Fatigue sensitivity to foundation modelling in different operational states for the DTU 10MW monopile-based offshore wind turbine

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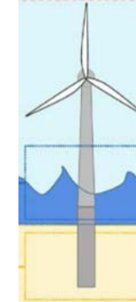
Norwegian University of Science and Technology



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EERA DeepWind'19, Trondheim, 17 January 2018

Source: University of Cambridge

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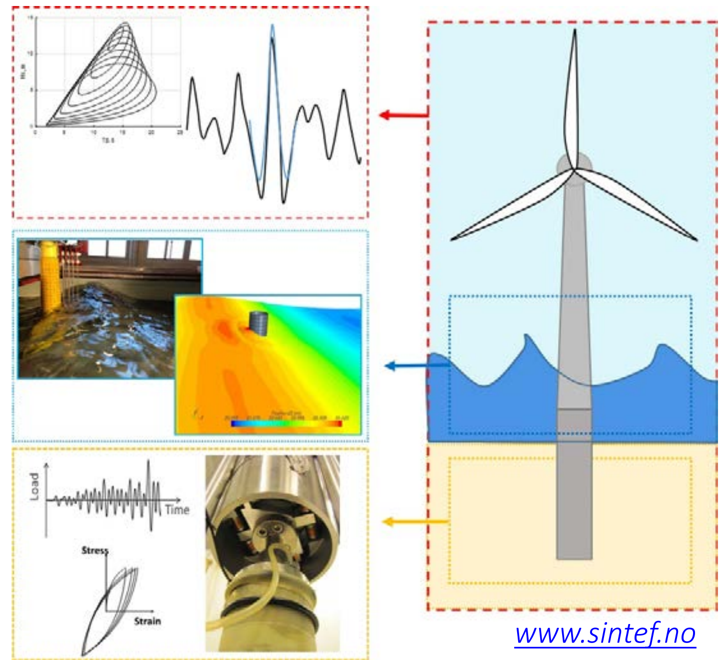
Part of WAS-XL project (Wave Loads and Soil Support for Extra Large Monopiles)

WAS-XL



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Primary objective: Reduction of uncertainties related to large-diameter monopile foundations.

Foundation modelling: Common methods (API *p-y*) not accurate -> more realistic representation of soil structure interaction is required.

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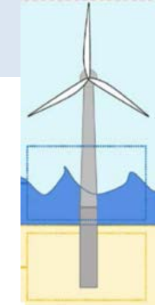
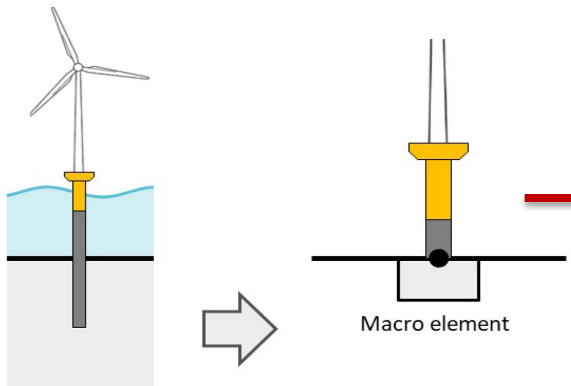
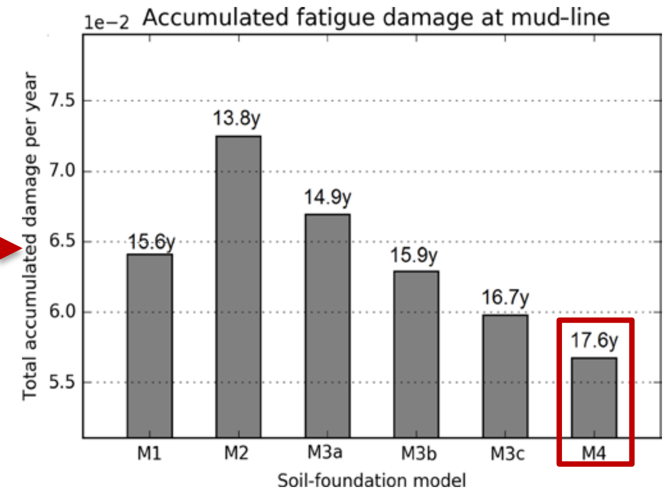


Macro – element formulation [1] results in fatigue damage reduction [2].





