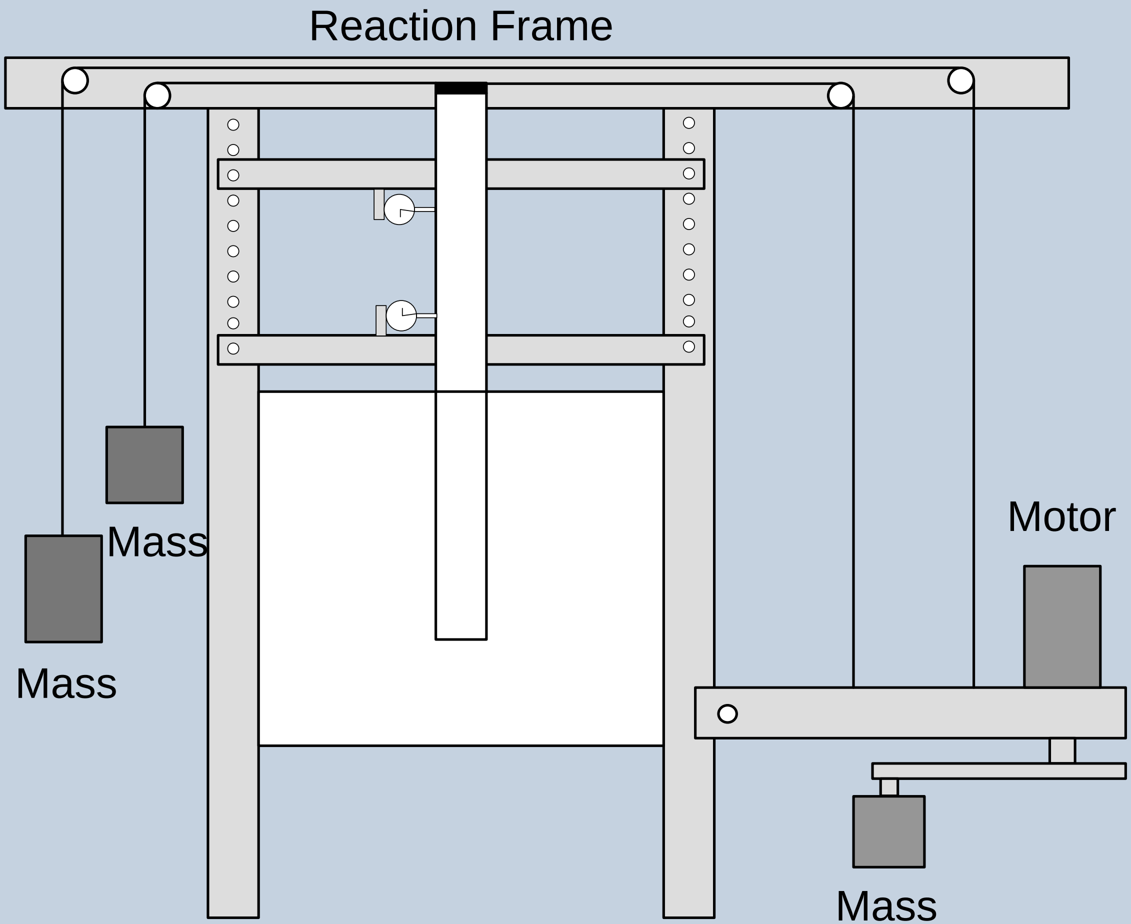


Cyclic loading

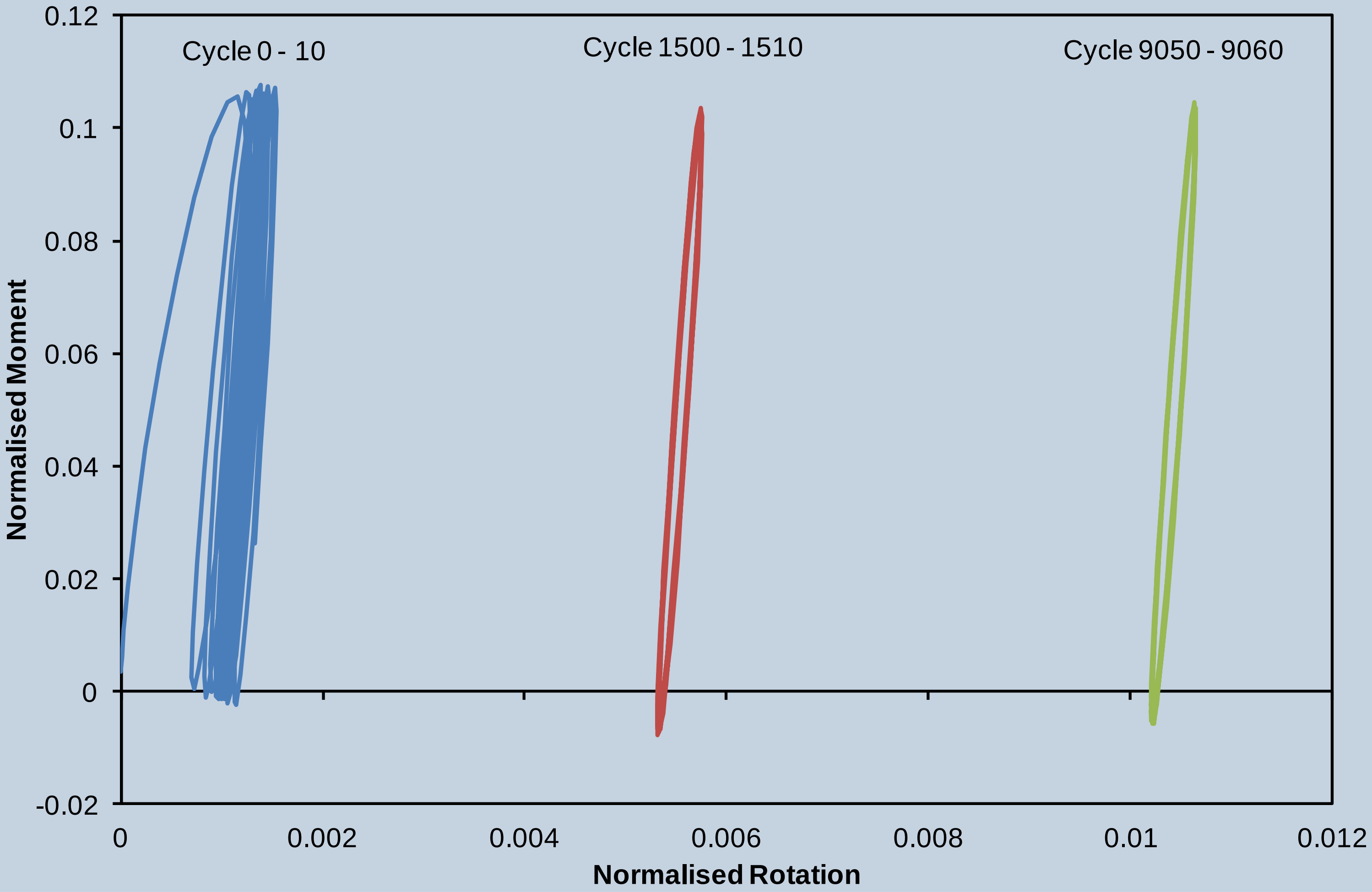



a
b
c
d

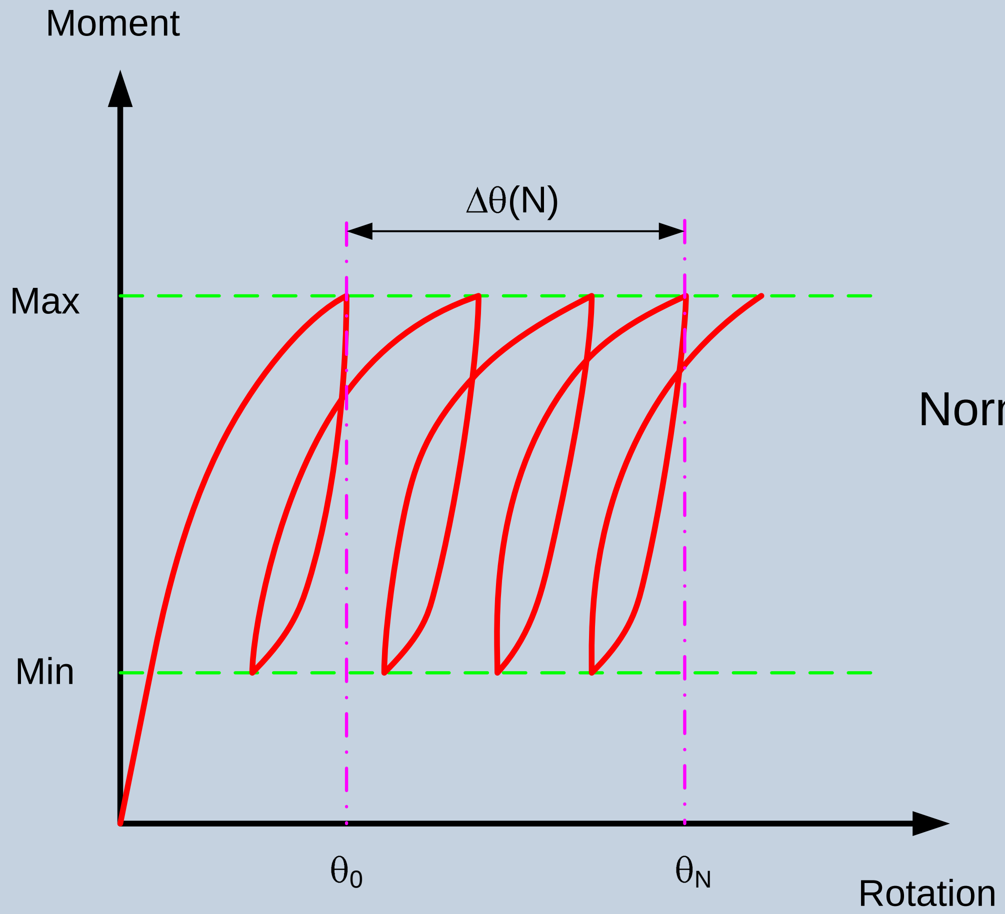
Testing Equipment



Example Cyclic Loading Results



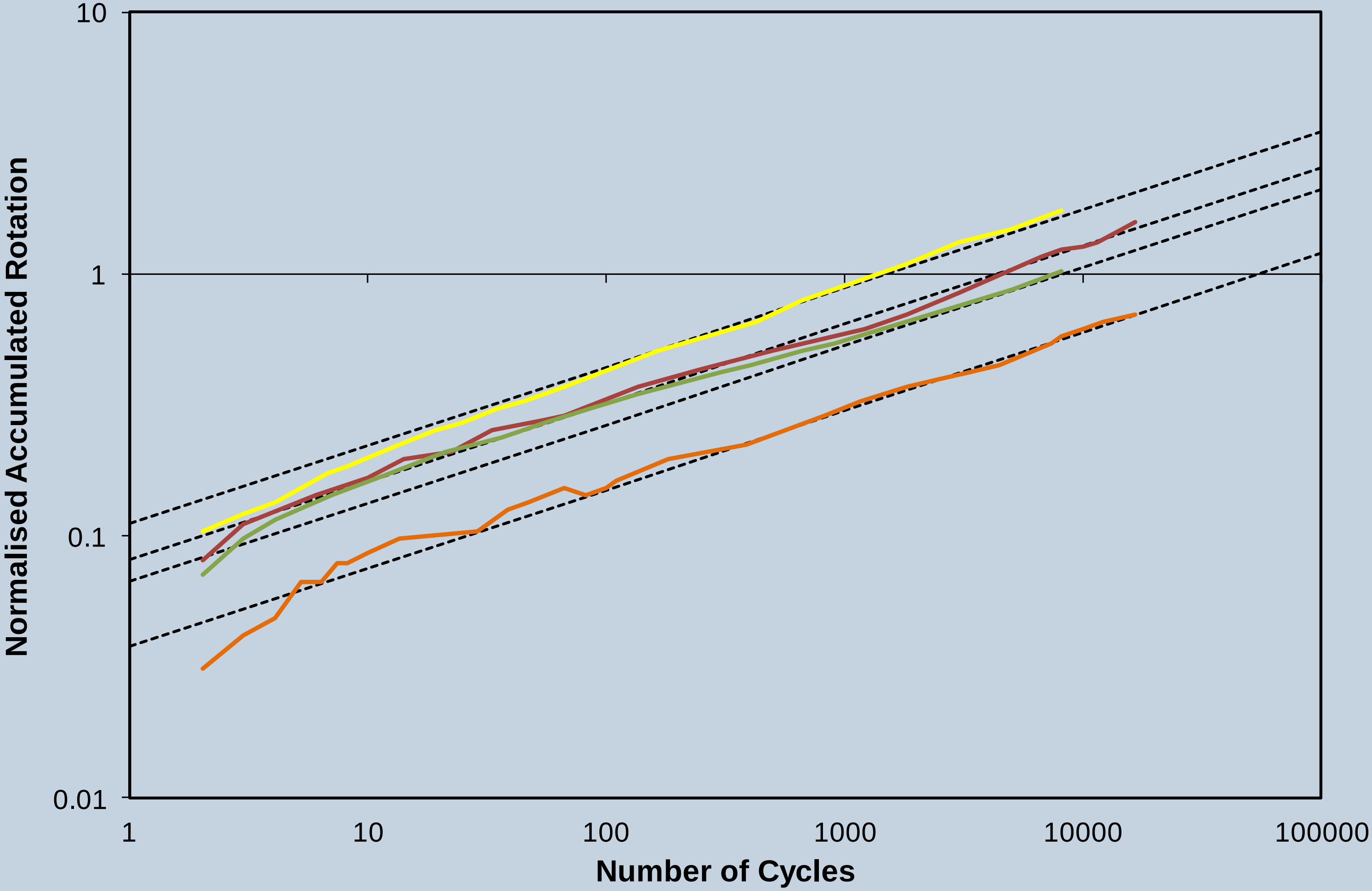
Definitions



Normalised Accumulated Rotation

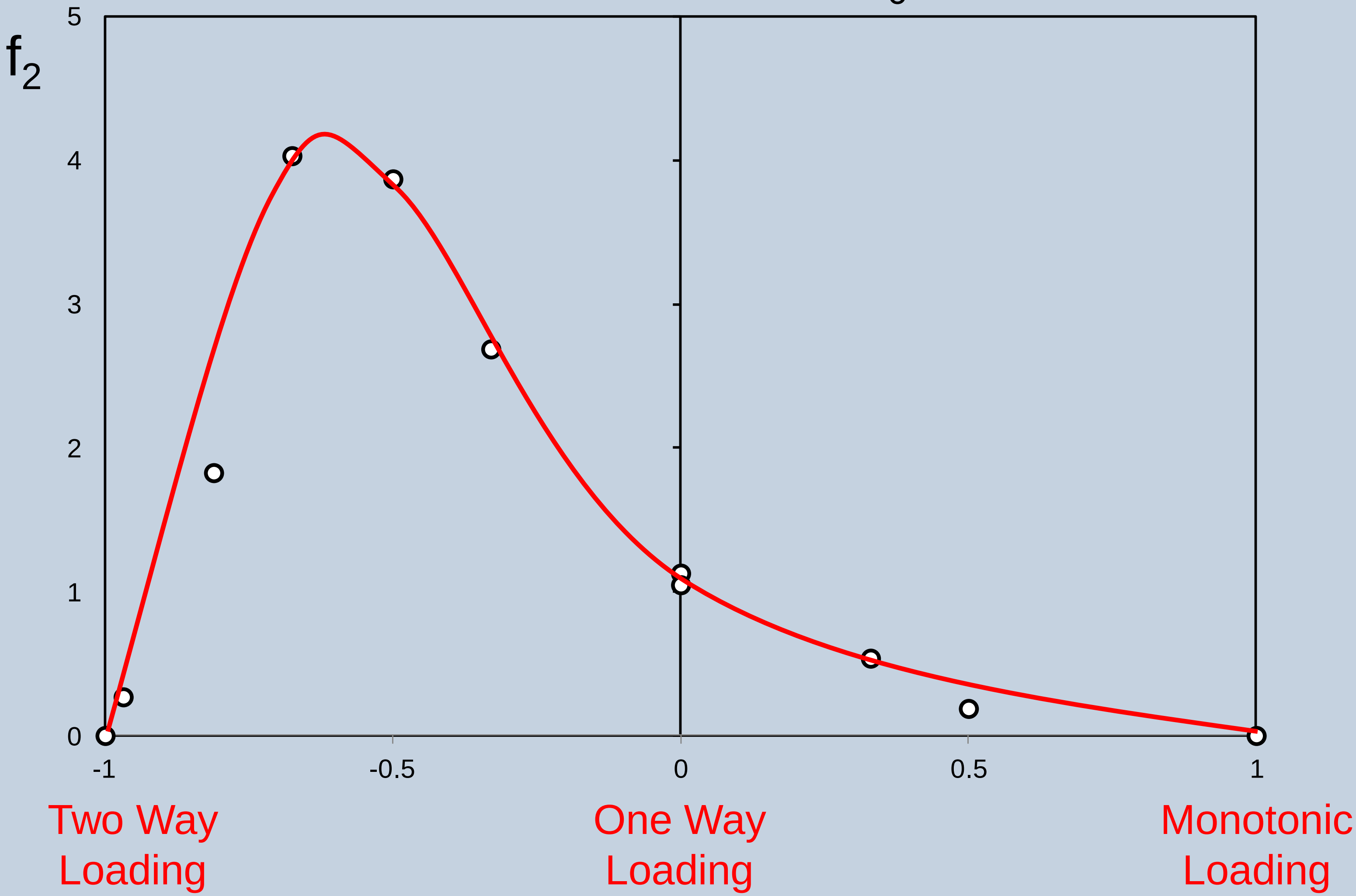
$$\frac{\Delta\theta(N)}{\theta_0}$$

Test Results – Accumulated Rotation

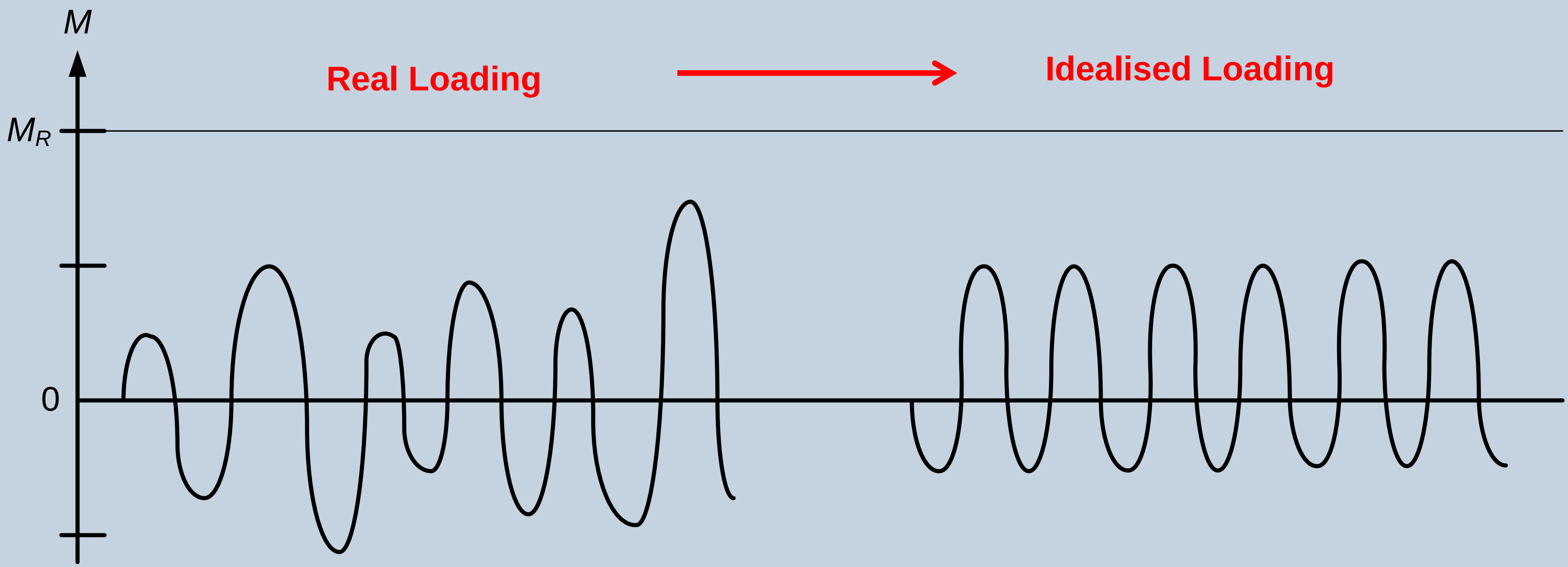


Analysis of Results

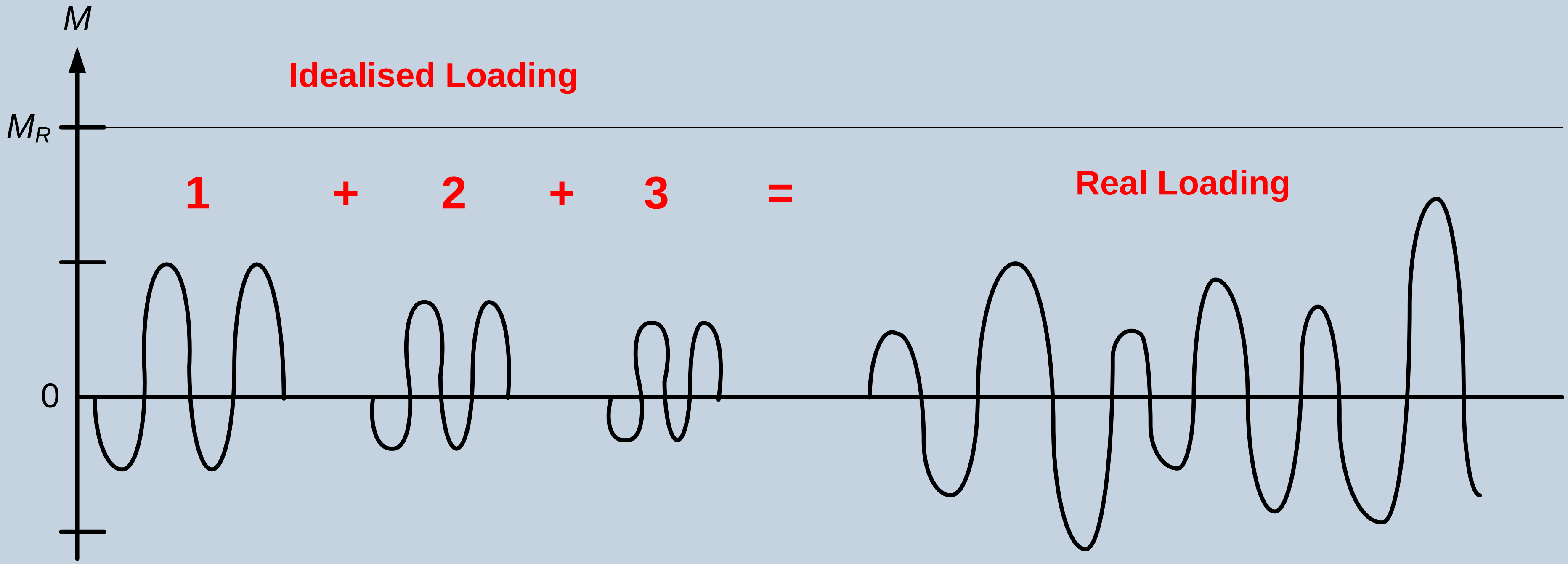
$$\frac{\Delta\theta(N)}{\theta_0} = f_1 \times f_2 \times N^a$$



