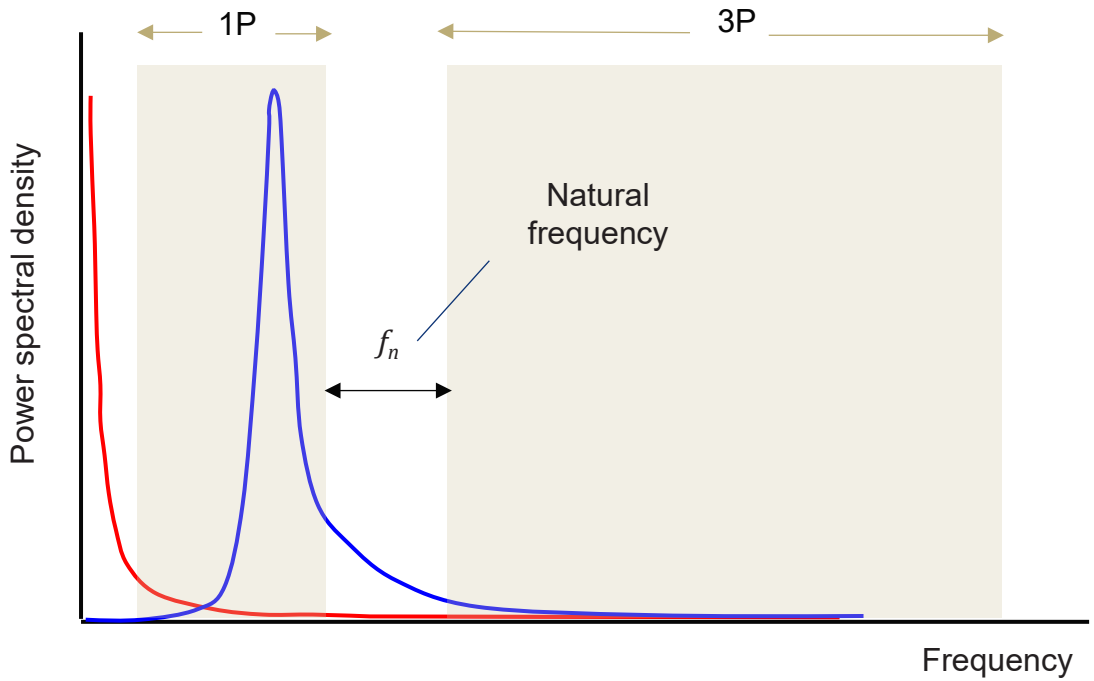
Addressing the effects of cyclic loading in monopile design: Bridging research and practice

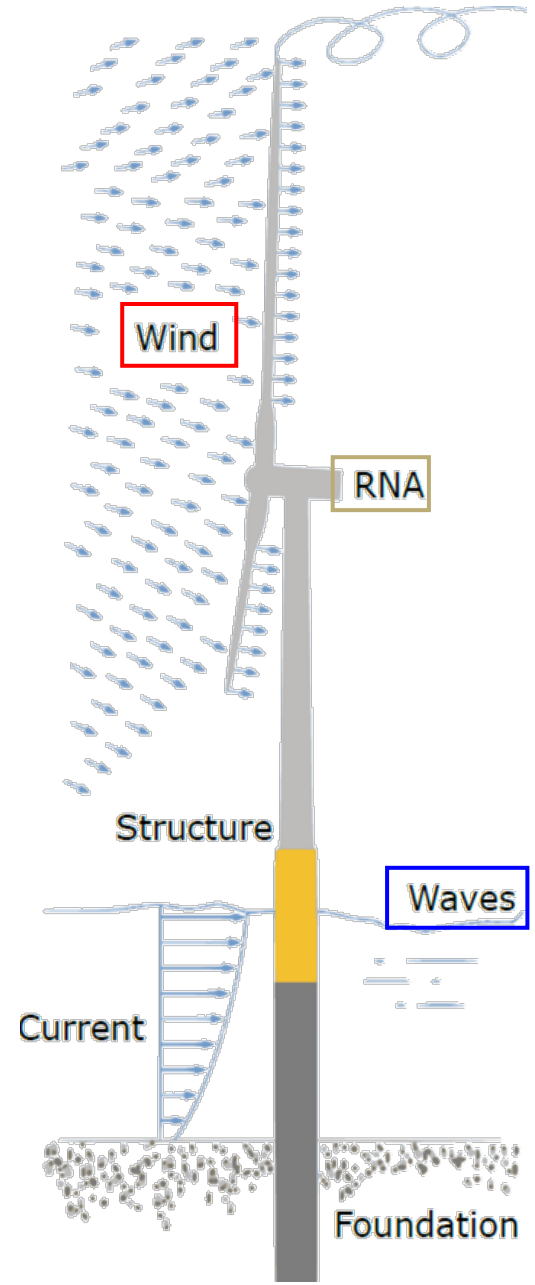
Ana Page (Ana.Page@ngi.no) + Rasmus Tofte Klinkvort, Nallathamby Sivasithamparam, …

Danish Geotechnical Society Seminar, 24th September 2024

Design of monopile-based Offshore Wind Turbines

Monopiles are subjected to repeated loads from wind, waves, current and the operation of the OWT:





The soil might show a different response under cyclic loading, and therefore, their effects have to be accounted for in the design.

NGI

Design of monopile-based Offshore Wind Turbines

DNV-ST-0126 Support structures for wind turbines

Standard

Edition 2021-12

7.4.4 Effects of cyclic loading

7.4.4.1 The effects of cyclic loading on the soil properties, called cyclic degradation, shall be considered in foundation design for wind turbine structures.

7.4.4.2 Cyclic shear stresses may lead to a gradual increase in pore pressure. Such pore pressure build-up and the accompanying increase in cyclic and permanent shear strains may reduce the shear strength of the soil. These effects shall be accounted for in the assessment of the characteristic shear strength for use in design within the applicable limit state categories. These effects shall also be accounted for in the assessment of permanent foundation rotations.

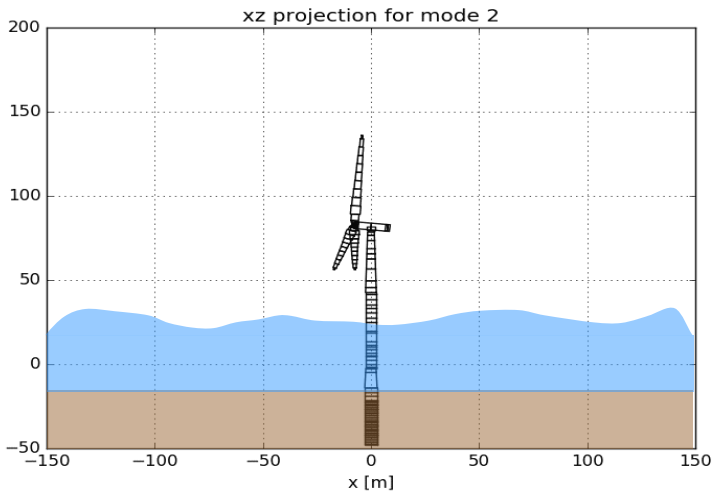
7.4.4.3 In the SLS design condition the effects of cyclic loading on the soil's shear modulus shall be corrected for as relevant when dynamic motions, settlements and permanent (long-term) rotation shall be calculated. See also [7.5.6].

The soil might show a different response under cyclic loading,
and therefore, their effects have to be accounted for in the design.

NGI

Design of monopile-based Offshore Wind Turbines

How to account for the effects of cyclic loading on soils in monopile design?



In integrated load analyses

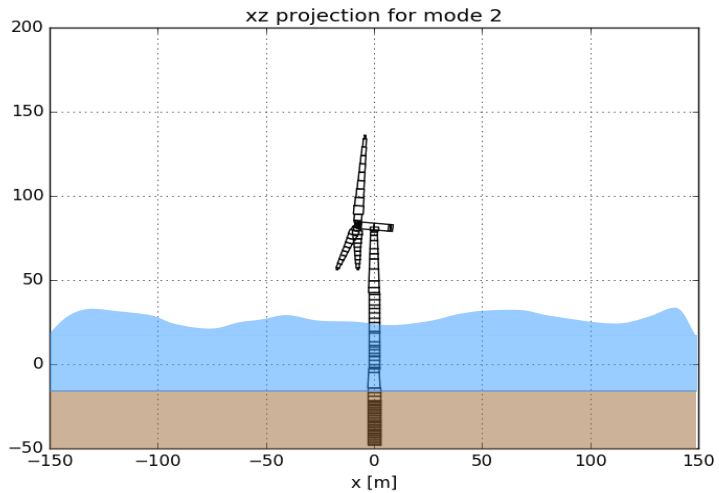
By providing an accurate estimation of foundation response in integrated analyses

In foundation design

By including them in the different limit states

Design of monopile-based Offshore Wind Turbines

The soil might show a different response under cyclic loading, and therefore, their effects have to be accounted for in the design:



In integrated load analyses

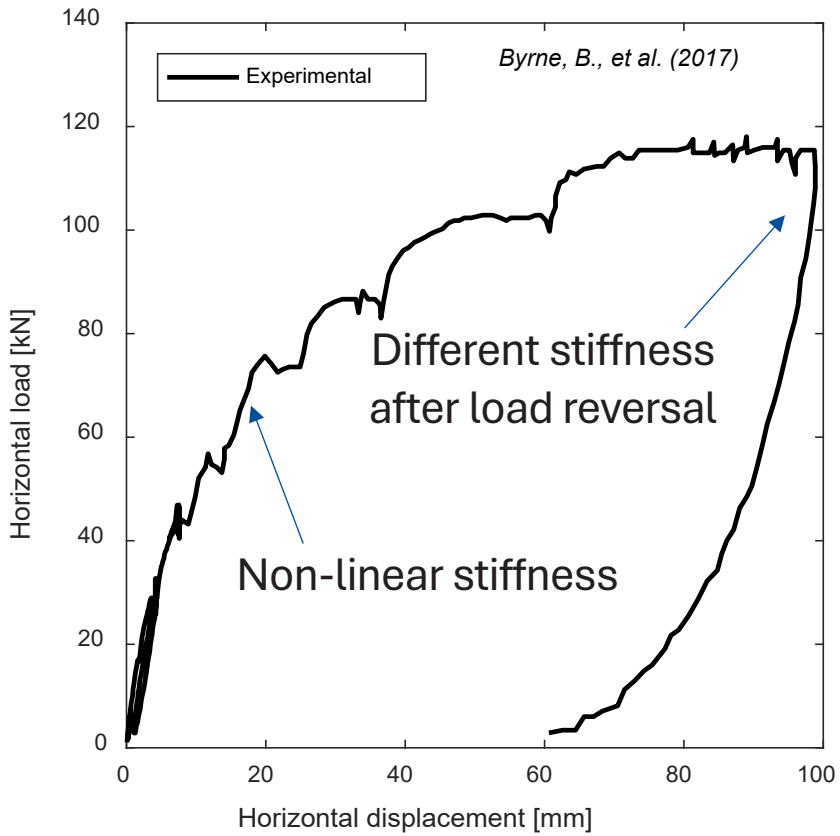
By providing an accurate estimation of foundation response in integrated analyses

In foundation design

By including them in the different limit states

Response of monopiles for integrated load analyses

Which features of the soil and monopile behaviour should be included in integrated analyses?



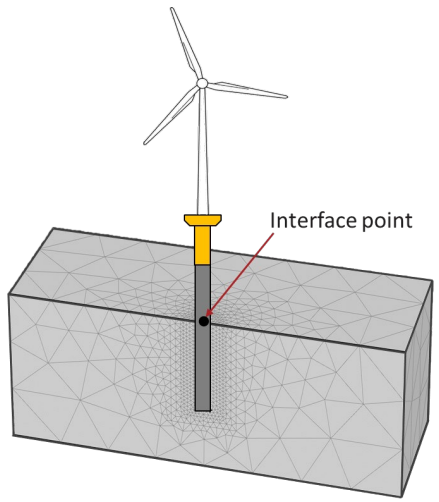
- [x] Non-linear stiffness
- [x] Different loading and unloading stiffness
- [x] Hysteretic damping
- [ ] Radiation damping
- [ ] Ratcheting

REDWIN project

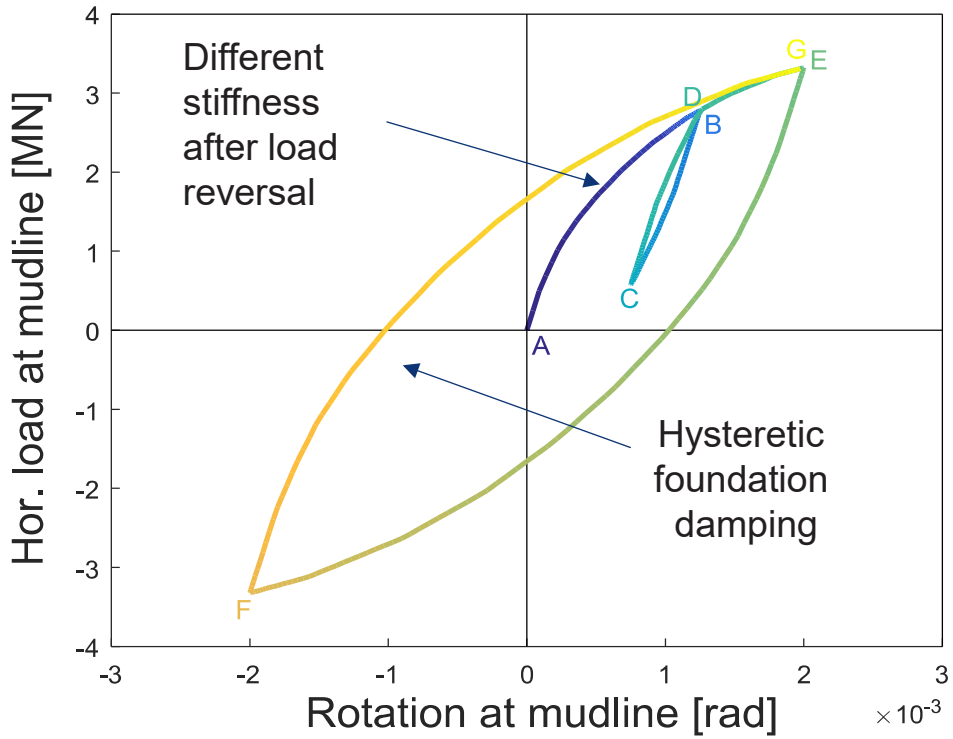
NGI

The REDWIN model

Macro-element model that provides the load-displacement response of the foundation + soil at one interface point

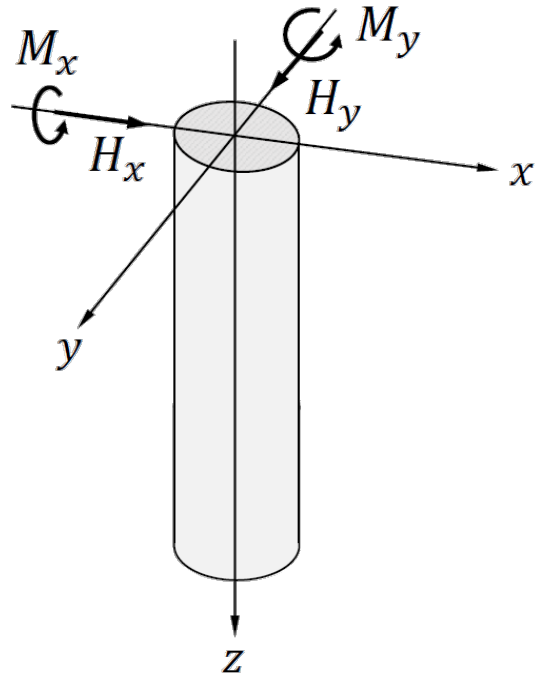


Page et al. (2017)



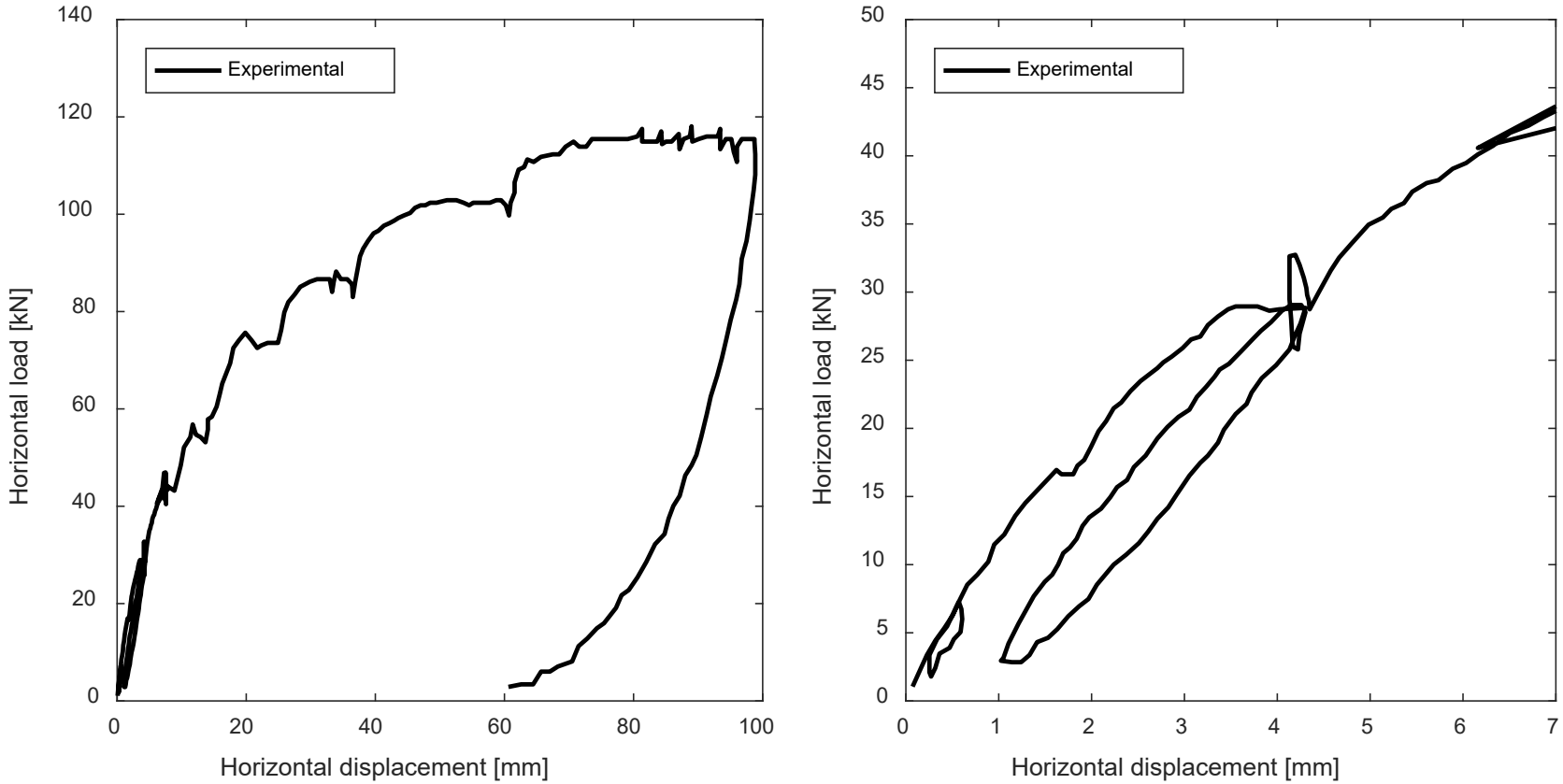
Elasto-plastic formulation based on multi-surface plasticity

