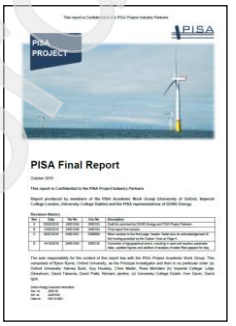
Ørsted

UNIVERSITY OF OXFORD

# PICASO – Design for Cyclic Loading




**Professor Byron W. Byrne**
**Ørsted / Royal Academy of Engineering Research Chair**
**University of Oxford**

Danish Geotechnical Society Seminar 2024
Ørsted, Gentofte, Copenhagen

UNIVERSITY OF OXFORD

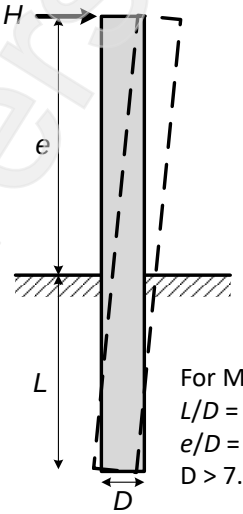
ROYAL ACADEMY OF ENGINEERING

Ørsted

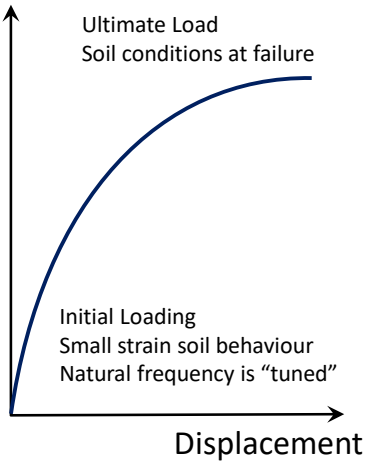
1

## Monotonic Design

Photos from Dan Kallehave (Ørsted)




For Monopiles
$L/D$ = 2 to 6
$e/D$ = 5 to 15
D > 7.5 m




UNIVERSITY OF OXFORD

ROYAL ACADEMY OF ENGINEERING

Ørsted

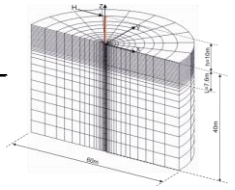
2

Contact: byron.byrne@eng.ox.ac.uk

https://www.icevirtuallibrary.com/toc/jgeot/70/11 - 9 papers available free to download from *Géotechnique*

## PISA Project Overview – 2013 – 2018

**Advanced Numerical Modelling**

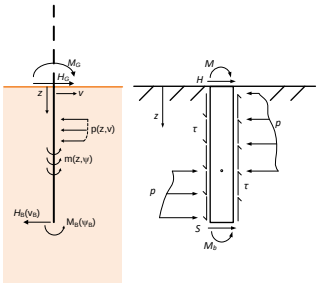


Design

Validate

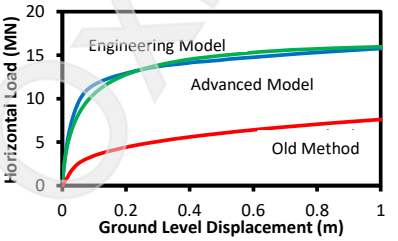
**Field Tests (28 Pile Tests, 2 Sites)**

**Simplified Engineering Models**



Apply to Design

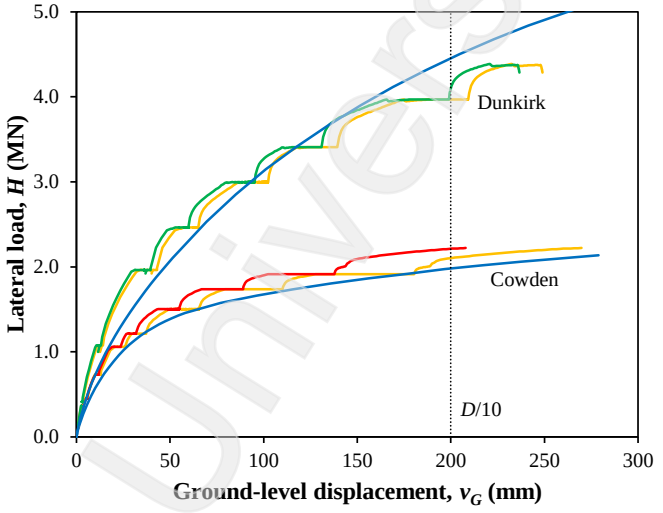
**Accurate Response Prediction**




UNIVERSITY OF OXFORD · Imperial College London · UCD DUBLIN · ROYAL ACADEMY OF ENGINEERING · PISA · Ørsted