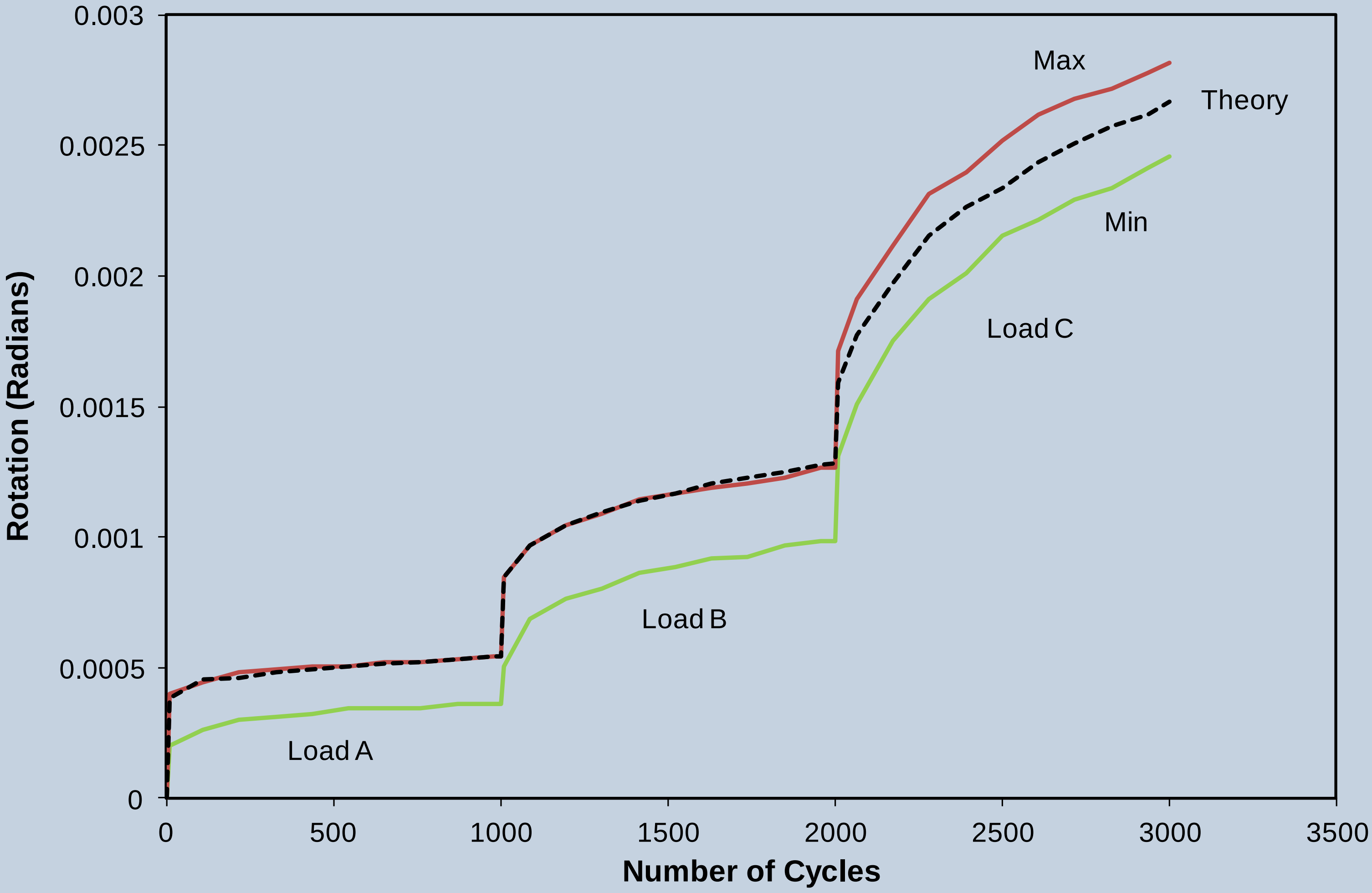
Cyclic loading



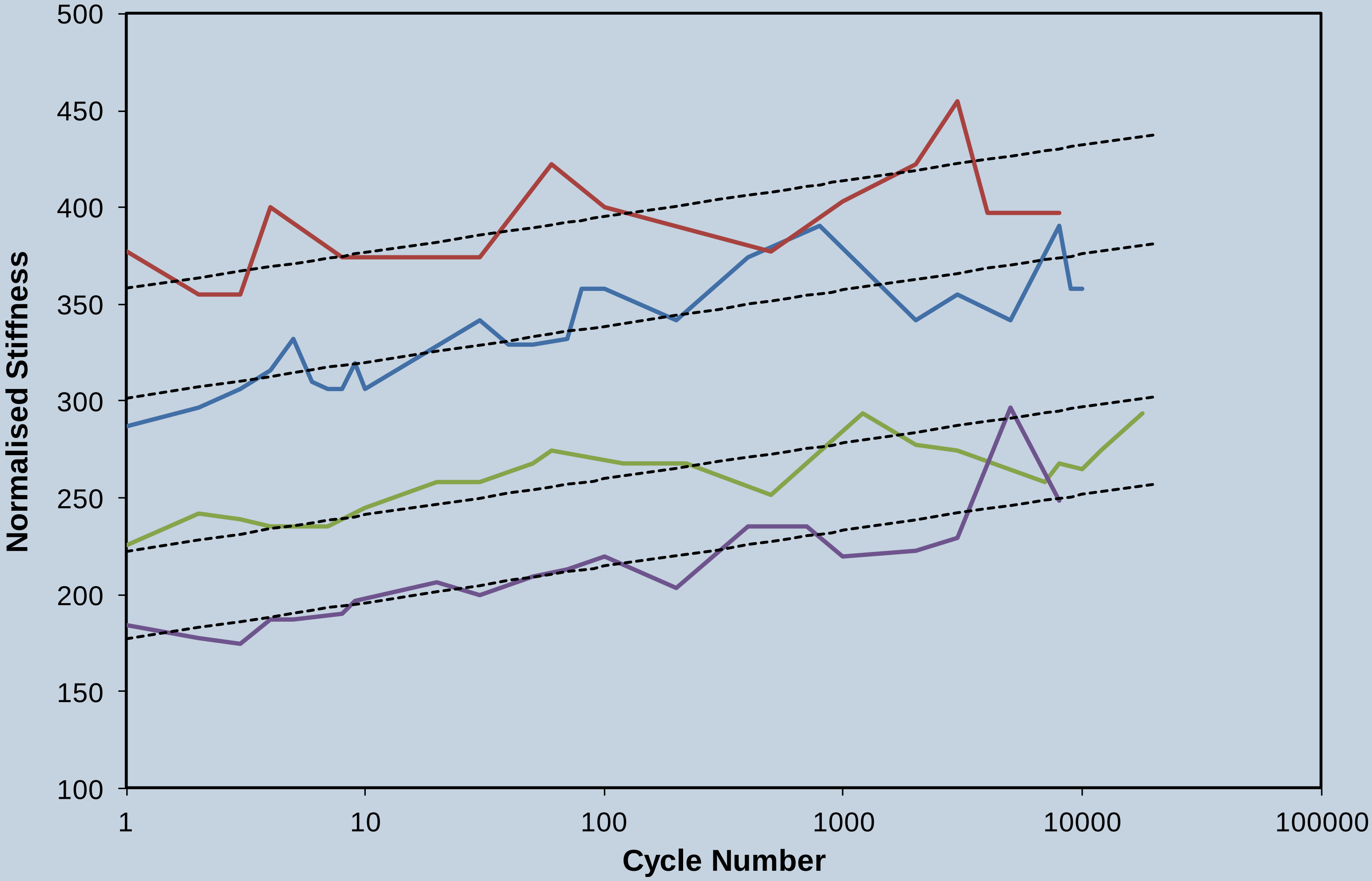
Cyclic loading



Experiment – Theory Comparison



Test Results – Stiffness

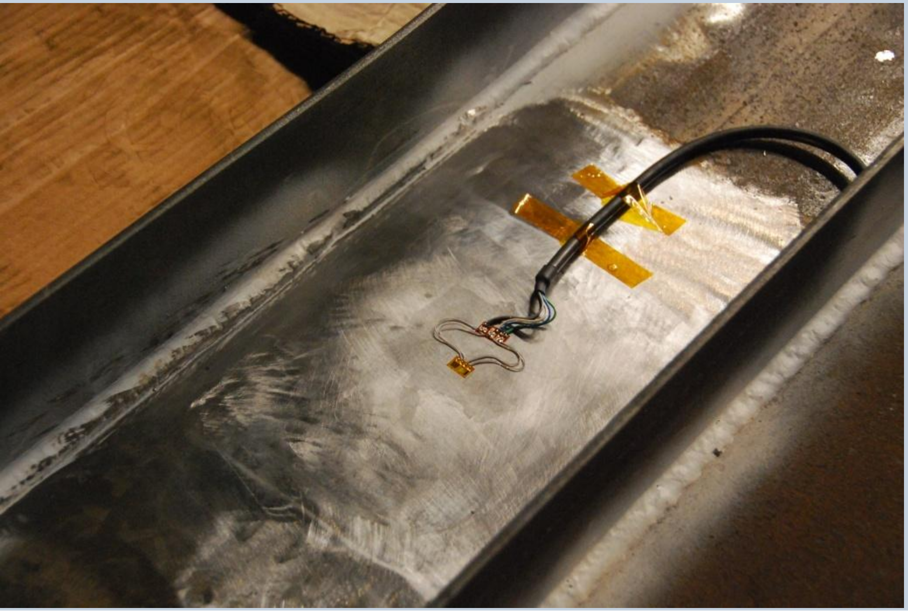


Observations – Mono-Pile Foundations

- Framework for calculating accumulated rotation
- Change in stiffness could mean a change in structural natural frequency – serious factor in the fatigue design
- Scaling
  - Larger scale field tests or centrifuge tests
  - Actual field measurements from installed mono-piles
- Larger number of cycles
  - Current tests only up to 100,000 cycles (i.e. around 7 to 10 days)
  - Do we need tests in the region of 100m cycles?
- Effect of change in load direction
  - Loading is unlikely to be uni-directional
  - Is this more onerous?
- Frequency effects / Excess pore water pressures

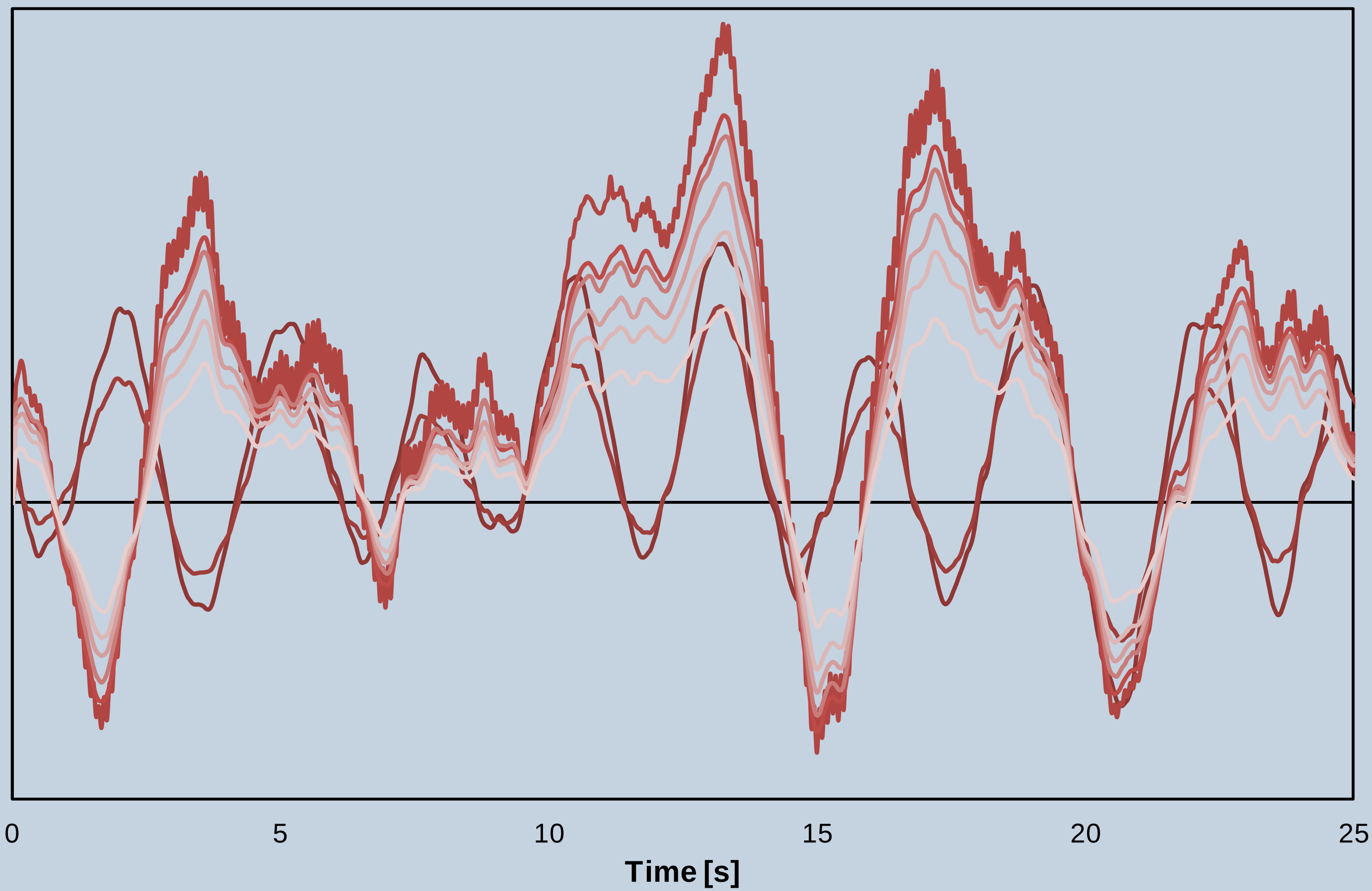
IMPORTANT
Field Monitoring

- Data needed from installed piles!