Includes coupling between loads



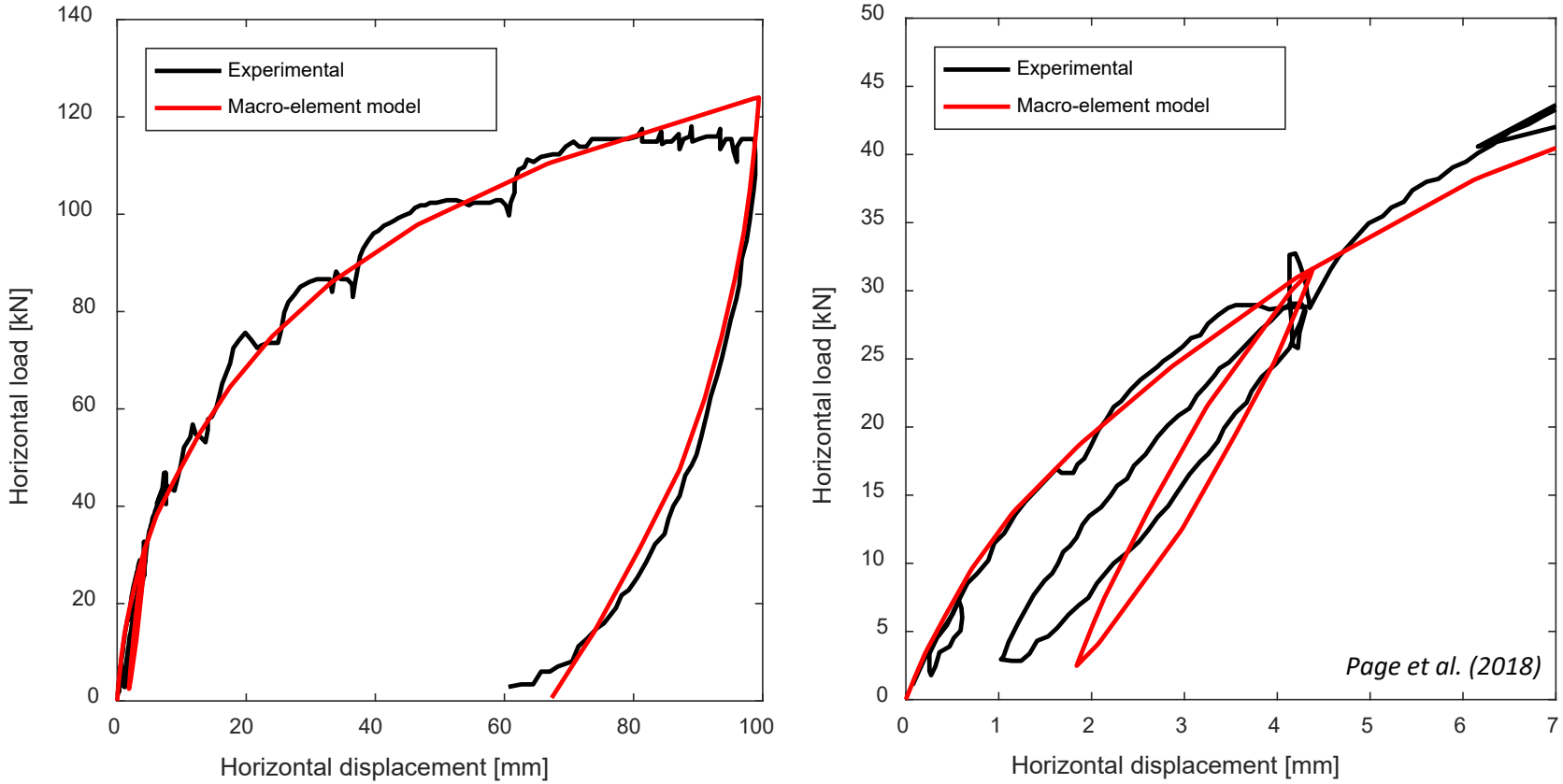
NGI

The REDWIN model: comparison against measurements



Source: Byrne, B., et al. (2017), PISA: new design methods for offshore wind turbine monopiles, in Proceedings of the Society for Underwater Technology Offshore Site Investigation and Geotechnics.

The REDWIN model: comparison against measurements



Source: Byrne, B., et al. (2017), PISA: new design methods for offshore wind turbine monopiles, in Proceedings of the Society for Underwater Technology Offshore Site Investigation and Geotechnics.

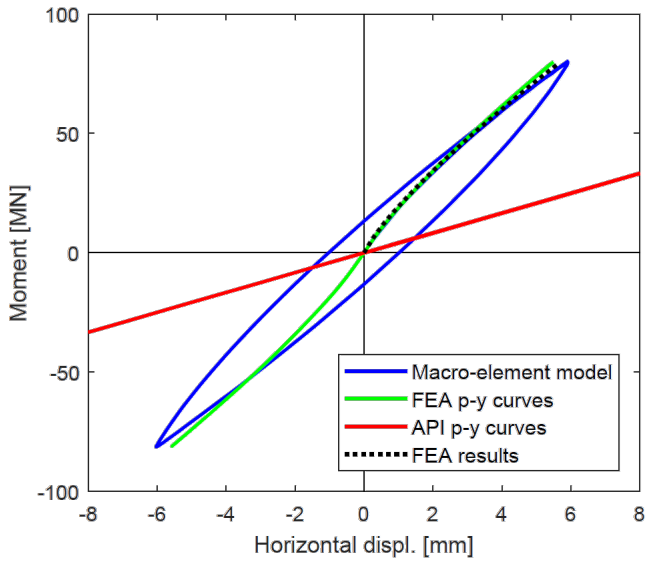
NGI

The REDWIN model: comparison against measurements

Full-scale field data of an OWT in the North Sea

vs.

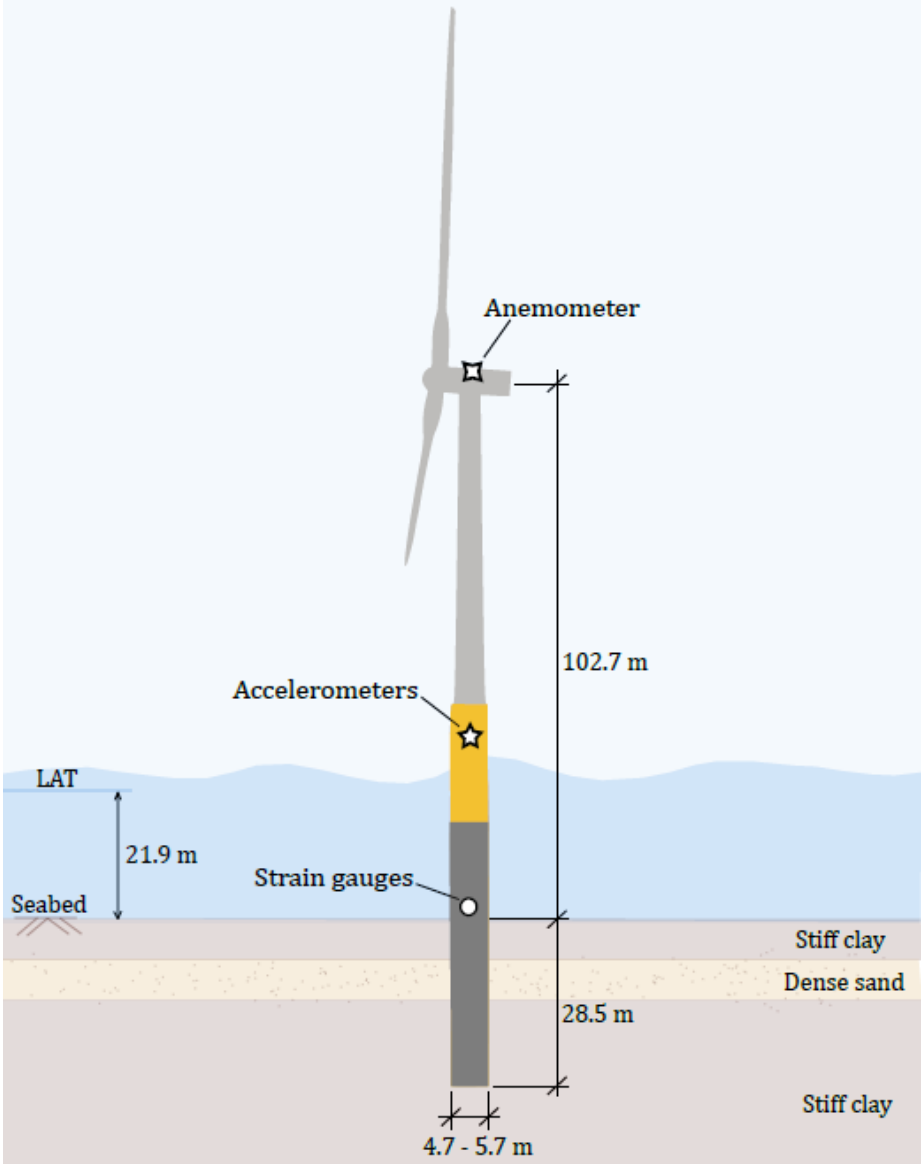
Simulations with different foundation models:



API *p-y* curves

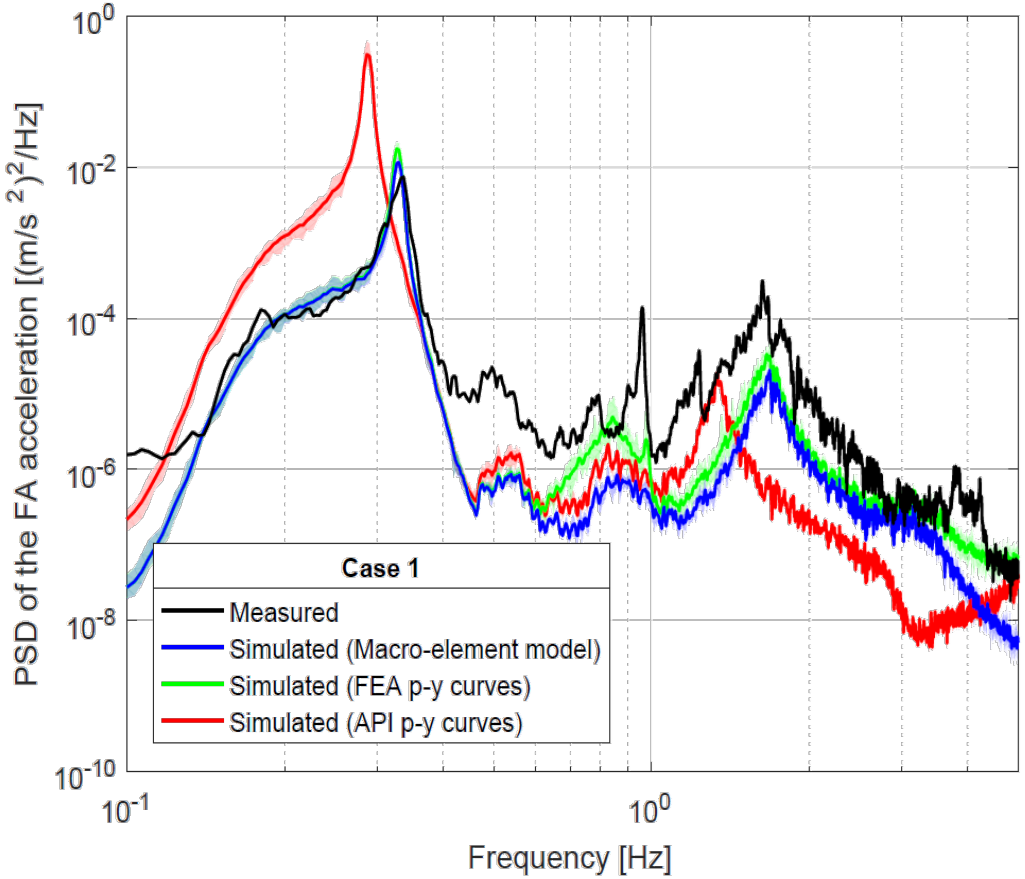
FEA *p-y* curves

REDWIN 2 macro-element

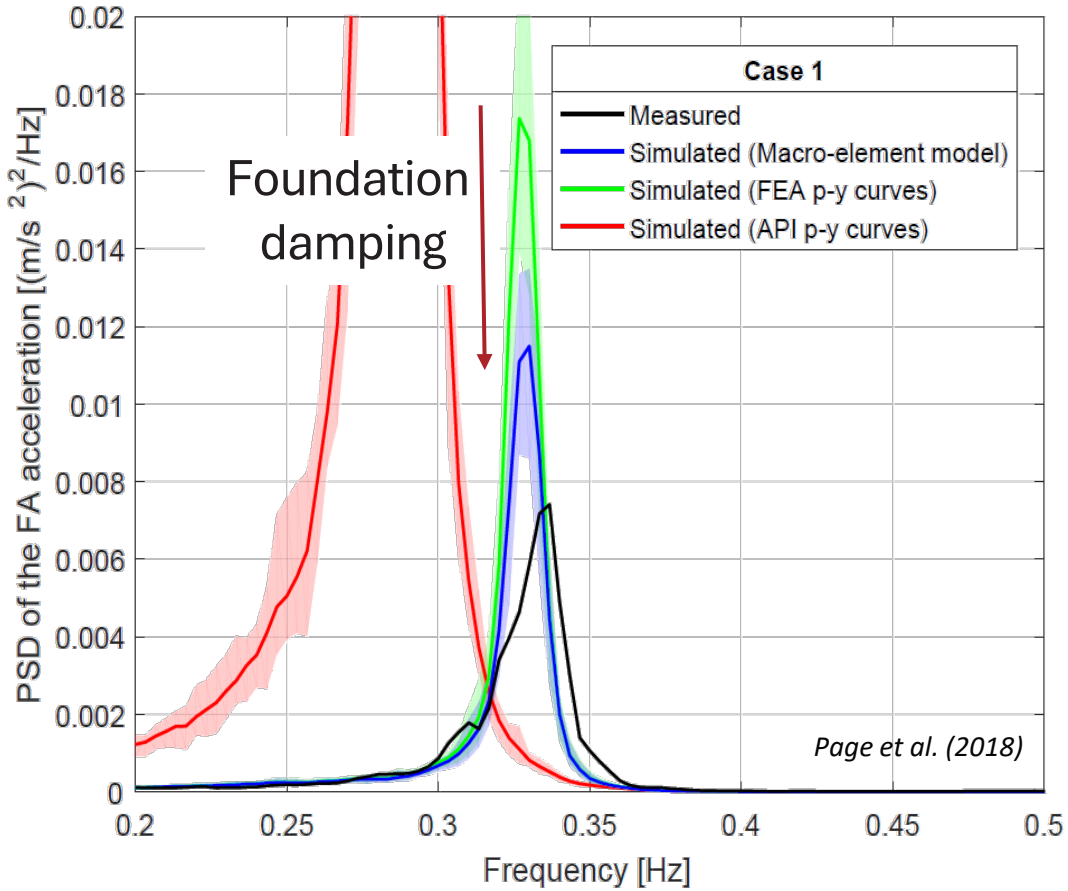


Page et al. (2019)