3

## 2.0 m Diameter Pile Tests

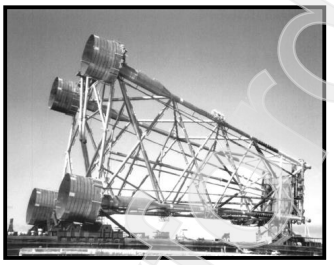


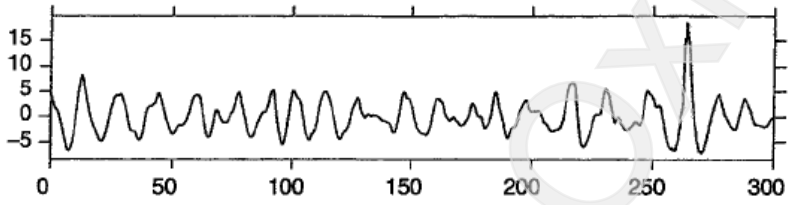

UNIVERSITY OF OXFORD · Imperial College London · UCD DUBLIN · ROYAL ACADEMY OF ENGINEERING · PISA · Ørsted

4

## 1995 New Year Wave – Draupner E: 1 in 100 Wave

- Structure and foundations fully monitored
- Forces on foundations well within design loads
- Max H = 25.6 m
- Many large waves (trough to crest)!



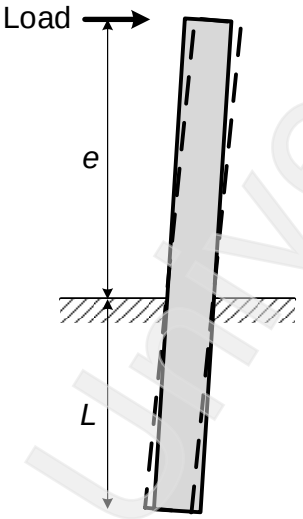


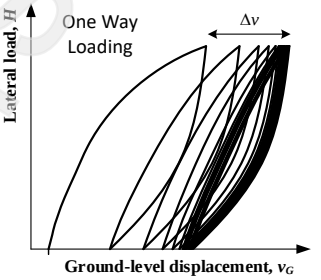

**Source: Hansteen, O.E., Jostad, H.P. and Tjelta, T.I. (2003). Observed platform response to a "monster" wave.** *Proceedings of conference on Field Measurements in Geomechanics.*
**Source: Andersen, K.H., Jostad, H.P. and Dyvik, R. (2008)** "Penetration resistance of offshore skirted foundations and anchors in dense sand", Proc ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol 134, No 1, pp 106 - 116.

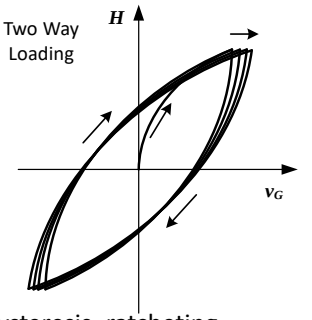
UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted

5

## Cyclic Loading: Basics



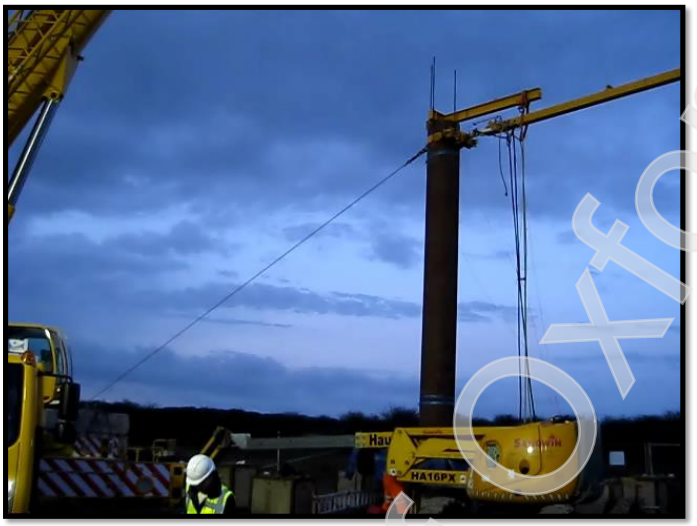




- Cyclic loading models must capture hysteresis, ratcheting behaviour and stiffness change
- Ultimate capacity after cycling
- Cyclic loading is irregular / pseudo random
- Time domain calculations important
- **<u>Monotonic loading</u> is *essential* for any cyclic loading calculation**

UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted

6

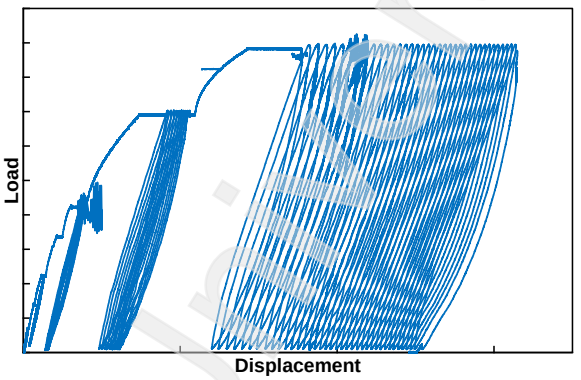
## PISA Cyclic Loading

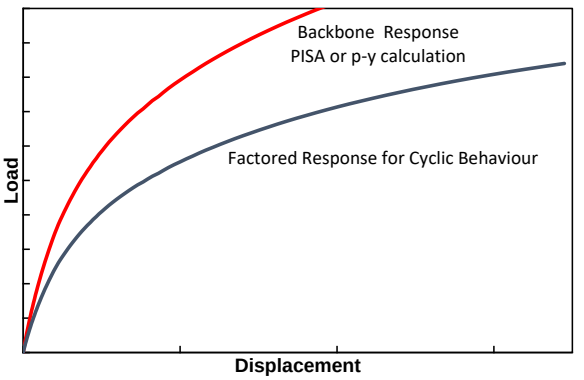


UNIVERSITY OF OXFORD · Imperial College London · UCD DUBLIN · ROYAL ACADEMY OF ENGINEERING · PISA · Ørsted