  - Verify design calculations
  - Guidance for future designs
  - Database for the industry?



Data and photos from Dong Energy: Christian LeBlanc Thilsted and Dan Kallehave

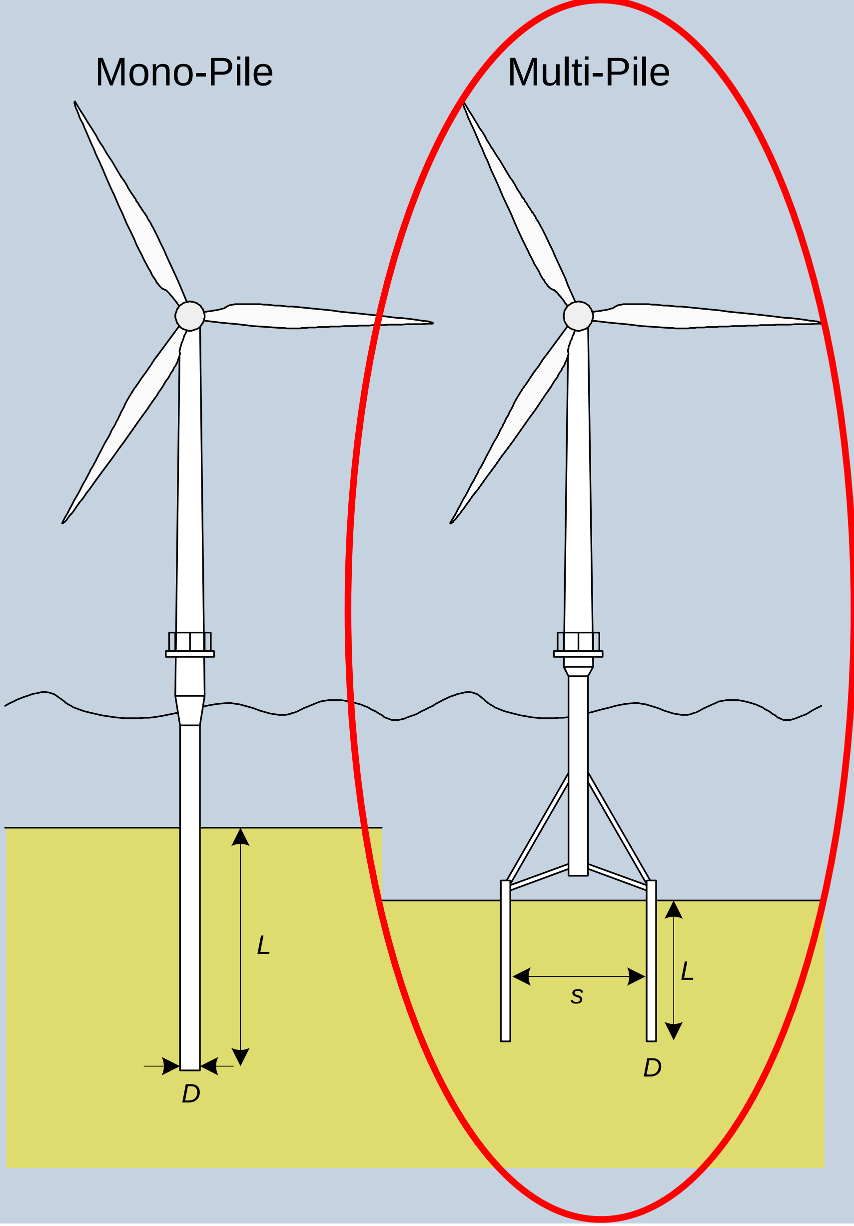
Measured Strains



Data and photos from Dong Energy: Christian LeBlanc Thilsted and Dan Kallehave

Multi-Pile Foundations

- Much more like typical oil and gas pile design
- …except…
- Any cyclic degradation of the axial response must be well understood



Current designs


Alpha Ventus

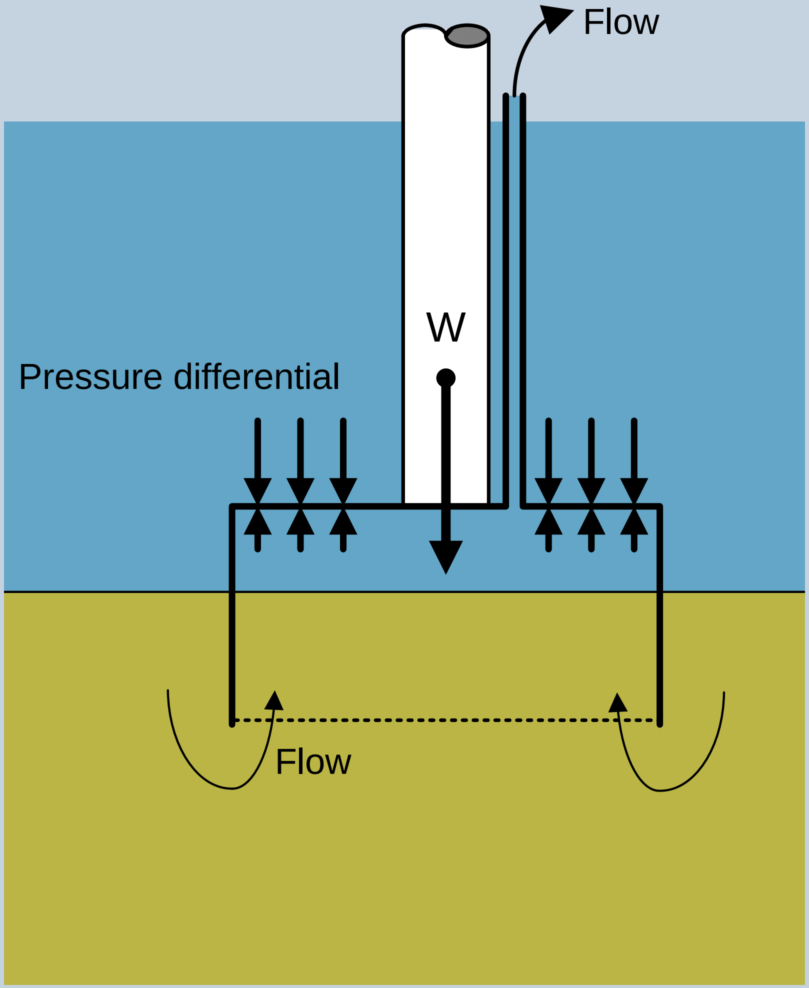

Beatrice


Bard Offshore 1

FUTURE DESIGNS?

SUCTION CAISSONS

Suction Caissons

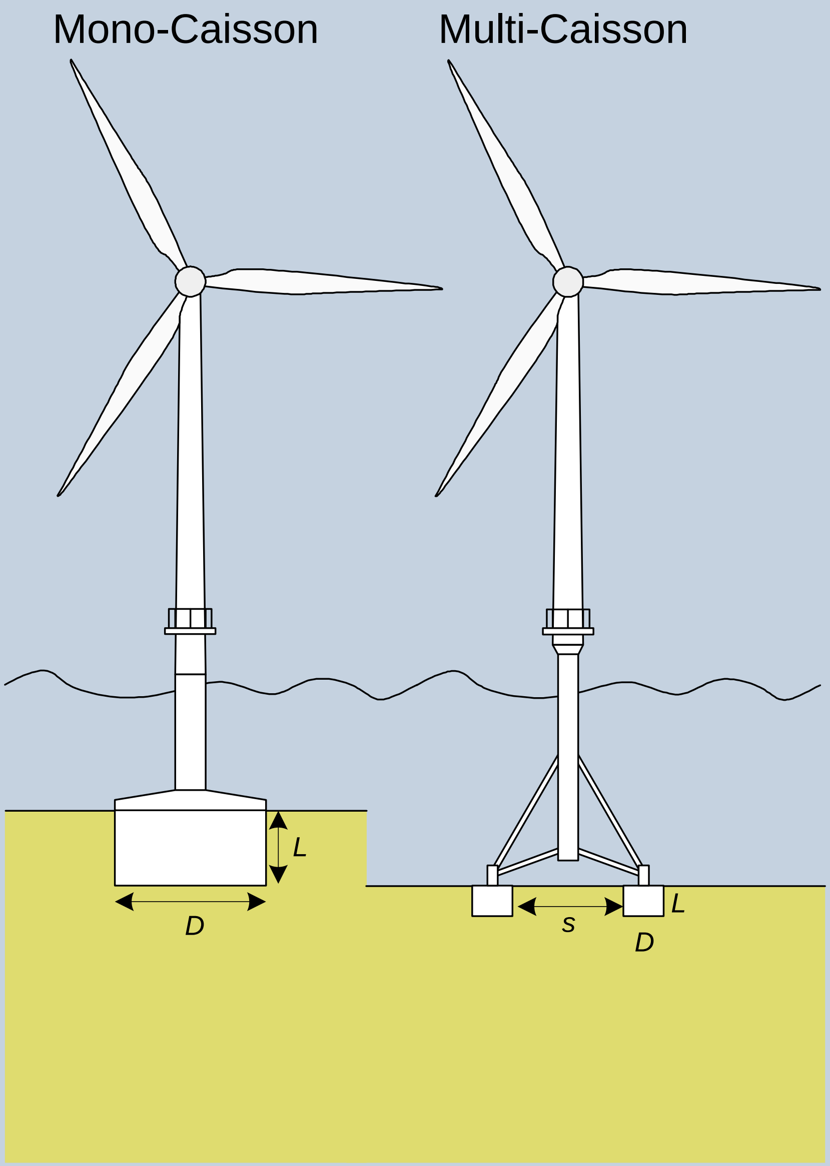


Source: Houlsby, G.T., Ibsen, L.B. and Byrne, B.W (2005) "Suction caissons for wind turbines", Invited Theme Lecture, Proc. International Symposium on Frontiers in Offshore Geotechnics, Perth, Australia, 19-21 September, Taylor and Francis, pp 75-94, ISBN 0415 39063 X

