Innovative Solutions for Offshore Wind Turbine Support Structures

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AALBORG UNIVERSITY

Department of Civil Engineering | Offshore Wind Turbine Foundations Group

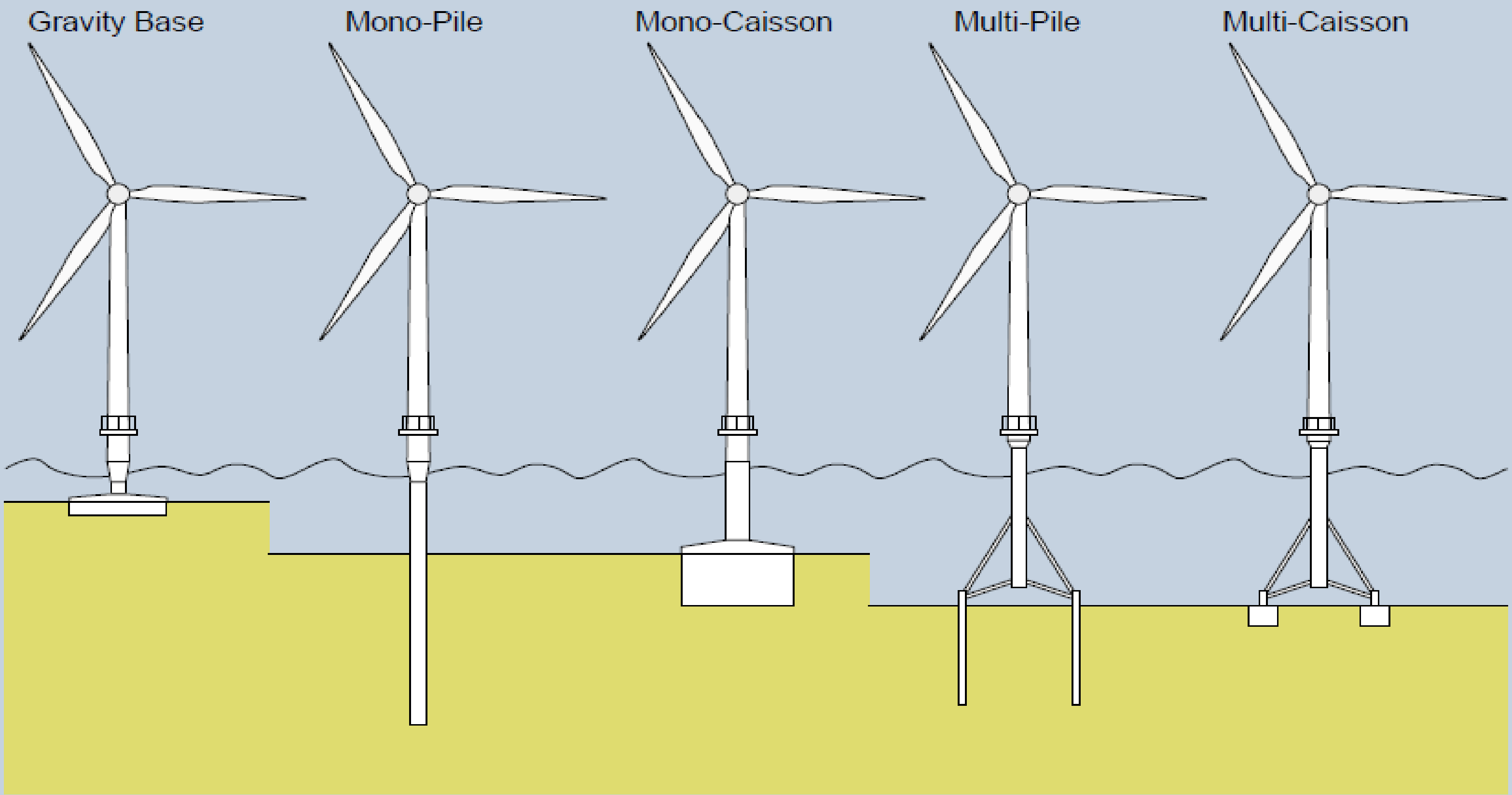
Horns Rev 2

Cost Makeup

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

- Oppurtunity to reduce costs by using alternative foundation concepts and installation process
- … as well as by improving the design approaches

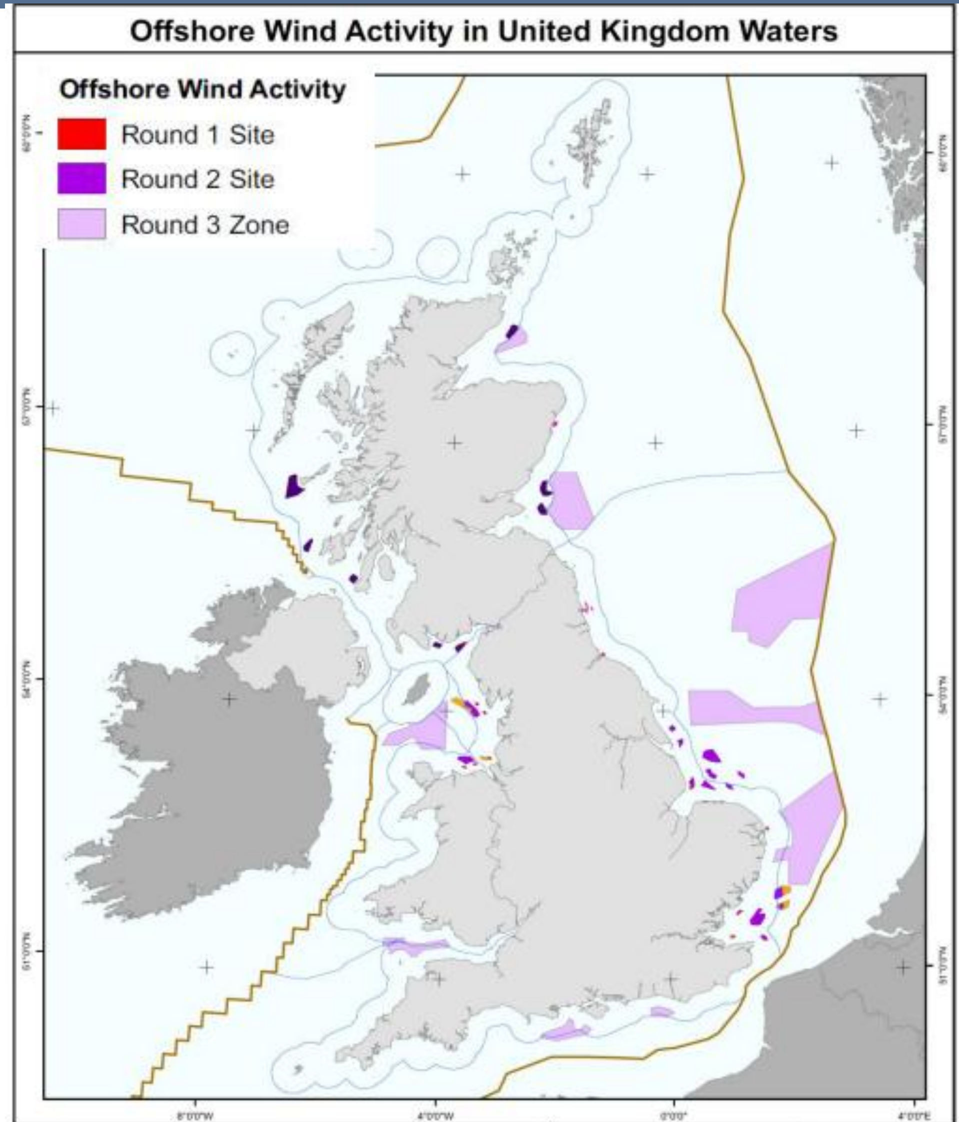
Options for Foundations



Offshore Sites

- ❑ Currently 1.5 GW of electricity comes from offshore wind farms
- ❑ An additional 28 GW will be required by 2020.
- ❑ 6000 separate turbine structures are required to meet the EU policies.