7

## Cyclic Results from PISA – Current Design Approach (?)



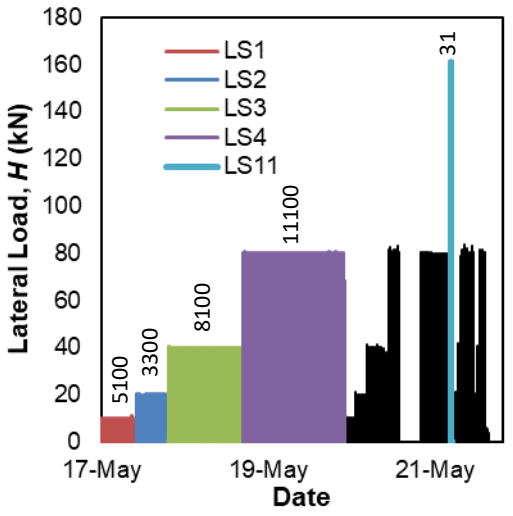

UNIVERSITY OF OXFORD · ROYAL ACADEMY OF ENGINEERING · Ørsted

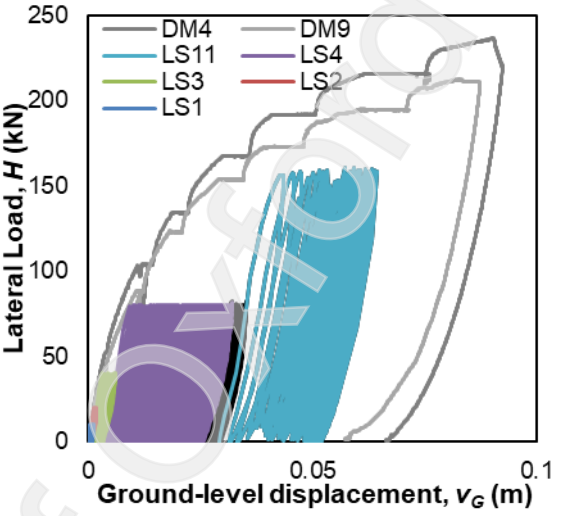
8



Contact: byron.byrne@eng.ox.ac.uk

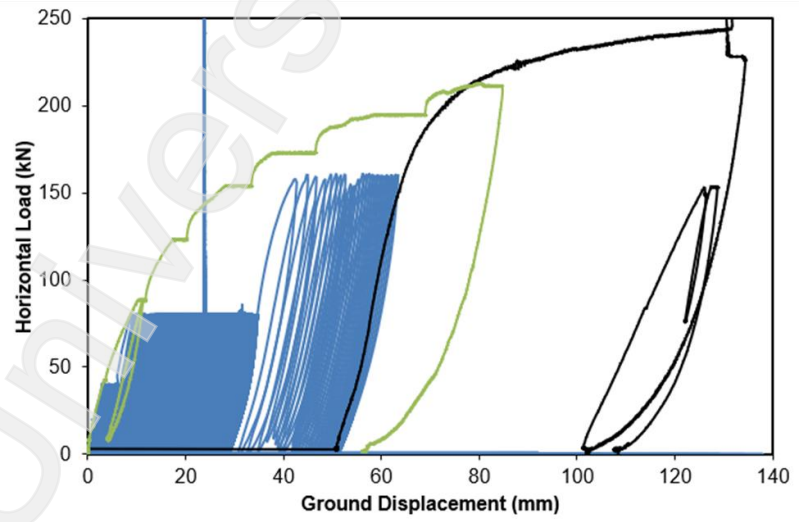
## Dunkirk: DM2 – 1 Way Cyclic Loading




9

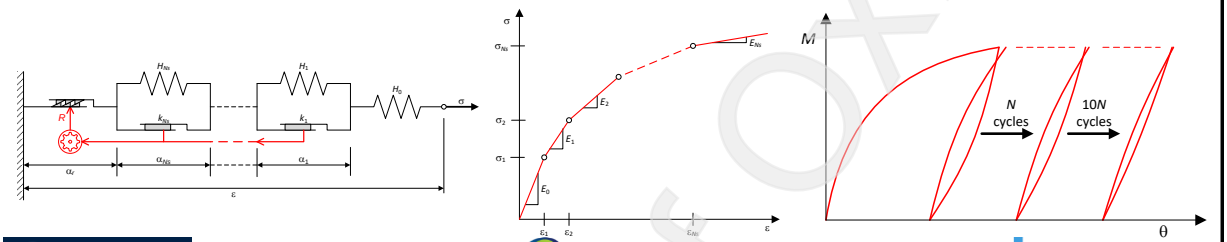
## Dunkirk: Post-Cyclic Response




10

## Hyperplastic Accelerated Ratcheting Model (HARM)

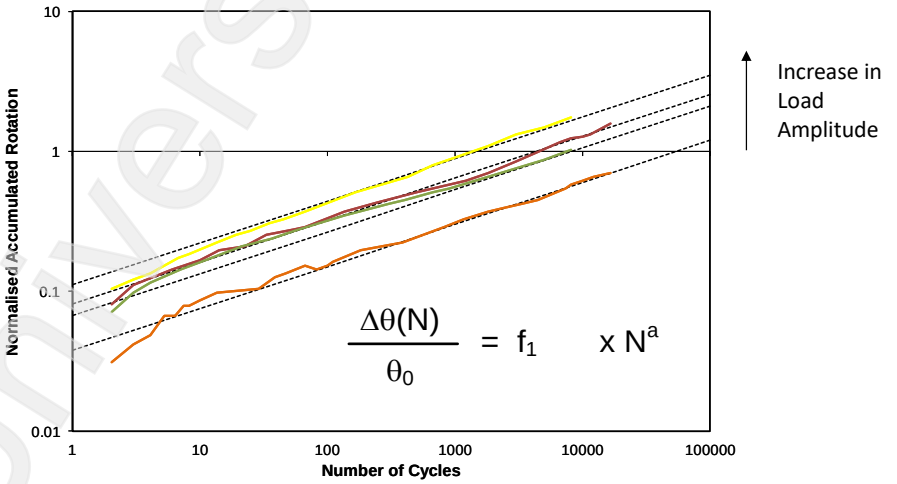
- Hyperplasticity, an approach to plasticity theory based on thermodynamic principles, developed by Guy Houlsby
- Entire model specified by just two functions with output derived using standard mathematical procedures
- Can be applied at 0D macro model, 1D generalised Winkler model or at the 3D continuum level
- See Abadie 2015, Beuckelaers 2017, Richards 2019, Balaam 2020




UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted

11

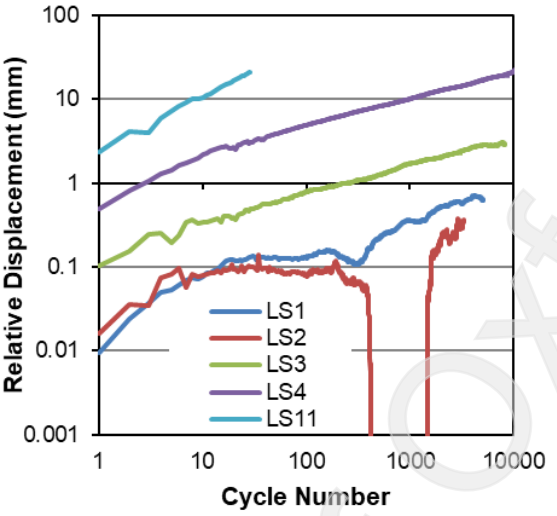
## Model Test Results – Accumulated Rotation – Leblanc 2010




UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted

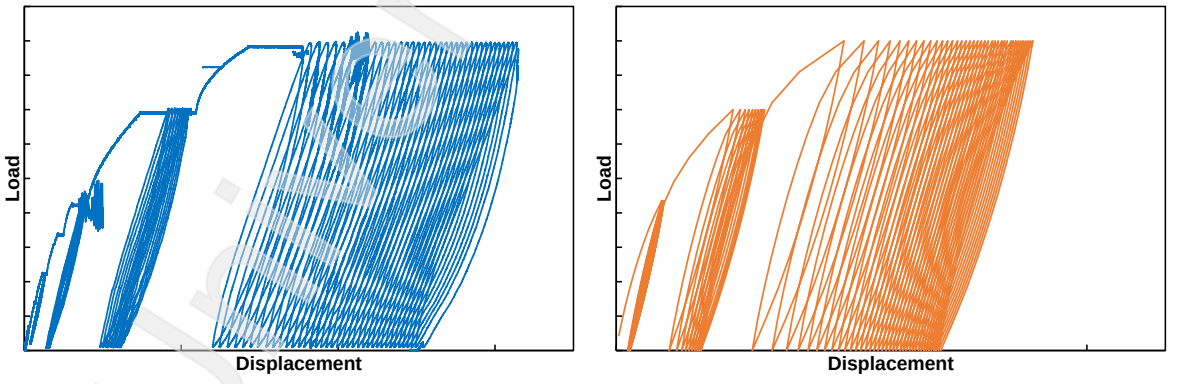
12

## Dunkirk: DM2 – 1 Way Cyclic Loading



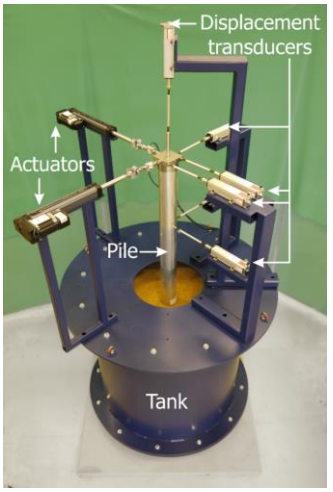

13

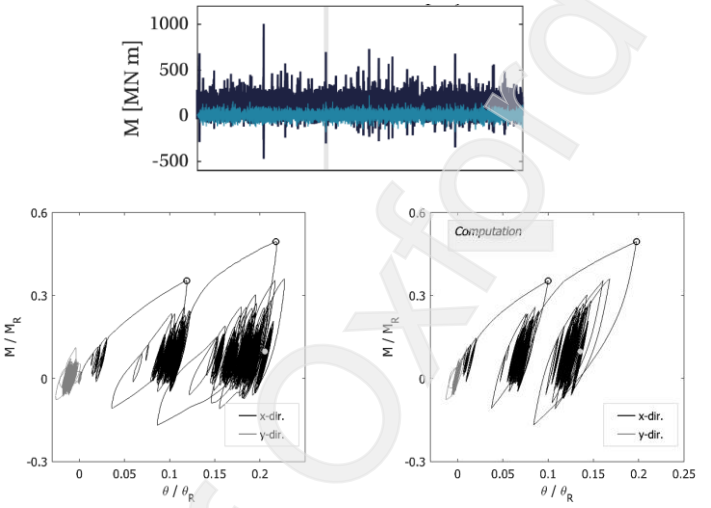
## Modelling Results from PISA (1D): HARM – Beuckelaers 2017




14

## 0D HARM - Complex Loading – Richards 2019



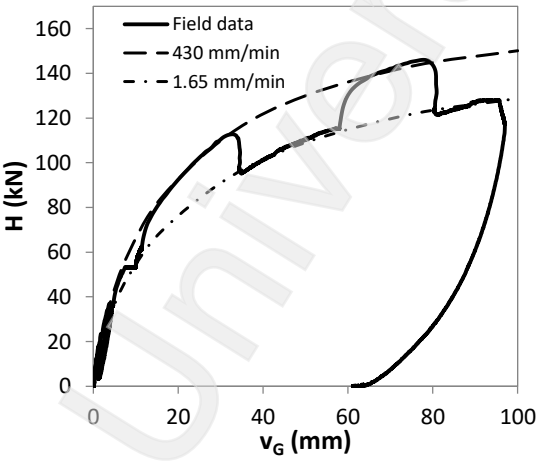




UNIVERSITY OF OXFORD · ROYAL ACADEMY OF ENGINEERING · Ørsted

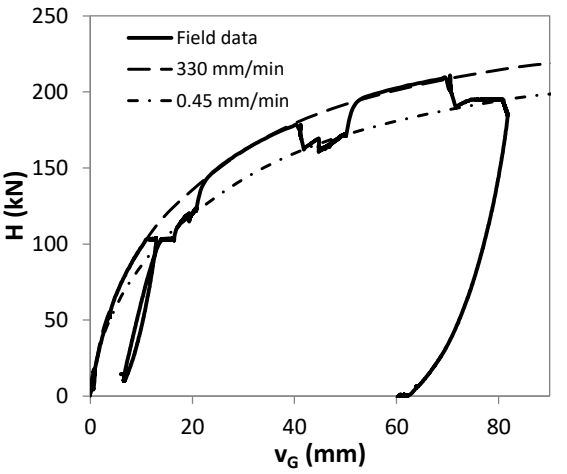
15

## PISA Rate Effects

Cowden – CM1




Dunkirk – DM6

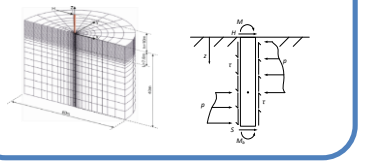



UNIVERSITY OF OXFORD · Imperial College London · UCD DUBLIN · ROYAL ACADEMY OF ENGINEERING · PISA · Ørsted

16

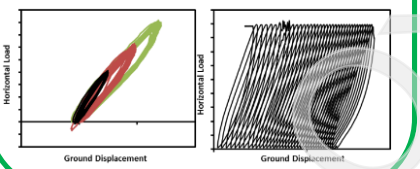
## PICASO: Oxford – Ørsted Collaboration – 2018 - Present