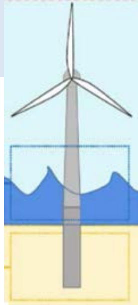
[REDWIN - Reducing cost of offshore wind by integrated structural and geotechnical design [1]]

[Aasen et al. "Effect of foundation modelling on the fatigue lifetime of a monopile-based offshore wind turbine" [2]]

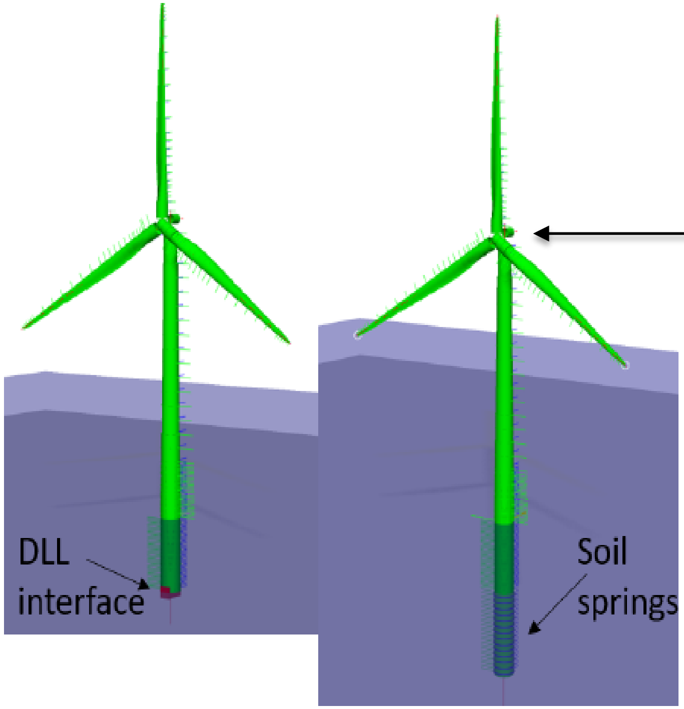
Aim of the present study

Importance of foundation modelling in fatigue damage *when aerodynamic damping is not effective.*

Parked States & Wind - Wave Misalignment Conditions



Wind Turbine model in *SIMO-RIFLEX*

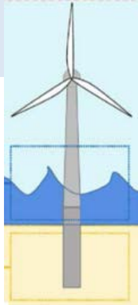


Hub-height: 119m

Cut-in speed : 4m/s
Cut-out speed : 25 m/s

Monopile structural characteristics

Diameter [m]	Thickness [m]	Penetration Length [m]	Young's modulus [GPa]	Shear Modulus [GPa]
9.0	0.11	36	210	81



Depth:30m

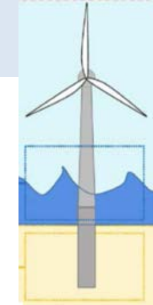
Example (Wind Bin 14 – 16 m/s)

Hs [m]	Spectral Peak Period [s]																
	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18
	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5
0.25																	
0.75			3.79E-06	5.29E-06	5.83E-07					7.41E-07	3.35E-07						
1.25			1.14E-05	4.83E-04	1.95E-04	3.80E-05	1.05E-05	1.75E-06	1.67E-06	3.43E-06	2.32E-06	4.45E-07	1.13E-06	5.36E-07			
1.75				5.16E-04	4.30E-03	1.53E-03	9.03E-05	5.07E-05	1.51E-05	1.49E-05	1.88E-05	5.24E-06	1.16E-05	8.84E-07			
2.25					1.35E-03	8.93E-03	2.02E-03	3.64E-04	1.04E-04	2.32E-05	2.30E-05	3.32E-05	1.87E-05	4.53E-06			
2.75					1.97E-03	[illegible]	3.54E-03	2.03E-03	3.07E-04	9.18E-05	2.96E-05	4.32E-05	7.30E-05	1.52E-05	2.04E-06		
3.25						1.70E-04	1.20E-03	7.76E-04	4.14E-04	2.66E-04	8.84E-05	1.89E-05	3.53E-05	6.06E-06			
3.75							3.73E-04	2.80E-04	1.85E-04	1.73E-04	7.82E-05	8.76E-06	5.78E-05	9.23E-06			
4.25							4.76E-05	5.48E-05	5.18E-05	6.88E-05	3.86E-05	2.96E-05	3.40E-05				
4.75									2.31E-05	1.51E-05		3.23E-05	4.58E-05				
5.25												1.48E-05	4.13E-05				

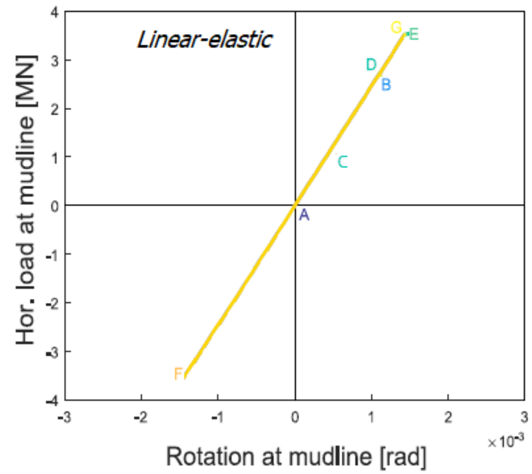
Selection of most contributing sea-states to the long-term fatigue damage for 5 wind bins.