- ❑ **Round 1 – 1.4 GW**
- ❑ **Round 2 – 7.3 Gw**
- ❑ **Round 3 – 21 GW**



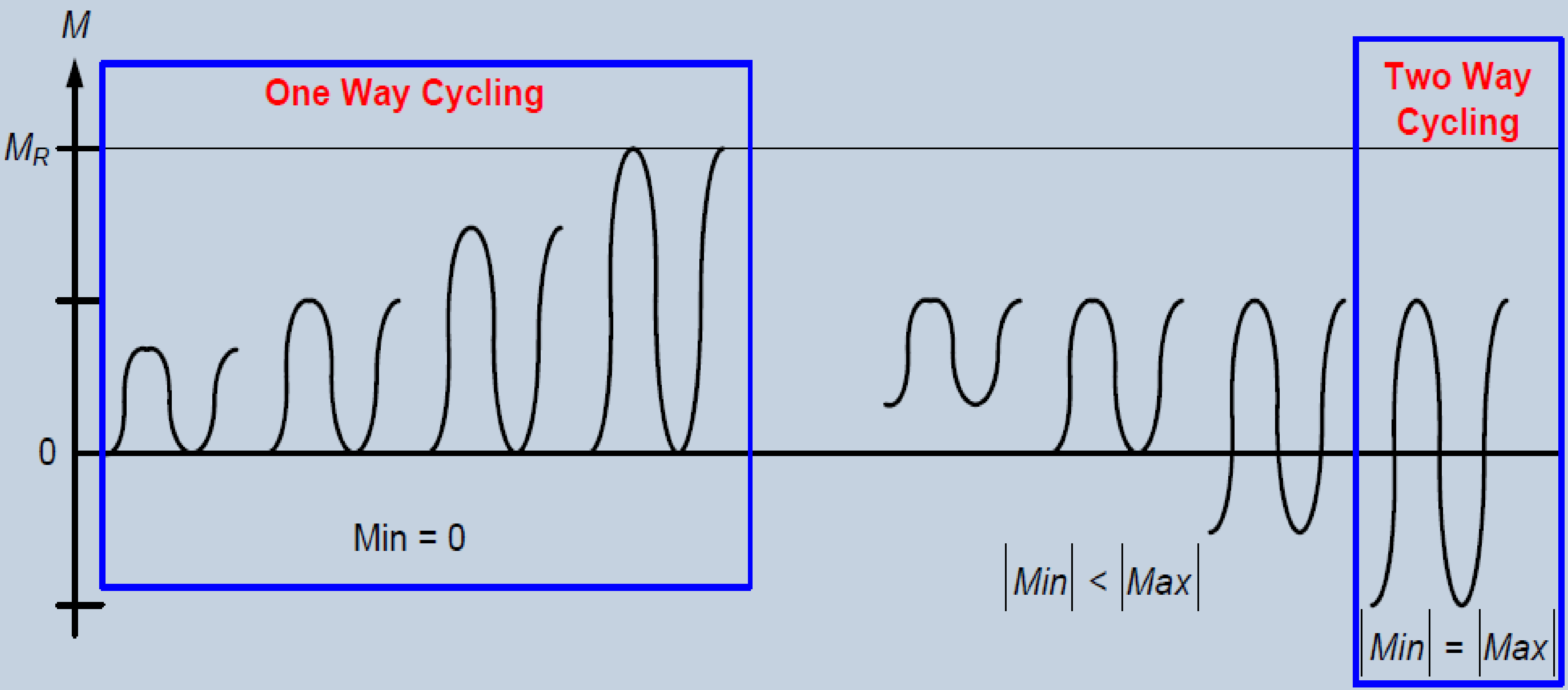
Mono-Pile Foundations

- Walney Wind Farm- UK (367.2 MW)

Design Issues for Offshore Monopiles

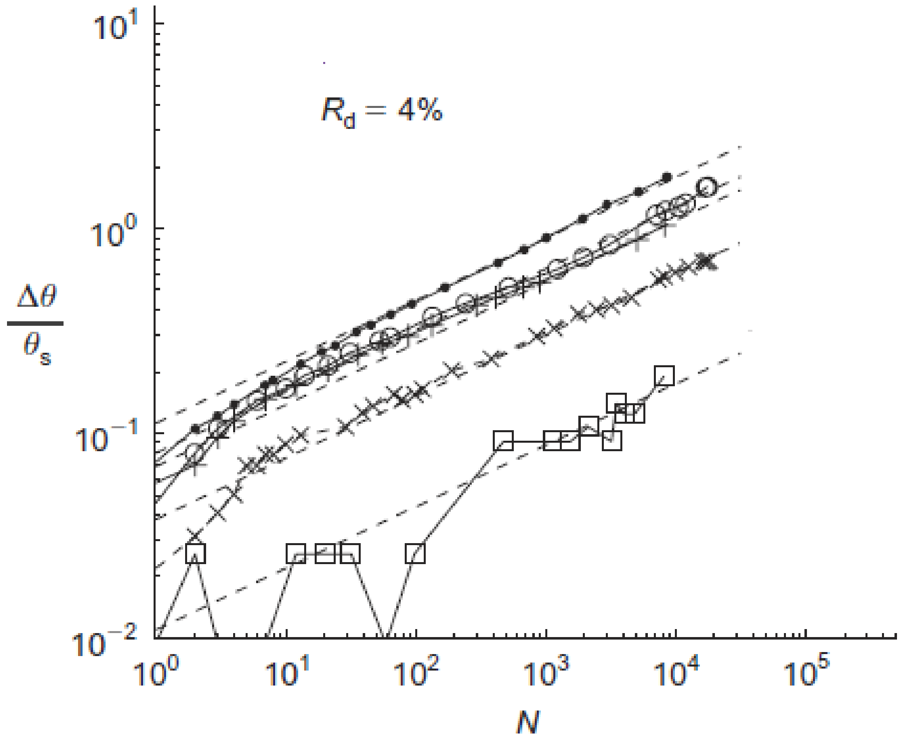
- ❑ Offshore design approaches are based on much more flexible piles
- ❑ Typical offshore pile say L/D~ 30-50 whilst wind-farm pile L/D ~ 4 - 8.
- ❑ Conventional design approaches ?
- ❑ Performance under cyclic loading is important but there is very limited guidance for designers (if any at all…)
- ❑ Accumulated rotations? Stiffness response?

Cyclic loading



A non-dimensional framework for determination of accumulated rotation

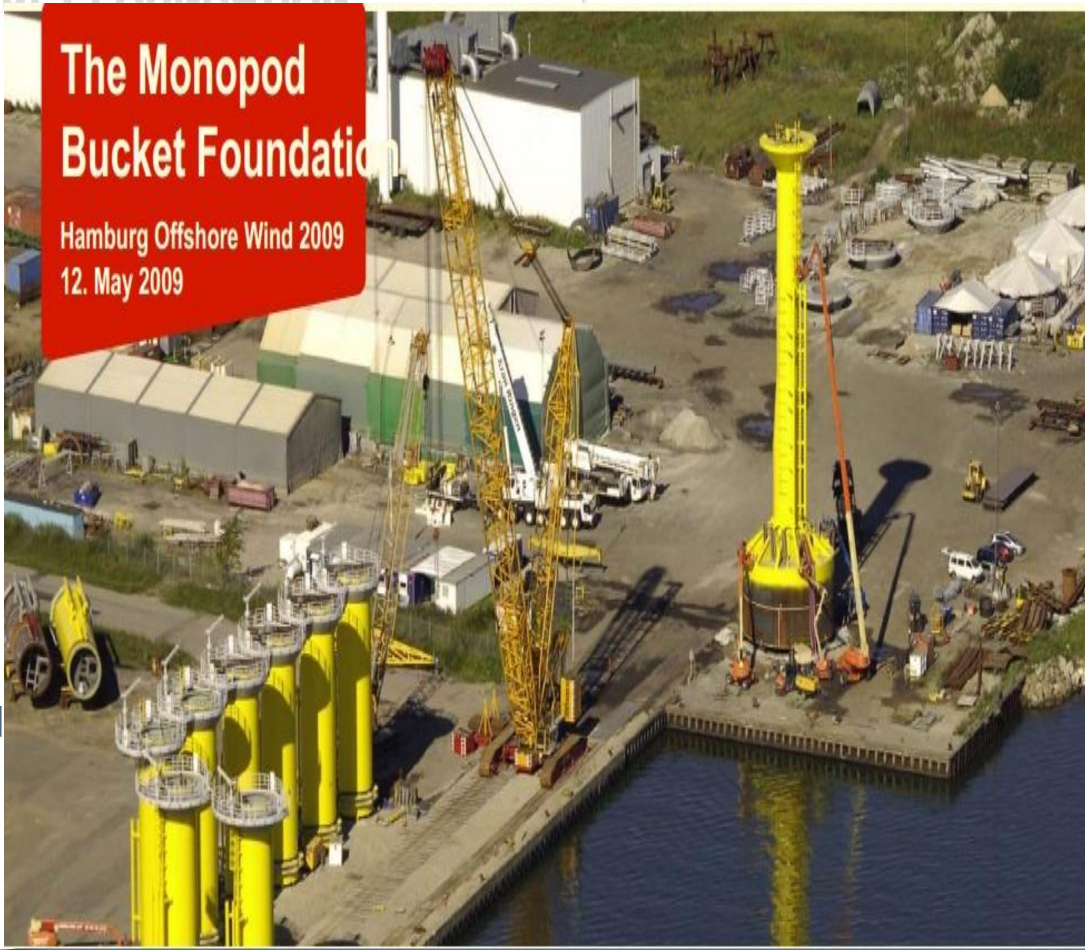
$$\frac{\Delta\theta(N)}{\theta_s} = f\left(M_R, M_{\min}, M_{\max}, R_D\right).N^b$$



Emerging Green Energy Technologies

BUCKET FOUNDATION

- The bucket foundation is a welded steel structure consisting of a tubular center column connected to a steel bucket.
- The bucket is installed by means of suction.
- The installed bucket foundation is influenced by vertical load and a large moment induced By a horizontal load.



