REMS RENEWABLE ENERGY MARINE STRUCTURES
Cranfield University
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Theoretical Developments for Soil Behaviour under Cyclic Loading

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Introduction

82% of offshore wind turbines (OWT) **foundations** are **monopiles in Europe.** [1]

Larger OWT and larger pile diameter

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Moving from ULS to SLS & FLS design

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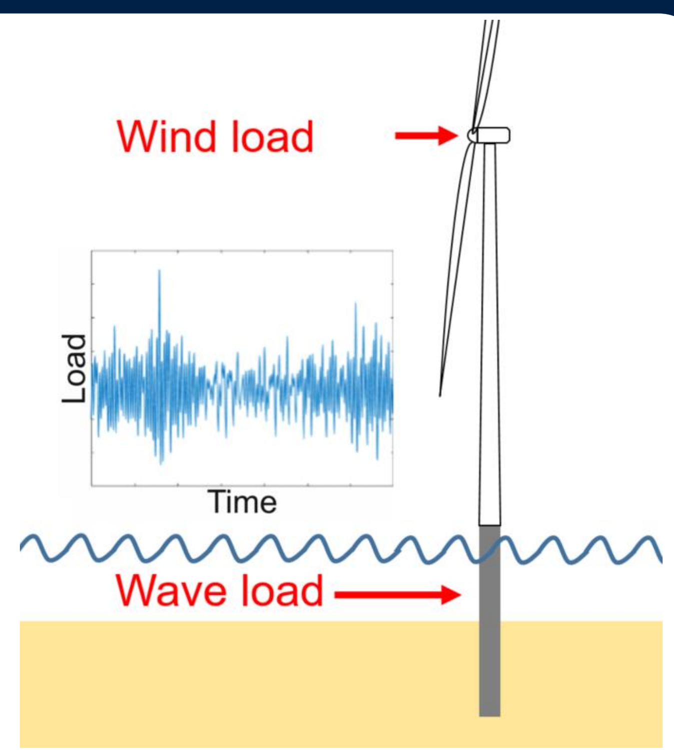
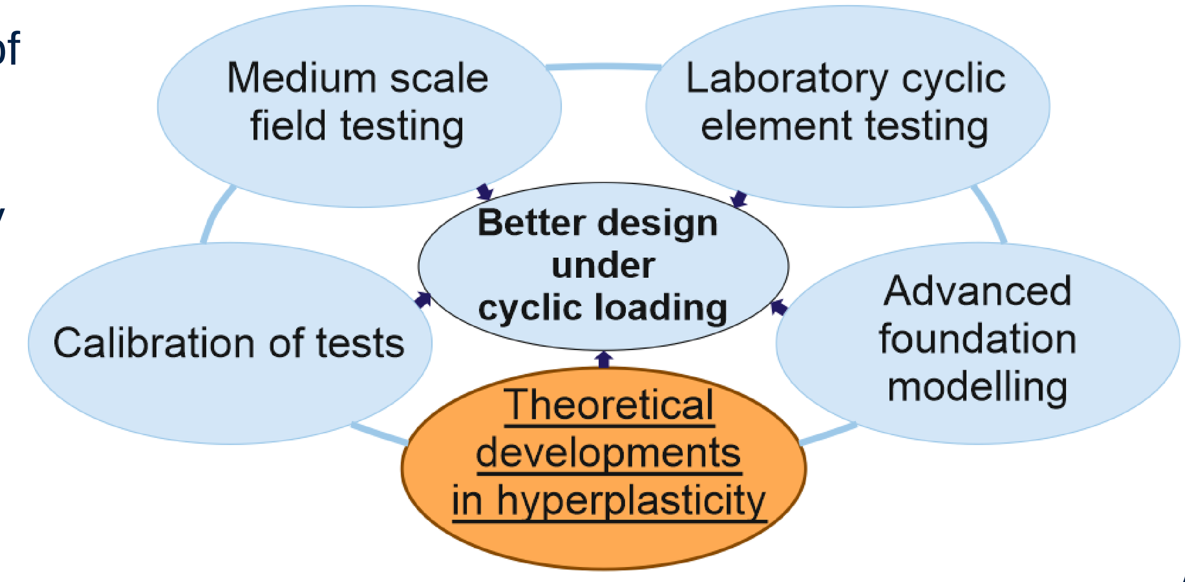
Foundation response to cyclic loading: Accumulated rotation (ratcheting), evolution of secant stiffness and damping