WP1: Modelling

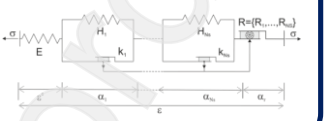


WP2: Calibration Methods

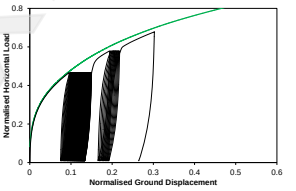

WP4: Field Testing




WP3: Theoretical Methods



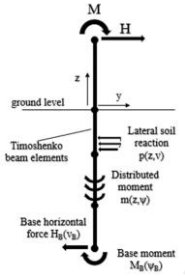
WP5: Application to Design




UNIVERSITY OF OXFORD · ROYAL ACADEMY OF ENGINEERING · Ørsted

17

## PICASO Data-Driven 1D Model – Kamas 2023



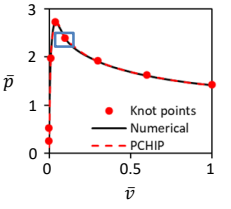

Use PISA 1D model to predict pile monotonic response

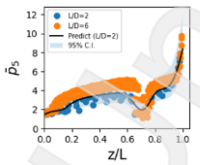
Perform 3D FEA for soil profiles and a pile calibration space

Predict the depth variation of the knot parameters

Supply pile geometry & soil profile

8-knot soil reaction curves




Based on Suryasentana et al. (2021)
Confidential WP1 Report3

Inputs:
Pile geometry & soil profile data

Train

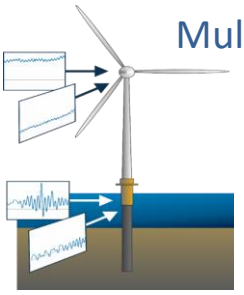
Gaussian Process Regression M.L. model

DATABASE

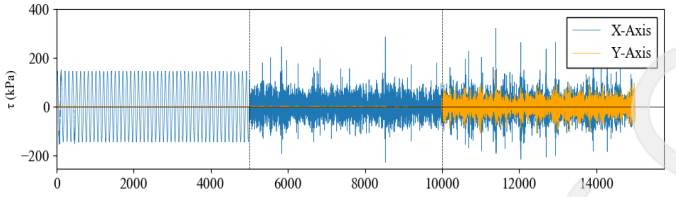
UNIVERSITY OF OXFORD · ROYAL ACADEMY OF ENGINEERING · Ørsted

18

## Multi-Directional Simple Shear Testing – Qiu 2023







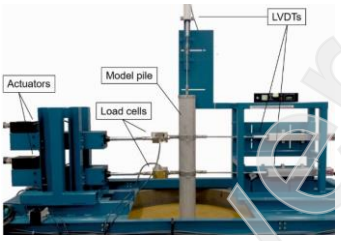

UNIVERSITY OF OXFORD

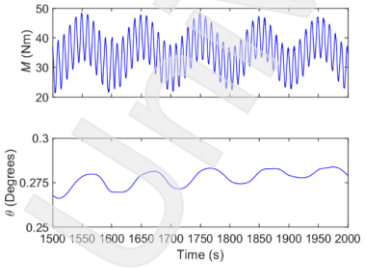
ROYAL ACADEMY OF ENGINEERING

Ørsted

19

## In-Situ Model Scale Pile Tests – Wu 2022





UNIVERSITY OF OXFORD

ROYAL ACADEMY OF ENGINEERING

Ørsted

20

## HySand – A New Approach to Modelling – Simonin 2023

Gibbs energy: $g = -\frac{p_r}{k_r(1-m)(2-m)}\left(\frac{p_0}{p_r}\right)^{2-m} - q\frac{1}{N}\sum_{n=1}^{N}\alpha_q^{(n)} - p\frac{1}{N}\sum_{n=1}^{N}\left(\alpha_p^{(n)} + \alpha_{pc}^{(n)}\right)$

Non-linear Elasticity | Shear Plasticity | Volumetric Plasticity

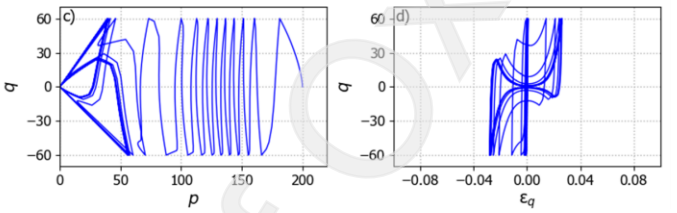
Triaxial formulation:

Yield functions: $y^{(n)} = \frac{\left(N\chi_q^{(n)} - h_n\left(p,q,\alpha_q^{(n)}\right) - a\beta^{(n)}N\chi_p^{(n)} + A(1-|a|)\chi_a\right)^2}{4\left(\frac{n}{N}\mu\right)^2\left(p+\frac{2}{3}q\right)\left(p-\frac{q}{3}\right)} + \left(\frac{N\chi_{pc}^{(n)}}{p_c^{(n)}}\right)^r - 1$

Hardening | Dilation | Anisotropy | Consolidation

Matsuoka-Nakai shape

Simulation of a cyclic undrained stress-controlled test on medium dense Karlsruhe fine sand:




