DIMSELO KPN Project

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DIMSELO

Dimensioning Sea Loads (2014-2017)

- Knowledge Building Project
  - Awarded by NFR
- Challenge standard design practice for Offshore Wind Turbines
- Consequences of advanced engineering models

- IFE
  - Project responsible
- DTU, NTNU
  - Academic Partners
- Statoil, Statkraft
  - Industrial partners

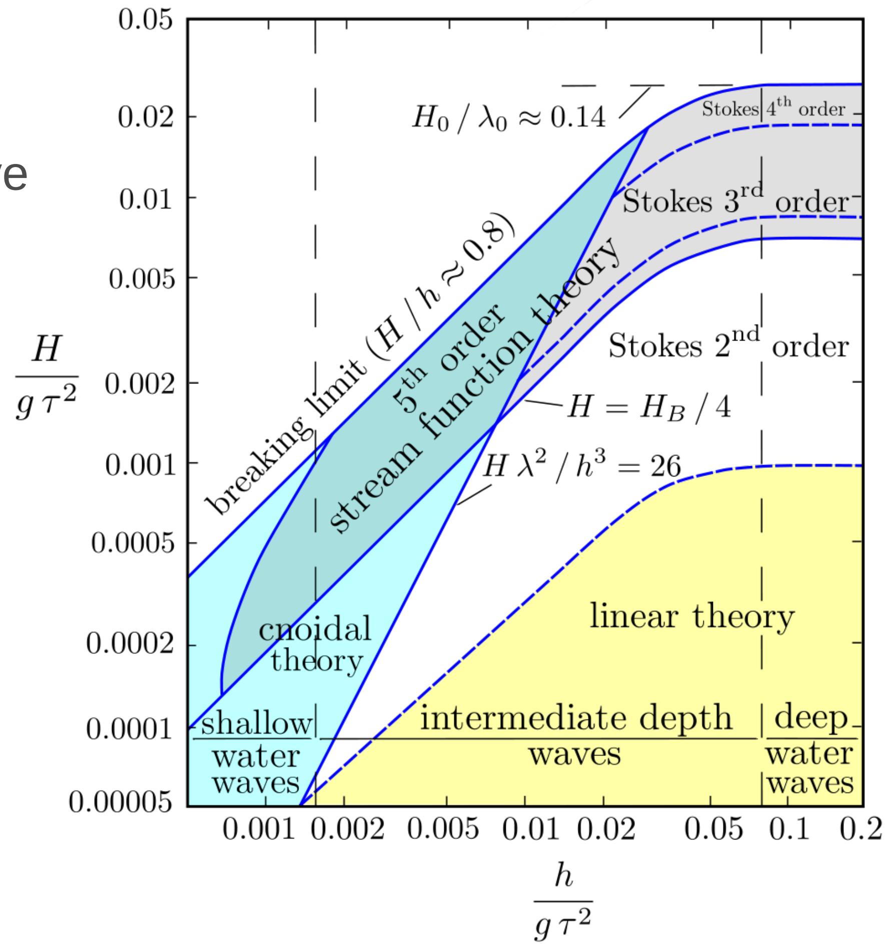
Wave models

- Deep water
  - Low steepness (A/λ) of the wave
  - Linear solution is satisfactory

- Shallower waters
  - $h = 25m - 40m$
  - High steepness
  - Nonlinear effects

- **Bottom-fixed wind farms are positioned at this depth**

Le Mehaute (1976)



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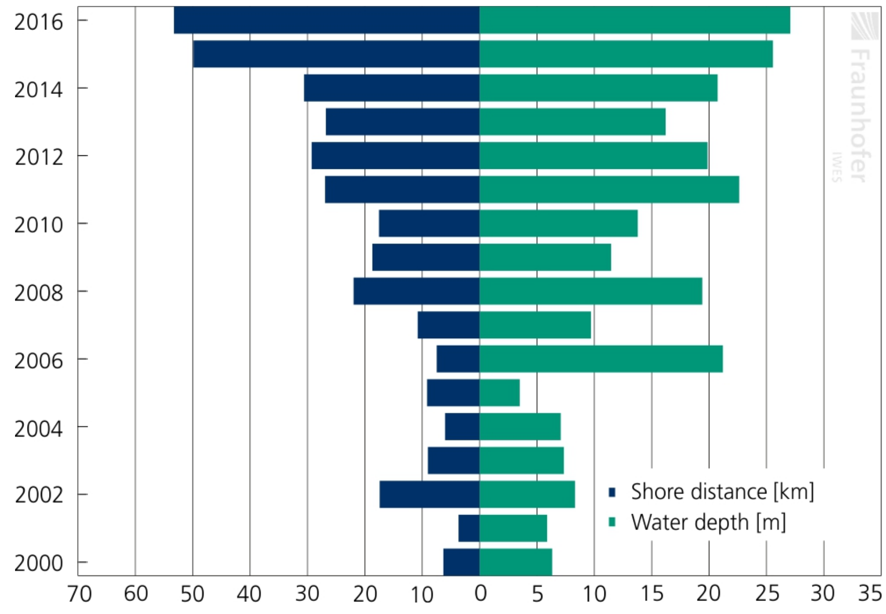


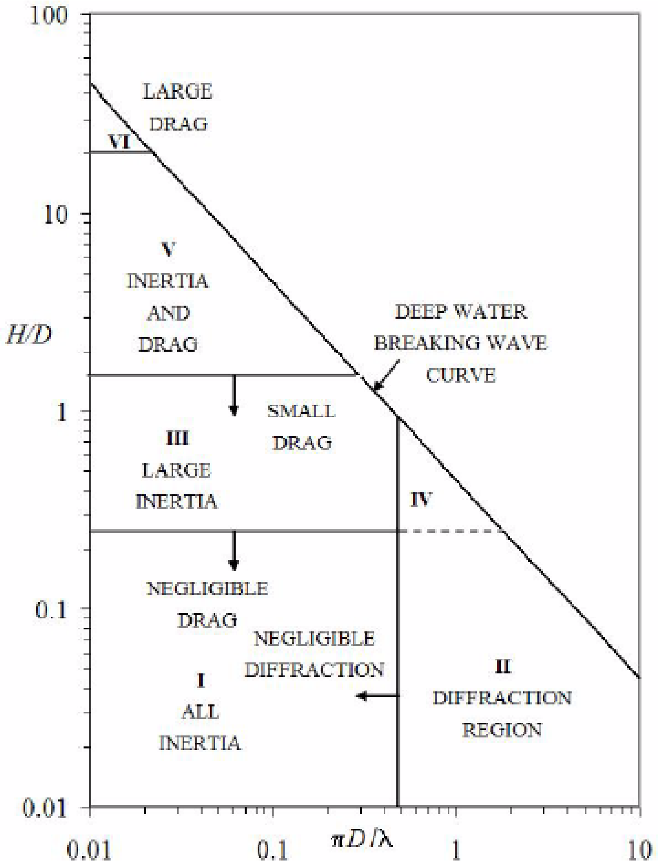
IWES (2016)

Diffraction of waves

- Large structures scatter incoming waves
- Leads to reduction in loads

- **Important for large monopiles**
  - $T = 2.5\ s$
  - $h = 30\ m$

$D = \lambda = 10\ m$



Chakrabarti (1987)

Design calculations via integrated models Current practice

	Fatigue	Extreme loads
Kinematics model	Linear irregular waves	Embedded 50-yr nonlinear wave
Load Model	Morison equation LPT	Morison equation
Challenges	Non-linearity Wave diffraction	Accuracy of non-linearity Directionality

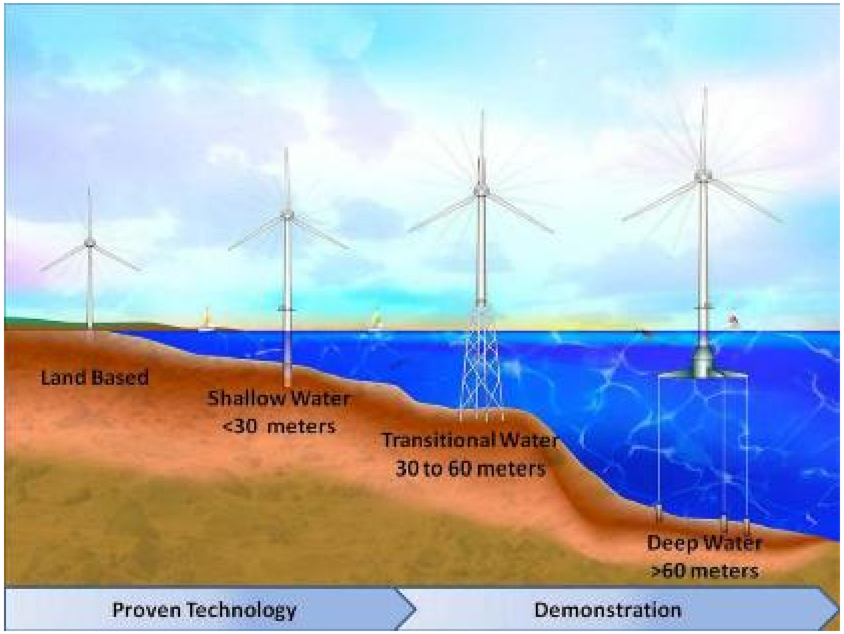
Questions at the base of DIMSELO

Kinematic loads can drive the design

1. How conservative are standard kinematics and force models?

2. Are the better engineering models? Can they be used?

3. *Can we quantify* the consequences of applying them?



NREL (2016)

DIMSELO

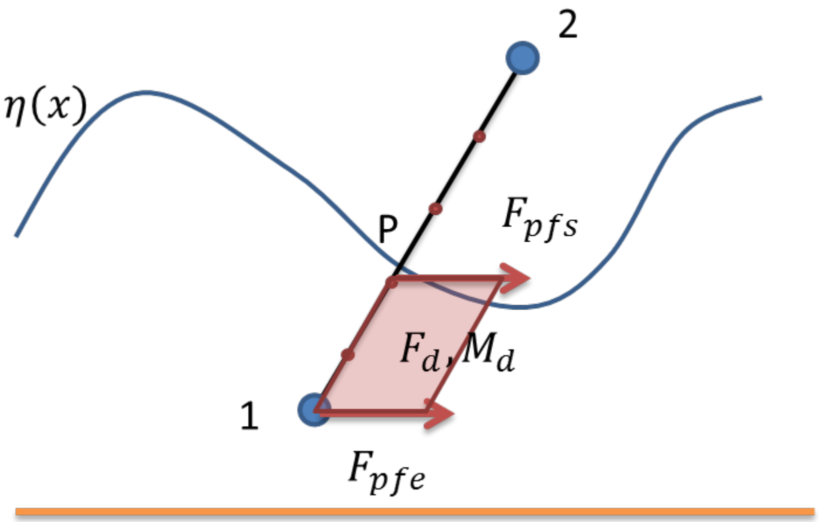
Structure of the project:

WP1 Sea Load Modeling	WP2 Wave Modeling	WP3 Aerodynamics VLR
• Slender body models • Large cylinders (First order Diffraction)	• Irregular 2nd order waves • Embedment of nonlinear waves	• Coherence of turbulence spectra • 6p and 2nd order bending moment interaction

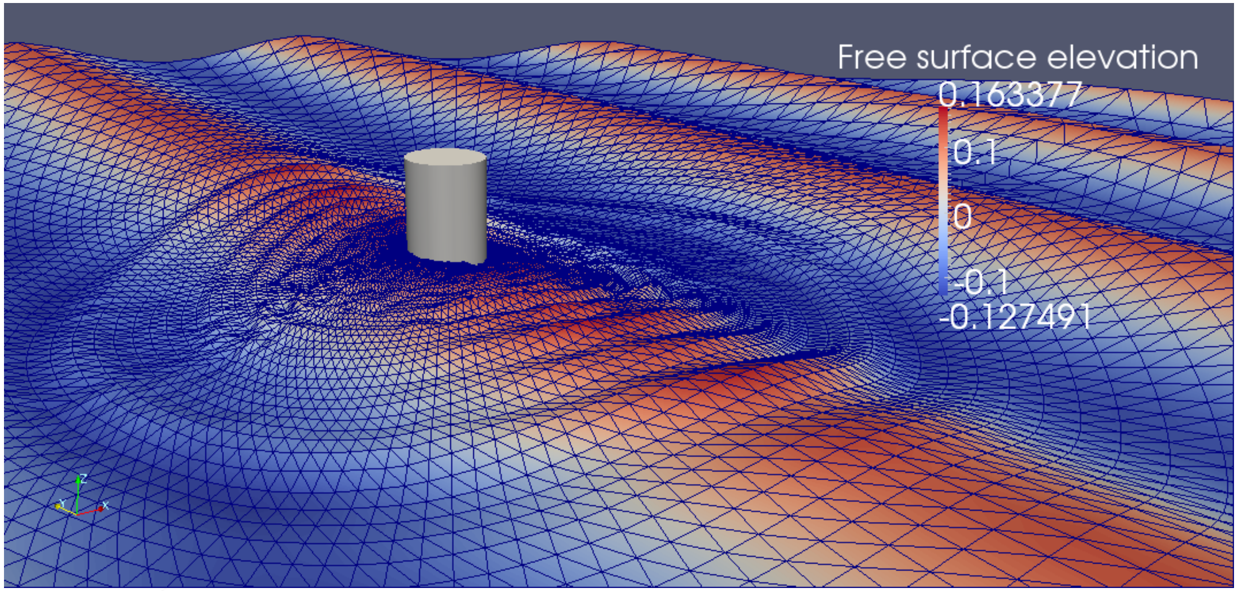
WP1
Rainey slender body model

- Based on an energy balance methodology and not on pressure integration considerations

- Three contributions on a submerged structure
  - Distributed force F_d
  - Distributed moment M_d
  - Force on free end F_{pfe}
  - Force on piercing point F_{pfs}