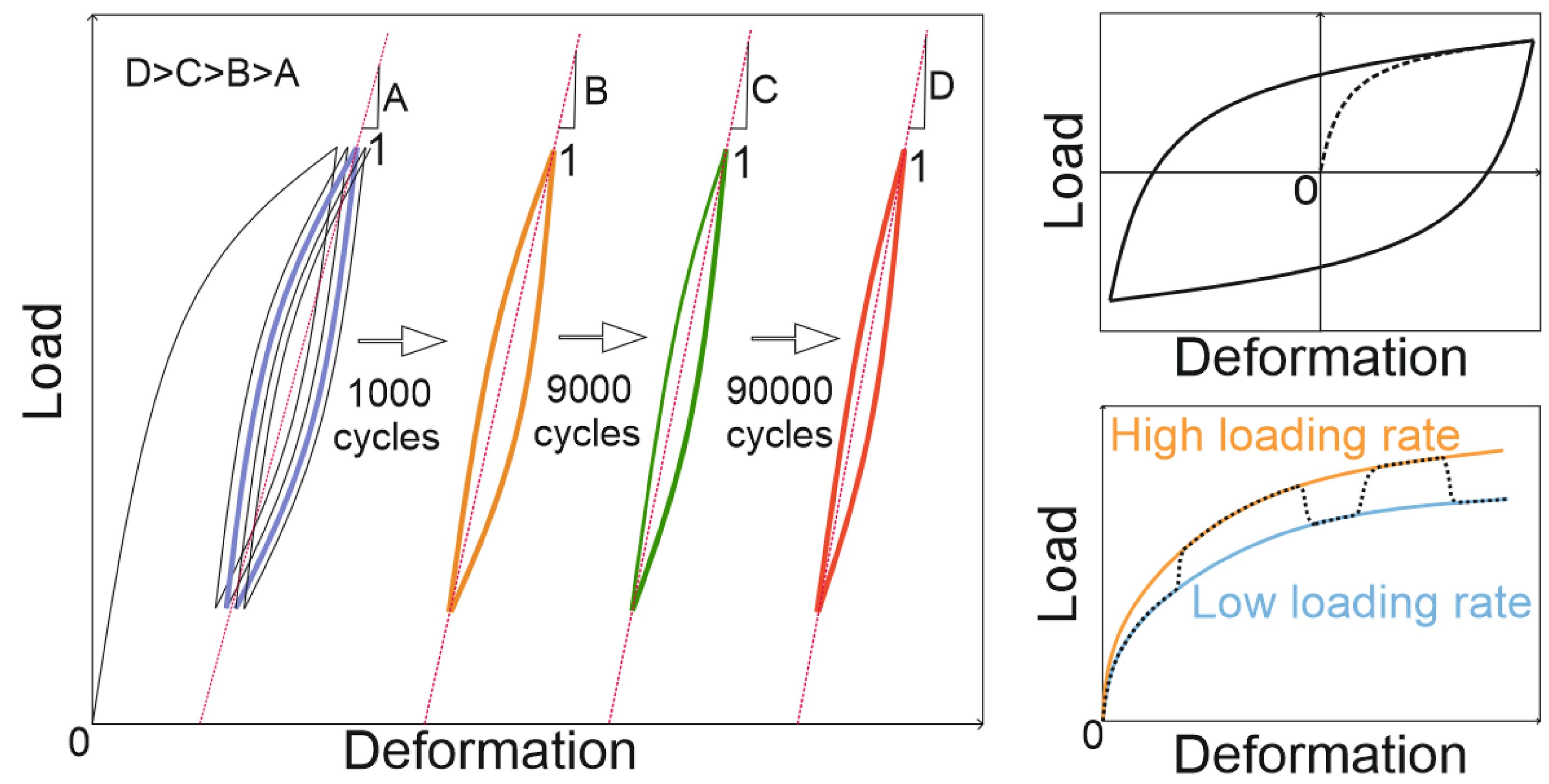
Project Structure

Building on the success of PISA projects [2]: Ørsted and the University of Oxford collaborate to understand the impact of cyclic loading on OWT monopiles.