UNIVERSITY OF OXFORD | ROYAL ACADEMY OF ENGINEERING | Ørsted

21

## PICASO Field Test Sites


UNIVERSITY OF OXFORD | ROYAL ACADEMY OF ENGINEERING | Ørsted

22

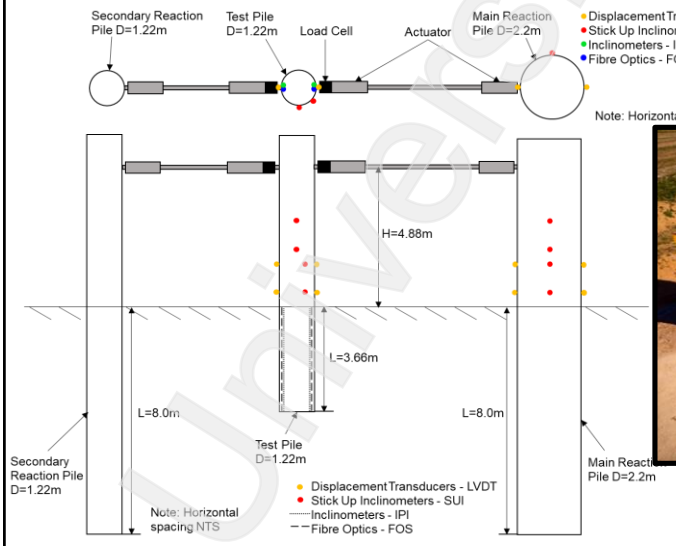
8 by 1.22 m diameter
3 by 2.50 m diameter
$L/D = 3$
$h/D = 4$