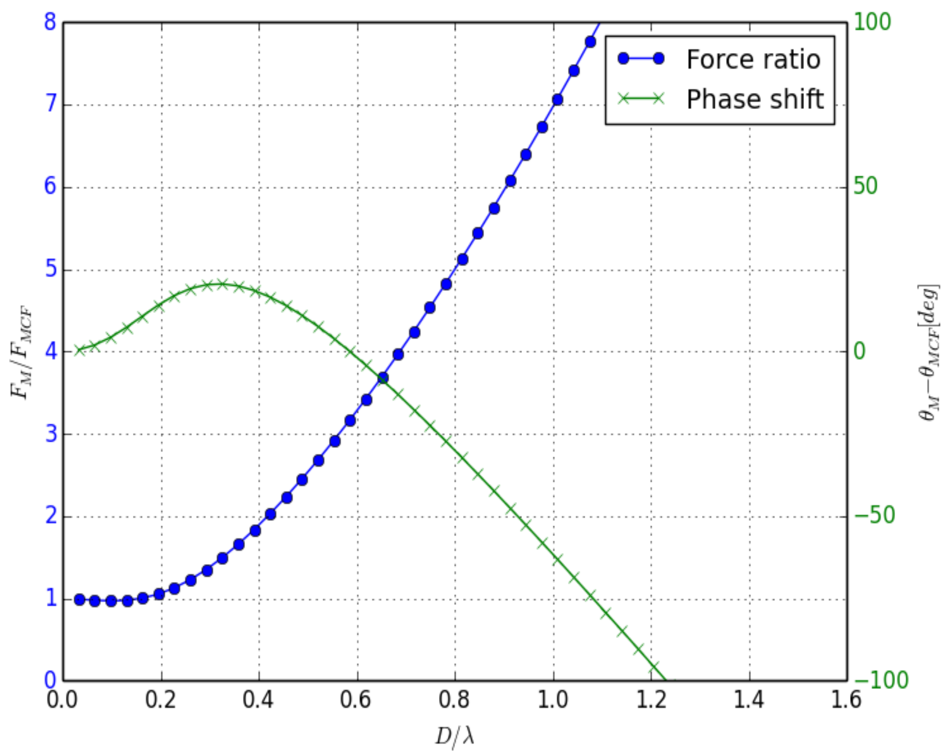


WP1
McCamy-Fuchs load model



Scatter of waves by cylinder

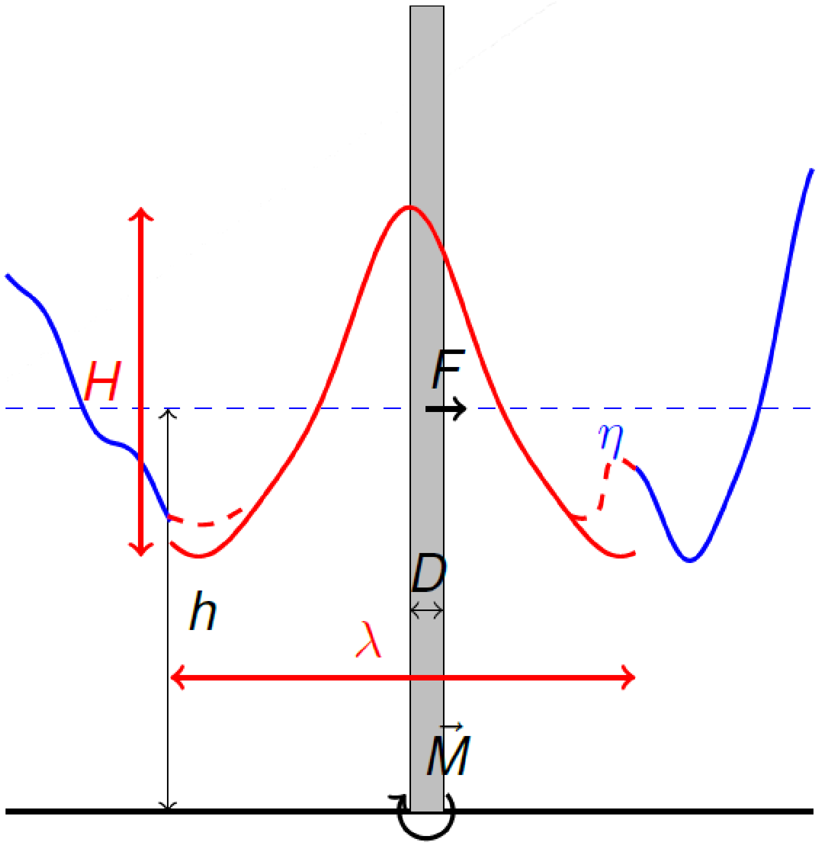
WP1
McCamy-Fuchs load model



Ratio of force predicted by Morison force model over MacCamy-Fuchs force model

WP2
Embedment of streamfunction waves

- **Standard**: 50-yr wave «cut-and-paste» in irregular linear waves
- **DIMSELO:** «Find and replace» highest linear wave with nonlinear SF wave
- Use of the Hilbert transfer to calculate the embedment period
  - Pierella, F., Stenbro, R., Oggiano, L., de Vaal, J., Nygaard, T. A., & Krokstad, J. (2017, July). Stream Function Wave Embedment into Linear Irregular Seas: A New Method Based on the Hilbert Transform. In *The 27th International Ocean and Polar Engineering Conference*. (ISOPE 2017)

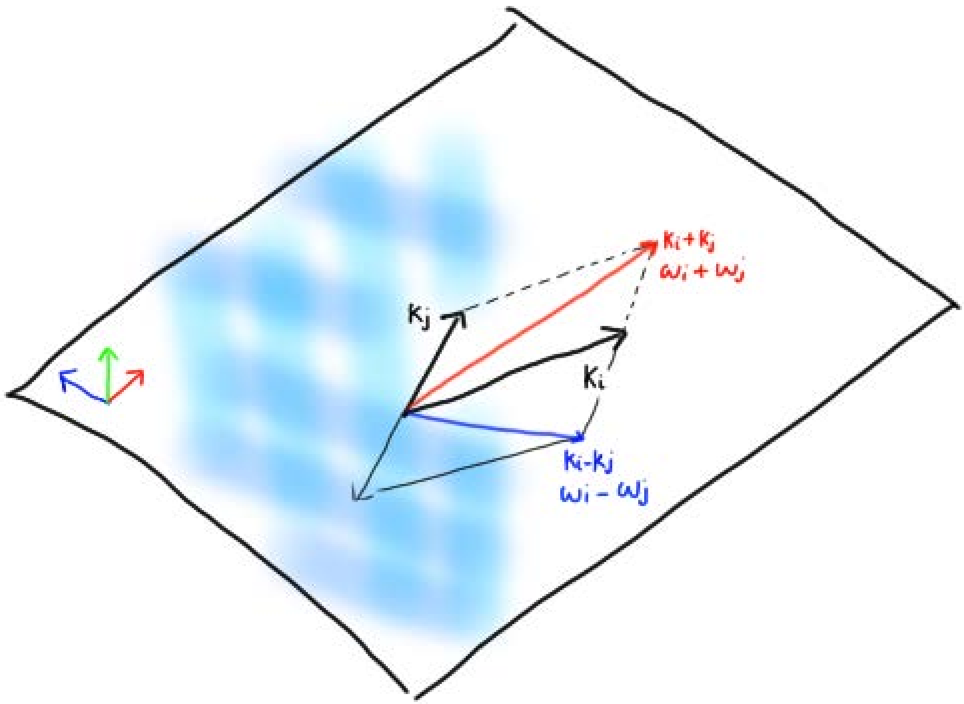


WP2
Second-order irregular short-crested

- Full second-order short-crested waves
  - Sharma and Dean (1981)

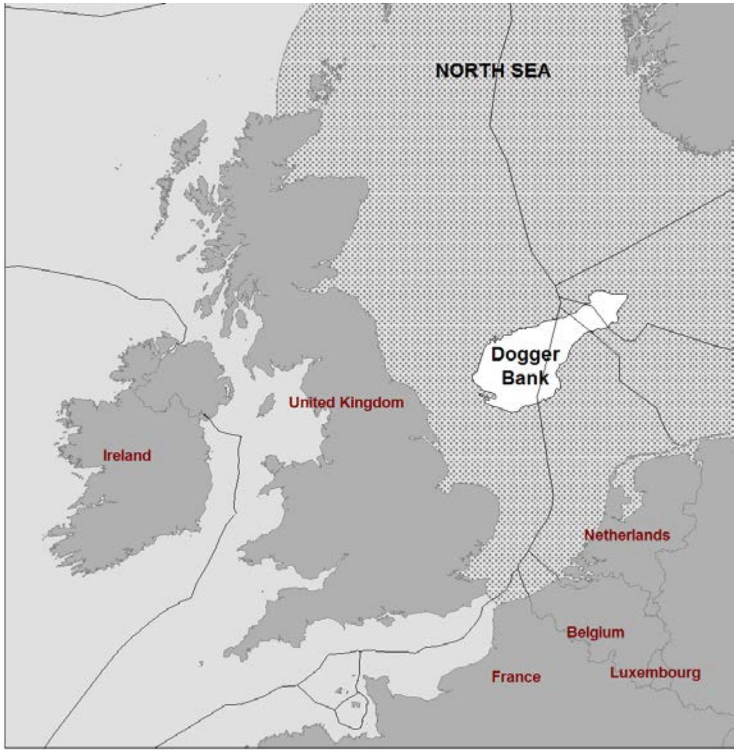
- **Standard**: not possible without simplifications

- **DIMSELO**: Full theory implemented
  - 2D FFT calculation in space



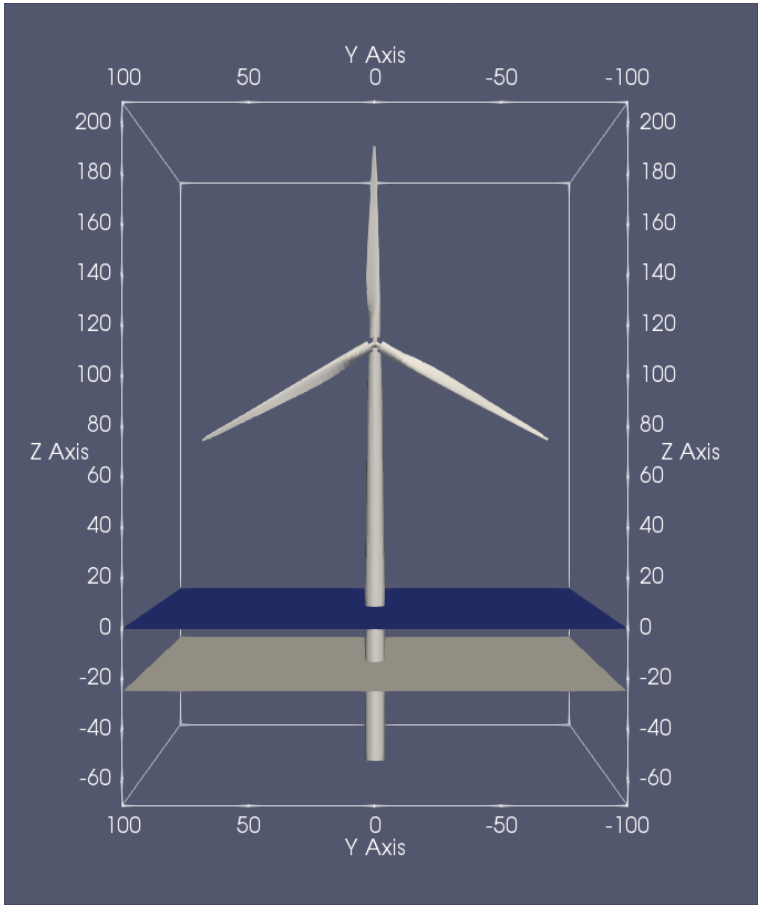
DIMSELO Reference wind turbines

- Site
  - Dogger Bank
- Water depth
  - $h = 25m$; $h = 35m$
- Metocean conditions: Statoil
- Foundations
  1. XL Monopile 25m
  2. XL Monopile 35m
  3. Jacket 35m
     - Designed by Kasper Sandal (DTU)



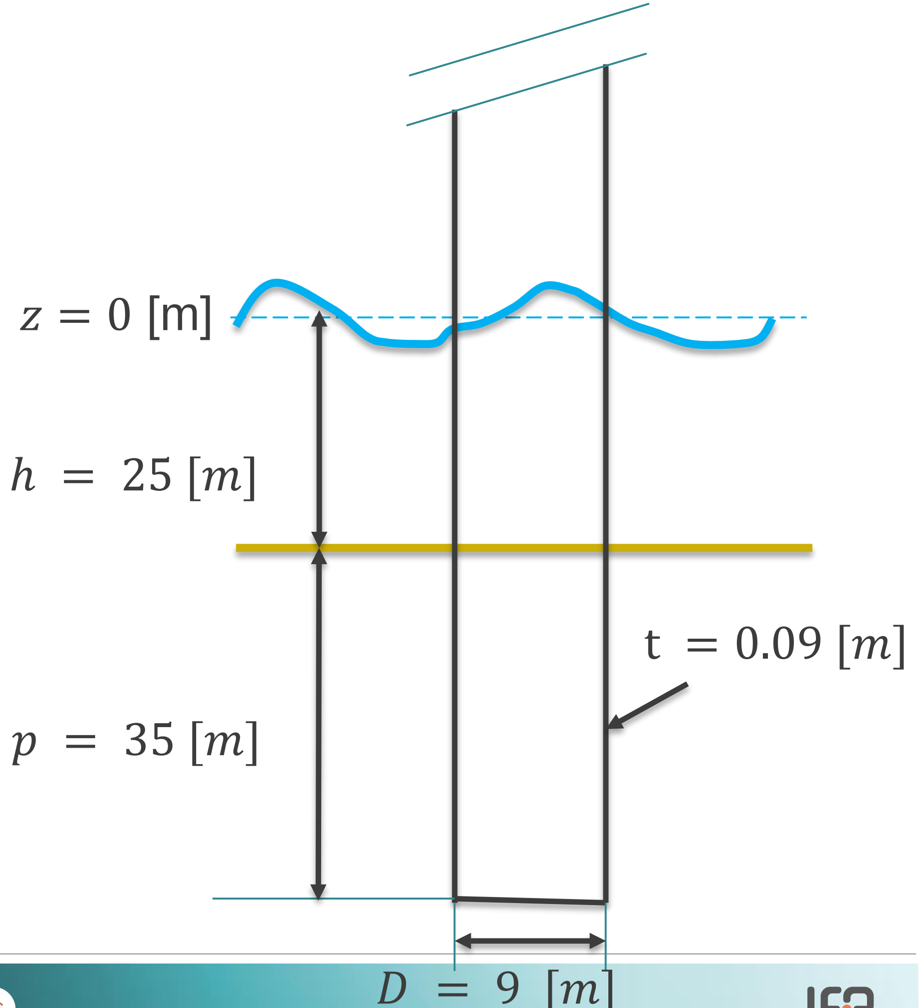
Monopile 25m 10MW

- Turbine
  - DTU 10MW reference wind turbine
  - $H_{hub} = 119. [m]$
- DTU controller
- Tower
  - Steel, onshore tower
- Substructure
  - Designed ad-hoc
- **Fatigue and Extreme loads**