The REDWIN model: comparison against measurements



Accelerations at the TP



NGI

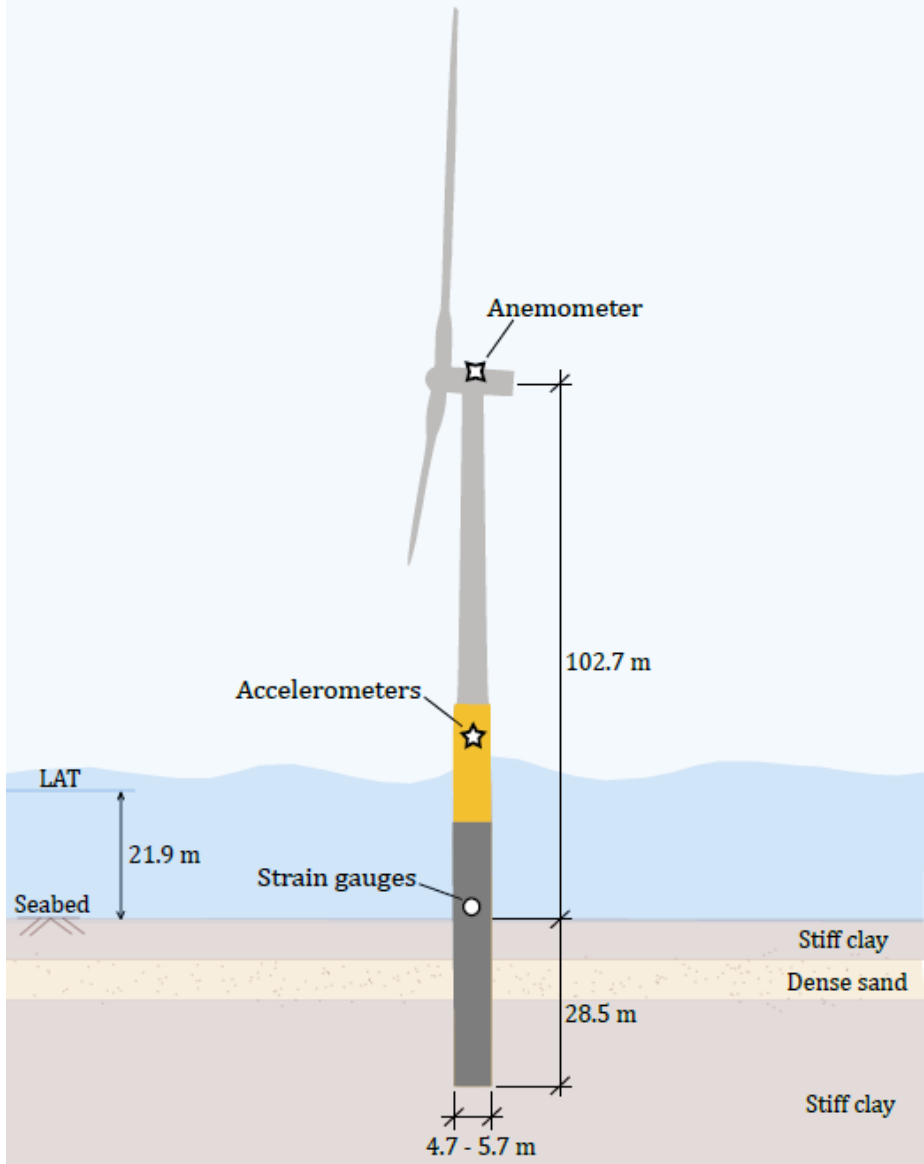
The REDWIN model: comparison against measurements

Fatigue Damage Equivalent Loads (DEL)

	REDWIN model 2	FEA *p-y* curves	API *p-y* curves
Simulated DEL / Measured DEL	1.15	1.26	2.66

7 % is foundation damping

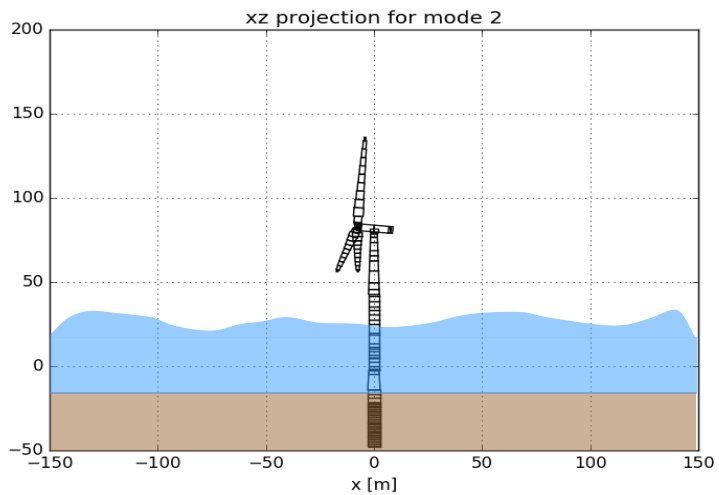
93 % is foundation stiffness



Page et al. (2019)

Design of monopile-based Offshore Wind Turbines

The soil might show a different response under cyclic loading, and therefore, their effects have to be accounted for in the design:



In integrated load analyses

By providing an accurate estimation of foundation response in integrated analyses

In foundation design

By including them in the different limit states

Design of monopile-based Offshore Wind Turbines

The soil might show a different response under cyclic loading, and therefore, their effects have to be accounted for in the design:

In integrated load analyses

By providing an accurate estimation of foundation response in integrated analyses

In foundation design

By including them in the different limit states

NGI

Geotechnical design of monopiles

The purpose of the monopile foundation is to transfer all the loads from the wind turbine structure to the ground safely and within the allowable deformations.

The design should satisfy:

- Ultimate Limit State (ULS)
- Serviceability Limit State (SLS)
- Fatigue Limit State (FLS)
- Target natural frequency
- Pile driveability

NGI

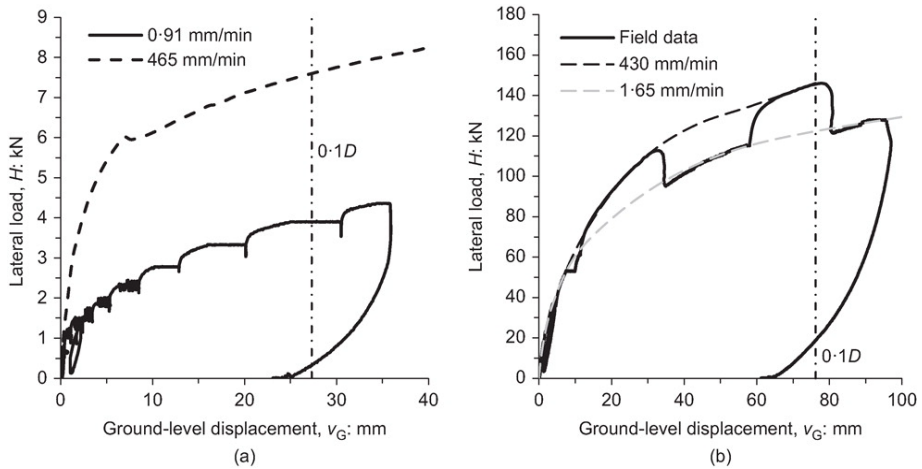
Effects of cyclic loading on soils

1. Effect of loading rate

Byrne, B. W. *et al.* (2020). *Géotechnique* **70**, No. 11, 970–985 [https://doi.org/10.1680/jgeot.18.PISA.003]

Monotonic laterally loaded pile testing in a stiff glacial clay till at Cowden

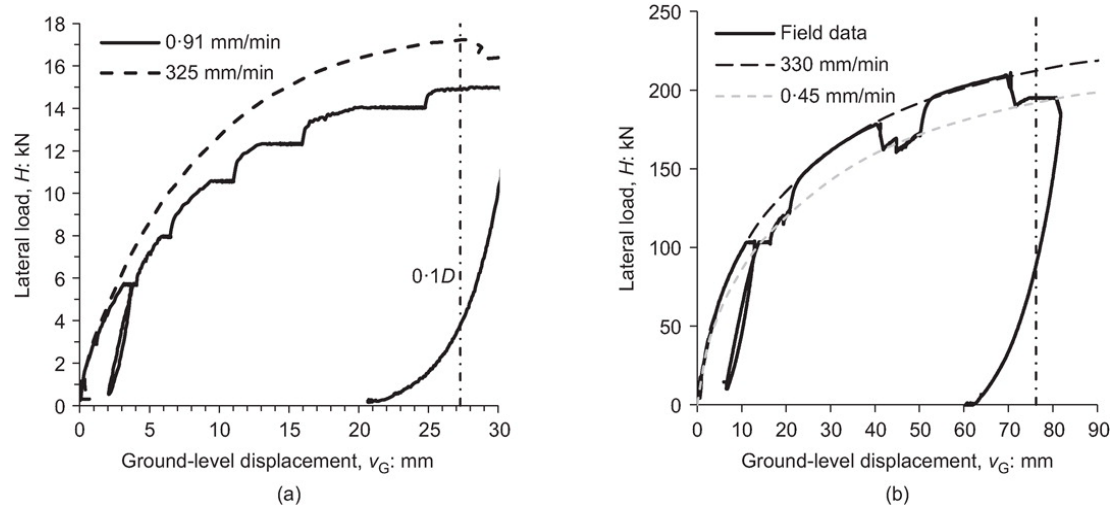
BYRON W. BYRNE*, ROSS A. MCADAM*, HARVEY J. BURD*, WILLIAM J. A. P. BEUCKELAERS†, KENNETH G. GAVIN‡, GUY T. HOULSBY*, DAVID J. P. IGOE§, RICHARD J. JARDINE‖, CHRISTOPHER M. MARTIN*, ALASTAIR MUIR WOOD¶, DAVID M. POTTS‖, JESPER SKOV GRETLUND**, DAVID M. G. TABORDA‖ and LIDIJA ZDRAVKOVIĆ‖



McAdam, R. A. *et al.* (2020). *Géotechnique* **70**, No. 11, 986–998 [https://doi.org/10.1680/jgeot.18.PISA.004]

Monotonic laterally loaded pile testing in a dense marine sand at Dunkirk

ROSS A. MCADAM*, BYRON W. BYRNE*, GUY T. HOULSBY*, WILLIAM J. A. P. BEUCKELAERS†, HARVEY J. BURD*, KENNETH G. GAVIN‡, DAVID J. P. IGOE§, RICHARD J. JARDINE‖, CHRISTOPHER M. MARTIN*, ALASTAIR MUIR WOOD¶, DAVID M. POTTS‖, JESPER SKOV GRETLUND**, DAVID M. G. TABORDA‖ and LIDIJA ZDRAVKOVIĆ‖