Prototype bucket foundation

- In November 2002, the first bucket foundation for a fully operational wind turbine was installed in Frederikshavn, a city in the northern part of Jutland, Denmark.

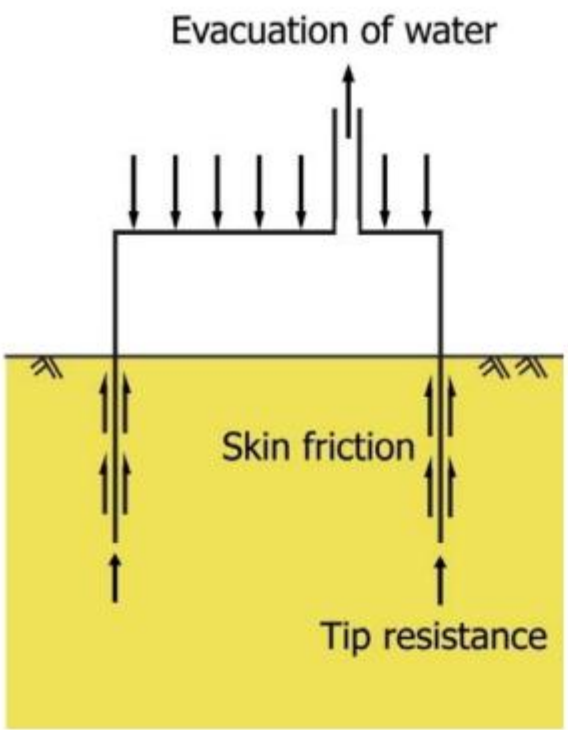
- When installed, the Vestas V90-3.0MW wind turbine was the largest wind turbine in Denmark, with a total height of 125 m.

- The bucket foundation had a diameter of 12 m, skirt length of 6 m, and total weight of 135 tons.

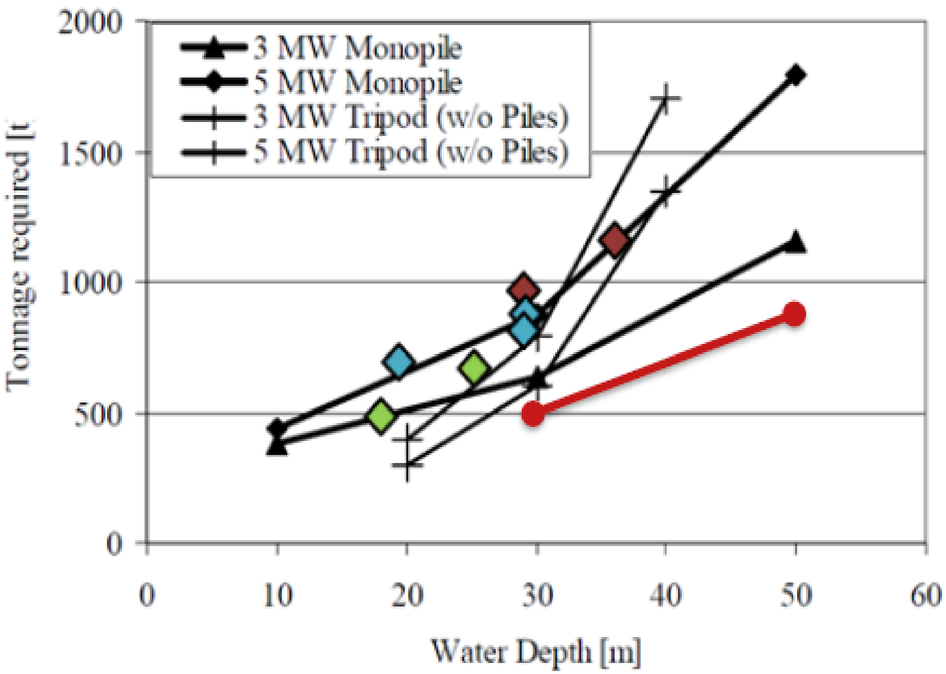
- The bucket foundation is shown in the figures prior to and upon installation, respectively.

Mobile Met mast (Horns Reef, 2009)

Installation

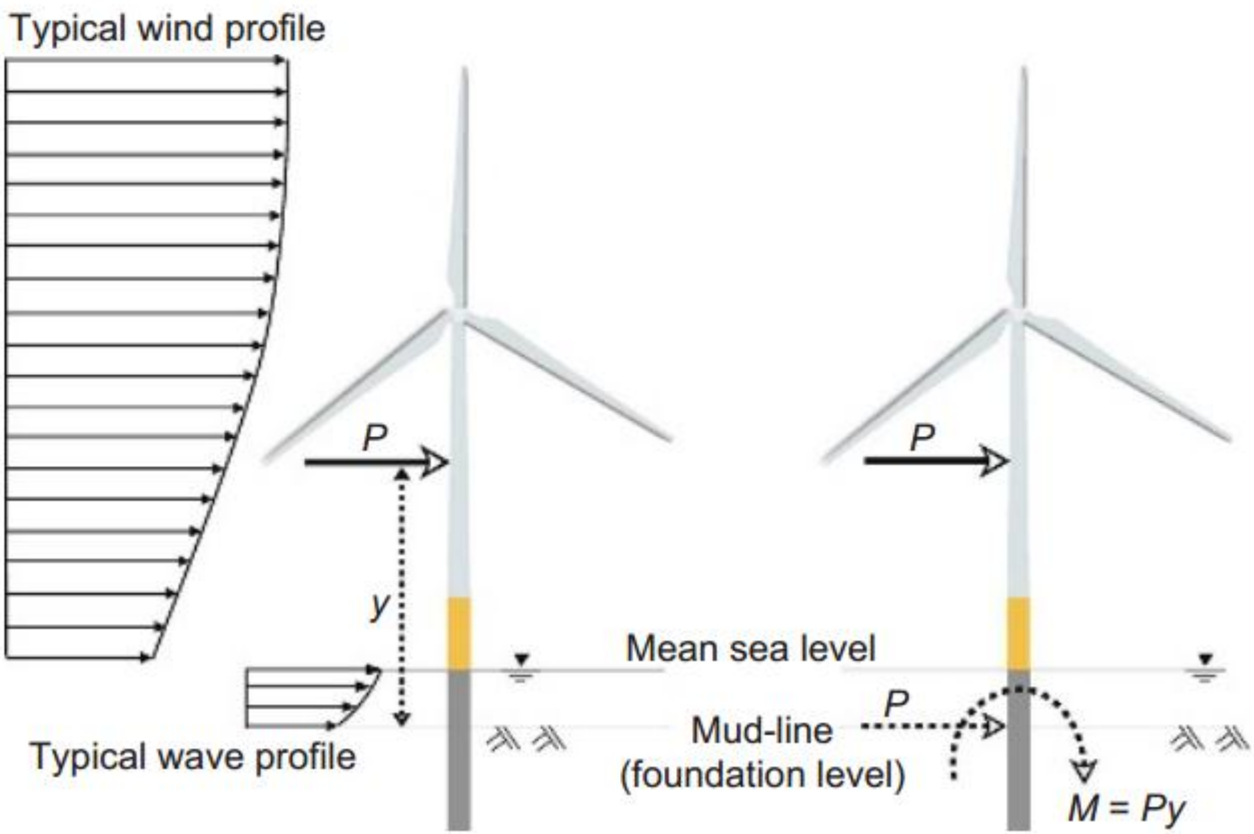


25% less steel than comparable Monopile



	8.0MW BF	*Comp. MP*
25m	610 t	*820 t*
35m	760 t	*n/a*
45m	980 t	*n/a*
55m	1.200 t	*n/a*