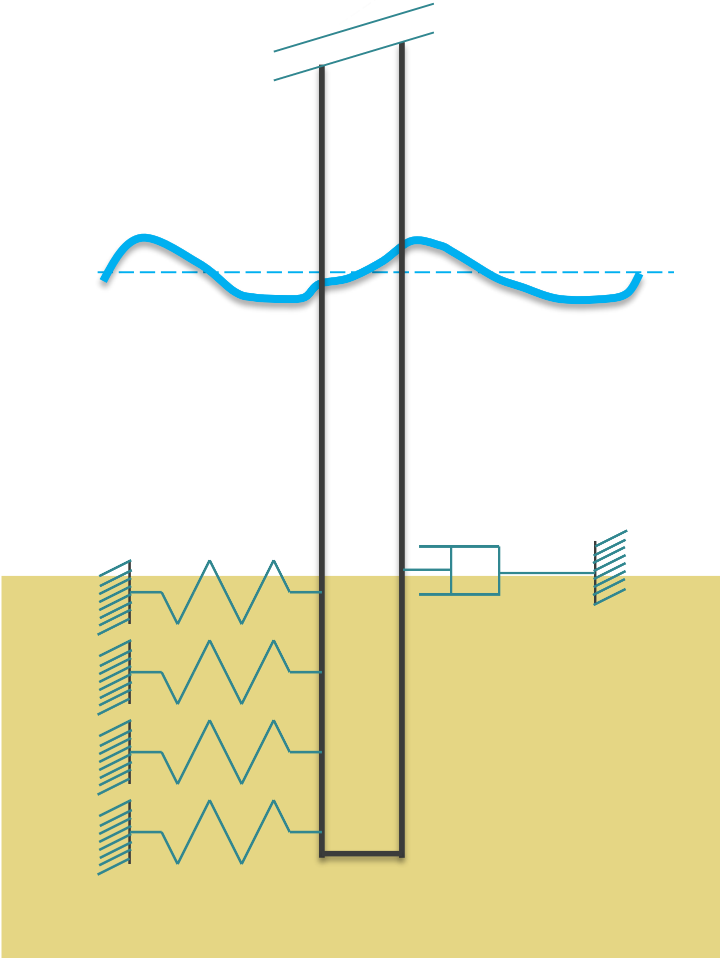
10 MW Monopile 25m: design characteristics

- 1st bending natural frequency
  - $f = 0.23\ [Hz]$
  - Between 1p and 3p
- Transition piece
  - Point mass $z = 19\ [m]$
- Pile
  - Steel

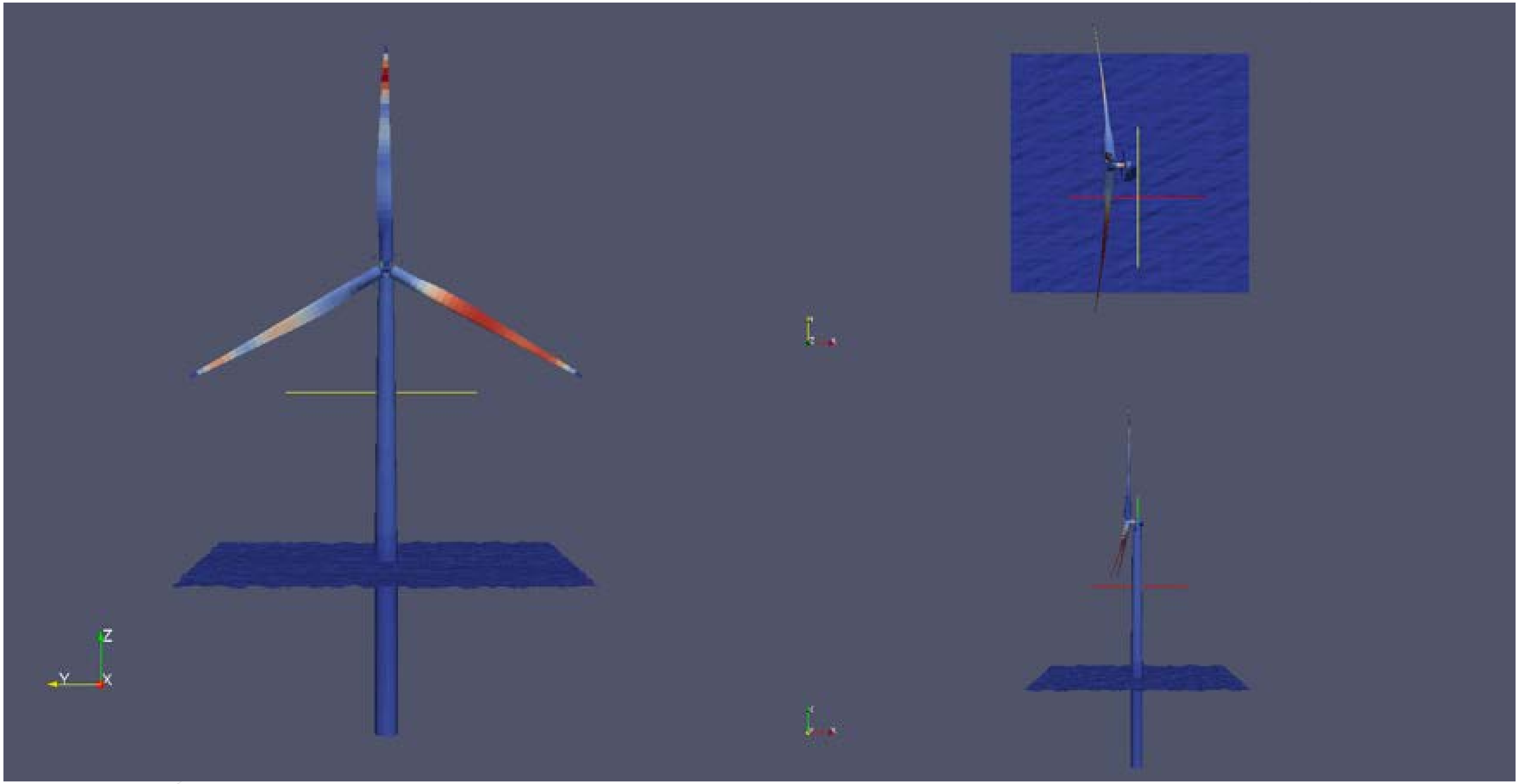


Monopile 25m: Soil model

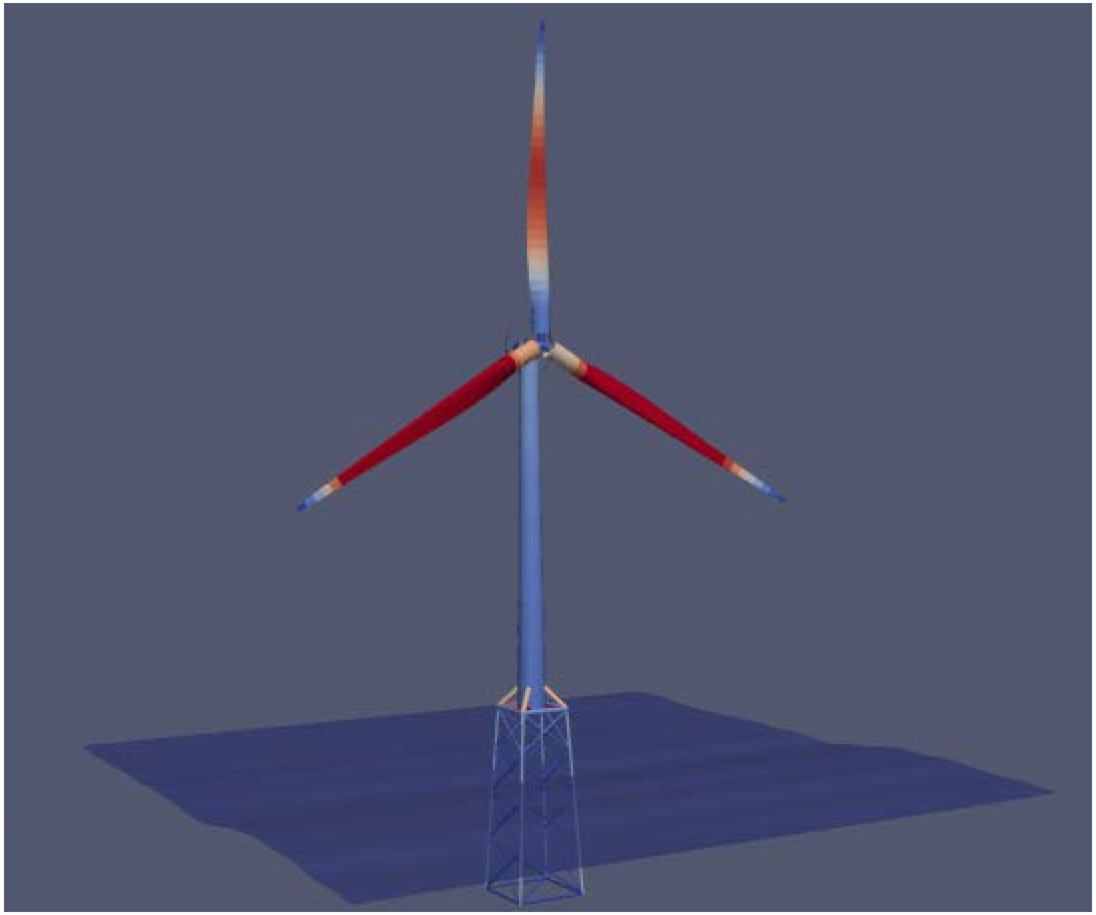
- P-y soil springs
- Logarithmic decrement of 1st tower bending oscillation
  - $\delta = \frac{1}{n} \ln \frac{x_n}{x_{n+1}}$
- 1.5 % damping as a fraction of critical
  - $\zeta = \frac{\delta}{2\pi} = 0.015$
- Achieved by installing dampers at the mudline