Caisson Foundations

- Design Issues
  - Suction installation
  - Combined Loading (mono-caisson)
  - Vertical Loading (multi-caisson)
- Research
  - Laboratory testing
  - Field scale testing
  - Theoretical investigations
  - Numerical modelling

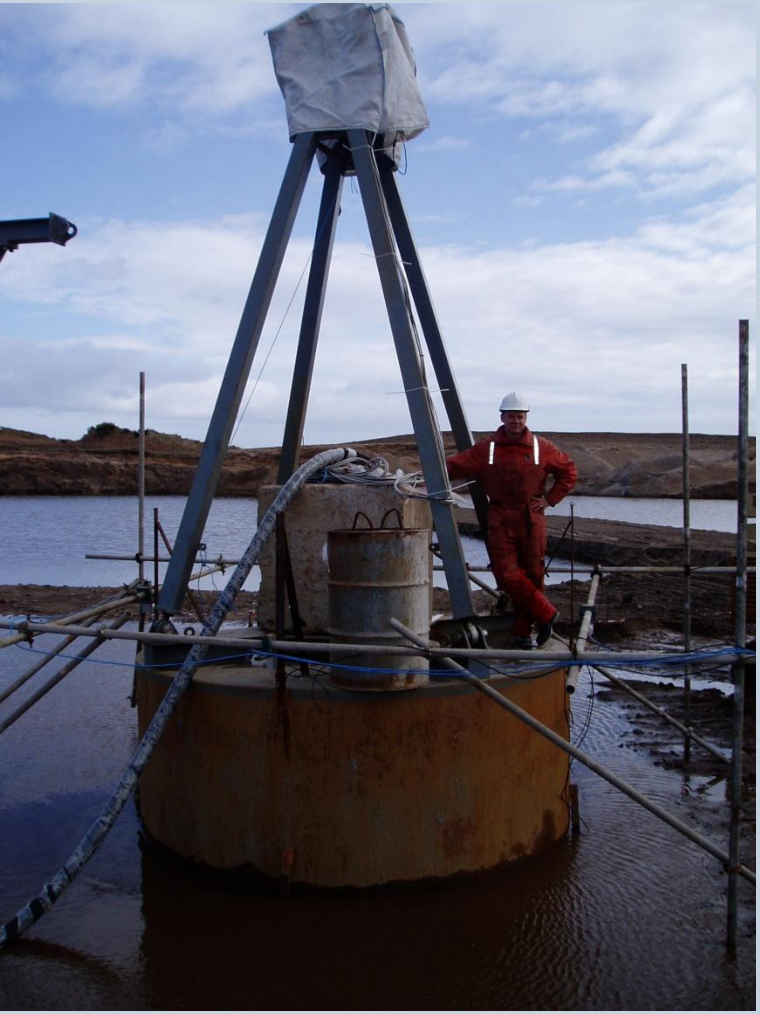
- Focus here is on work at Oxford

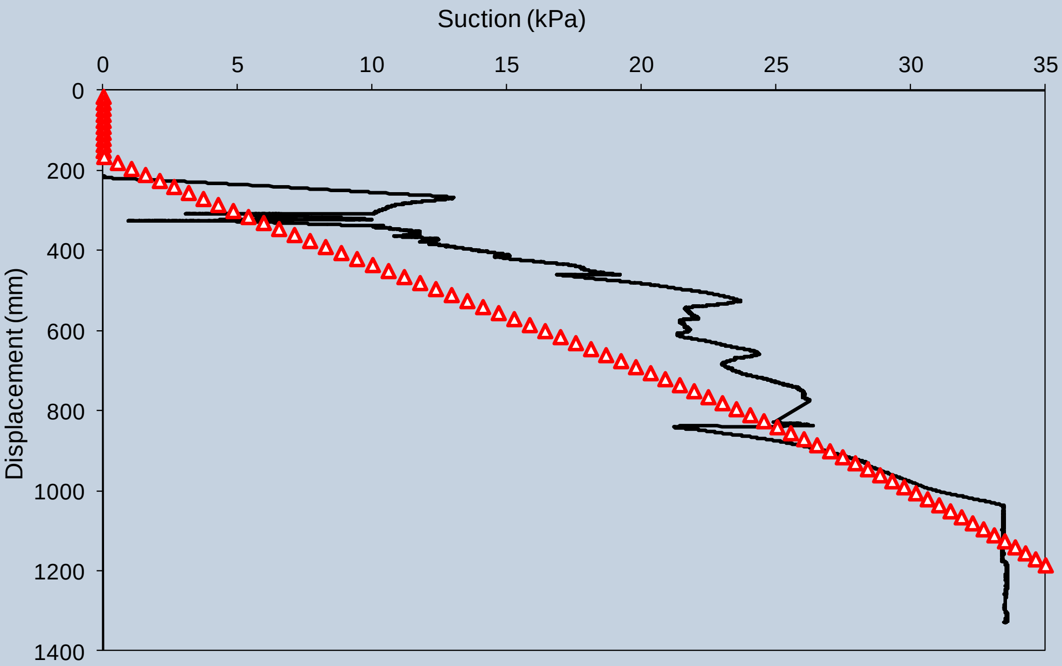


Installation

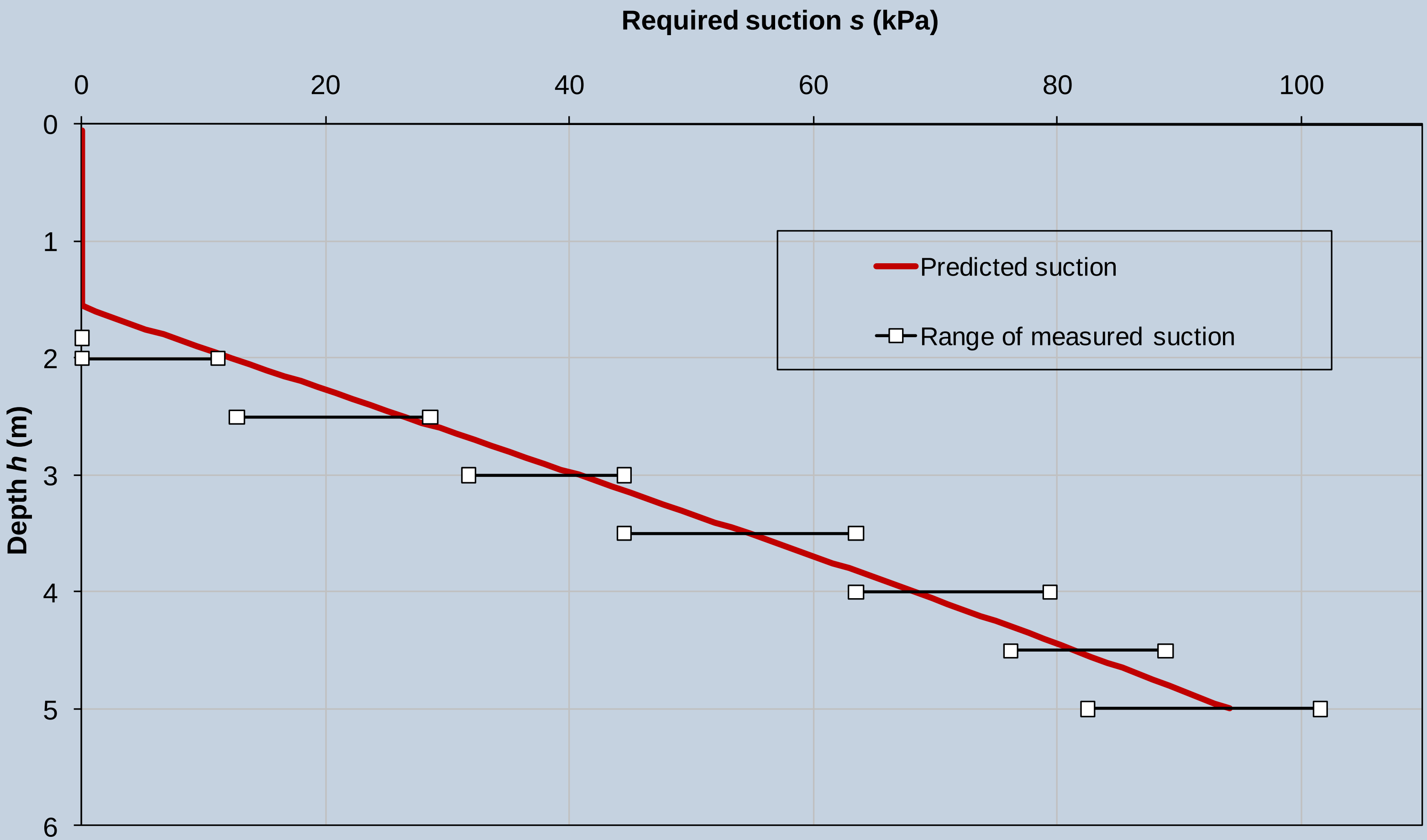
- Theoretical calculations for design (ICE Proceedings)
- Separate calculations for sand and for clay
- Self weight calculation and suction installation
- In sand seepage gradients are important.
  - Beneficial reduction of the end bearing resistance
  - Penetration possible in very dense sand
- Guidance on the limiting aspect ratios for both cases
- More recent work on installation in layered soils

Field Installation - 3m diameter





Statoil's Sleipner T (14m diameter)



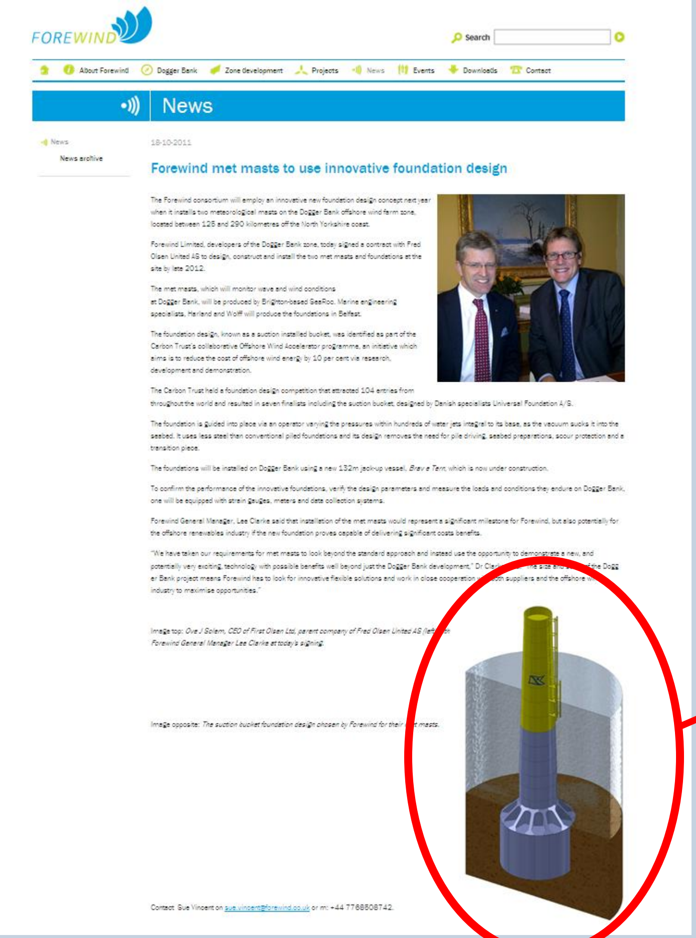
COMBINED LOADING

MONO-CAISSON STRUCTURE

Mobile met mast (Denmark, 2009)

Source: LeBlanc, C. (2009). *Design of offshore wind turbine support structures; selected topics in the field of geotechnical engineering*. PhD Thesis, Aalborg University.

Breaking News Oct 2011
Dogger Bank Met Masts



FOREWIND

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18-10-2011

Forewind met masts to use innovative foundation design

The Forewind consortium will employ an innovative new foundation design concept next year when it installs two meteorological masts on the Dogger Bank offshore wind farm zone, located between 125 and 290 kilometres off the North Yorkshire coast.

Forewind Limited, developers of the Dogger Bank zone, today signed a contract with Fred Olsen United AS to design, construct and install the two met masts and foundations at the site by late 2012.

The met masts, which will monitor wave and wind conditions at Dogger Bank, will be produced by Brighton-based SeaRoc. Marine engineering specialists, Harland and Wolff will produce the foundations in Belfast.

The foundation design, known as a suction installed bucket, was identified as part of the Carbon Trust's collaborative Offshore Wind Accelerator programme, an initiative which aims is to reduce the cost of offshore wind energy by 10 per cent via research, development and demonstration.

The Carbon Trust held a foundation design competition that attracted 104 entries from throughout the world and resulted in seven finalists including the suction bucket, designed by Danish specialists Universal Foundation A/S.

The foundation is guided into place via an operator varying the pressures within hundreds of water jets integral to its base, as the vacuum sucks it into the seabed. It uses less steel than conventional piled foundations and its design removes the need for pile driving, seabed preparations, scour protection and a transition piece.

The foundations will be installed on Dogger Bank using a new 132m jack-up vessel, *Brave Tern*, which is now under construction.

To confirm the performance of the innovative foundations, verify the design parameters and measure the loads and conditions they endure on Dogger Bank, one will be equipped with strain gauges, meters and data collection systems.

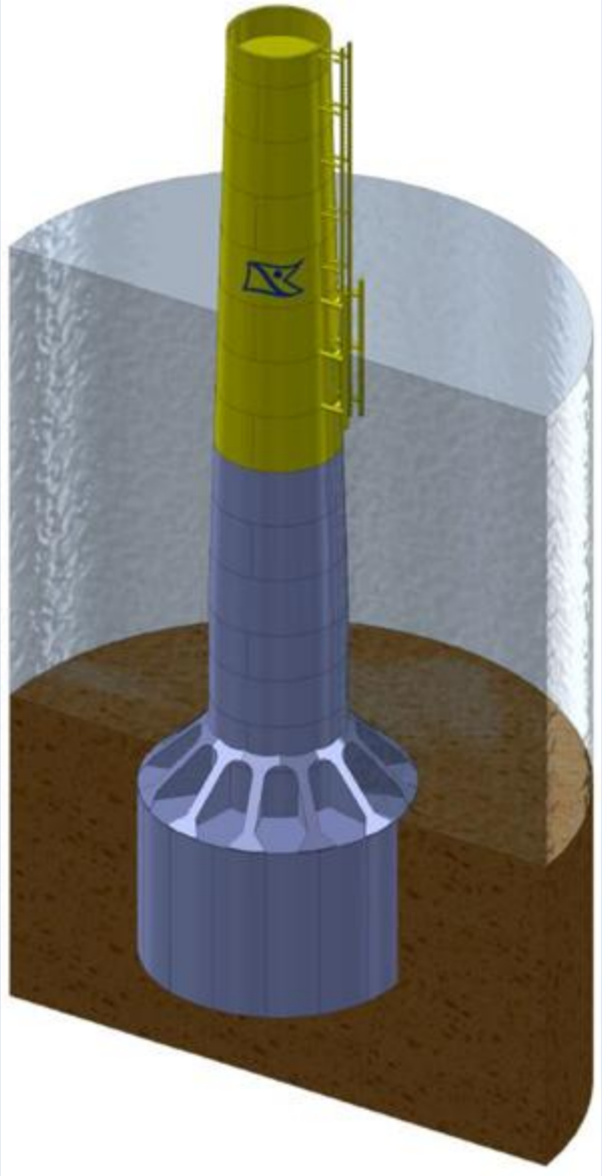
Forewind General Manager, Lee Clarke said that installation of the met masts would represent a significant milestone for Forewind, but also potentially for the offshore renewables industry if the new foundation proves capable of delivering significant costs benefits.