Loads on Offshore Wind Turbine Foundation

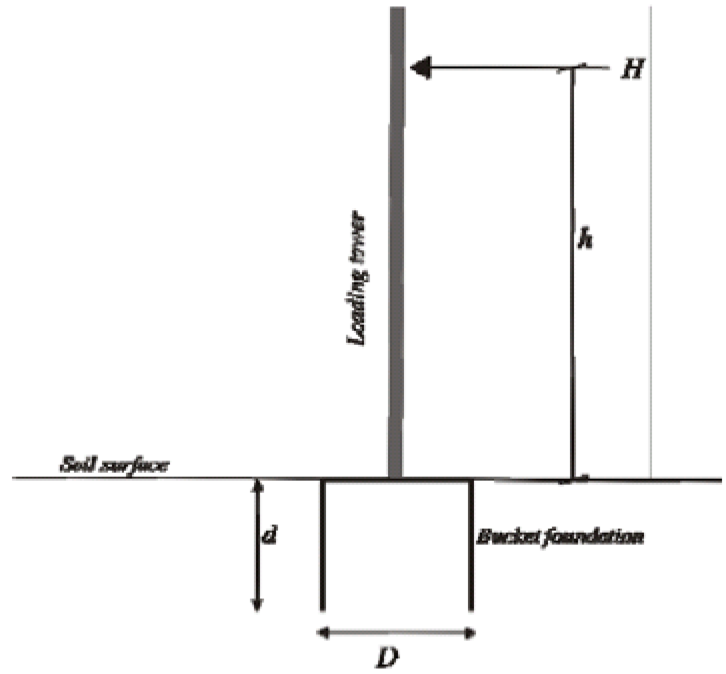


COMBINED LOADING

MONO-CAISSON STRUCTURE

OBJECTIVES

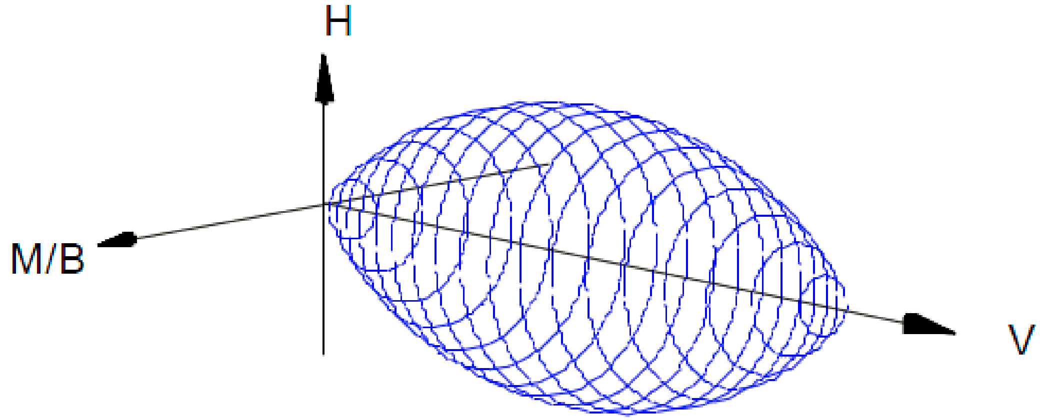
- To improve current design guidelines for bearing capacity of shallow foundations under environmental conditions
- To enable the design of low-cost and low-risk support structures for wind turbines

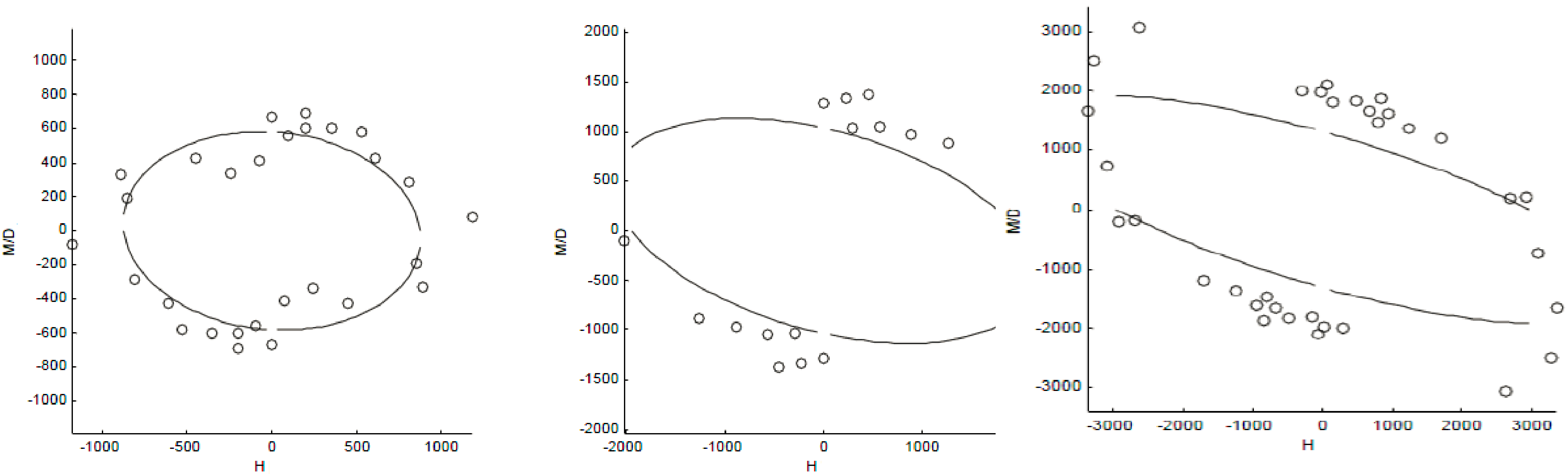


Byrne and Houlsby (1999)

$$f=\left(\frac{H}{h_0 V_{Peak}}\right)^2+\left(\frac{M}{m_0 D V_{peak}}\right)^2-2a\left(\frac{H}{h_0 V_{peak}}\right)\left(\frac{M}{m_0 D V_{peak}}\right)-$$

$$F\left(V\right)=0$$




M/D
H
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-500
500
2000
1500
-1500
-2000
3000
-3000

(a) (b) (c)

Calibration of Yield Surface Expression for Bucket

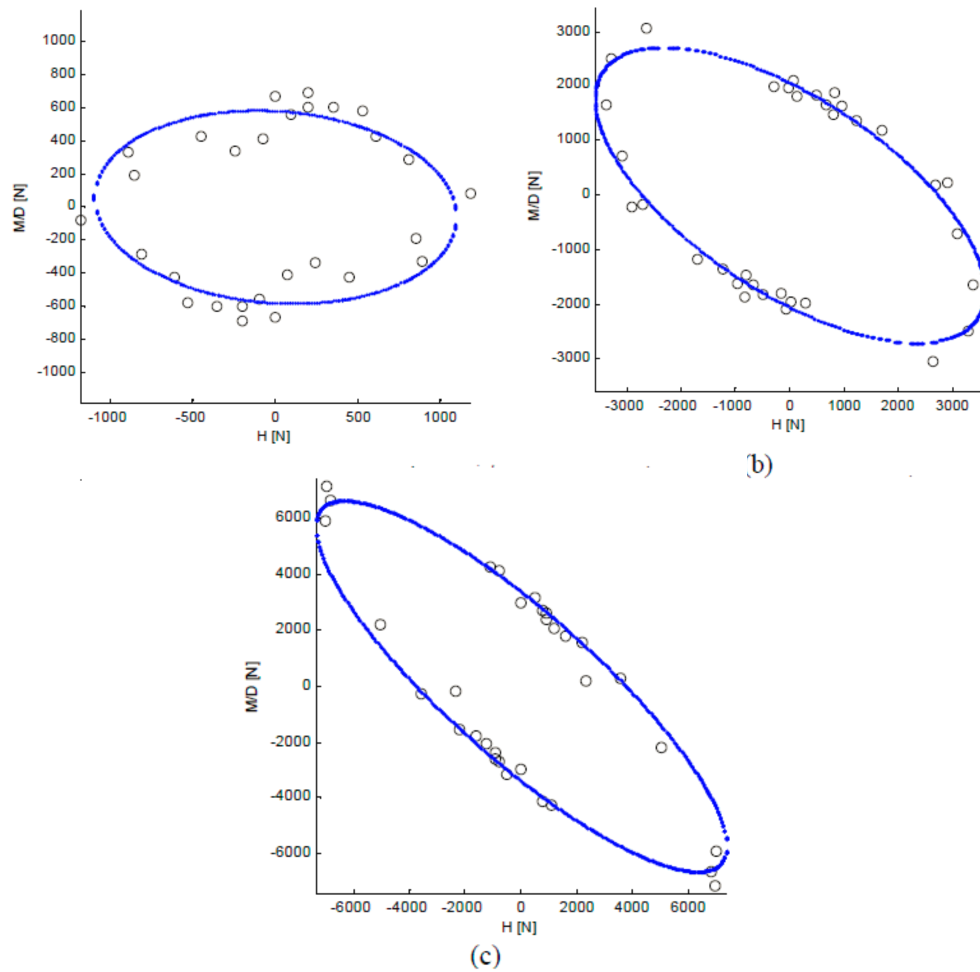
A yield surface expression based on the tensile capacity (Villalobos et al. 2005):