Monopile 25m

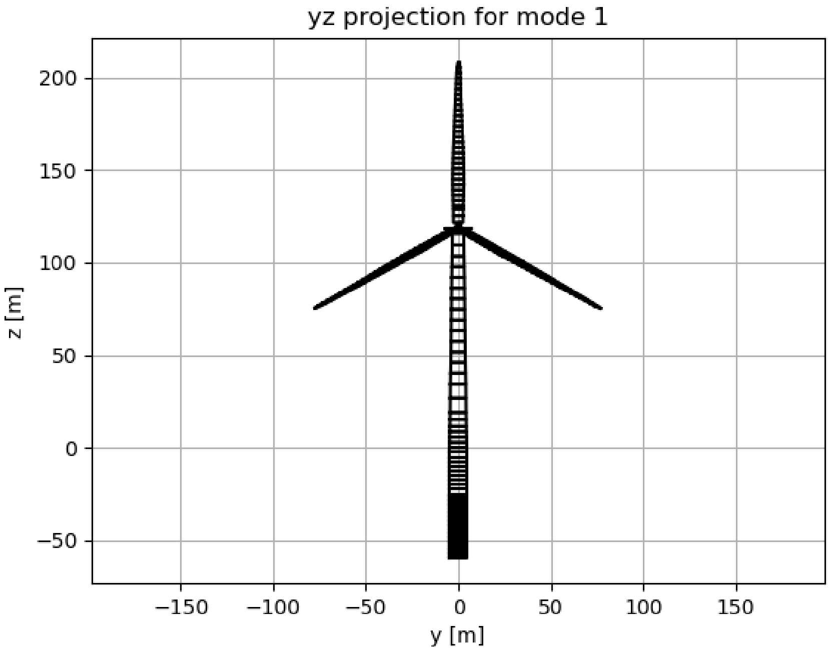


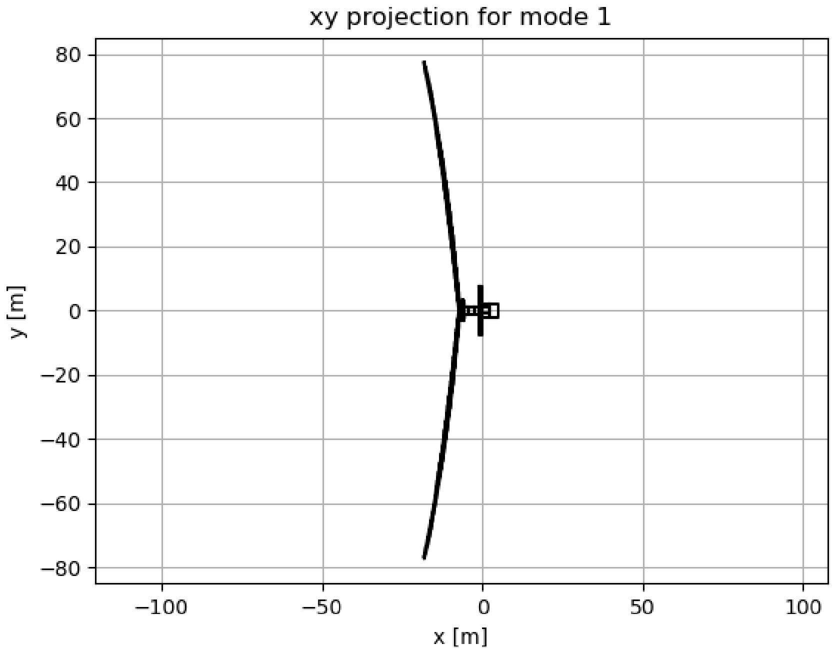
Jacket Model



Monopile 25m
Tower side-to-side bending

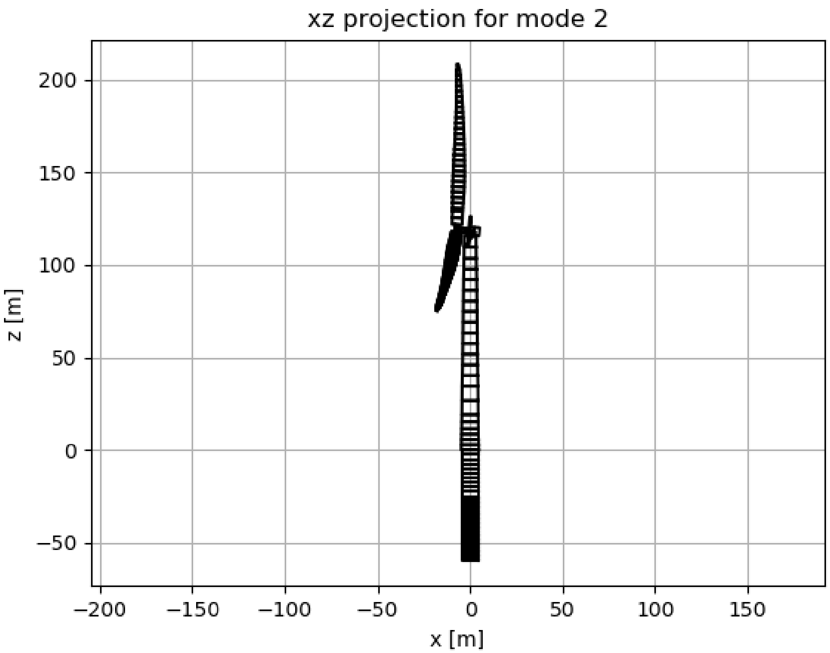
- $f = 0.23\ Hz$

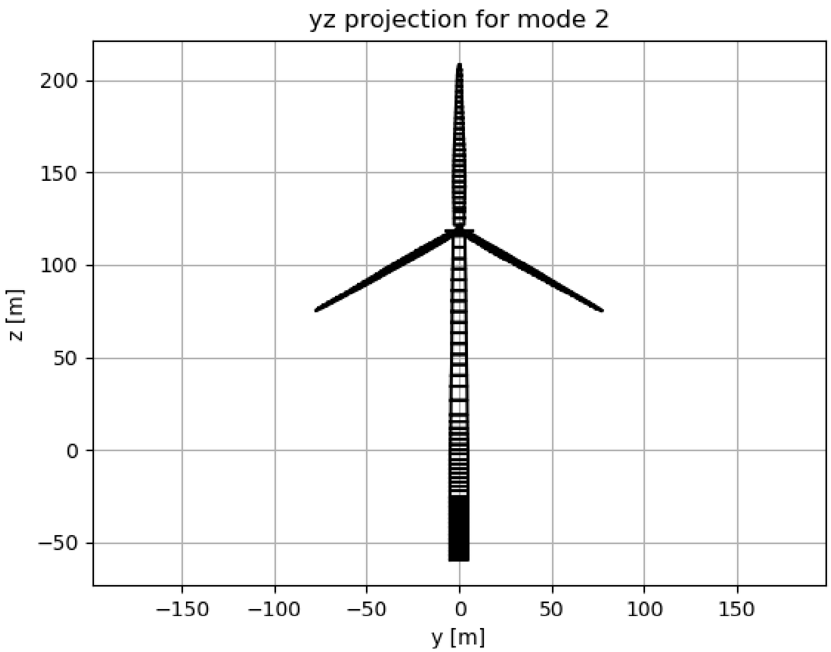




Monopile 25m
Rotor edgewise bending

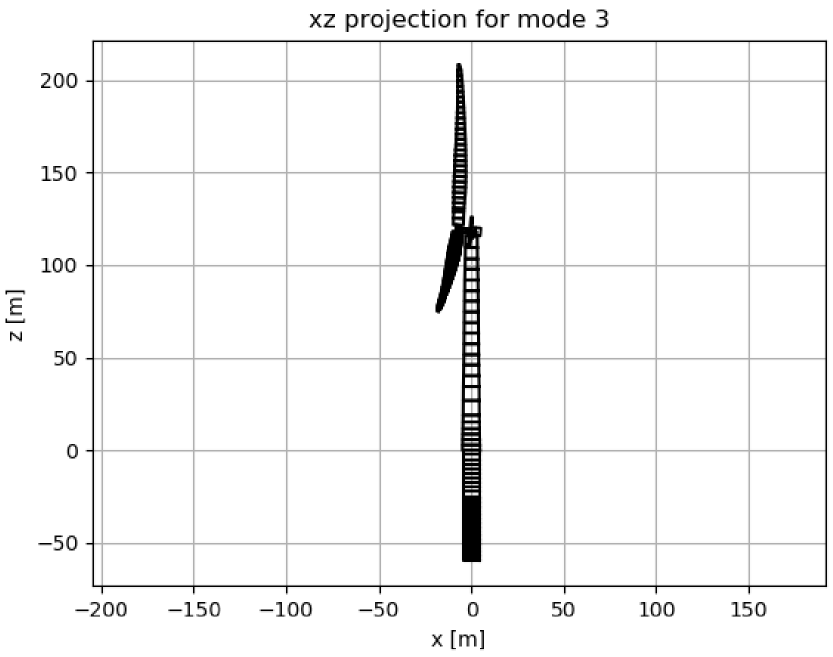
- $f = 0.48\ Hz$

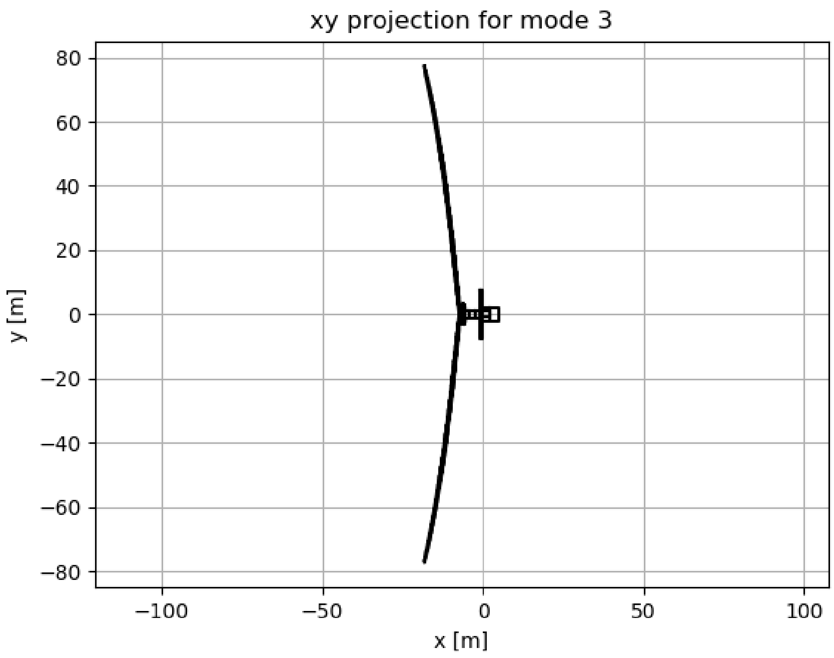




Monopile 25m
Rotor flapwise with yaw

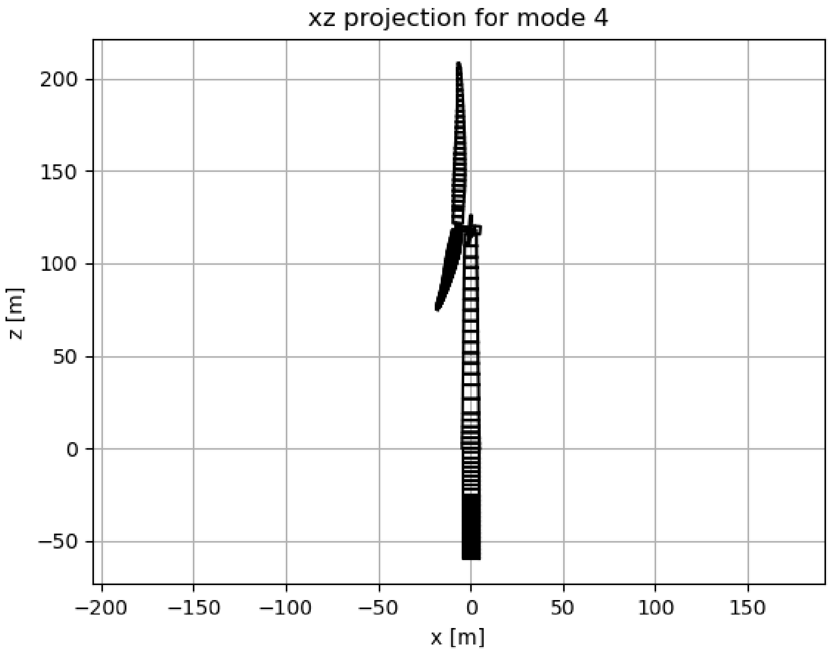
- $f = 0.57\ Hz$

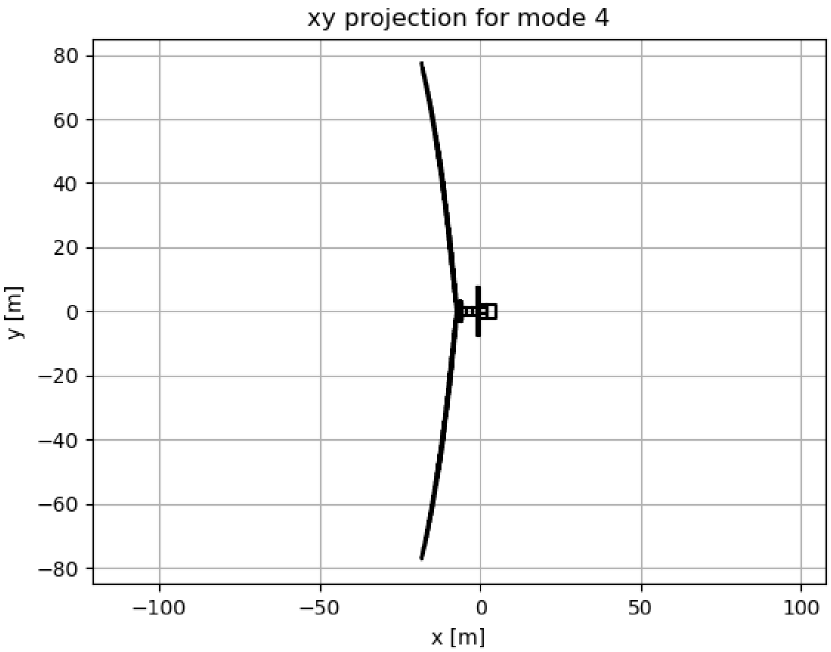




Monopile 25m
Rotor flapwise with tilt

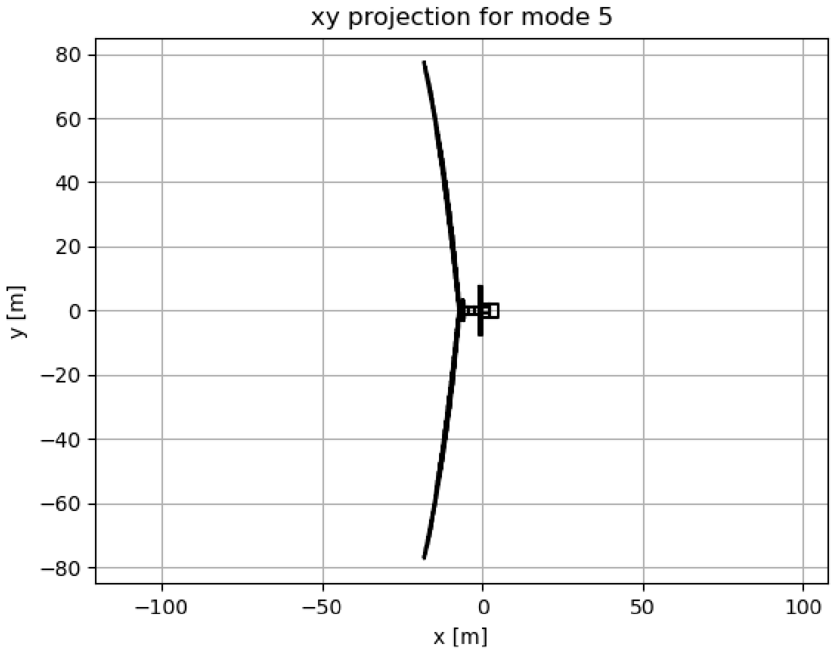
- $f = 0.59\ Hz$

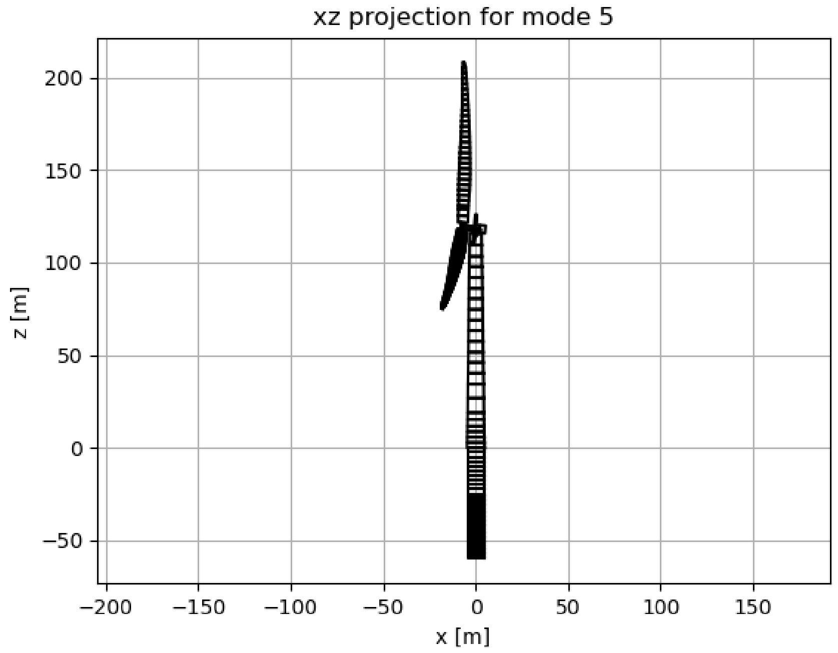




Monopile 25
Collective flapwise

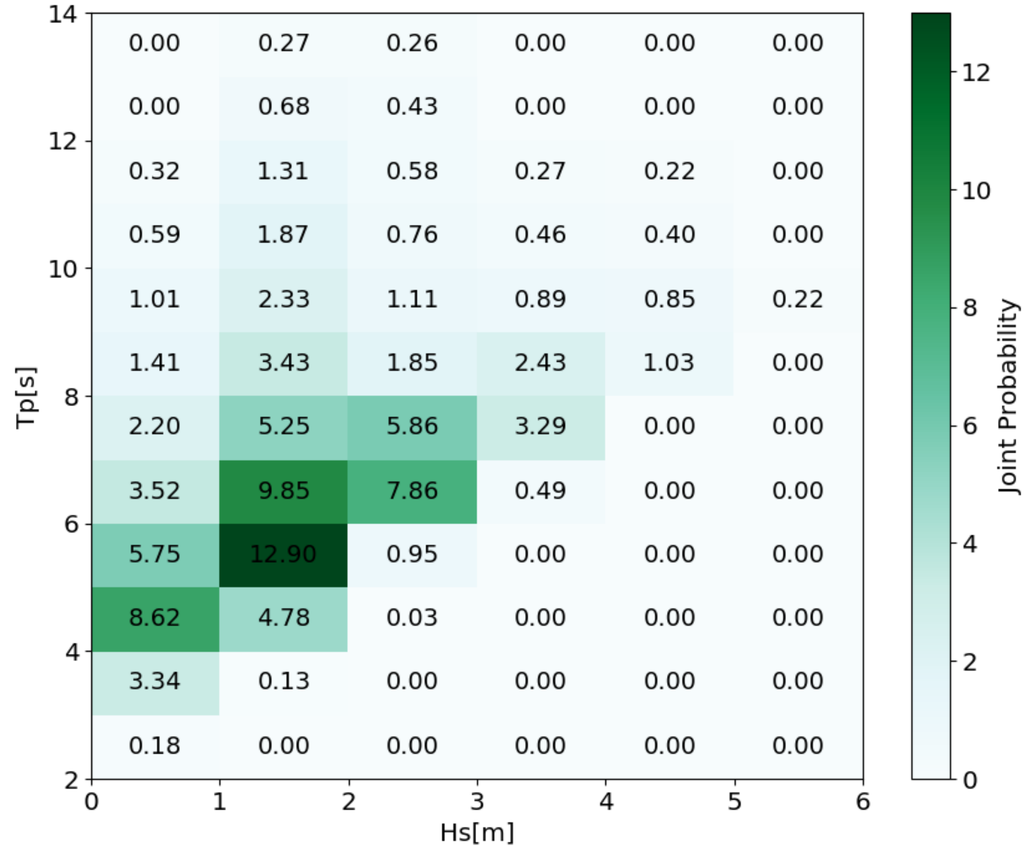
- $f = 0.62\ Hz$





MetOcean conditions for DIMSELO structures

- Northern sea location
  - Dogger Bank
- Wind speed
  - conditional on H_S
  - Aligned with waves
- Turbulence
  - IEC-61400-1
- $\sum P(H_S, T_P) = 100$