"We have taken our requirements for met masts to look beyond the standard approach and instead use the opportunity to demonstrate a new, and potentially very exciting, technology with possible benefits well beyond just the Dogger Bank development," Dr Clar[illegible] "The size and [illegible] of the Dogger Bank project means Forewind has to look for innovative flexible solutions and work in close cooperation w[illegible] both suppliers and the offshore w[illegible] industry to maximise opportunities."

Image top: *Ove J Solem, CEO of First Olsen Ltd, parent company of Fred Olsen United AS (left) [illegible] Forewind General Manager Lee Clarke at today's signing.*

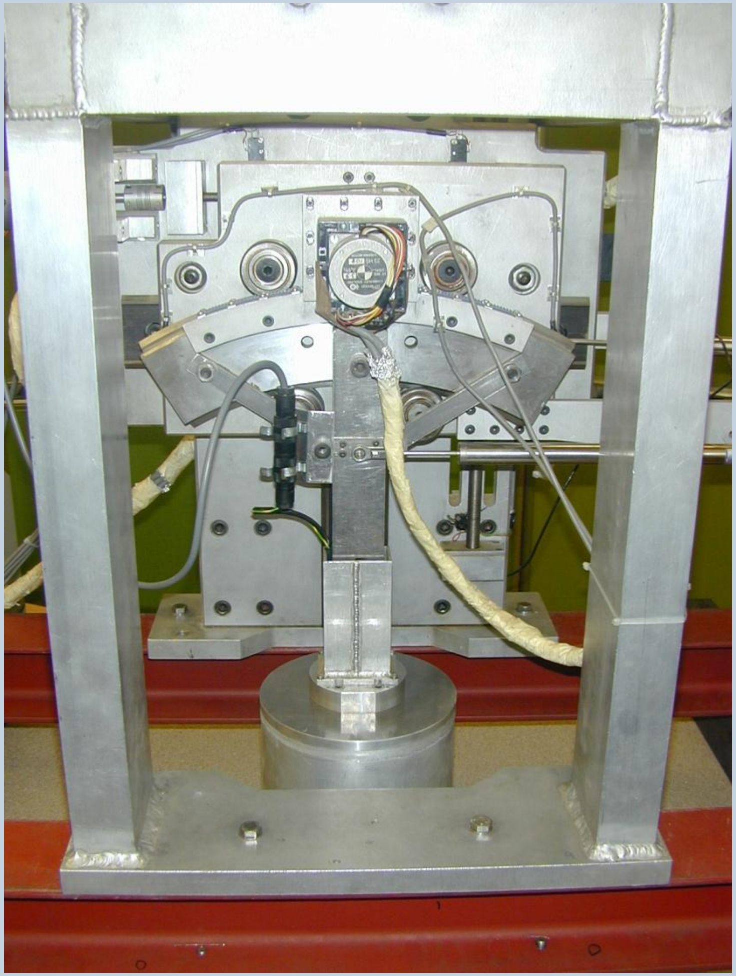
Image opposite: *The suction bucket foundation design chosen by Forewind for their [illegible] masts.*

Contact Sue Vincent on sue.vincent@forewind.co.uk or m: +44 7768608742.

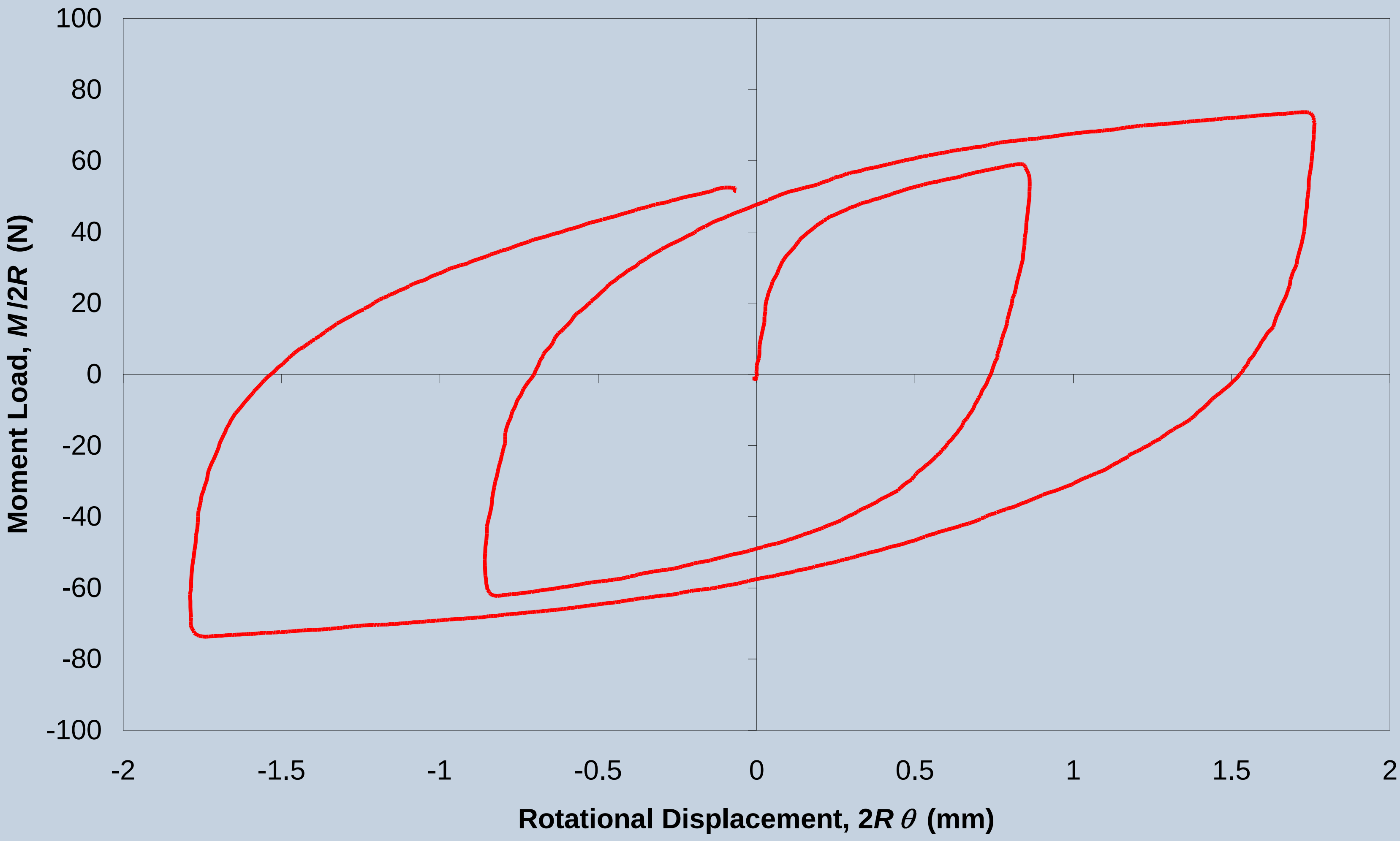


Source: Forewind website

Experimental equipment

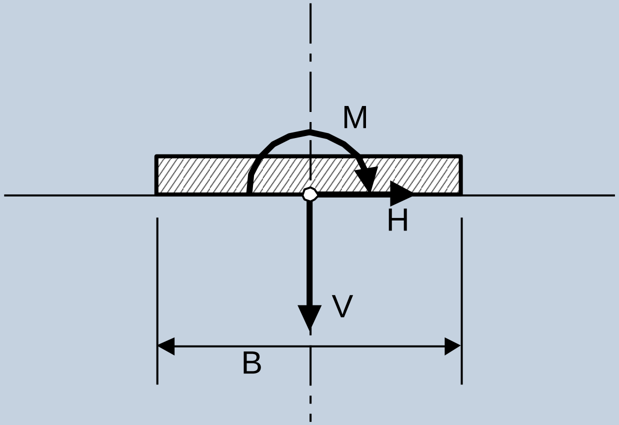


Moment Loading at Low Vertical Load



Source: G.T. Houlsby and R. Butterfield *Géotechnique* Lecture 2001

Conventional approach: effective area and inclination factors

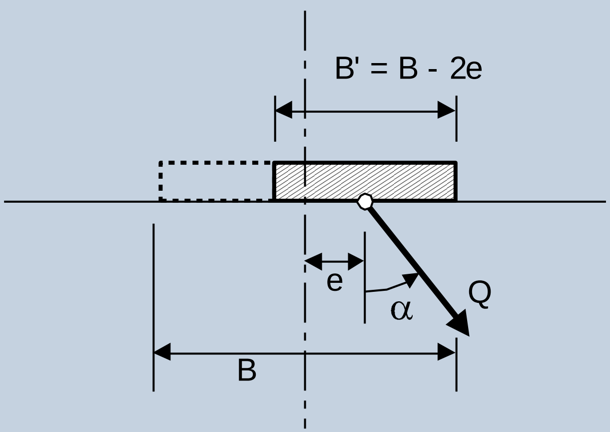


$V, M, H \longleftrightarrow Q, e, \alpha$

$$Q = \sqrt{V^2 + H^2}$$

$$e = M/V$$

$$\alpha = \arctan(H/V)$$

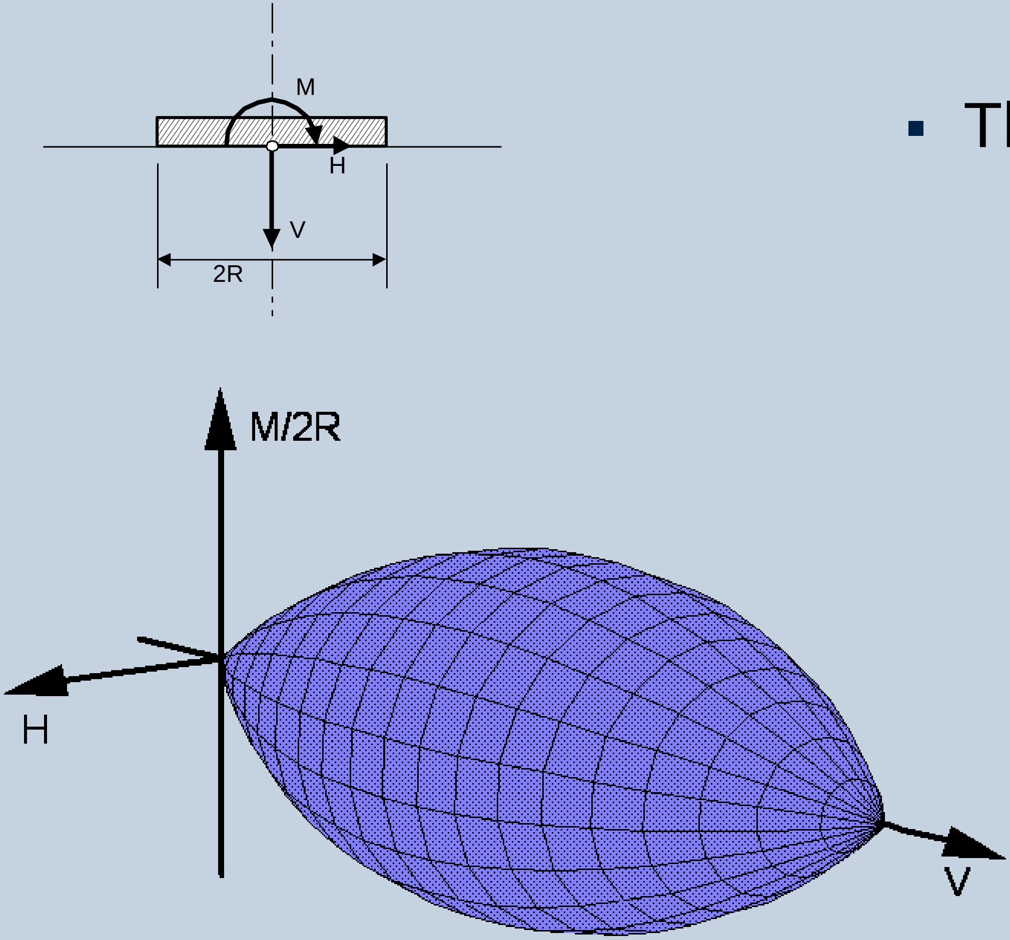


$$\frac{V}{B'} = c i_c N_c + \gamma D i_q N_q + \frac{\gamma B'}{2} i_\gamma N_\gamma$$

$$i_c, i_q, i_\gamma = f(\alpha)$$

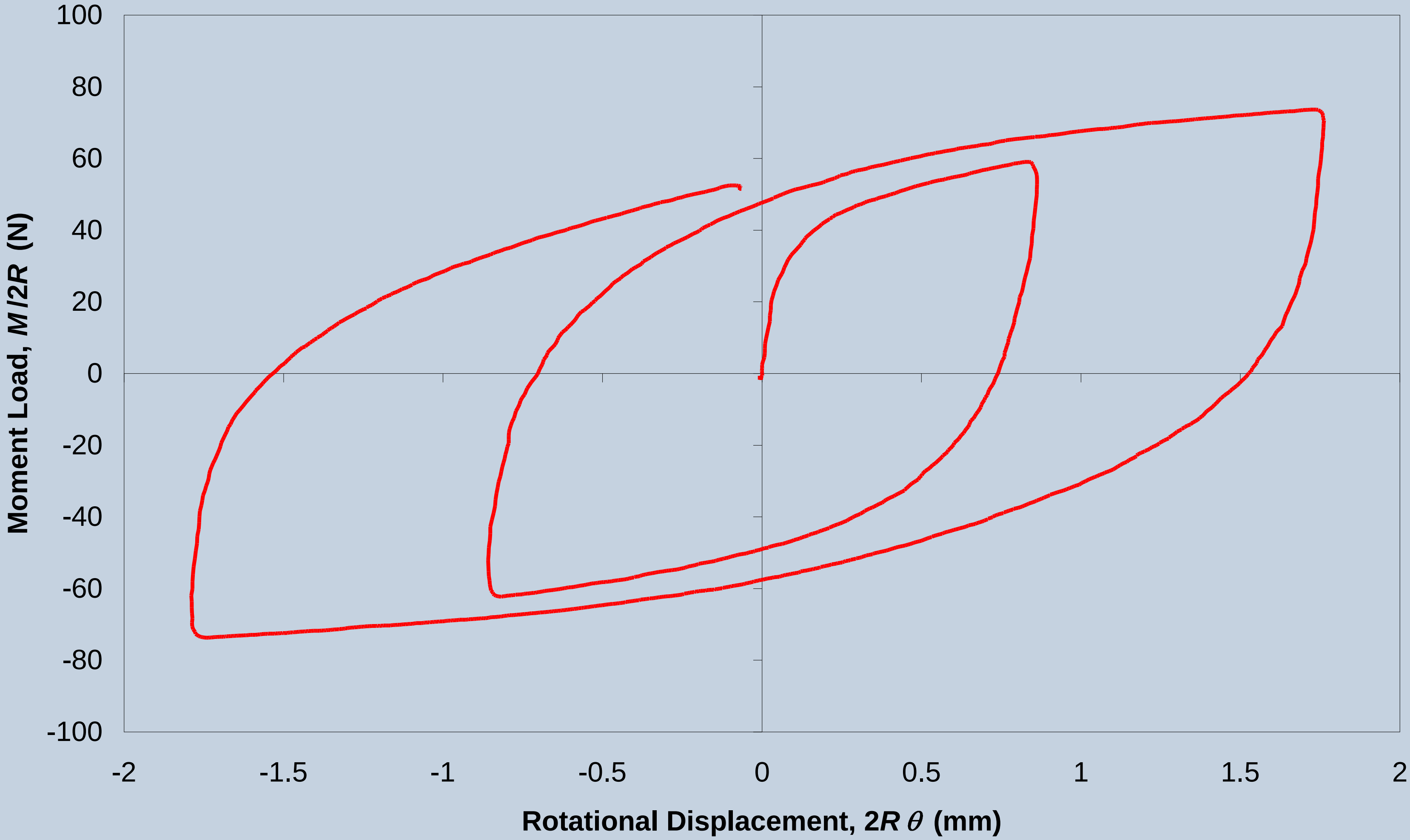
Source: G.T. Houlsby and R. Butterfield *Géotechnique* Lecture 2001