$$f=\left(\frac{H}{h_0V_{peak}}\right)^2+\left(\frac{M}{m_0DV_{peak}}\right)^2-2a\left(\frac{H}{h_0V_{peak}}\right)\left(\frac{M}{m_0DV_{peak}}\right)$$

$$-\left(\frac{\beta_{12}}{(t_0+1)^{(\beta_1+\beta_2)}}\right)\left(\frac{V}{V_{peak}}+t_0\right)^{2\beta_1}\left(1-\frac{V}{V_{peak}}\right)^{2\beta_2}=0$$

$$t_0=-\frac{V_t}{V_{peak}}$$

$$V_t=-\frac{\gamma' h^2}{2}(K\tan\delta)_o(\pi D_o)-\frac{\gamma' h^2}{2}(K\tan\delta)_i(\pi D_i)$$

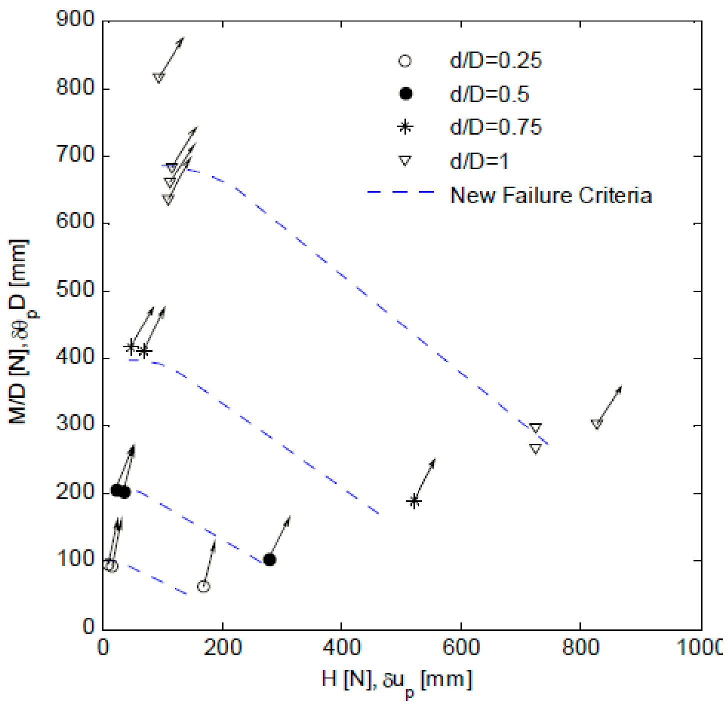


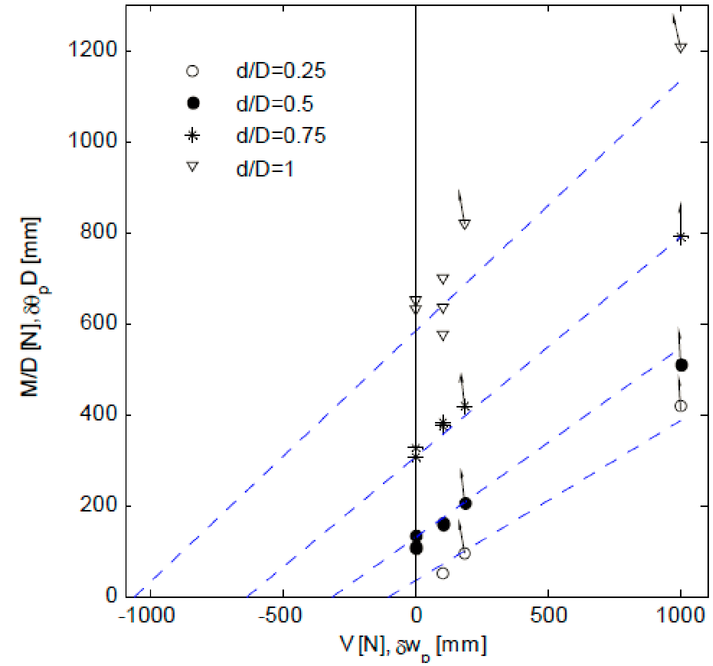
Linear Failure Criterion

$$M / D = \alpha \left(V - V_t \right)$$

$$\alpha = \left(f_1(k) + f_2(k) d / D \right)$$

$$k = M / DH$$





Offshore wind turbines: Challenges

- Dynamically sensitive because of tall and slender nature
- Offshore wind turbines are placed in adverse environmental conditions with strong wind and wave loading
- Wide range of cyclic loads with different forcing frequencies
- Monitoring the short term and long-term performnce
- Departure of the overall system dynamics from the design assumptions

Long Term Performance of Offshore Foundations

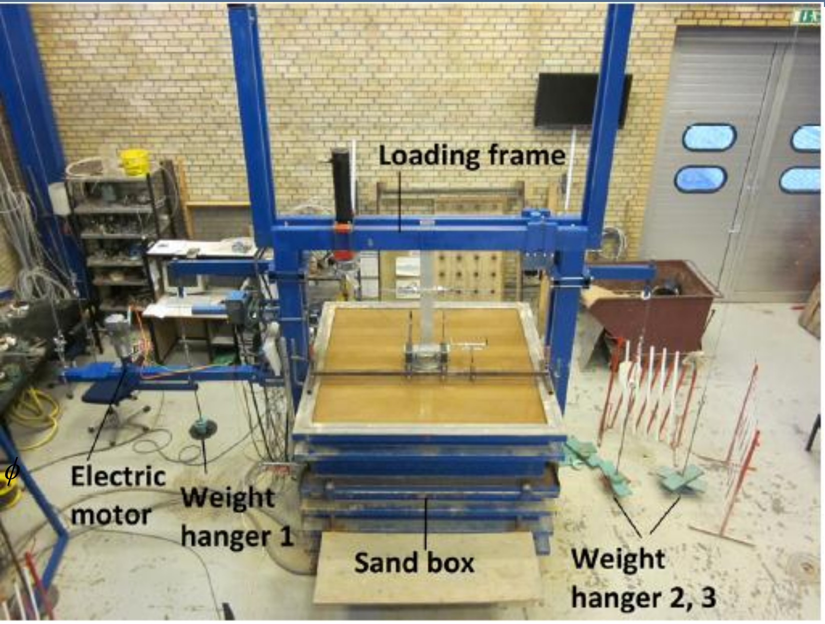
- Lack of data concerning Long Performance
- To Predict the future performance of such structures
- Argubly, this prediction can be carried out using small scale tests and numerical simulations
- The cyclic nature of the loading on the wind turbine placed in advers environmental conditions