Wind Speed@100 [m] [m/s] 5.8 9.1 13.5 17.6 21.0 23.8

Combination of models

- Force models
  - Rainey force model
  - McCamy-Fuchs force model
  - Morison force model

✖

- Wave kinematics
  - First-order irregular waves
  - Second-order irregular waves

✖

- Directional Spread
  - Short crested
  - Long crested

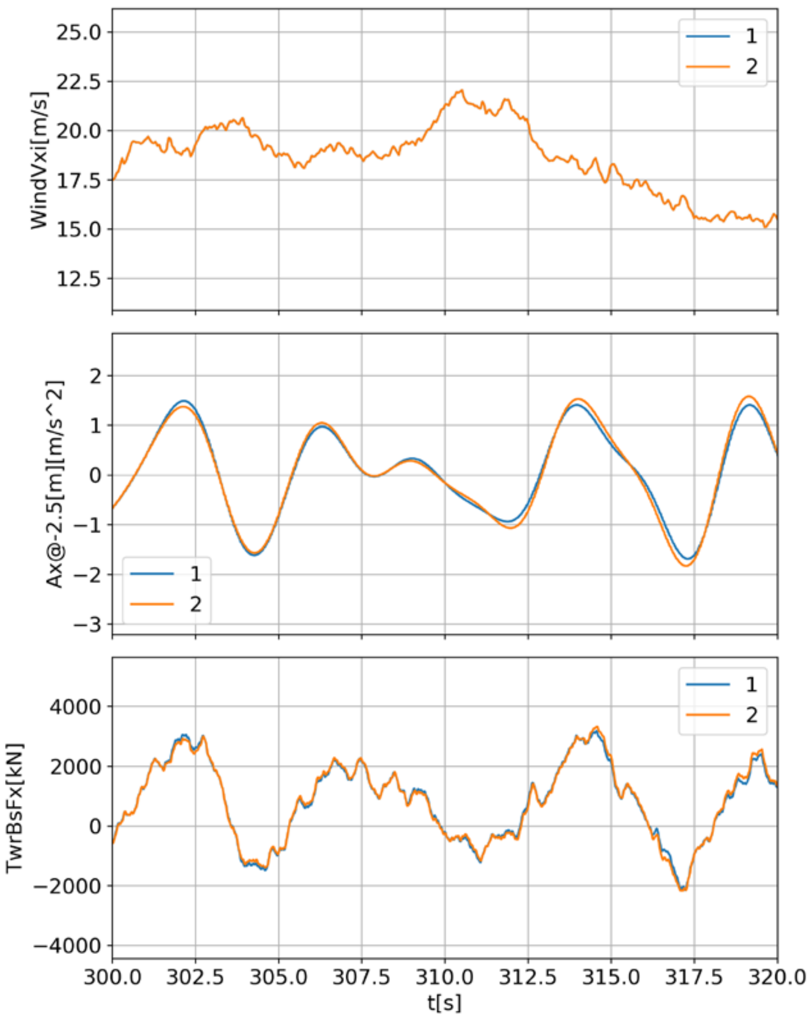
=

10 simulations
per (H_S, T_P)
Jonswap spectrum

Example: effect of kinematics 1st vs 2nd order

- Time series 30 min
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force

	1	2
Kinematics	1st order	2nd order
Load Model	Morison	Morison
Directonal spread	Long crested	Long crested



Example: effect of kinematics 1st vs 2nd order

- Histogram
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force

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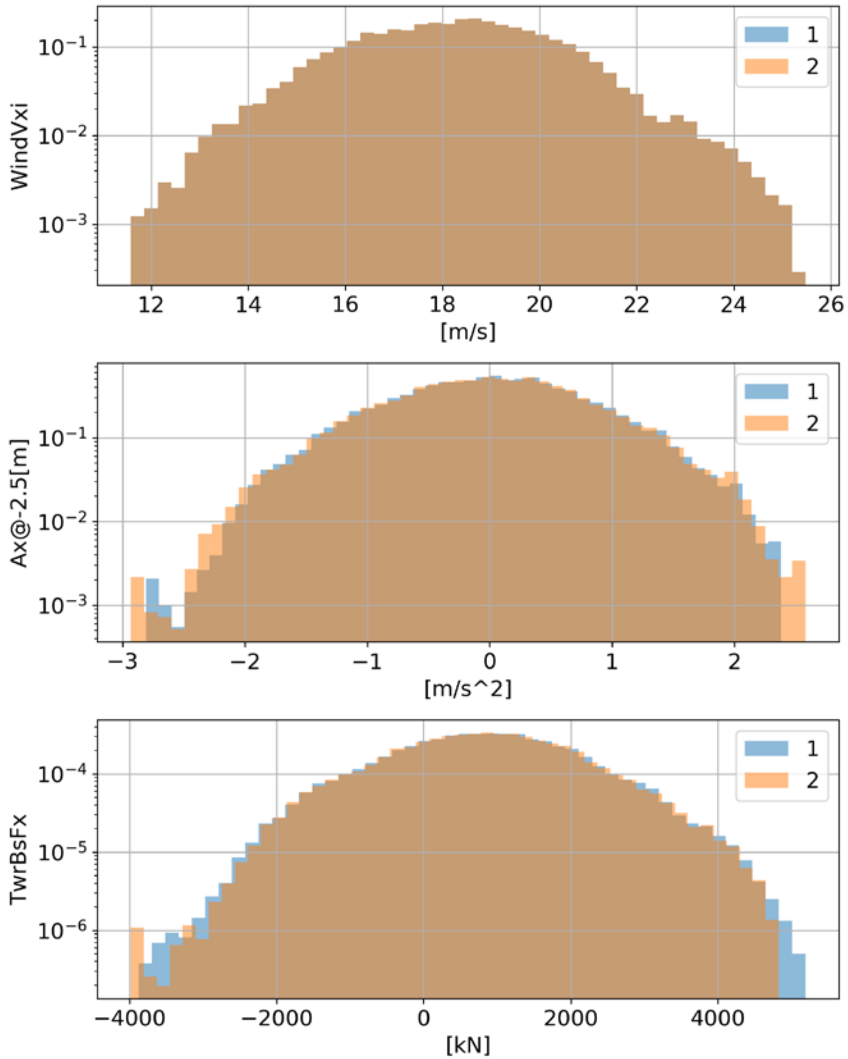
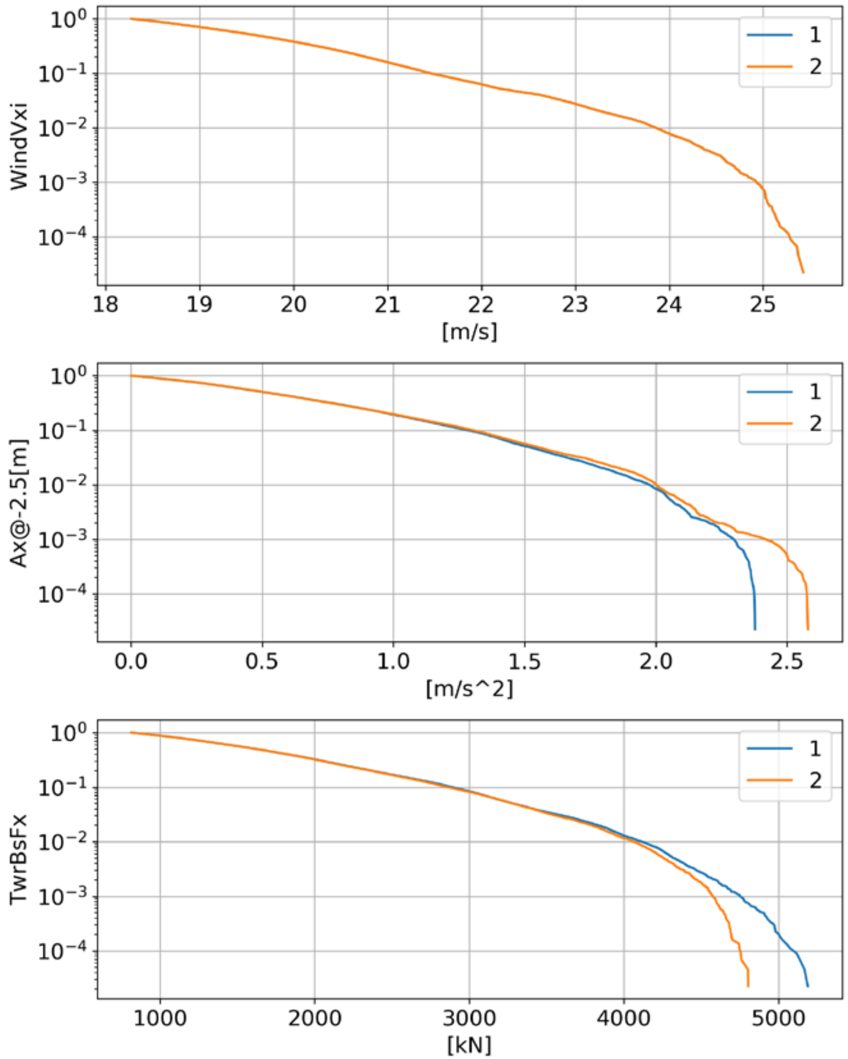


Example: effect of kinematics 1st vs 2nd order

- Exceedance probability
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force



	1	2
Kinematics	1st order	2nd order
Load Model	Morison	Morison
Directonal spread	Long crested	Long crested

A more compact view

- Fatigue IEC-61400-1
  - LC 1.6 → operation with NTM
- Simulate N series of 30 minutes
- Extract timeseries of important parameters
  - Mudline Fx [kN]
  - Mudline My[kNm]
  - Blade root Flapwise Mf[kNm]
- DAMAGE EQUIVALENT LOAD (DEL)
  - Regular load that would do the same damage as the irregular one if applied in a 1-min sinusoid

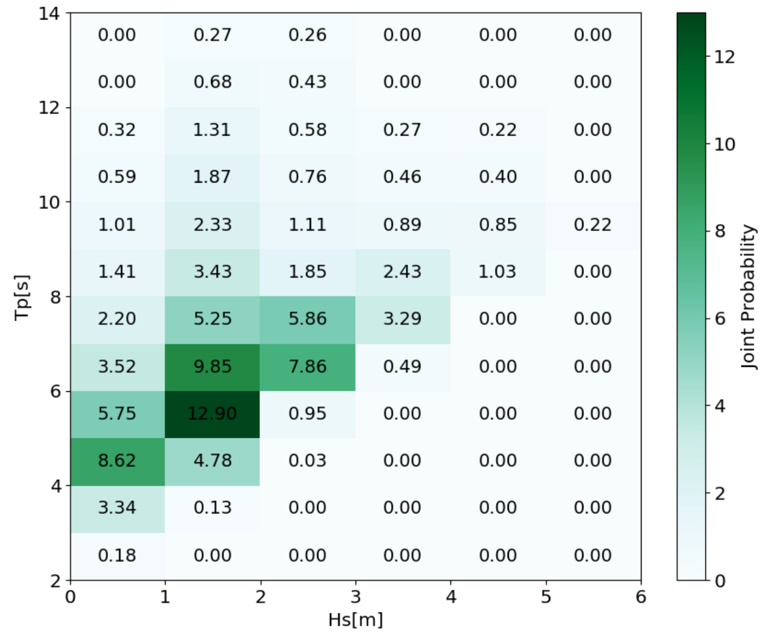
$$D \propto DEL^m$$

- **D :** damage (inverse of lifetime)
- **DEL :** damage equivalent load
- **m** : Wöhler exponent (m=3 for steel)

Morison – 1st order – Long Crested (Base case)