## Pile Testing at Cowden – Martin 2023


UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted
SOCOTEC

23

## Testing – Example Layout



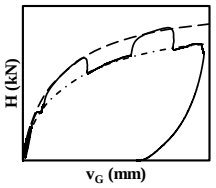

UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted
SOCOTEC

24

Contact: byron.byrne@eng.ox.ac.uk

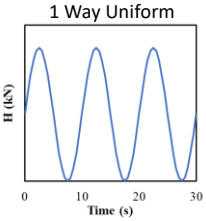
## Applied Load Paths

Calibration Tests

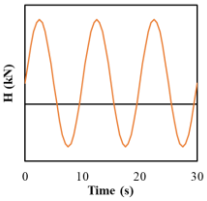



Monotonic
+
Rate

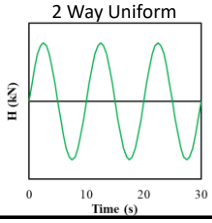
1 Way Uniform

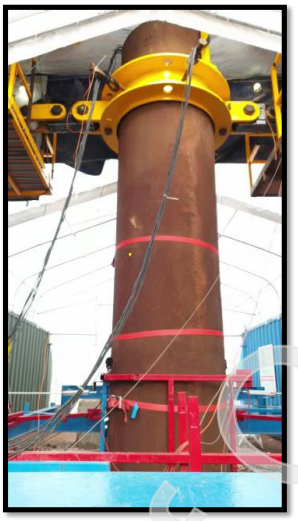



1.5 Way Uniform



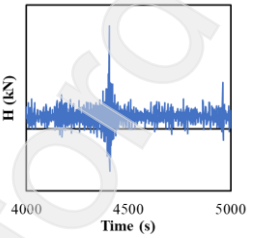

2 Way Uniform



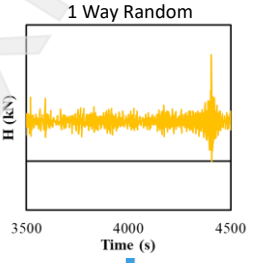



Validation Tests

1.5 Way Random




1 Way Random




UNIVERSITY OF OXFORD

ROYAL ACADEMY OF ENGINEERING

SOCOTEC

Ørsted

25

## Large Amplitude Cyclic Loading

UNIVERSITY OF OXFORD

ROYAL ACADEMY OF ENGINEERING

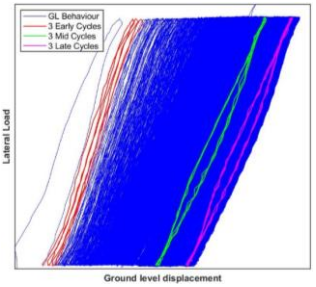
SOCOTEC

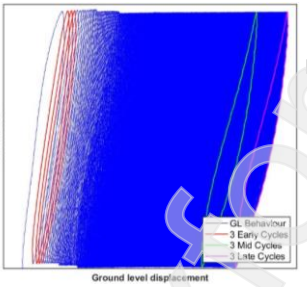
Ørsted

26

## Example Observations of Cyclic Behaviour

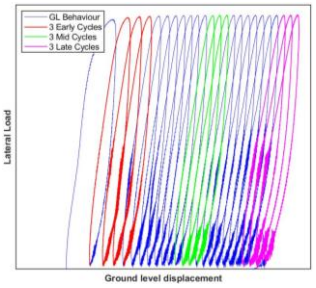
Low Amplitude
24 Hours

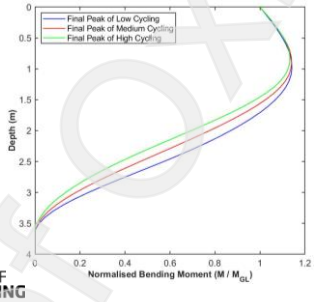



Medium Amplitude
12 Hours

High Amplitude
10 minutes

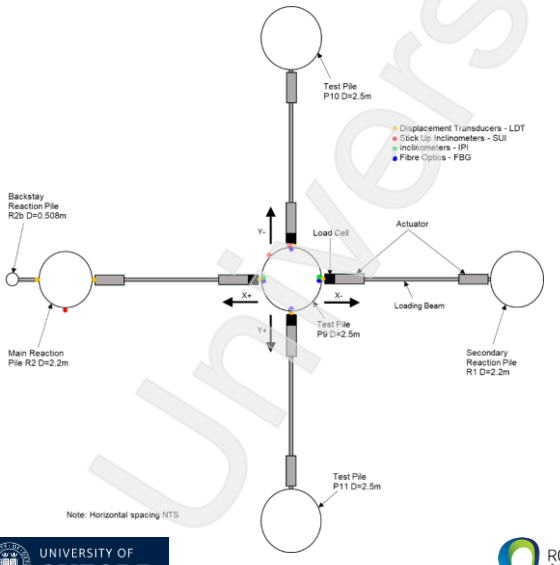



UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted
SOCOTEC

27

## Multi-Directional Testing Layout

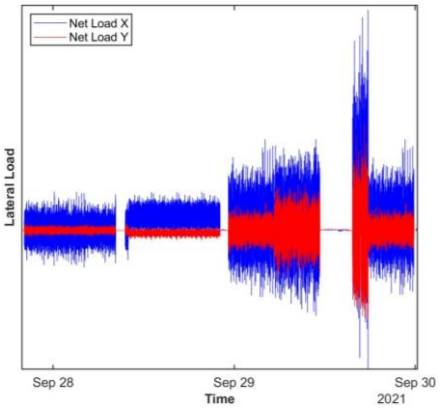



UNIVERSITY OF OXFORD
ROYAL ACADEMY OF ENGINEERING
Ørsted
SOCOTEC

28

Contact: byron.byrne@eng.ox.ac.uk

## Multi-Directional Random Amplitude Loading




29

## Pile Testing at Cuxhaven

8 by 1.22 m diameter
3 by 2.50 m diameter
$L/D = 3$
$h/D = 4$

30

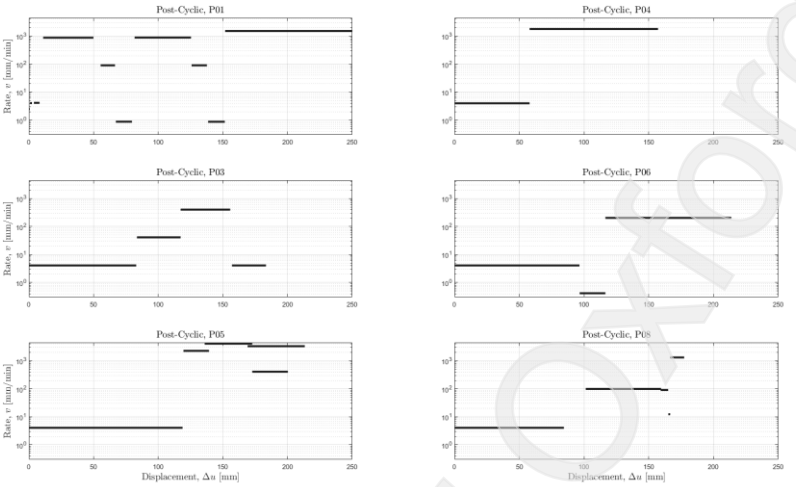
## Pile Testing at Cuxhaven

31

## Multi-Directional Test

32

## Post Cyclic Monotonic Rate Test




33

## Post Cyclic Monotonic Rate Test


34

## Concluding Remarks

- The development of new design methods is evidence-based at a range of scales and within an appropriate theoretical framework
- New PISA methods allow design of monotonic laterally loaded monopiles for site-wide optimisation, now in widespread use
- Cyclic loading is the most significant challenge to address for larger turbines and deeper water
- The PICASO project develops a new design framework for cyclic loading formulated within advanced plasticity theories including:
  - No degradation of monotonic response
  - Computation of displacements under pseudo-random loading
  - Integration of rate effects
- The procedure has been demonstrated for 1.22 m and 2.50 m diameter scale monopiles in a stiff clay and a medium dense silica sand

UNIVERSITY OF OXFORD ROYAL ACADEMY OF ENGINEERING Ørsted

35

## Special Mention to the Cuxhaven Field-Testing Team!

SOCOTEC


UNIVERSITY OF OXFORD ROYAL ACADEMY OF ENGINEERING Ørsted

36