Effects of cyclic loading on soils

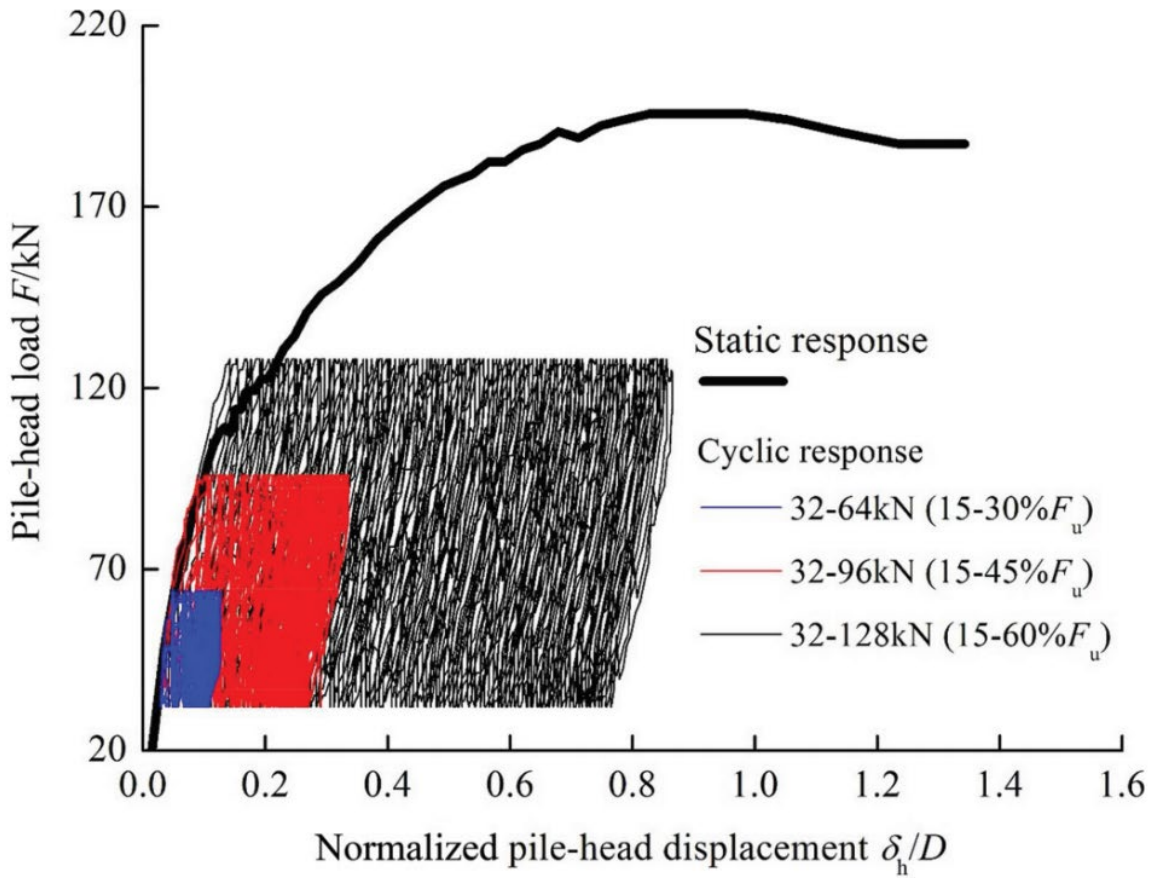
1. Effect of loading rate

2. Effect of repeated loading

3. Effect of average and cyclic loads

Cyclic lateral response and failure mechanisms of semi-rigid pile in soft clay: centrifuge tests and numerical modelling

Y. Hong, B. He, L.Z. Wang, Z. Wang, C.W.W. Ng, and D. Mašín



Effects of cyclic loading on soils: the NGI model

- The model includes the **effect of rate**

  Cyclic tests are tuned to wave frequencies

- The model includes **cyclic degradation**,

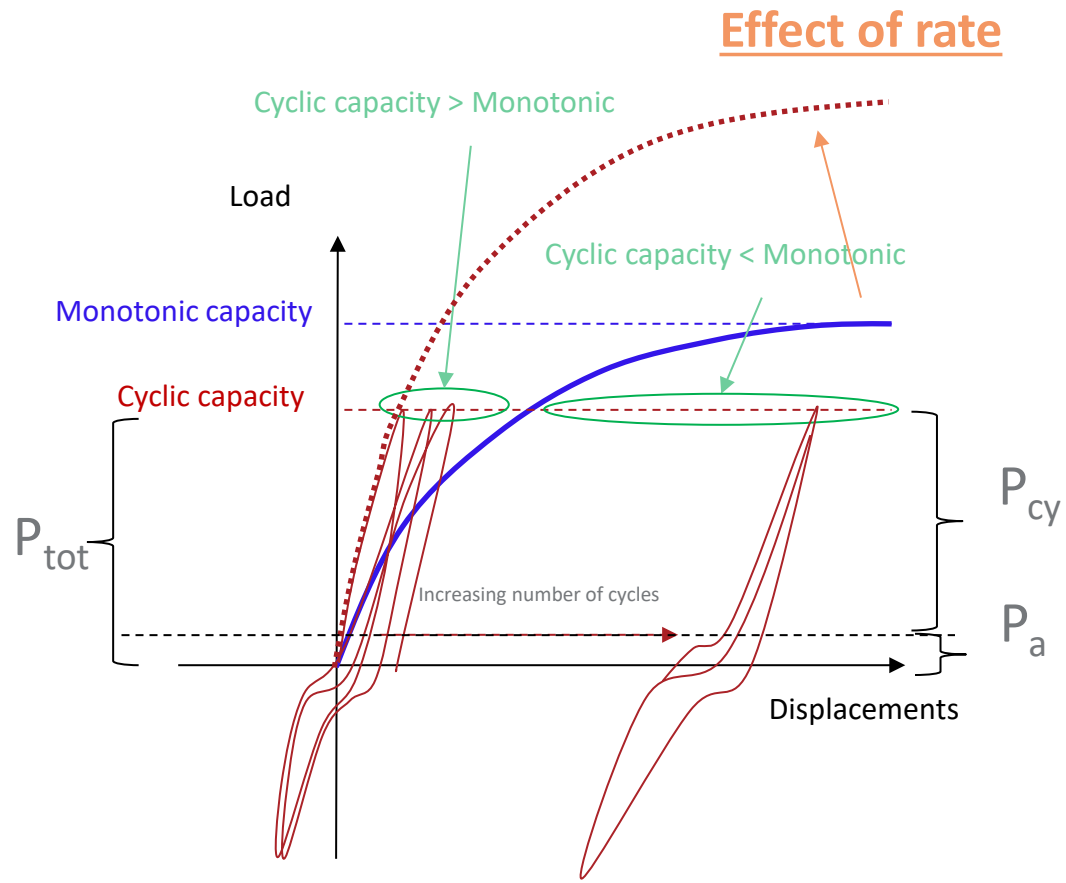
  i.e. the stiffness and shear strength decrease with increasing number of undrained cycles