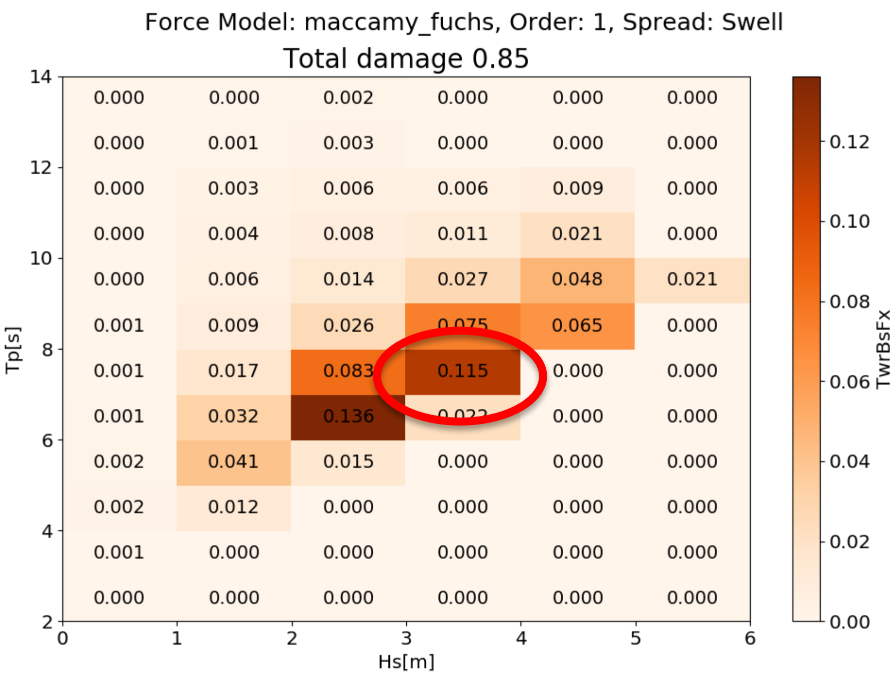
Fatigue due to Mudline Fx

(H_S, T_P) joint probability



MacCamy-Fuchs – 1st order – Long crested

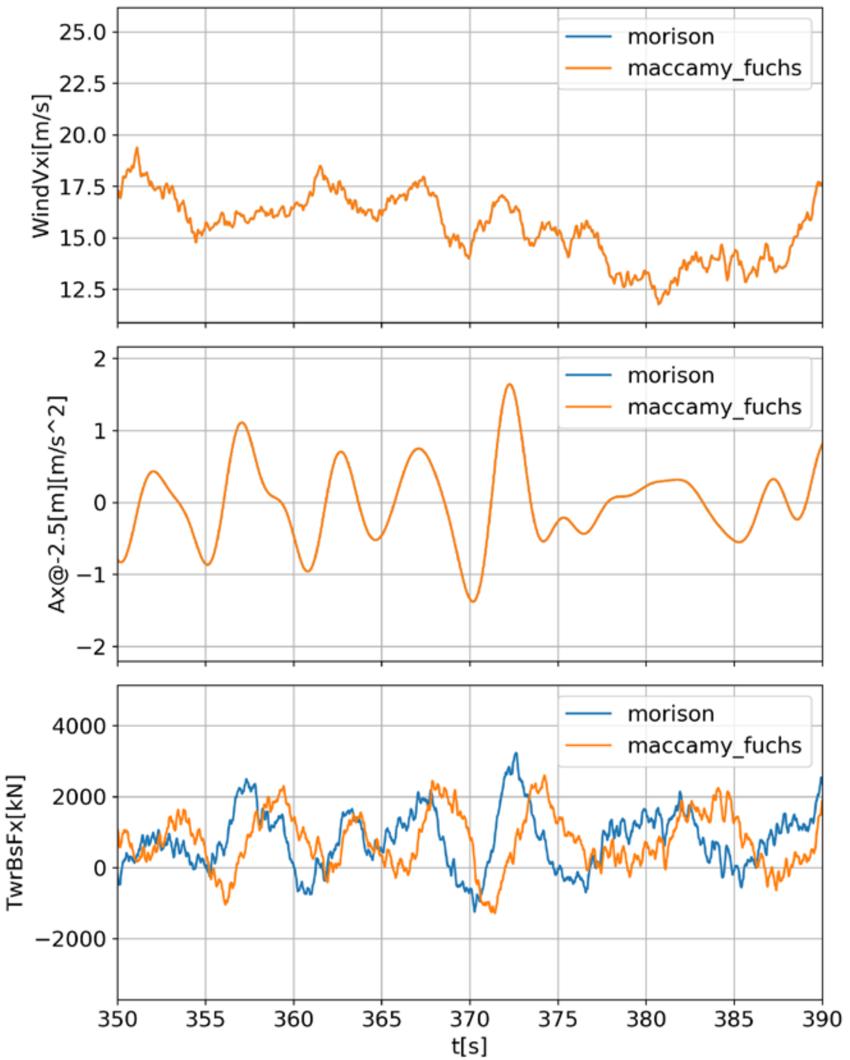
Fatigue due to Mudline Fx



Example: effect of force model

- Time series
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline Fx

	Morison	Maccamy
Kinematics	1st order	1st order
Load Model	Morison	MacCamy-Fuchs
Directional spread	Long crested	Long crested



Example: effect of force model

- Histogram
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
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	Morison	Maccamy
Kinematics	1st order	1st order
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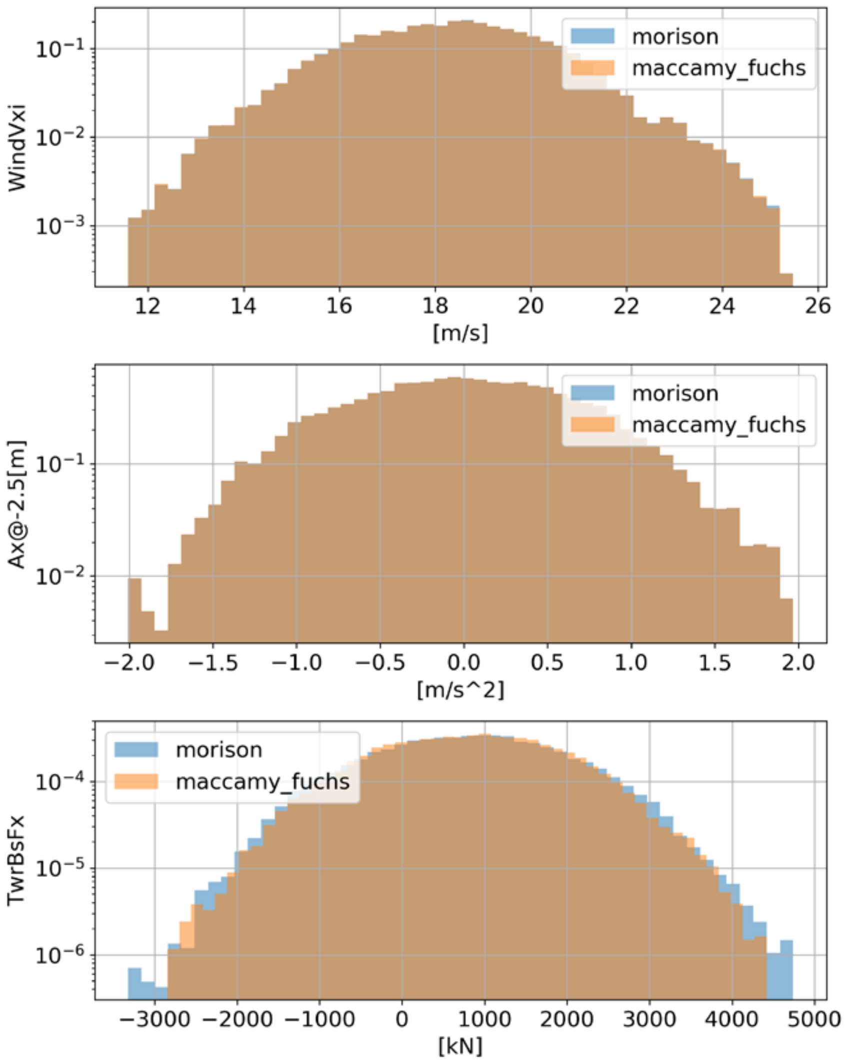
Directonal spread	Long crested	Long crested



Example: effect of force model

- Exceedance probability
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline Fx

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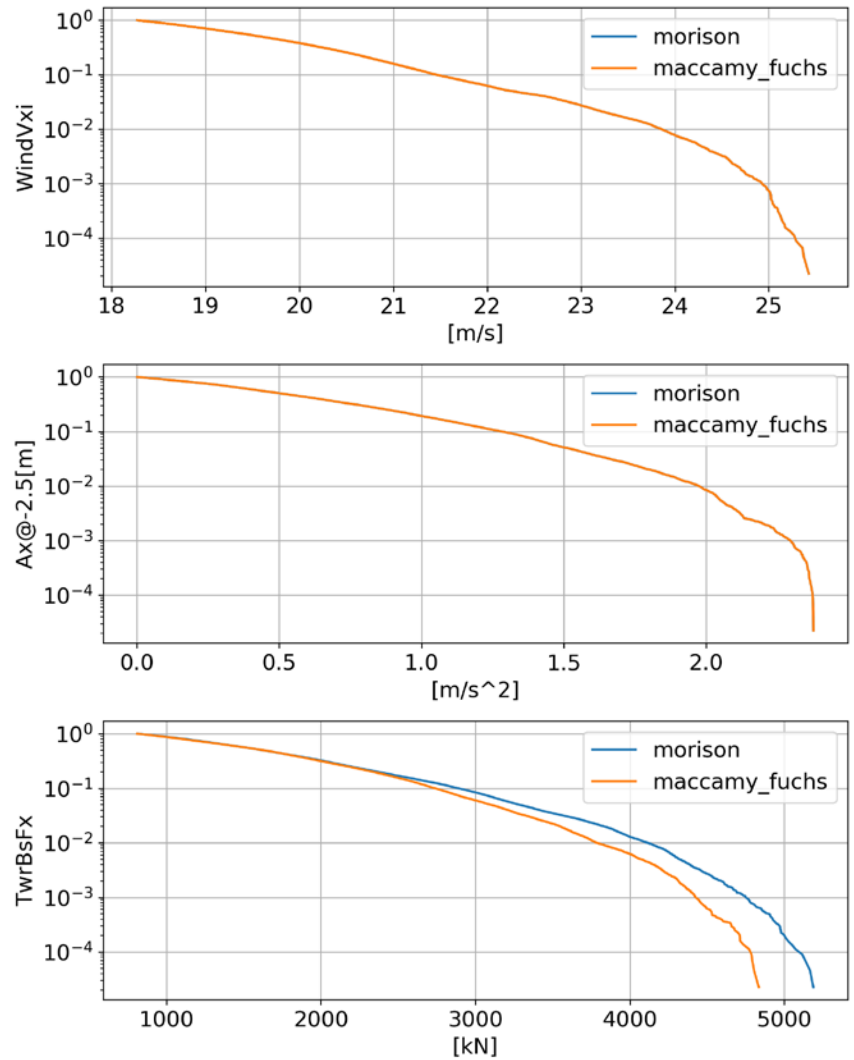
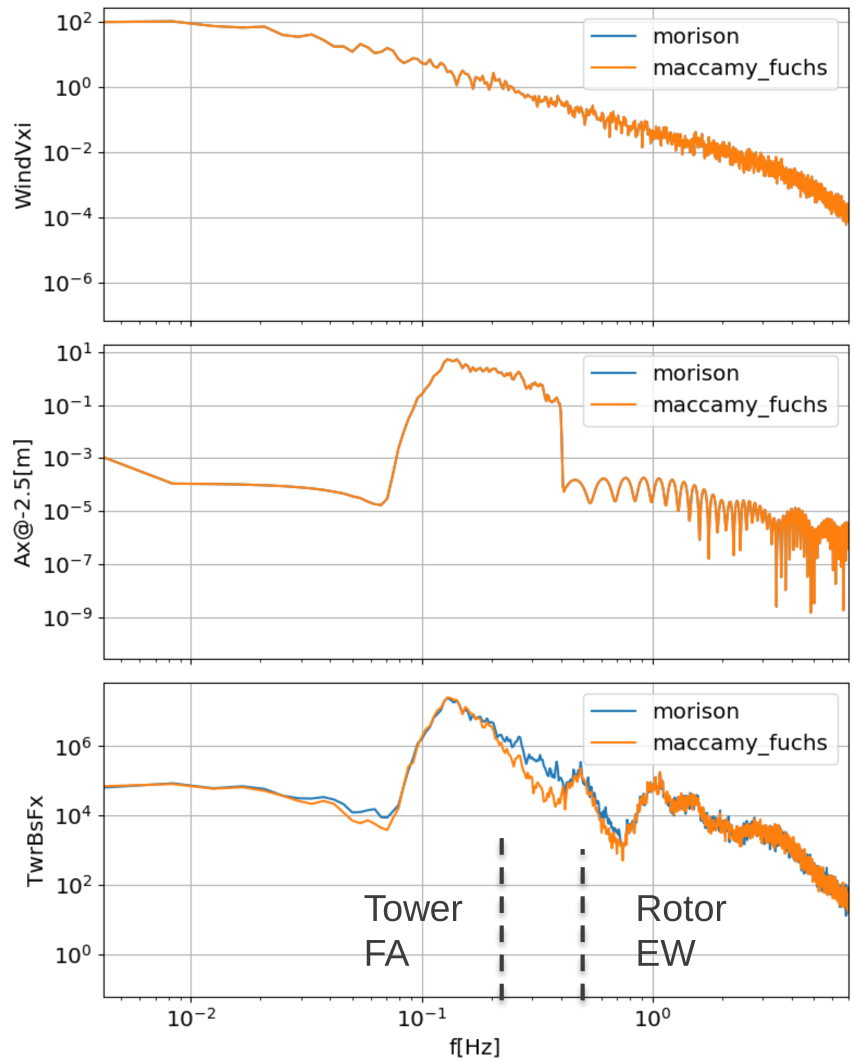


Example: effect of force model

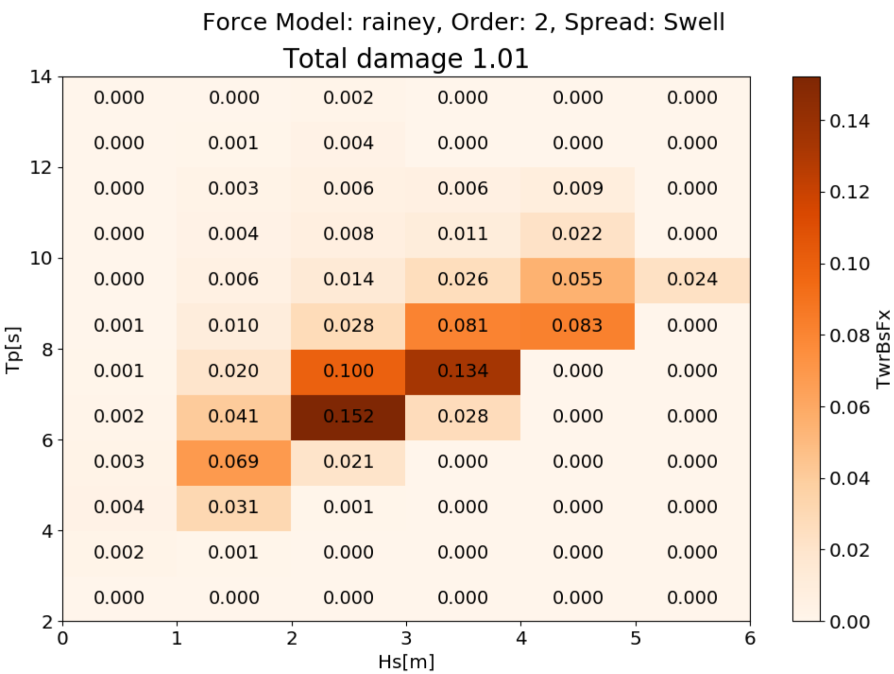
- Power spectral density
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline Fx