"Hardening Plasticity" Models

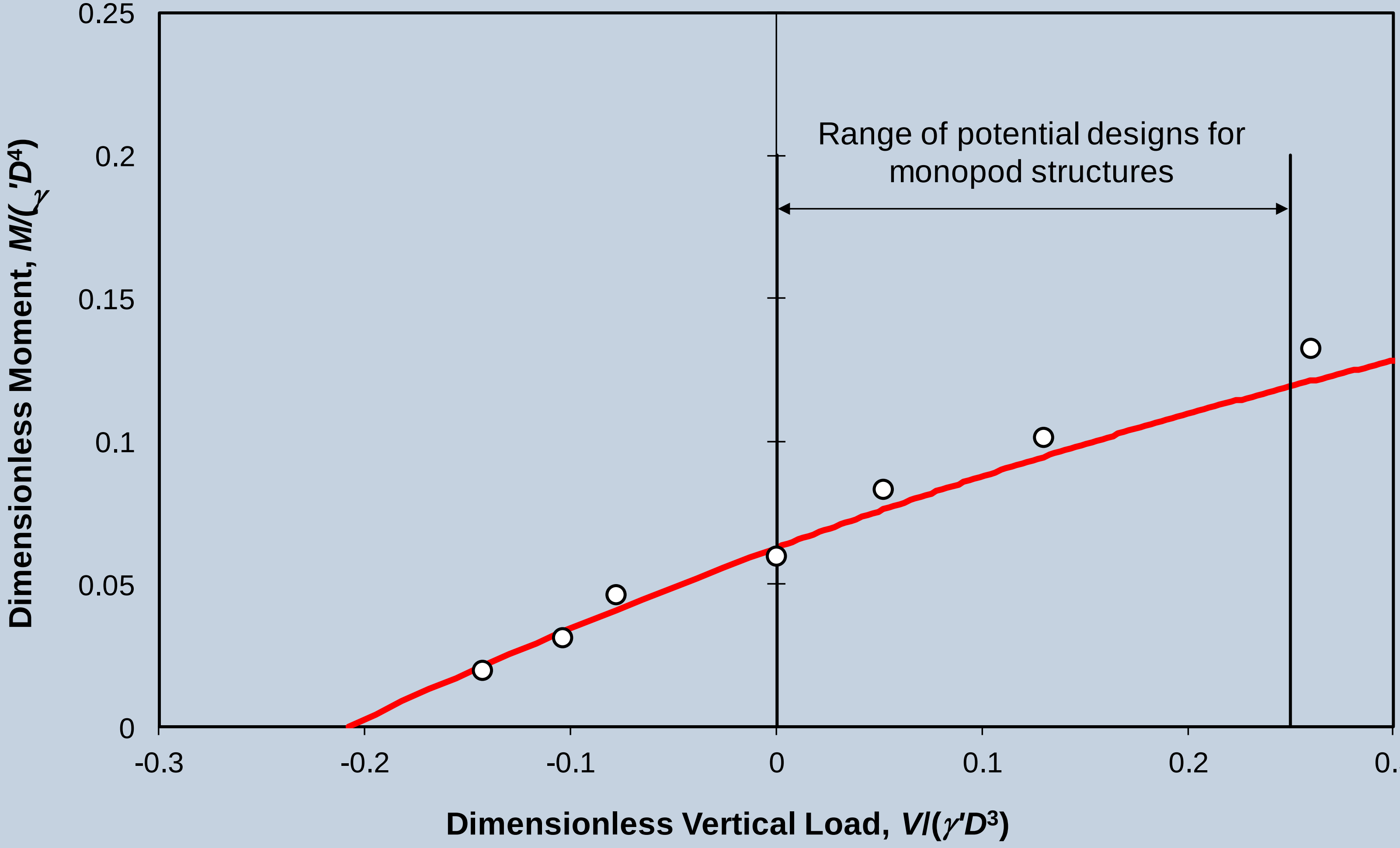


- The plasticity model requires
  - A yield surface to define allowable load combinations
  - Hardening rule to define yield surface expansion
  - Flow rules to define plastic movements at yield
  - Elasticity expressions to define pre-yield movements

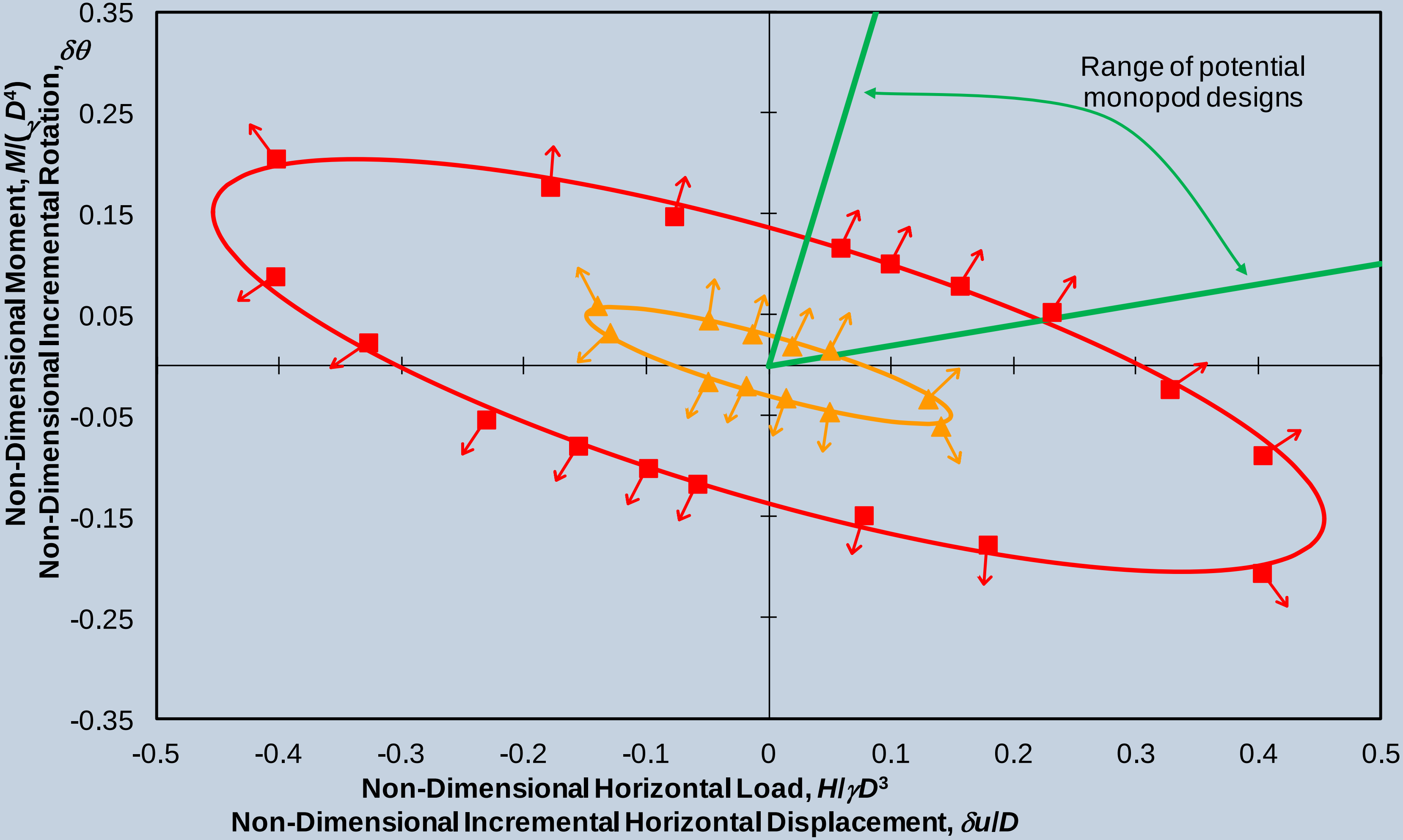
Moment Loading at Low Vertical Load



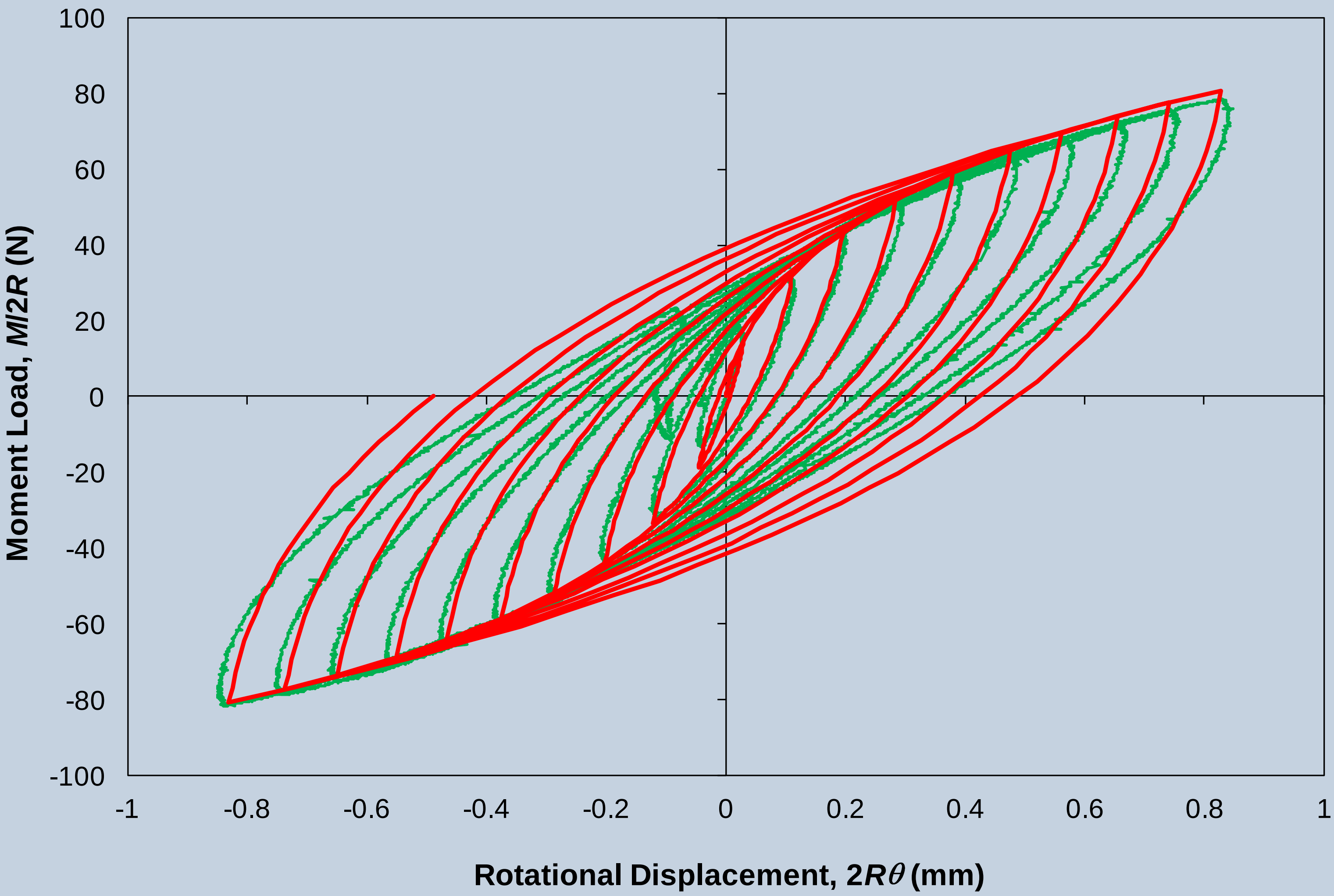
Yield Points and Design Curves 1 (Sand)



Yield Points and Design Curves 2 (Sand)