Observations on Cyclic Loading

- **Hysteretic response** conforming to **Masing rule**. [3]
- **Ratcheting in the direction of load bias** [4], at a **decreasing rate** with cycles [3].
- The **rate** and the **amplitude of loading** have an impact on the soil response [5].
- **Loading history**: effect of a storm can be limited after SLS loading [3], stiffness is not recovered after high amplitude loads [5].
- **Partial two-way loading** and **multi-directional loading** can **cause greater** accumulated **deformations** [4].

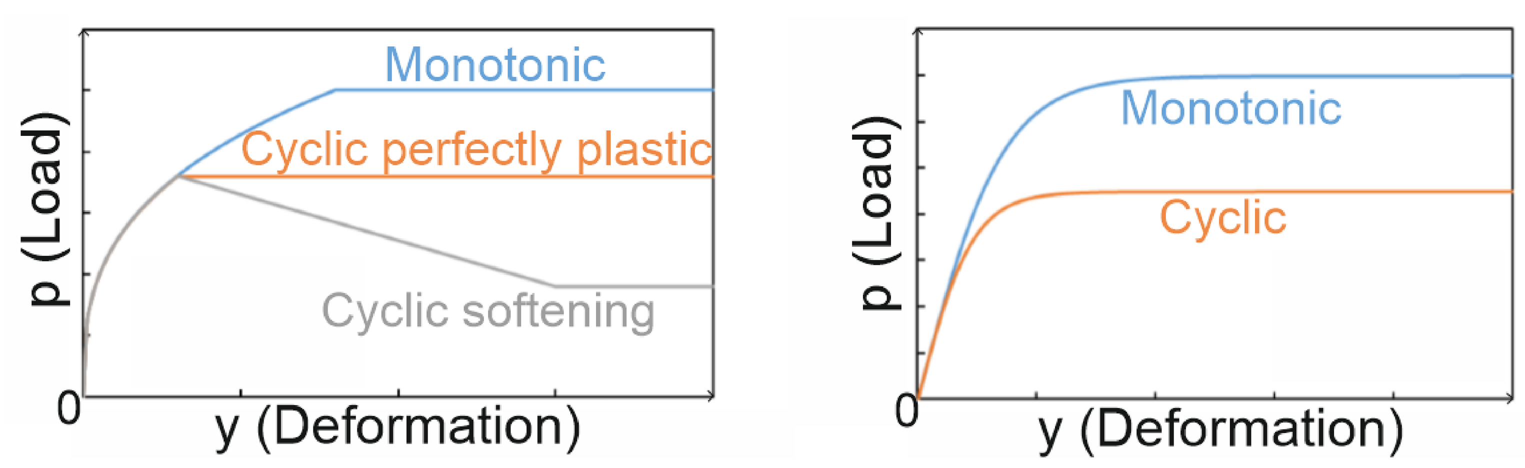


Left: Illustration of ratcheting and hysteresis loop evolution
Top right: hysteresis conforming to Masing rule & Bottom right: Illustration of rate effects

Cyclic Loading in Standards

Modified *p-y* curves are used for the design of monopiles under cyclic loading:

- Soil strength is assumed to be reduced.
- Lack or no consideration of: number of cycles, loading history, accumulated rotation, change in stiffness and damping.