Design Loads for Wind Turbines

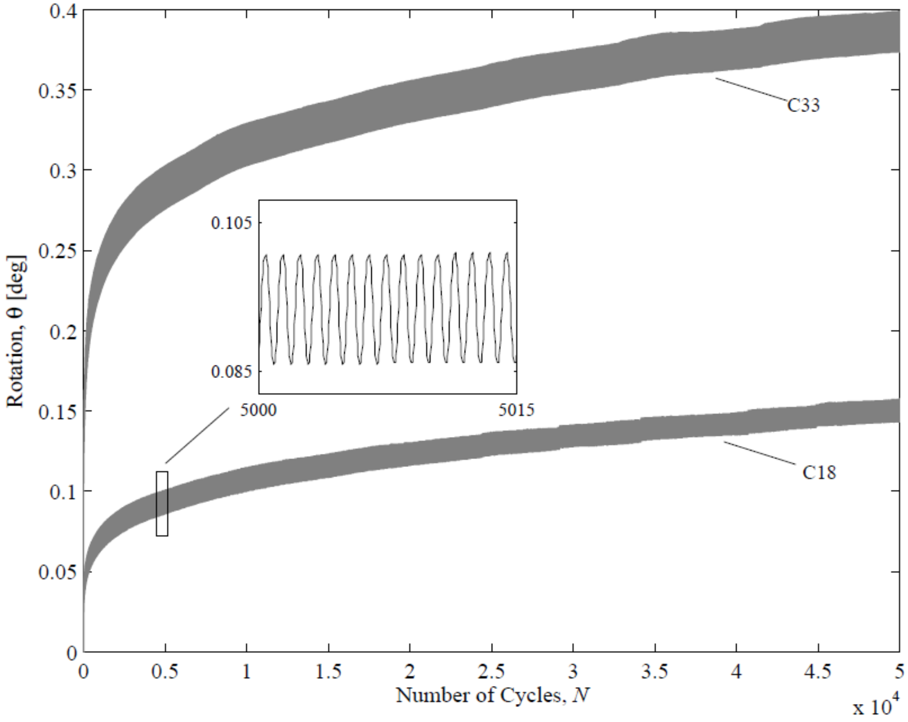
- The ultimate load capacity related to the limit state (ULS)
- The worst expected transient load equal to ULS/1.35
- The serviceability state (SLS) which occurs approximately 100 times.
- The fatigue limit state (FLS) which occurs approximately 10000000 times

Typical design loads for a 2 MW turbine

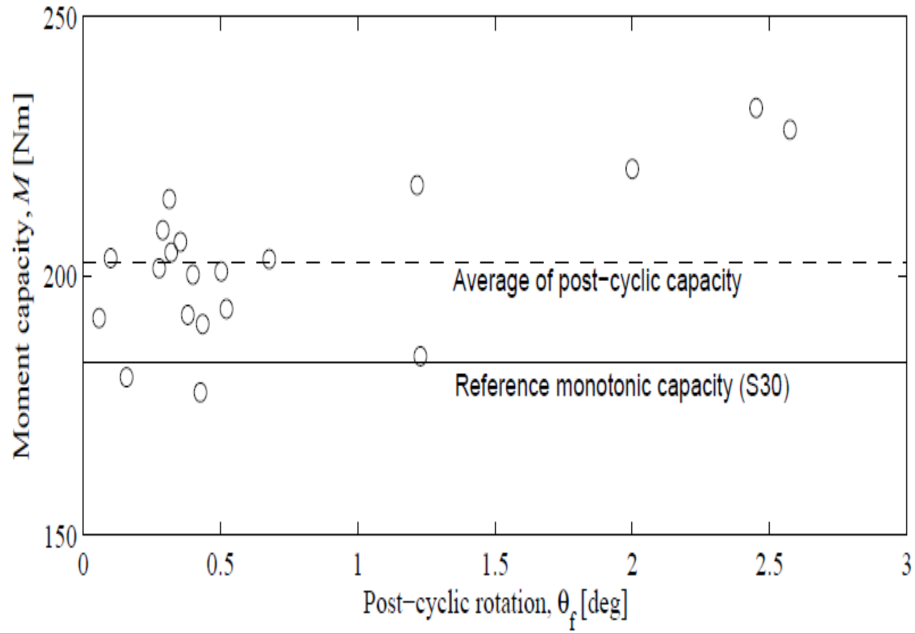
	N	M: MNm	H: MN	V:MN
ULS	1	95	4.6	5
ULS/1.35	1	70	3.4	5
SLS	10^2	45	2	5
FLS	10^7	28	1.4	5

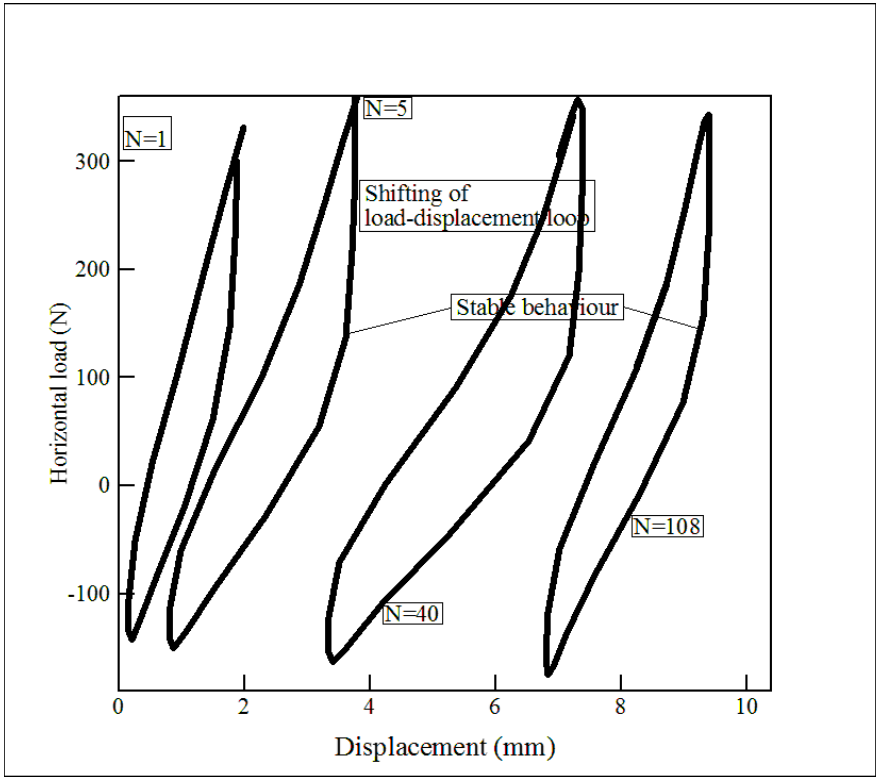


$$\tilde{\theta} = \frac{\theta_N - \theta_0}{\theta_s} = f_1 \times f_2 \times N^{\alpha}$$