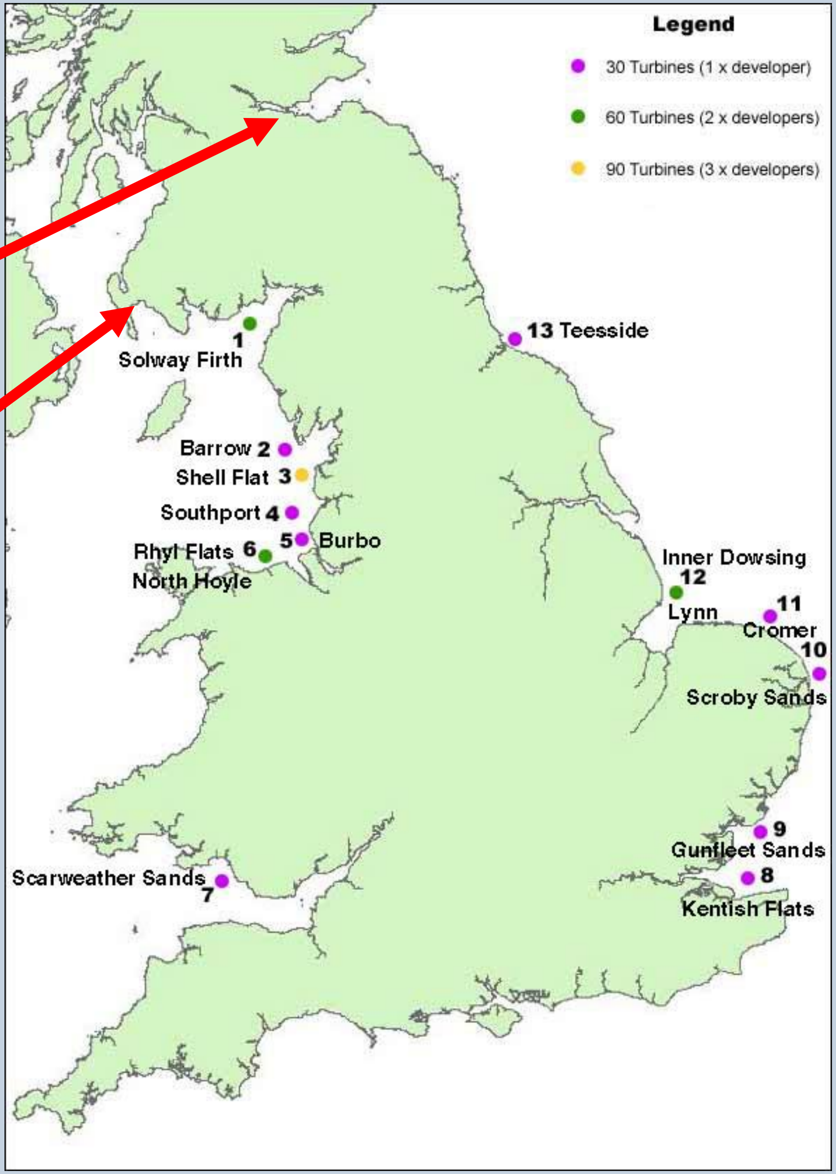
Comparison of Theory to Experiment



Field Testing

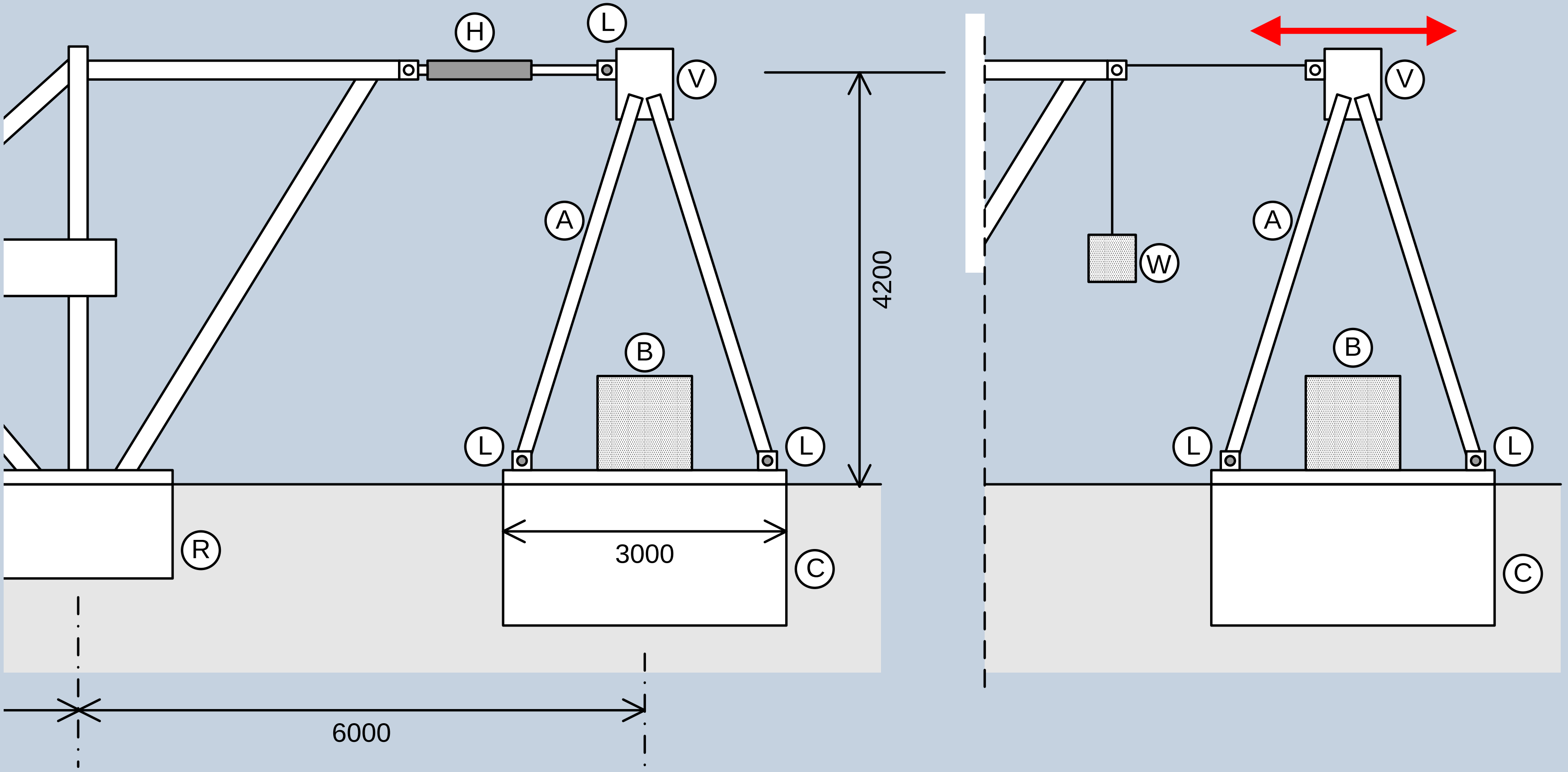
Bothkennar (clay)

Luce Bay (sand)

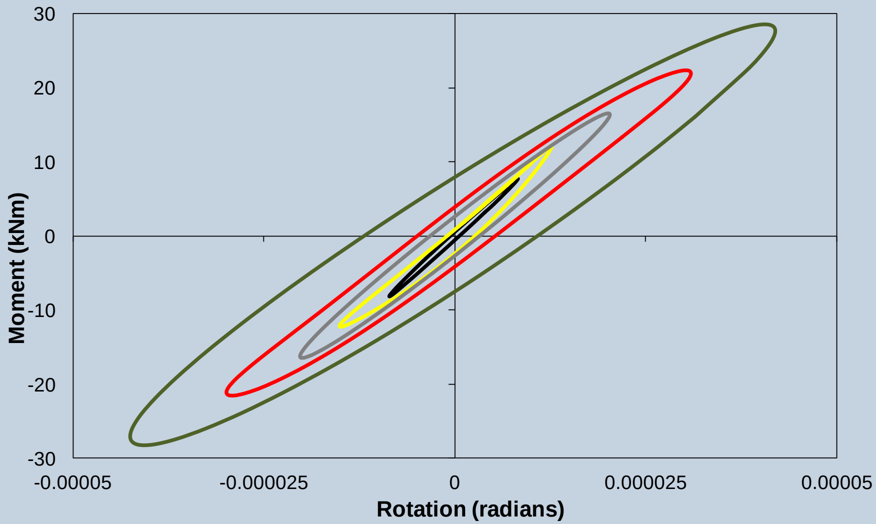


Field Testing at Bothkennar

Moment loading

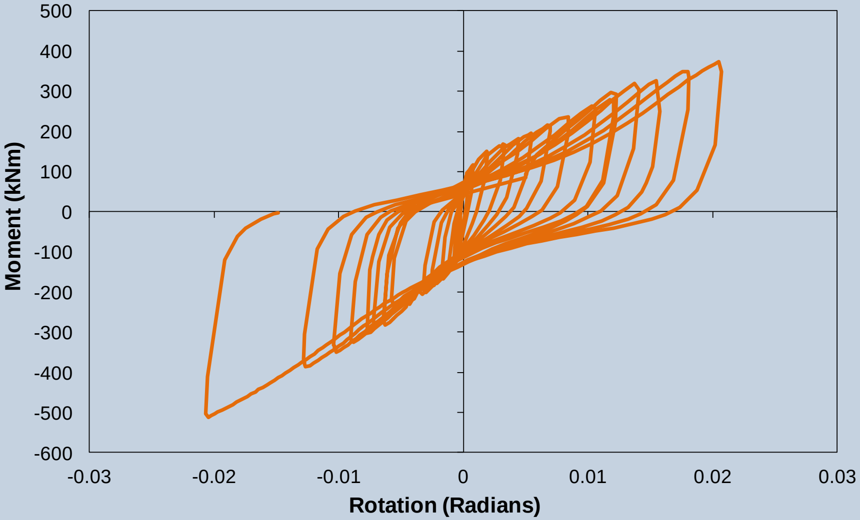


Moment tests at small and large rotations

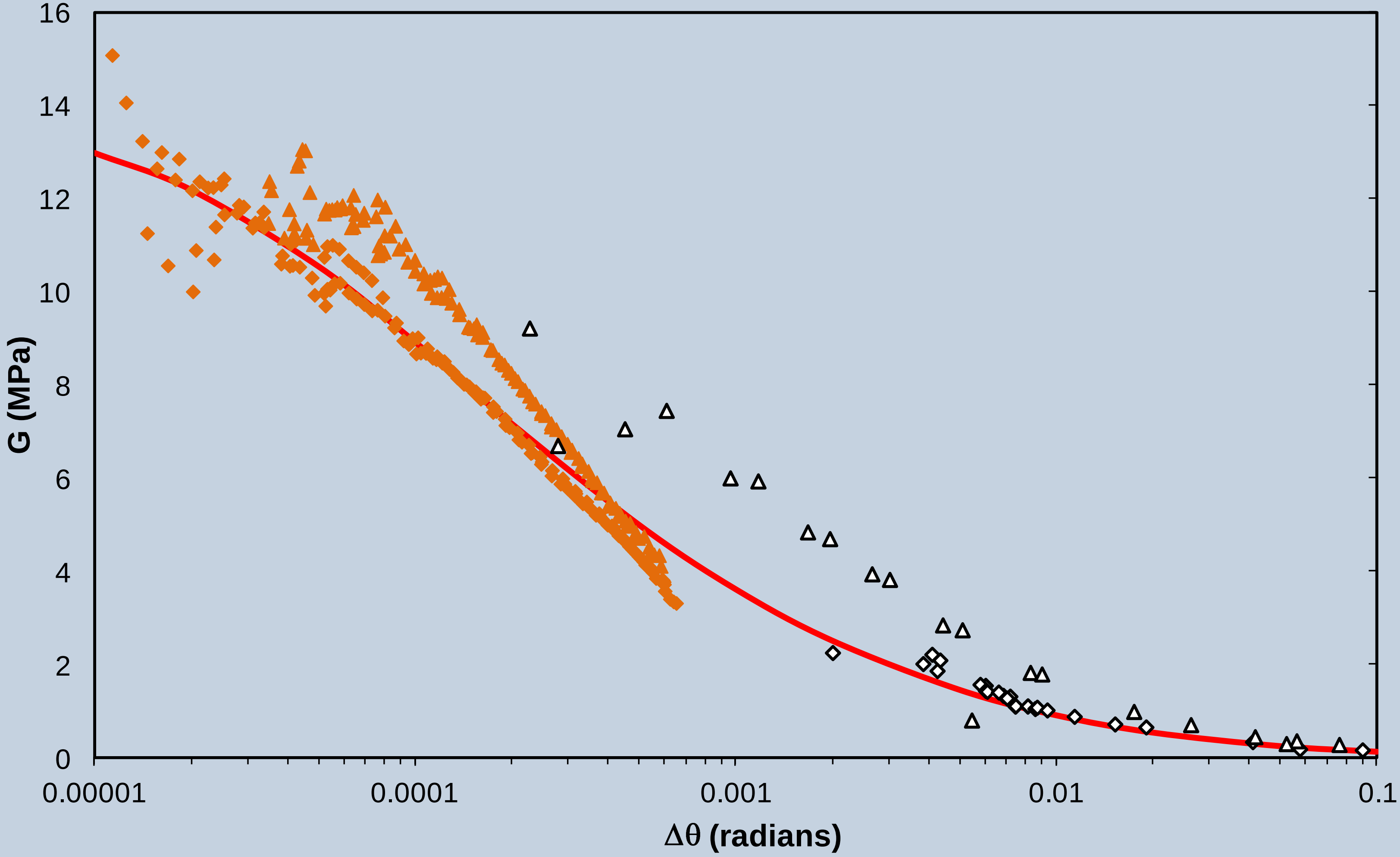


Small

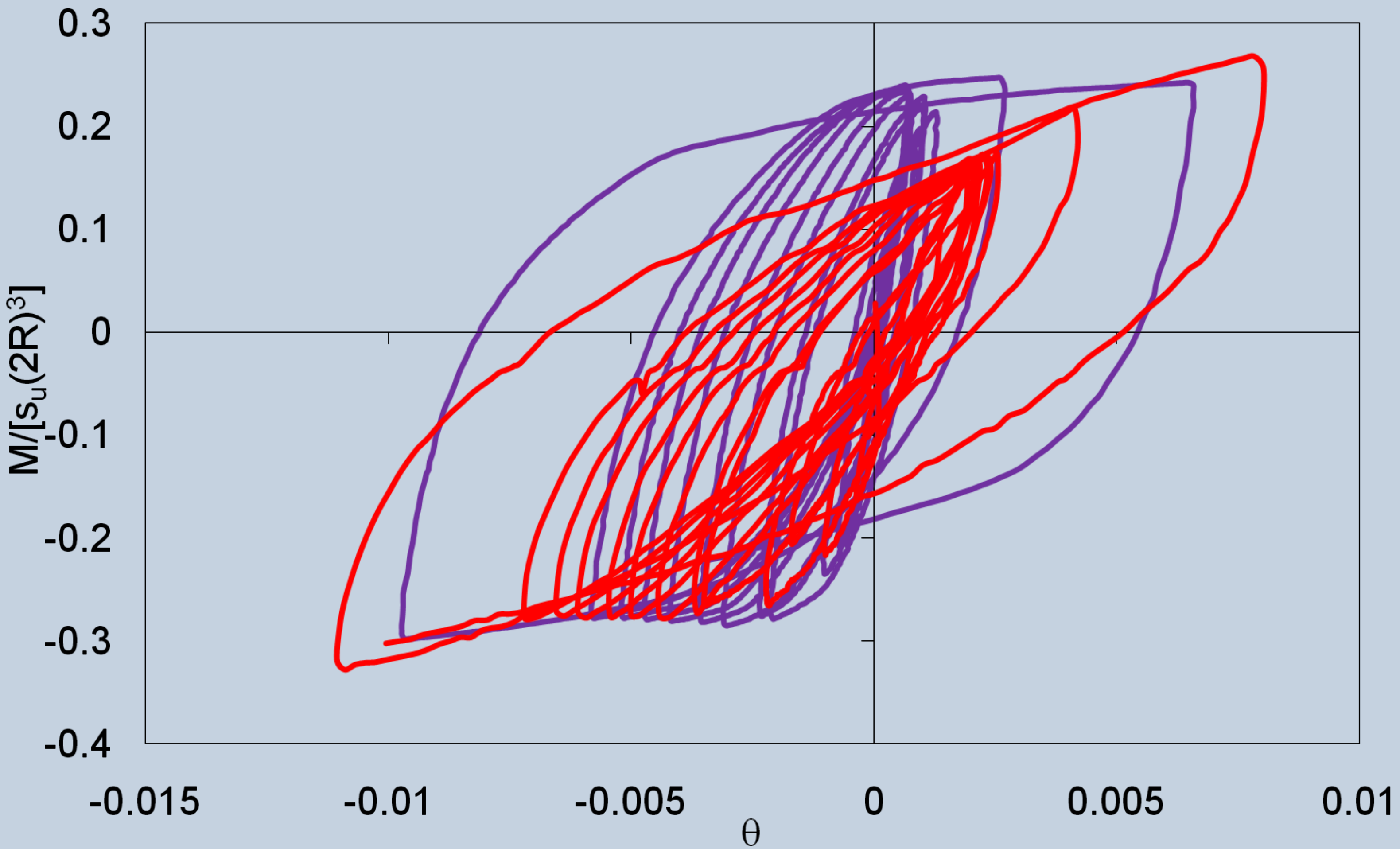
Large



Analysis of Results (Clay)



Moment Test Results (Clay)



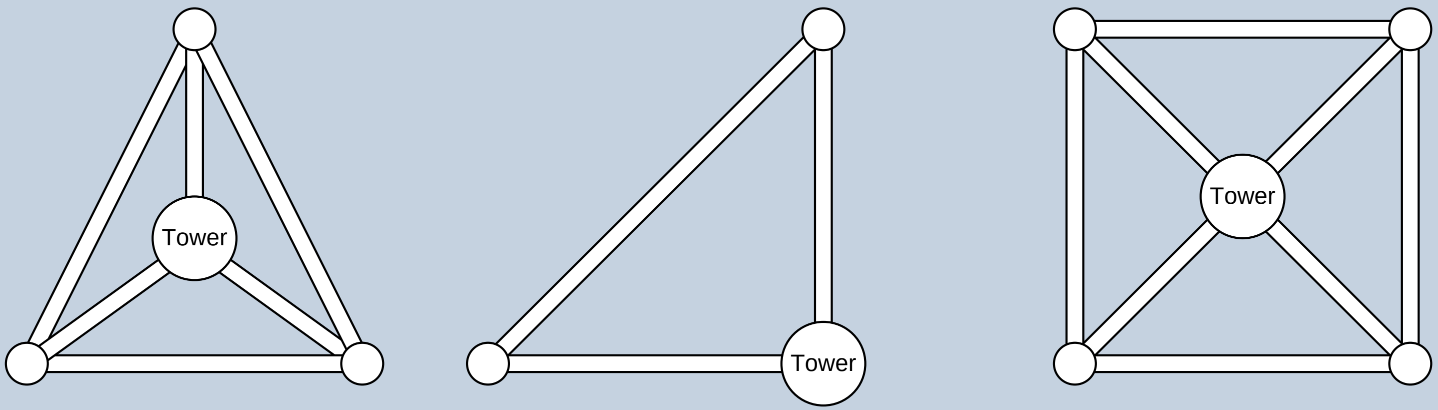
VERTICAL LOADING

MULTI-CAISSON STRUCTURE

Multiple caissons: Draupner E platform

Source: Andersen, K.H., Jostad, H.P. and Dyvik, R. (2008) "Penetration resistance of offshore skirted foundations and anchors in dense sand", Proc ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol 134, No 1, pp 106 - 116.