- The model includes the **effect of cyclic and average loads**

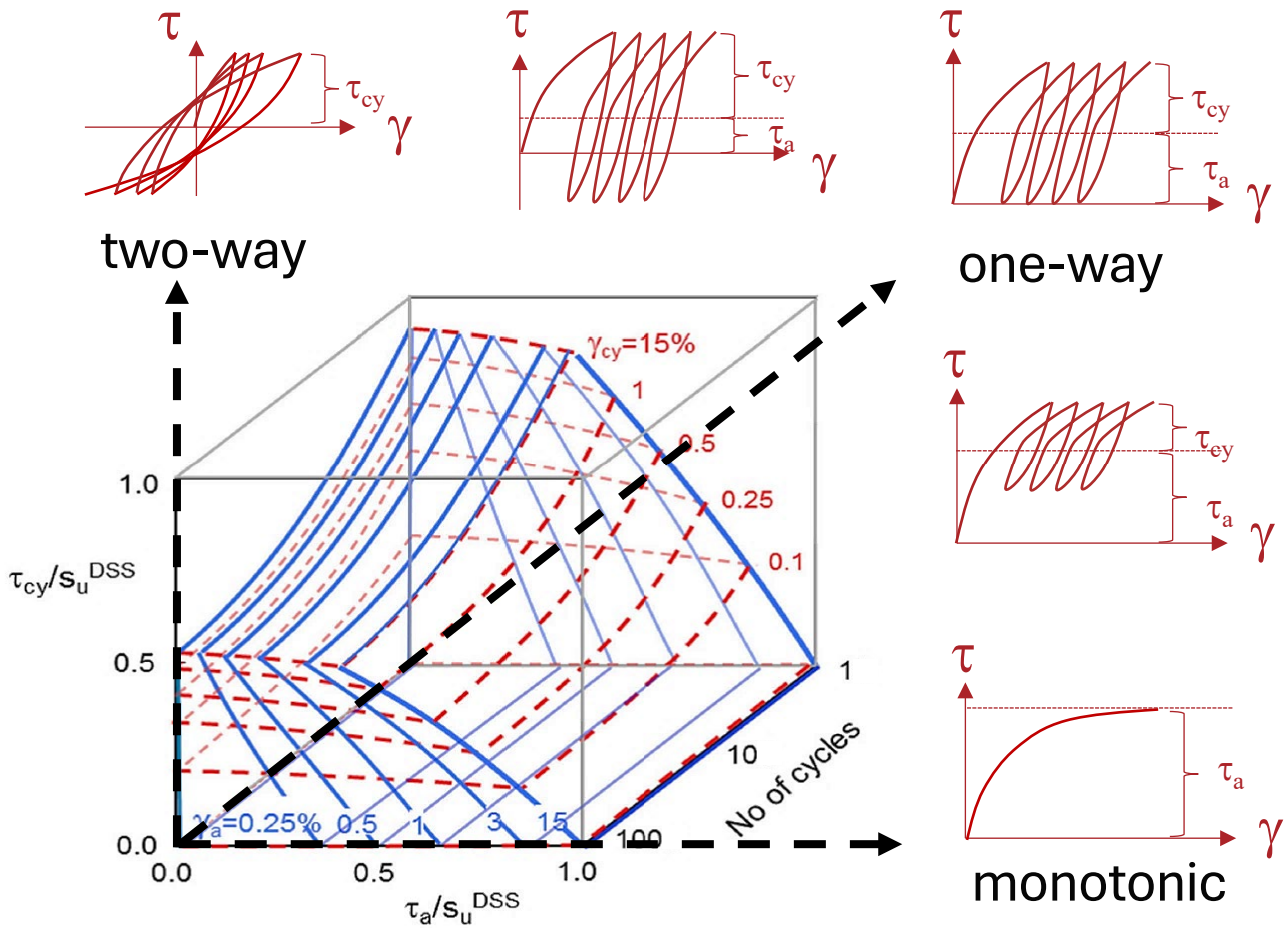
  $P_{tot}=P_a+P_{cy}$

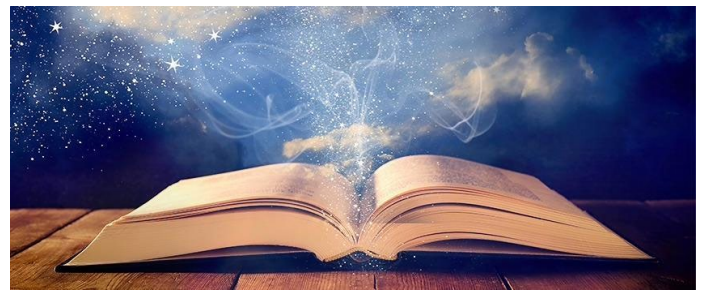
  and corresponding stress

  $t_{tot}=t_a+t_{cy}$



Effects of cyclic loading on soils: the NGI model

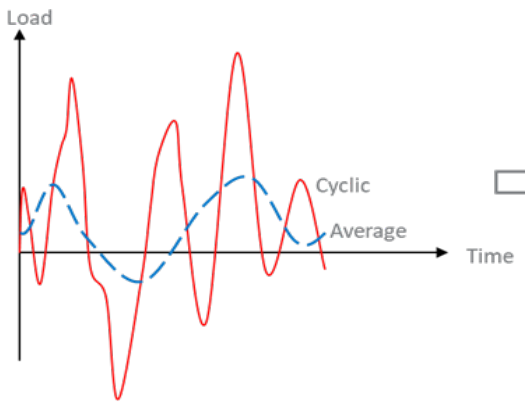




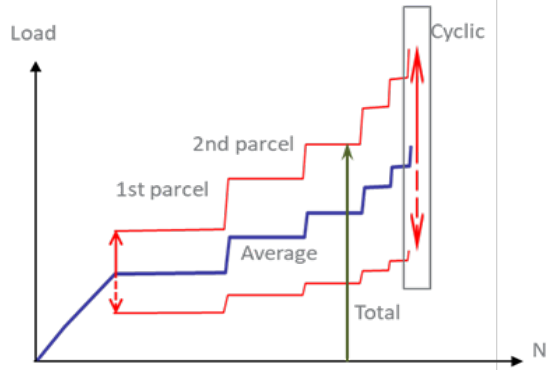
From cyclic properties to monopile design

Per soil unit

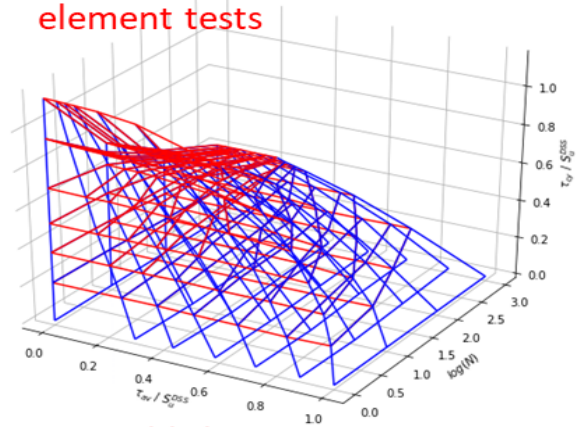
1. Loads from time domain analysis



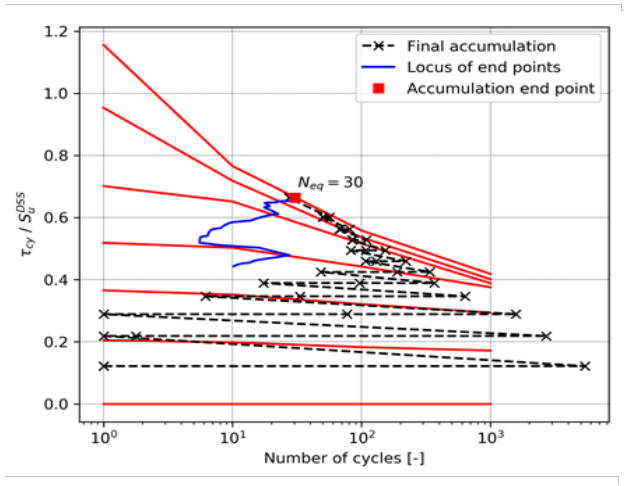
2. Geotechnical load history



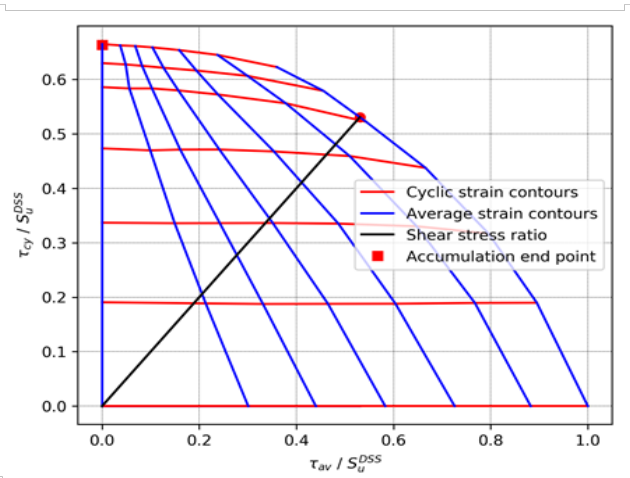
3. Contour diagram from cyclic element tests