	Morison	Maccamy
Kinematics	1st order	1st order
Load Model	Morison	MacCamy-Fuchs
Directonal spread	Long crested	Long crested



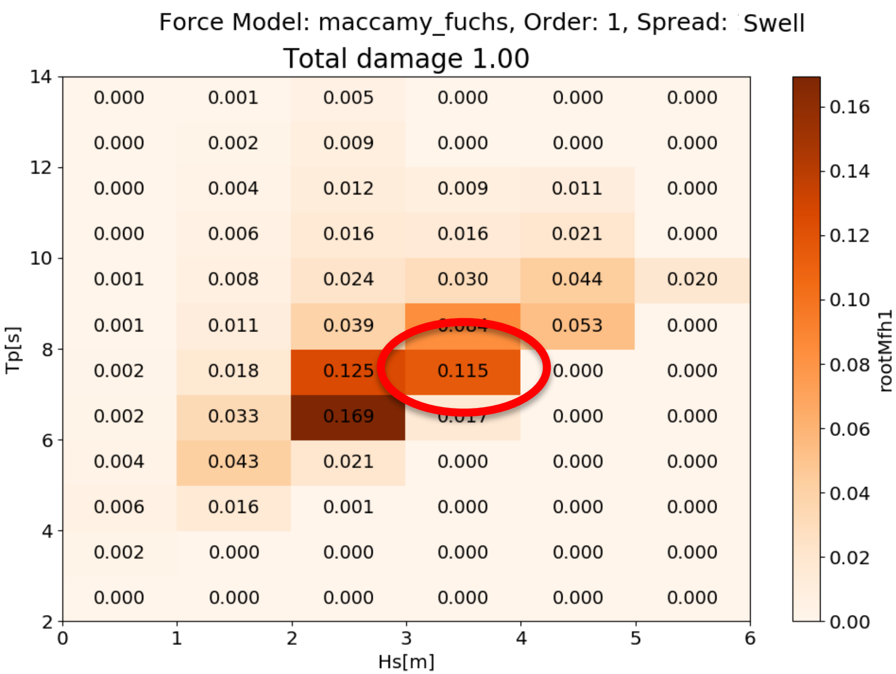
Rainey – 2nd order – Swell

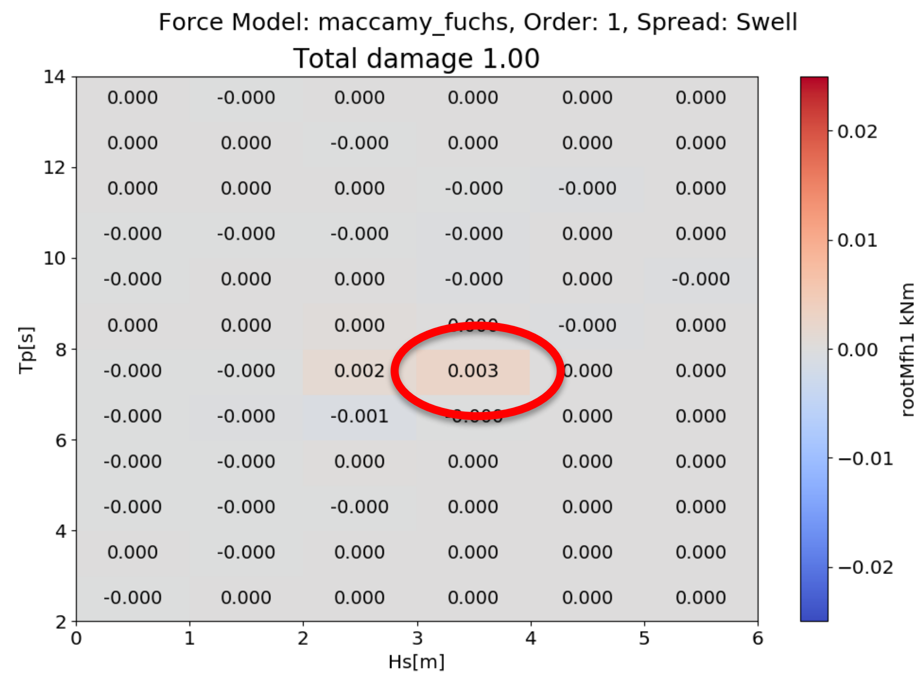
Fatigue due to Mudline Fx



MacCamy-Fuchs – 1st order – Swell

Fatigue due to Blade Root Flapwise moment



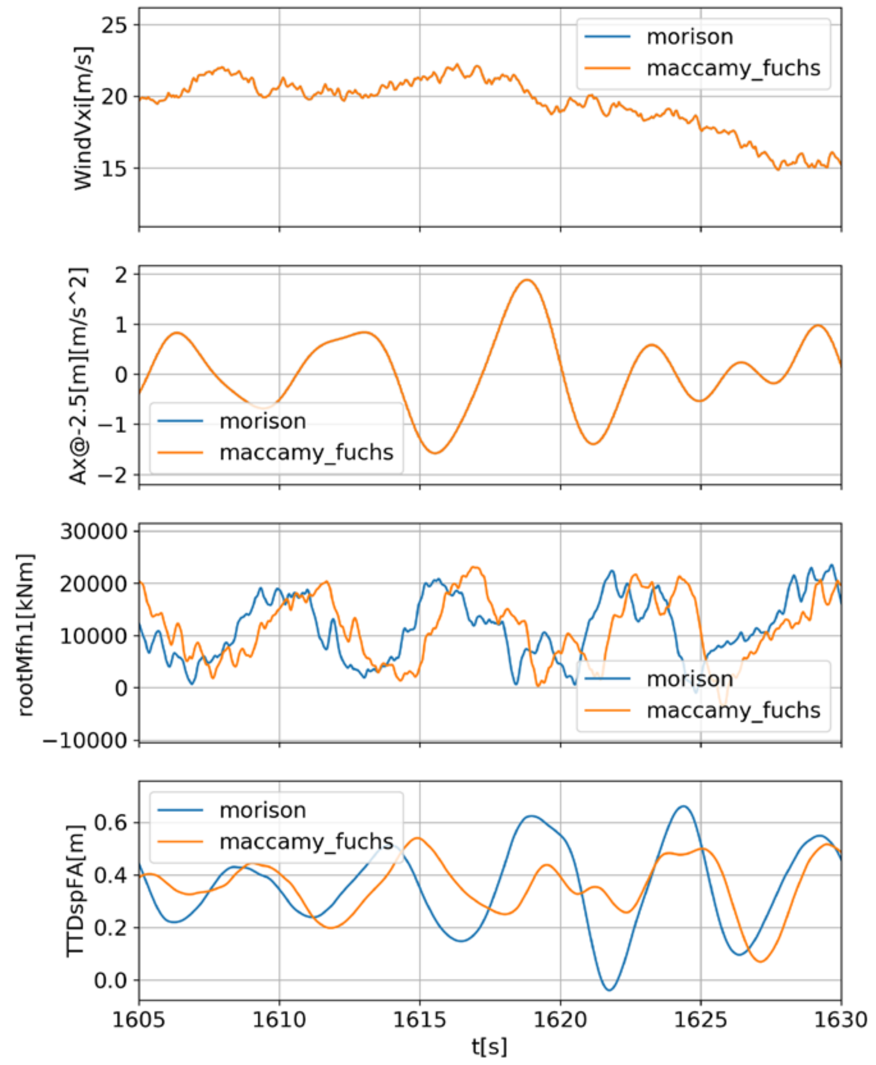


Example: effect of force model

- Power spectral density
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$

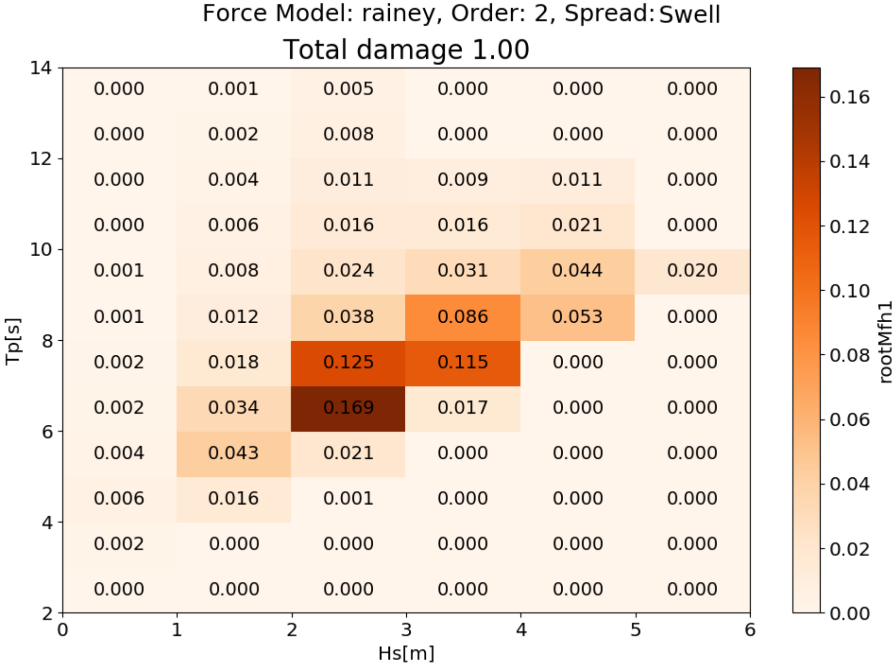
- Blade root Flapwise moment

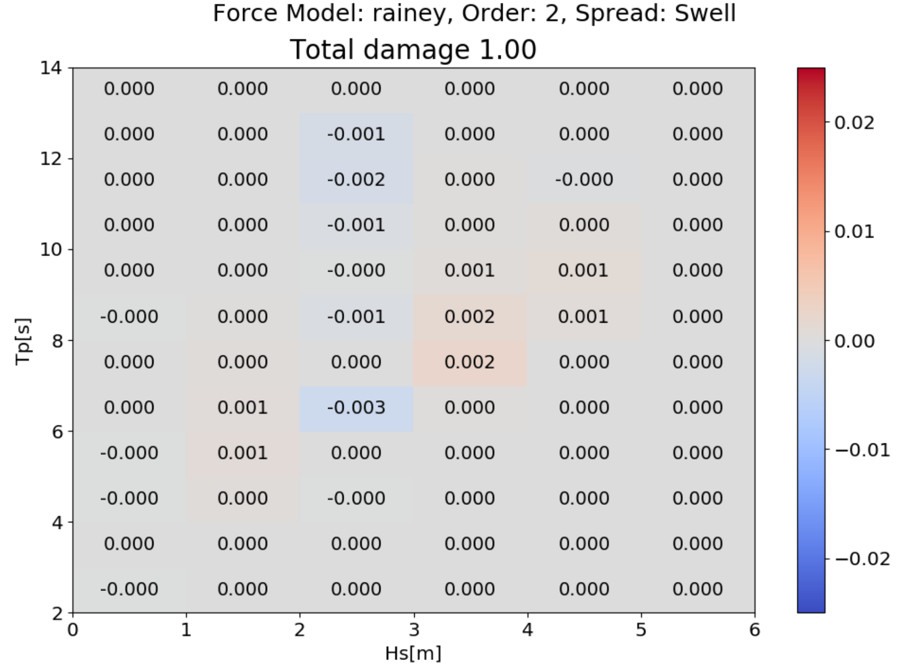
	Morison	Maccamy
Kinematics	1st order	1st order
Load Model	Morison	MacCamy-Fuchs
Directional spread	Long crested	Long crested



Rainey – 2nd order – Long crested waves

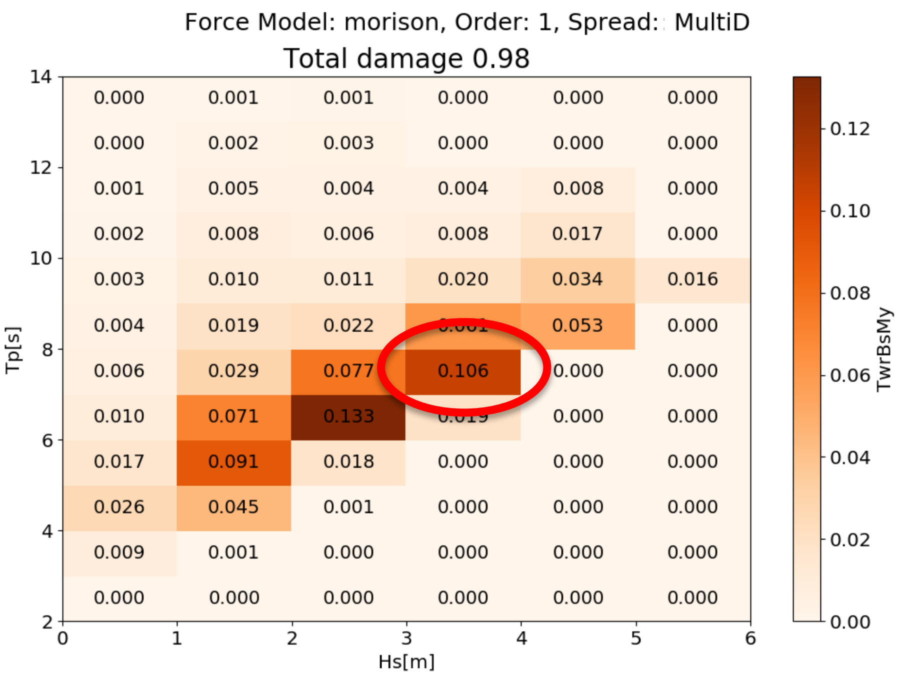
Fatigue due to Blade Root Flapwise moment