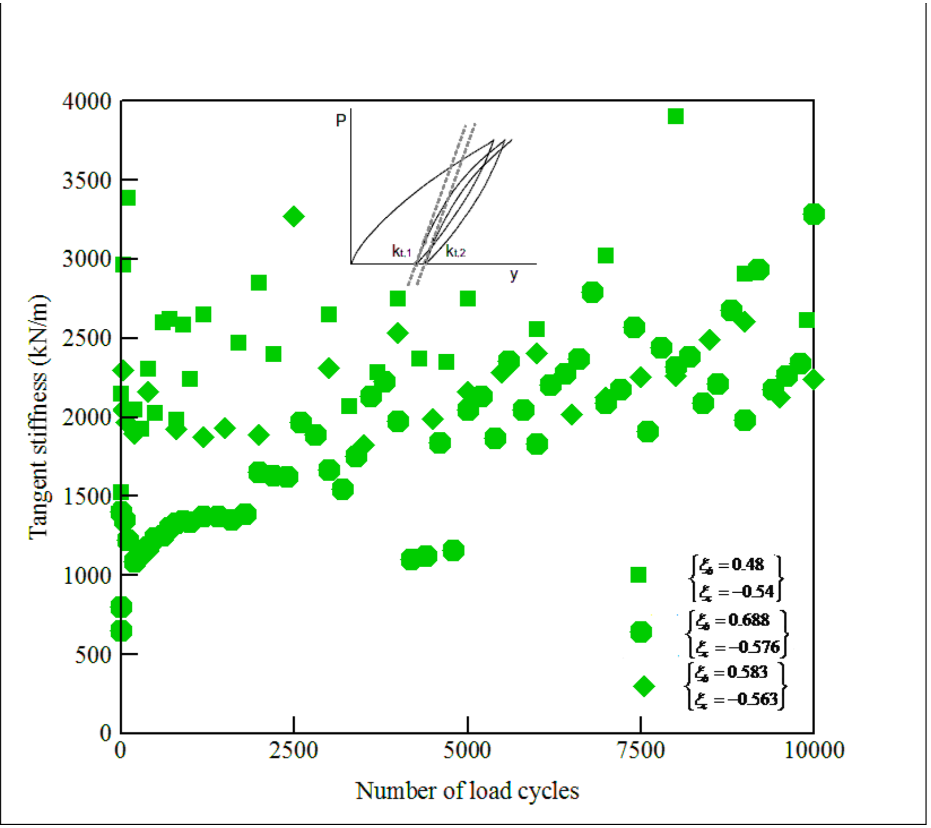


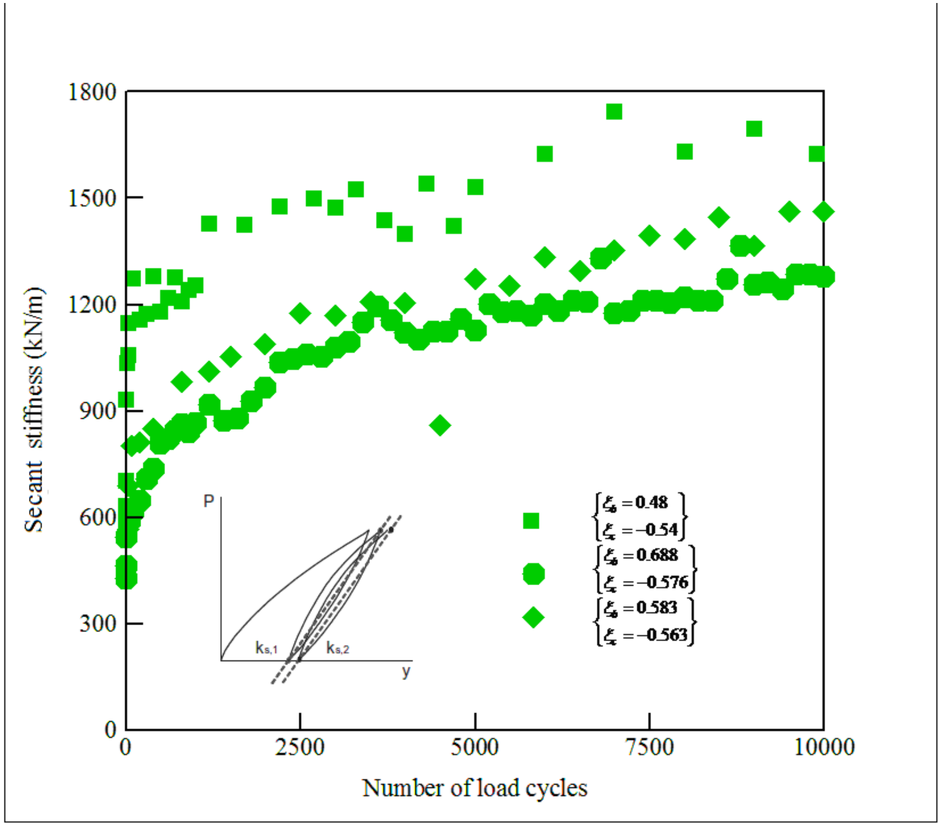
Stability Analysis



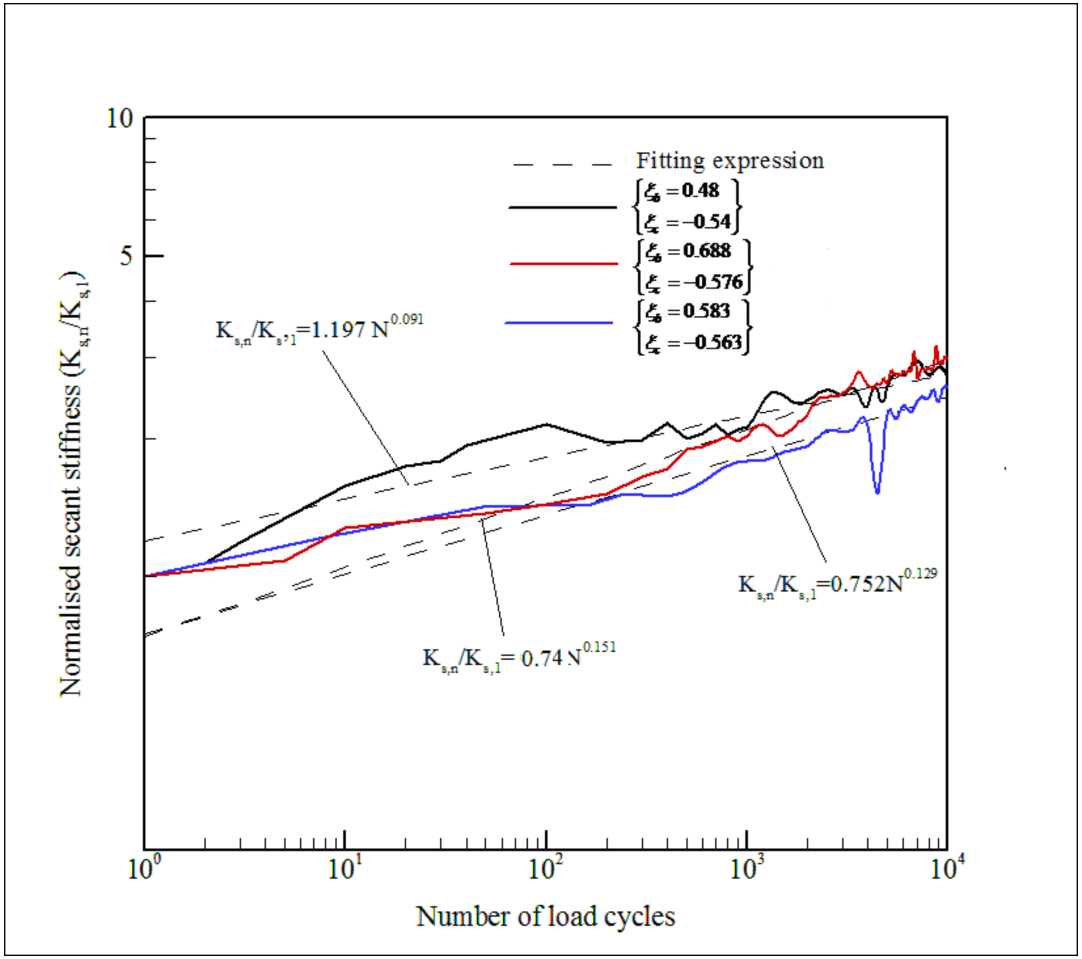


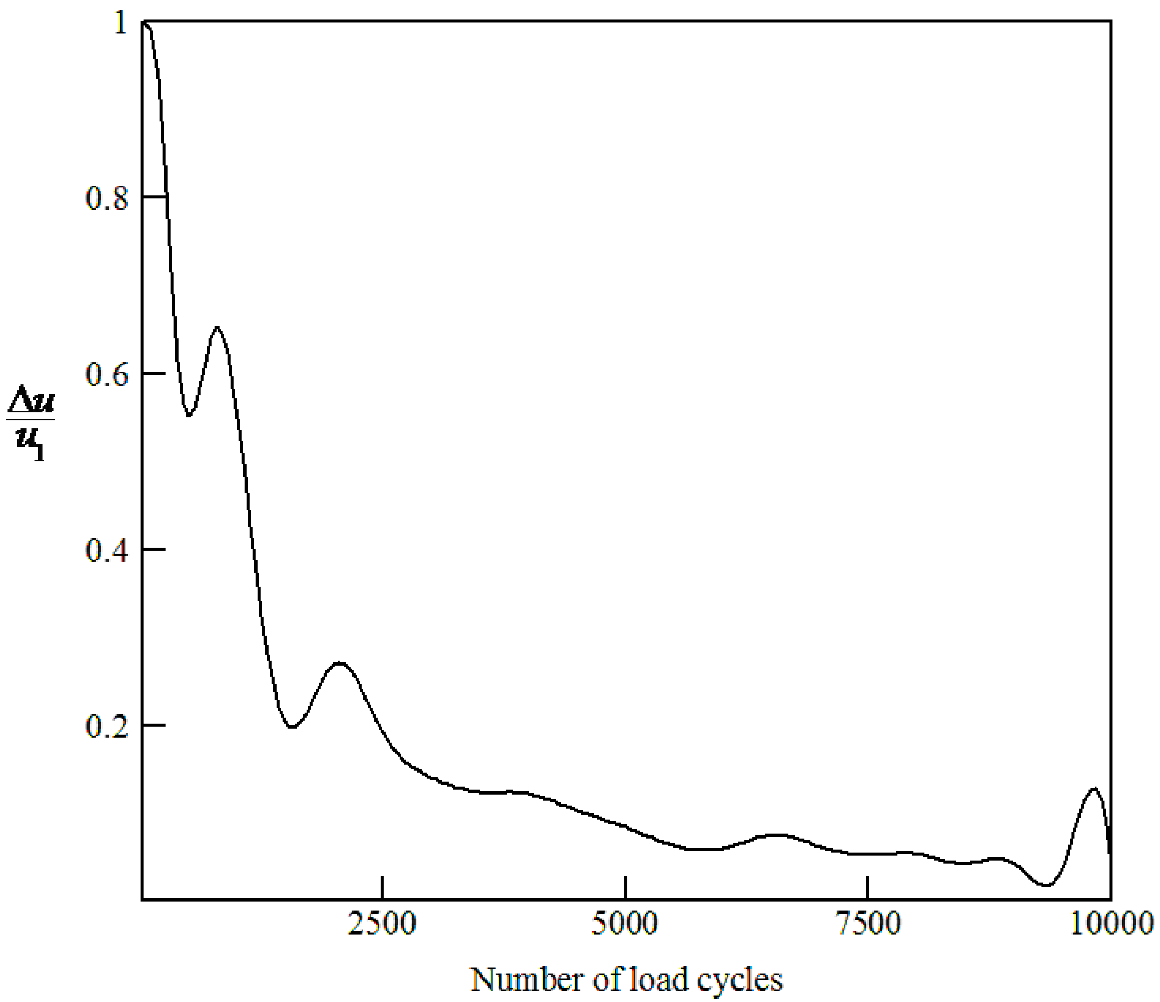
Performance based design



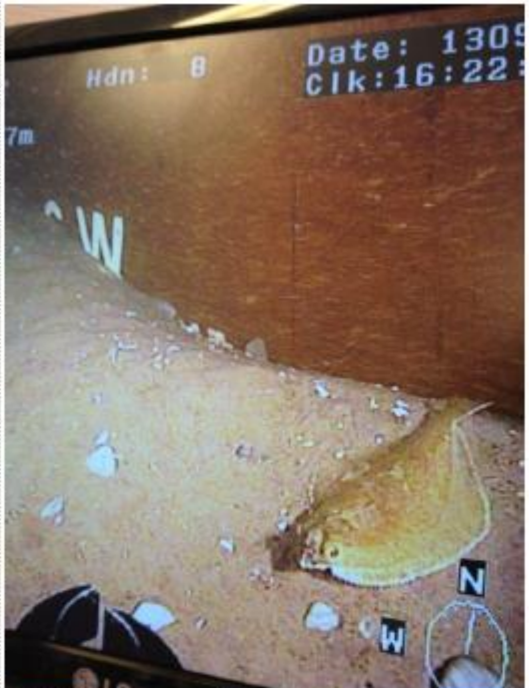


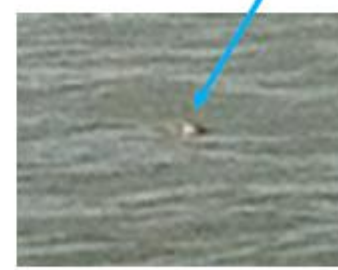
$$k = \frac{K_{s,n}}{K_{s,1}} = aN^{b}$$




1
0.8
0.6
0.4
0.2
Δu
u1
2500
5000
7500
10000
Number of load cycles

Noise free installation – wildlife unaffected





Summary and Recommendations

- Transition to deeper water makes more environmental loads from higher magnitude wind and waves, results in larger moments applied to the foundations

- Performance based design
  - Damping
  - Stiffness
  - Pore water pressure build up
  - Fatigue analysis

- Advanced Solutions must be implemented into design codes

THANK YOU FOR YOUR ATTENTION

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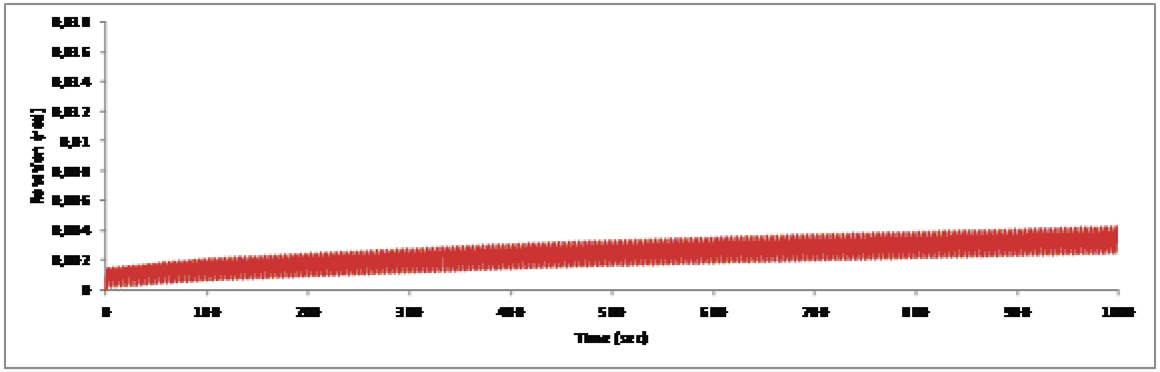
Future Research Plan

Prediction of accumulated deformations of offshore foundations under long-term cyclic loading

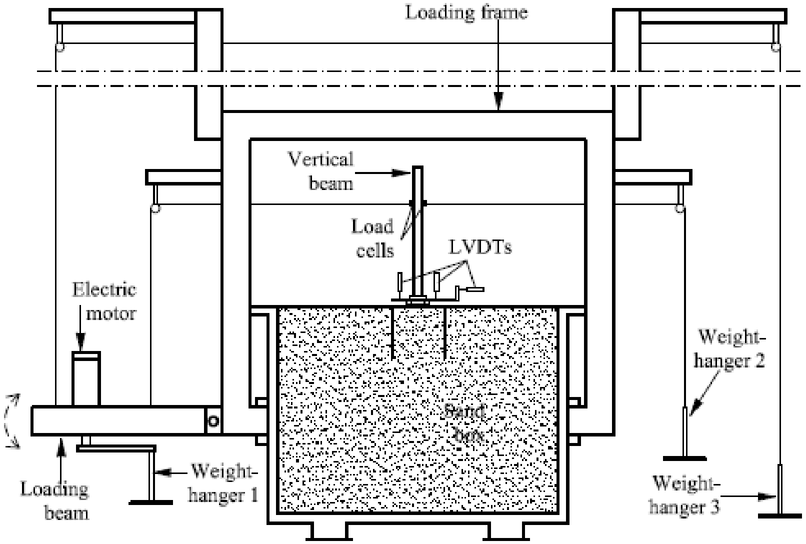