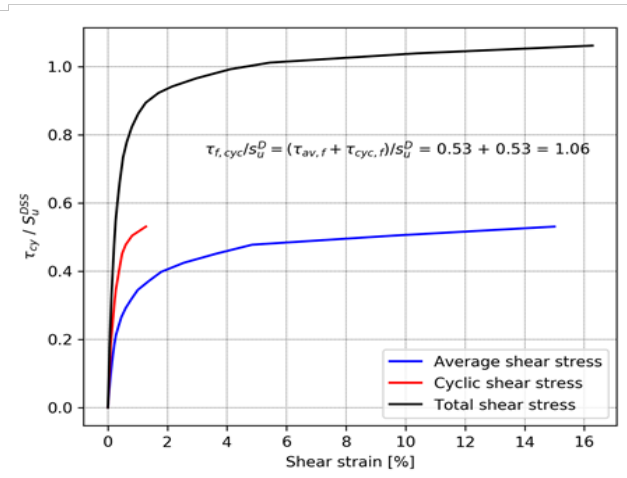
4. Cyclic accumulation, find N_{eq}



5. Use load ratio in Neq section



6. Establish stress-strain curves

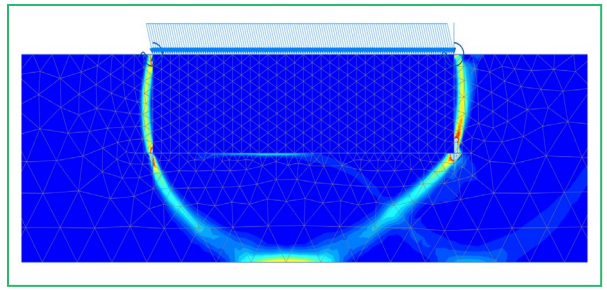


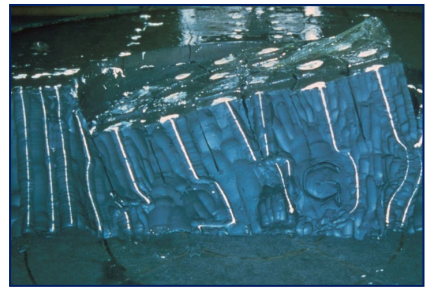
Klinkvort et al. 2020

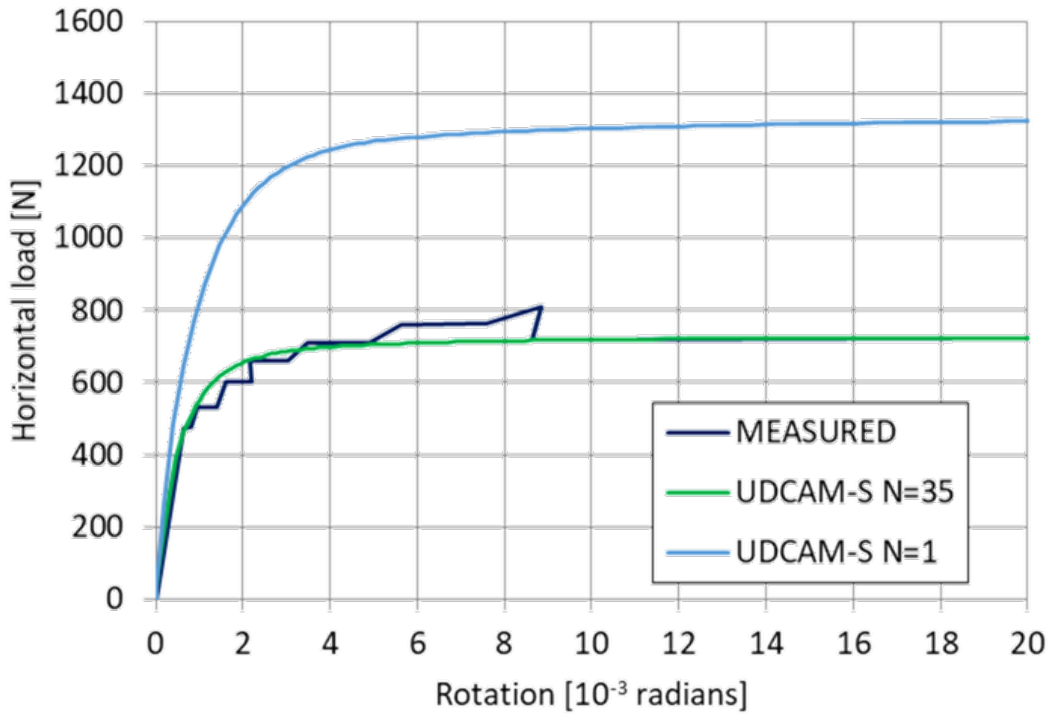
From cyclic properties to monopile design

Finite Element Analyses with cyclic soil properties

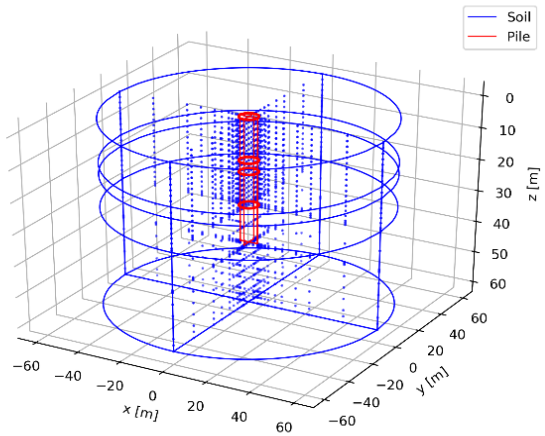
- UDCAM-S: for undrained soils
- PDCAM-S: for partially drained soils, taking into account the effect of pore pressure dissipation







Different 3D FE tools: ABAQUS, PLAXIS, Infidep

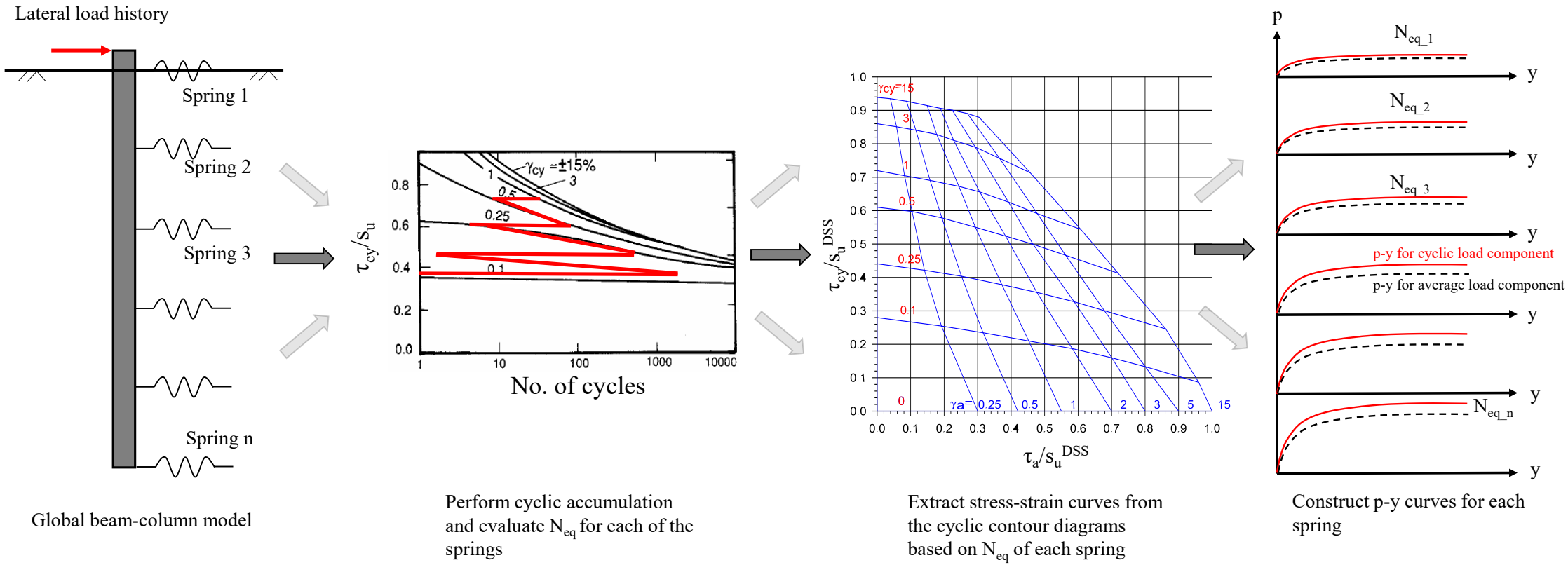


F²AT: Lisensing out this software with DNV

NGI

From cyclic properties to monopile design

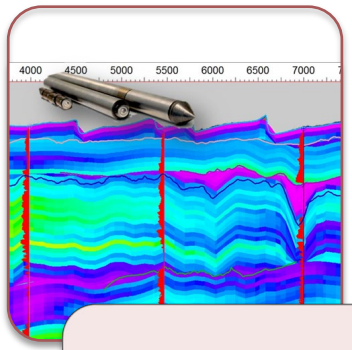
P-y curves with cyclic soil properties



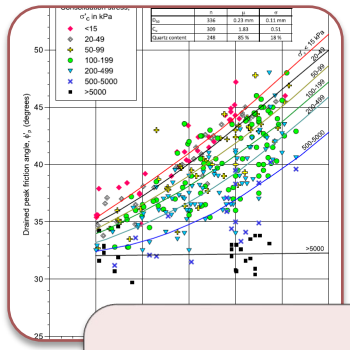
Zhang et al. 2016

Cyclic properties

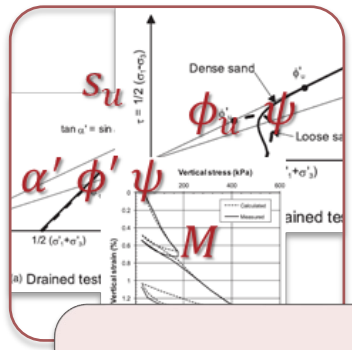
Estimation of monotonic and cyclic soil design parameters for design



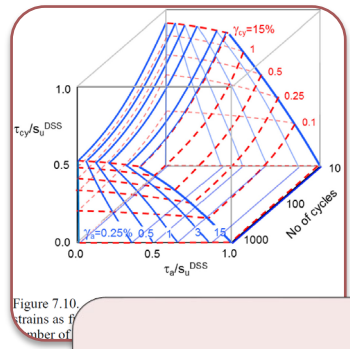
Ground model + CPT



Correlations (NGI's database)



Static Parameters



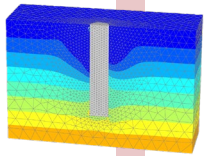
Cyclic Parameters

REDWIN 2 project:

NGI equinor NTNU The Research Council of Norway

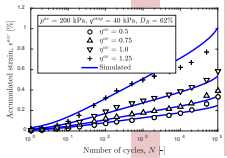
NGI

We let the problem define the methodology



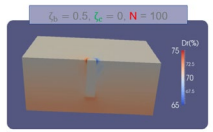
UDCAM

In Bifurc (internal software)



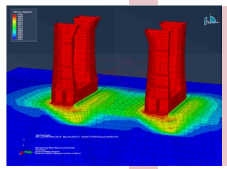
High Cycle Accumulation model

In PLAXIS 3D



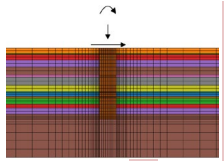
SANISAND-MS

In OpenSeas



Hypoplasticity with IGS

In ABAQUS



NGI-ADP elastic

IN F^{2}AT

NGI

On safe ground