Modified p-y curves for clay (left) and sand (right) based on equations in DNV

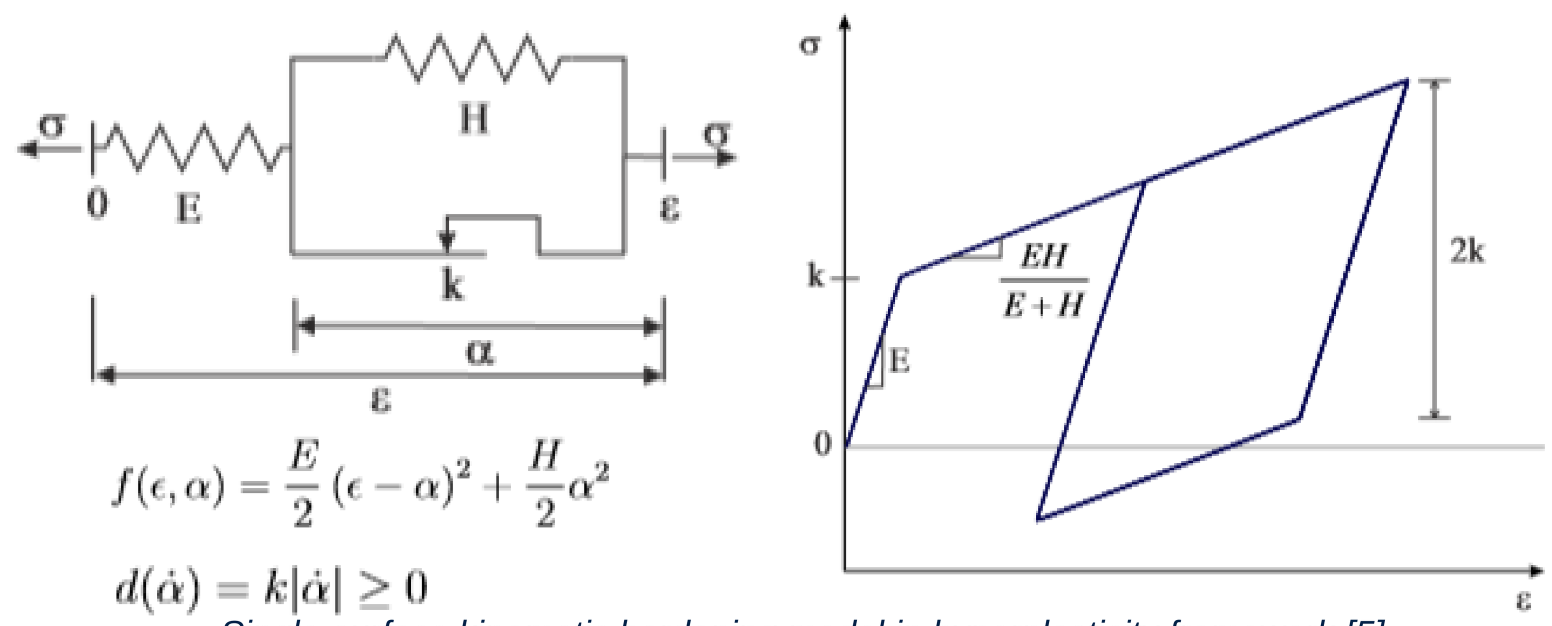
Research Plan - Hyperplasticity

- **Empirical relations are not sufficient to capture cyclic loading**. [4]
- **Constitutive models needed** to capture the behaviour through cycles.

	Monotonic	Cycling
0-D: Macromodel	Routine	Routine
1-D: p-y type	Routine	Available
3-D: Continuum	Available	Scope of the research

State of development in the hyperplasticity framework

- **Hyperplasticity** derives elastoplastic behaviour from the laws of **thermodynamics**. It is **modular, physically sound, clear and concise**.



Single-surface kinematic hardening model in hyperplasticity framework [5]

Future Work

- **Development of constitutive models in effective stress** readily implementable in **3D FEA** software.
- **Potential material**: **dense sand**. Cyclic test data are available.
- **Constitutive modelling in hyperplasticity framework**.

References:
[1] Wind Europe . 2019. *Offshore Wind in Europe – Key trends and statistics 2018*
[2] Byrne et al. 2017. PISA: New Design Methods for Offshore Wind Turbine Monopiles.
[3] Abadie, C. N. 2015. "Cyclic Lateral Loading of Monopile Foundations in Cohesionless Soils." DPhil thesis. University of Oxford.
[4] Richards et al. 2019. Monopile rotation under complex cyclic lateral loading in sand. Submitted
[5] Beuckelaers, W.J.A.P. 2017. "Numerical Modelling of Laterally Loaded Piles for Offshore Wind Turbines" DPhil thesis. University of Oxford.

Acknowledgement

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www.rems-cdt.ac.uk