- Damping
- Stiffness
- Pore water pressure build up
- Fatigue analysis

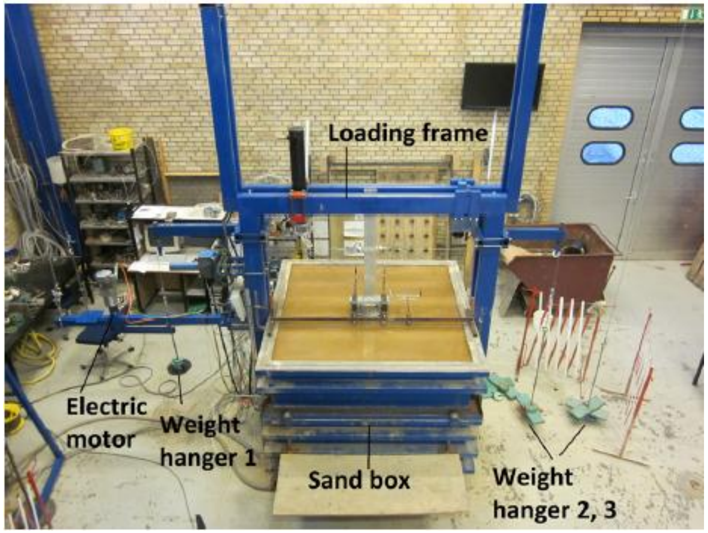
$$\left\{ \begin{array}{l} \dfrac{\theta_N}{\theta_1} = aN^b \\ \dfrac{\theta_N}{\theta_1} = a + \ln(N)^b \end{array} \right\}$$



Ongoing and Future Research Project

- The potential for the change in foundation stiffness and damping with time as a result of cyclic loading





- Numerical Investigations of Response of Suction Caissons to Transient Vertical Loading

Ongoing and Future Research Project

- Dynamic response of the offshore wind turbine structure with the large-scale bucket foundation
- Response of stiff monopiles in sand to long-term cyclic lateral loading
- Calibration of constitutive soil model for the cyclic behavior of Aalborg University sand (contractive/dilative behavior)
- Static capacity of bucket foundations under combined loading: Numerical simulations
- Nonlinear seismic analysis of pile-soil interaction using gap elements

Main Frequencies for wind turbines

Rotor frequency (1p): 0.115-0.2 HZ
Blade passing frequency (3p): 0.345-0.6 HZ