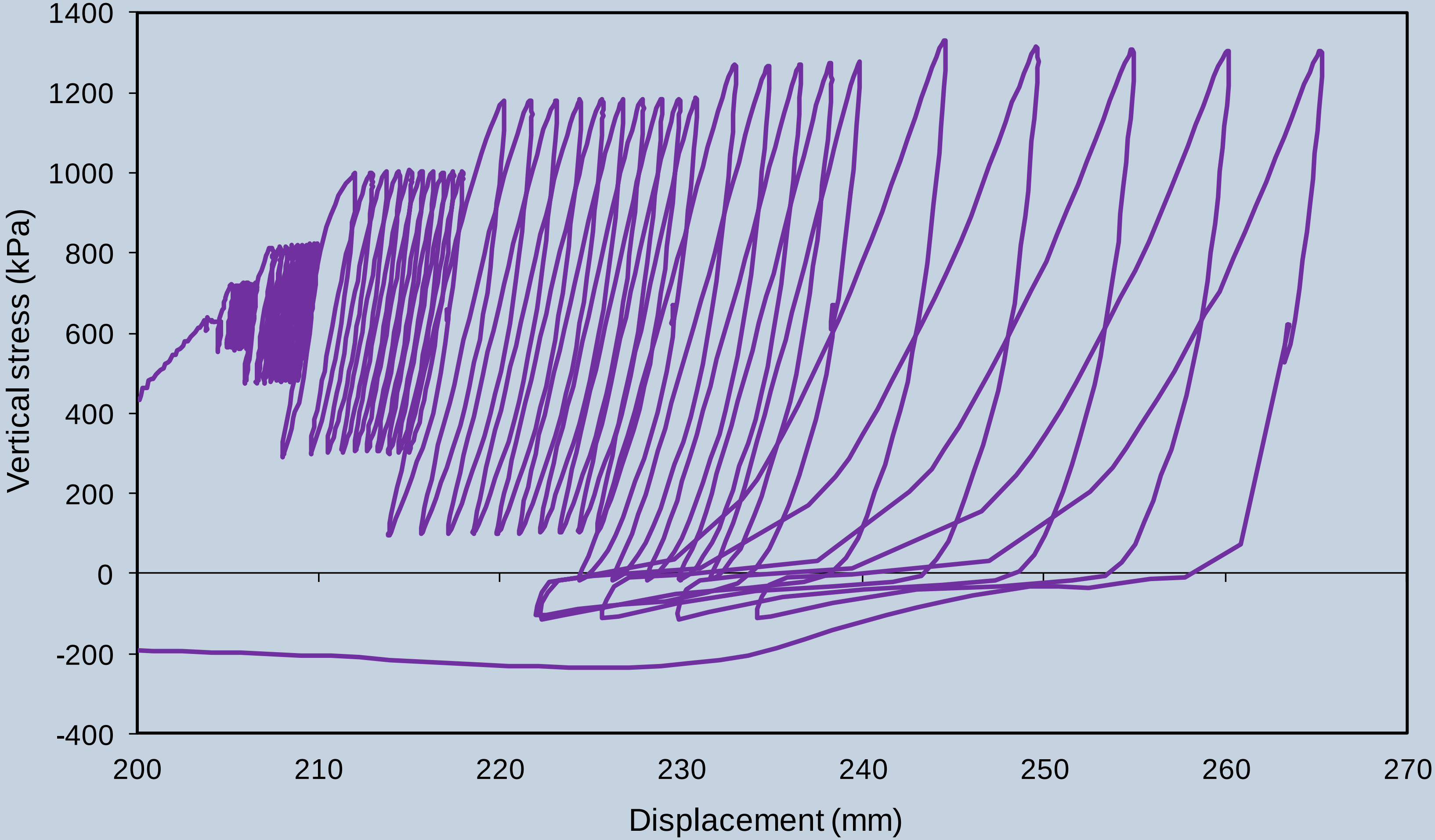
Tripod or tetrapod?



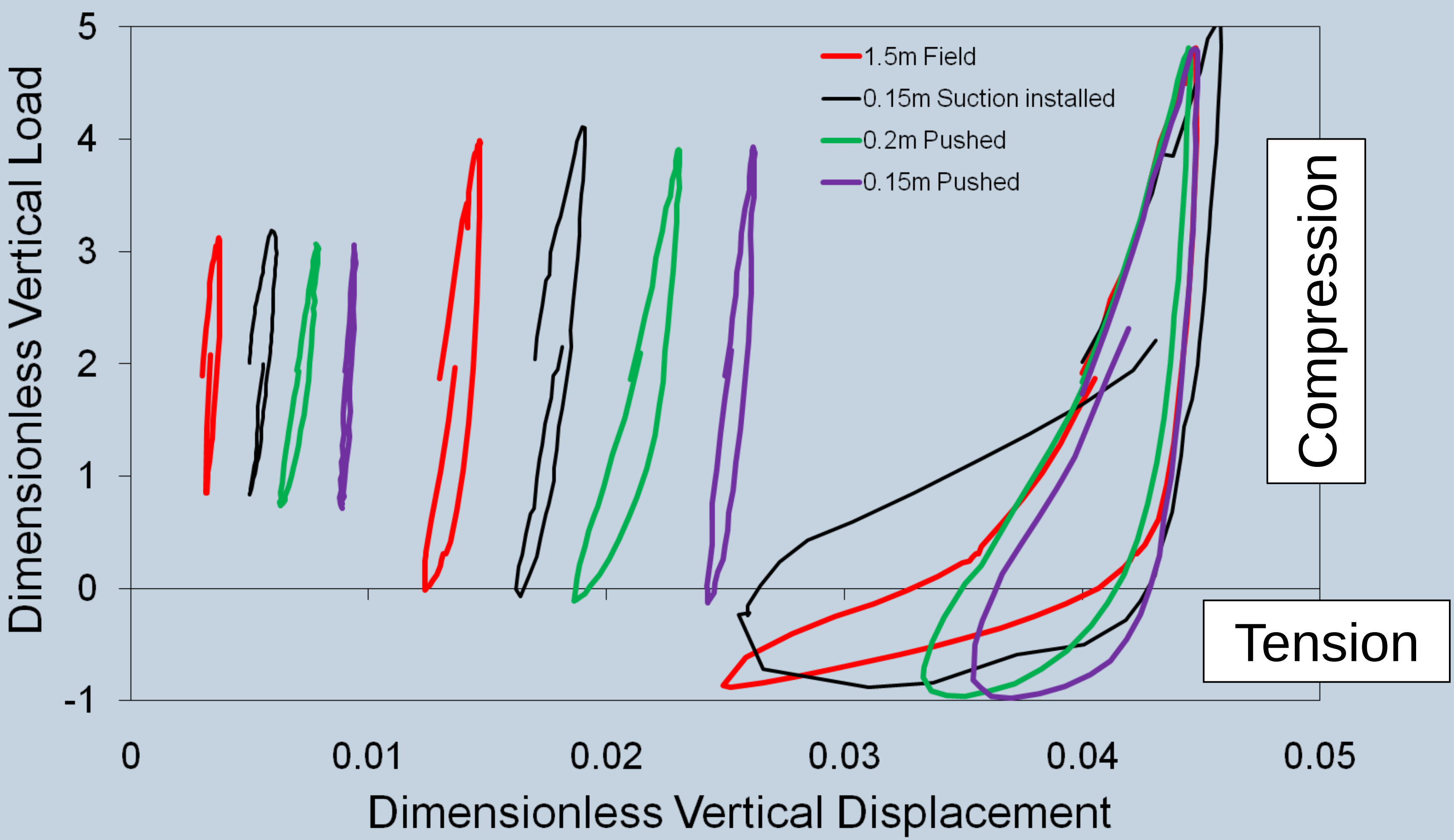
(a) (b) (c)

Vertical Loading Tests (in a Pressure Vessel)

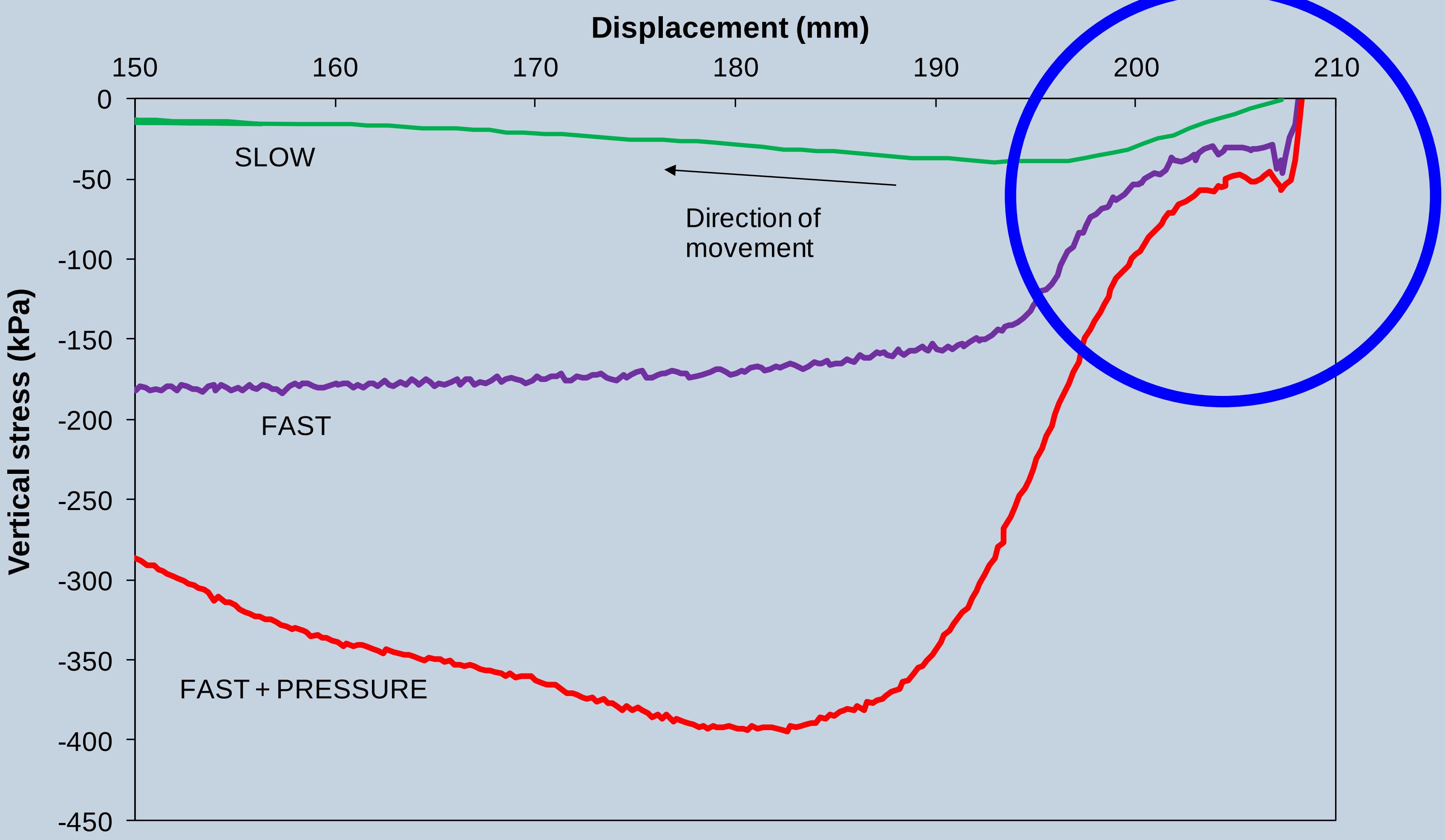
Cyclic Vertical Loading (Sand)



Vertical Loading Tests (Sand)



Capacity on tensile loading (Sand)



Observations – Caisson Foundations

- Significant body of work available for development of designs
- Both mono-caisson and multi-caisson structures can make contributions to offshore wind
  - Suitable to a range of soil conditions

    …but not all
- Initial structures must be monitored
  - To enable a better understanding of the foundation performance
    - To understand the limitations
    - To reduce conservatism

Concluding Comments

- Mono-piles will continue to be used in the short-term
  - Better understanding of long term cyclic loading needed
  - Better understanding of stiffness of response also needed?
- Suction caissons could be used for offshore wind turbines
  - A new technology will help to drive down costs
  - No pile-driving noise to worry about!
- Field monitoring of structures and foundations is essential
  - Instrumentation relatively inexpensive
  - Valuable information will lead to better design guidance
  - …and more confidence in new and improved designs

Acknowledgements

- The co-authors of the various papers covered in this lecture
  - Prof Guy Houlsby (Oxford University)
  - Dr Christian LeBlanc Thilsted (Dong Energy)
  - Dr Richard Kelly (Coffey Geotechnics, Australia)
  - John Huxtable (formerly Fugro, now at Doosan)
- Dr Chris Martin collaborated on the shallow foundation work
- A number of Colleagues at Oxford and elsewhere
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- Industry participants for the caisson work included SLP Engineering, Fugro, Garrad Hassan, GE Wind, NEG Micon, Shell Renewables, HR Wallingford.
- Dong Energy for information and photos related to Walney

Géotechnique Papers

1. Response of stiff piles to random two-way lateral loading.

   Géotechnique 60 9:715-721.

2. Response of stiff piles to long term cyclic loading.

   Géotechnique 60 2: 79-90.

3. Transient vertical loading of model suction caissons in a pressure chamber.

   Géotechnique 56 10: 665-675.

4. A comparison of field and laboratory caisson tests in sand and clay.

   Géotechnique 56 9: 617-626.

5. Field trials of suction caissons in sand for offshore wind turbine foundations.

   Géotechnique 56 1: 3-10.

6. Field trials of suction caissons in clay for offshore wind turbine foundations.

   Géotechnique 55 4: 287-296.

Contact byron.byrne@eng.ox.ac.uk for further information.

Blyth


North Hoyle


Scroby Sands

Barrow


Walney

Source – Various websites