Morison – 1st order – Short vs Long crested

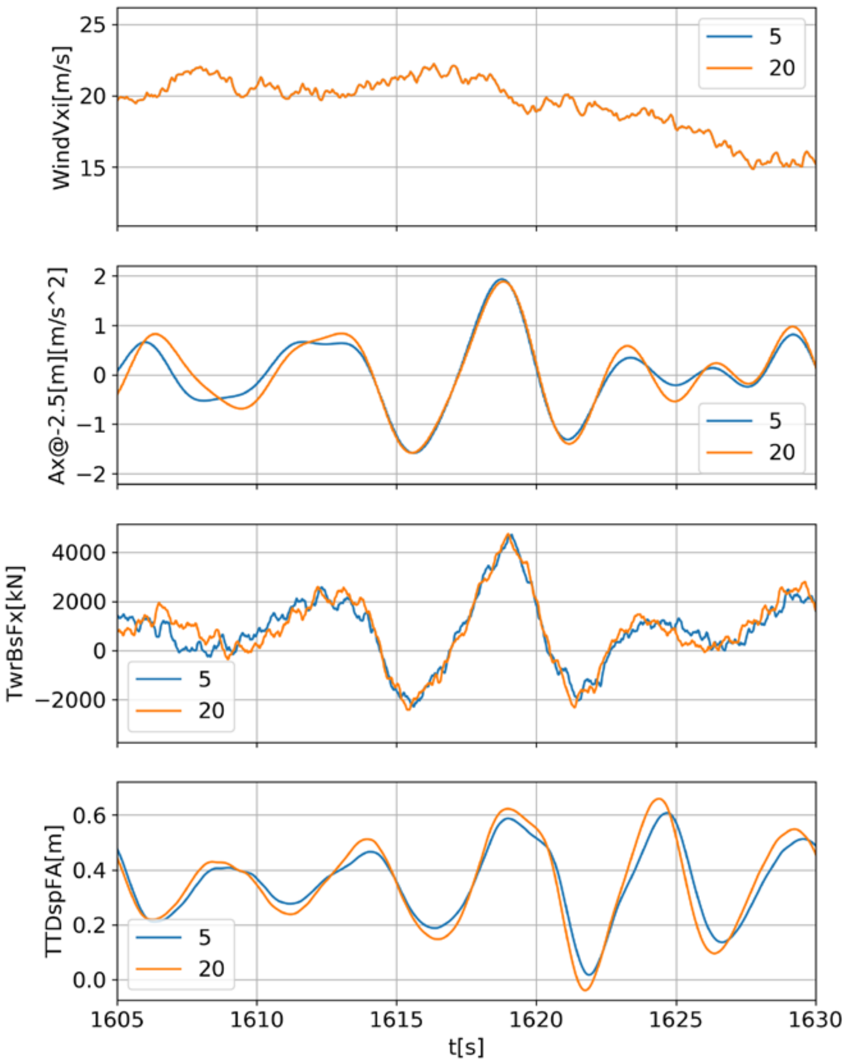
Fatigue due to Mudline moment around y-axis



Effect of wave spreading

- Time series
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force

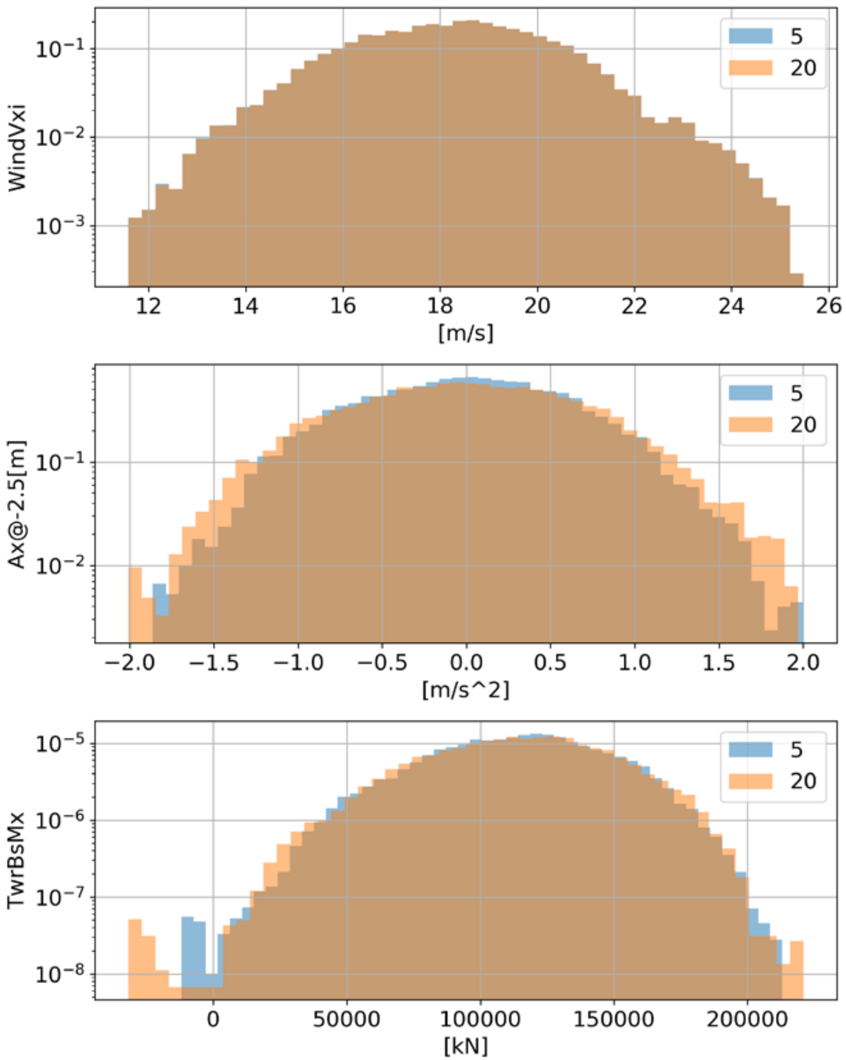
	5	20
Kinematics	1st order	1st order
Load Model	Morison	Morison
Directonal spread	Short crested	Long crested



Effect of wave spreading

- Histogram
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force

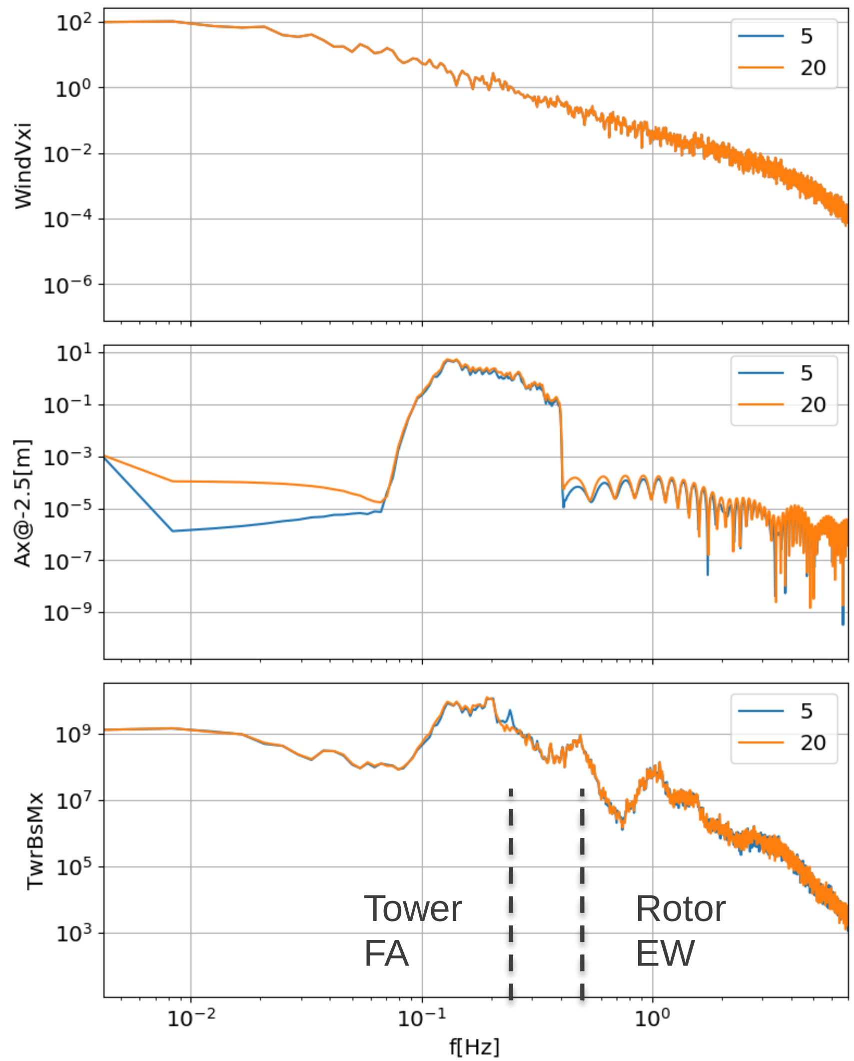
	5	20
Kinematics	1st order	1st order
Load Model	Morison	Morison
Directonal spread	Short crested	Long crested



Effect of wave spreading

- Power spectral density
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force

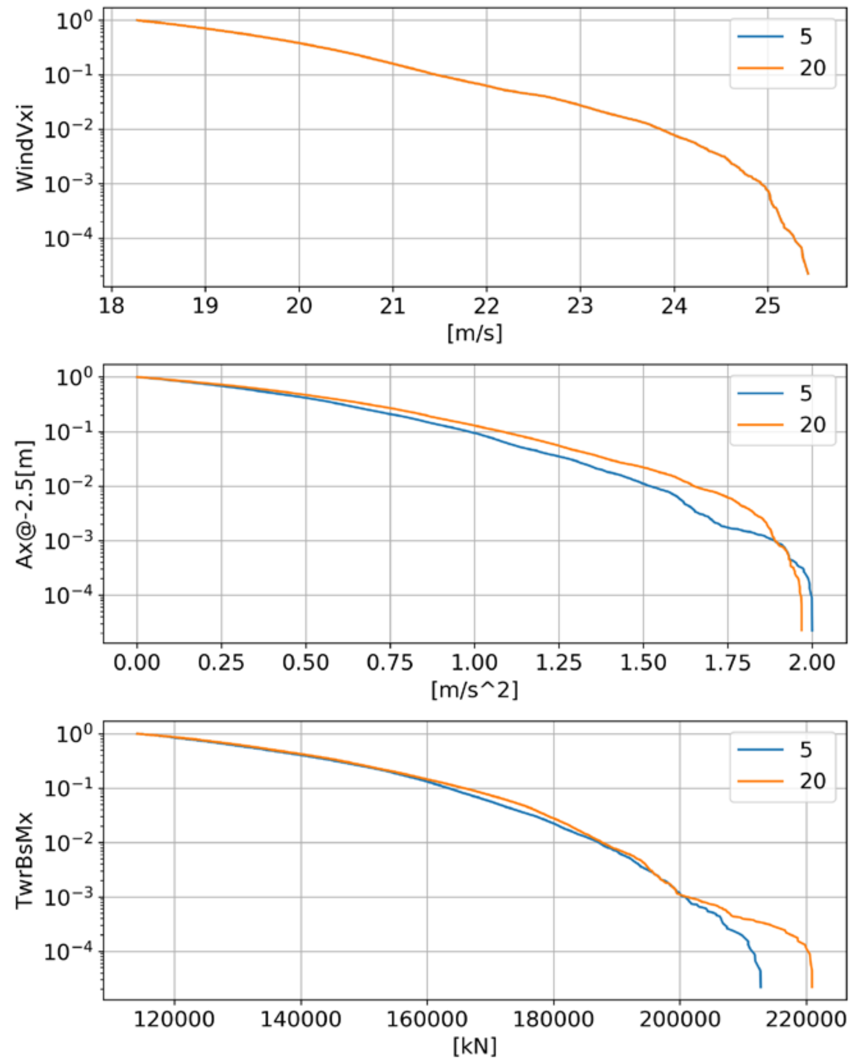
	5	20
Kinematics	1st order	1st order
Load Model	Morison	Morison
Directonal spread	Short crested	Long crested



Effect of wave spreading

- Exceedance probability
- Sea state
  - $H_S = 3.5\ [m], T_P = 7.5[m]$
- Mudline x-wise force

	5	20
Kinematics	1st order	1st order
Load Model	Morison	Morison
Directonal spread	Short crested	Long crested



Conclusions

- DIMSELO has shed light into effect of improved models on OWT dimensioning loads

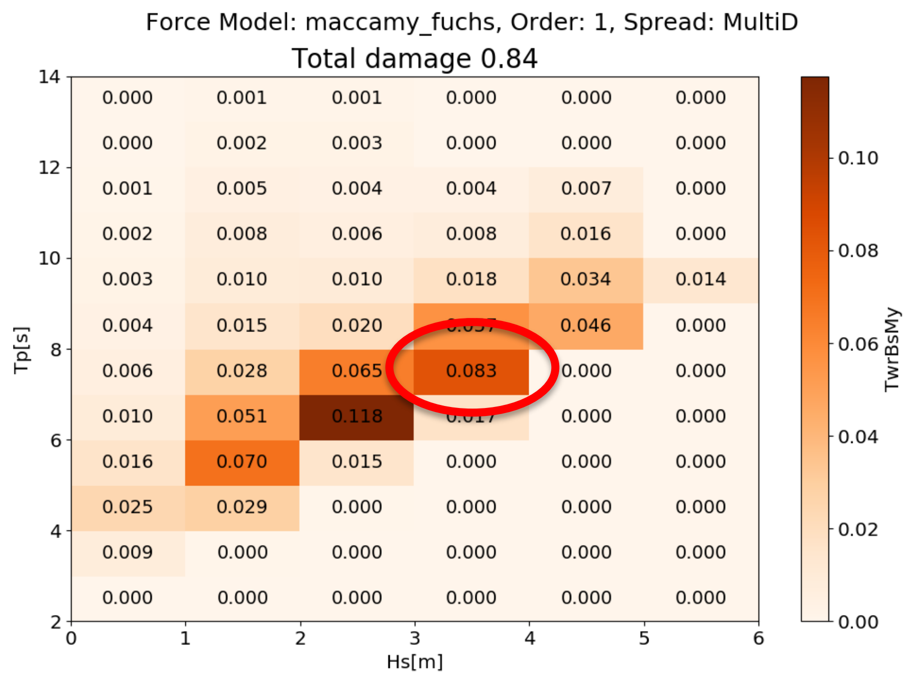
- It helped understand when it is useful to adopt a more complex wave **force** or **kinematics** model

- For example, on a 25m Monopile fatigue load case:
  - 1st order diffraction made a difference on tower base fatigue
  - the blade loads were insensitive to wave load models
  - 2nd order waves do not significantly influence fatigue loads

- Timeline: Complete the calculations and deliver final report

MacCamy-Fuchs – 1st order – MultiD

Mudline moment My



Design calculations: today's practice

- Fatigue calculations

- Linear irregular waves

- Morison equation

- Some critical points
  - Non-linearity in irregular waves
  - Non-linearity in the force model
  - What about wave diffraction of large monopiles?

- Extreme loads

- Embedment of a 50-yr nonlinear wave in long-crested waves
- Morison equation

- Some critical points
  - Directionality in the extreme loads?
  - Non-linearity of the force?
  - Statistical significance of extreme load?