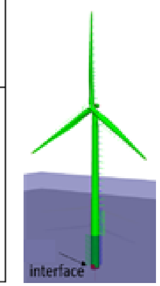
Simulation & Environmental Parameters

EC number	Time Simulation [s]	U_w [m/s]	H_s [m]	T_p [s]	Wind-Wave Misalignment [degrees]	Wave Spectrum
1	3600	5.06	0.75	5.50	0^o, 15^o, 30^o, 45^o, 90^o	Pierson–Moskowitz
2	3600	9.06	1.25	5.50		Pierson–Moskowitz
3	3600	14.94	2.25	6.50		Torsethaugen
4	3600	20.90	3.75	7.50		JONSWAP
5	3600	26.74	5.25	8.50		JONSWAP



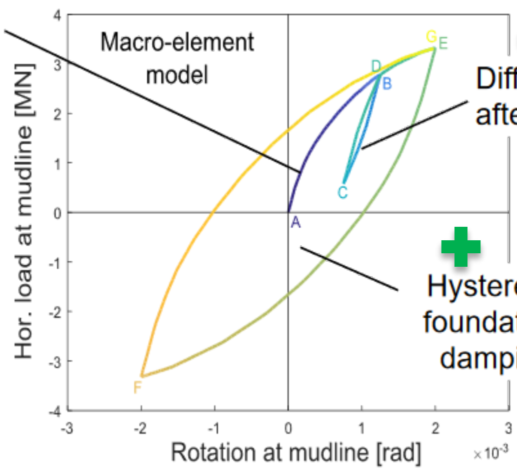
M2 - Linear elastic





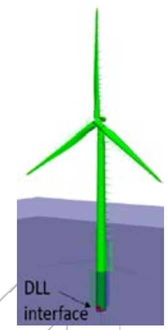
M1 - Nonlinear elasto-plastic

Accurate foundation stiffness from FEA

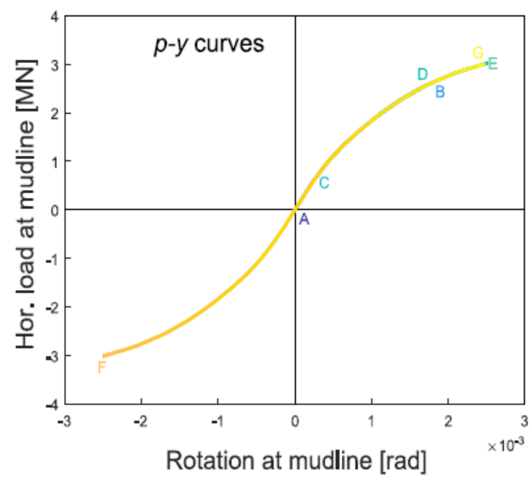


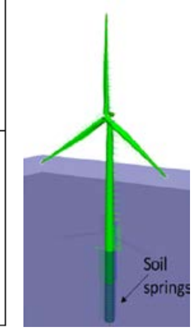
Different stiffness after load reversals

Hysteretic foundation damping

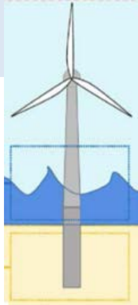


M3 - Nonlinear elastic

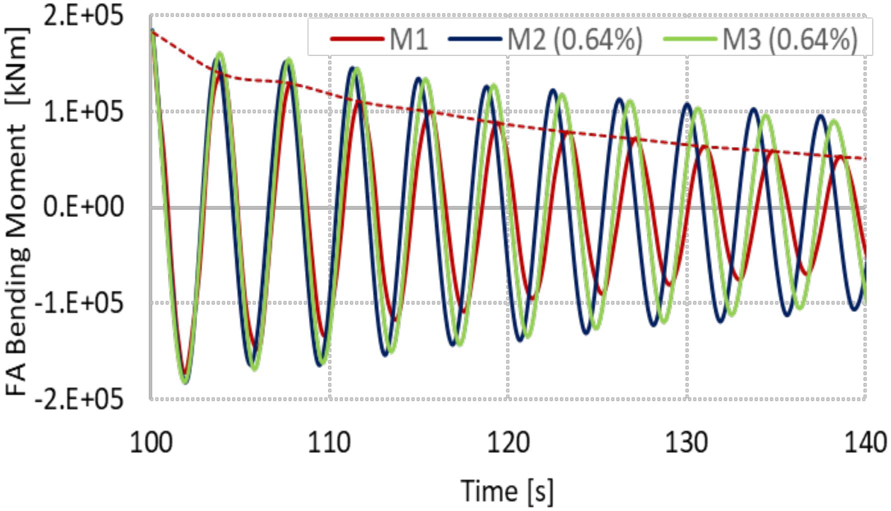




[Page et al. A macro-element pile foundation model for integrated analyses of monopile based offshore wind turbines [3]]

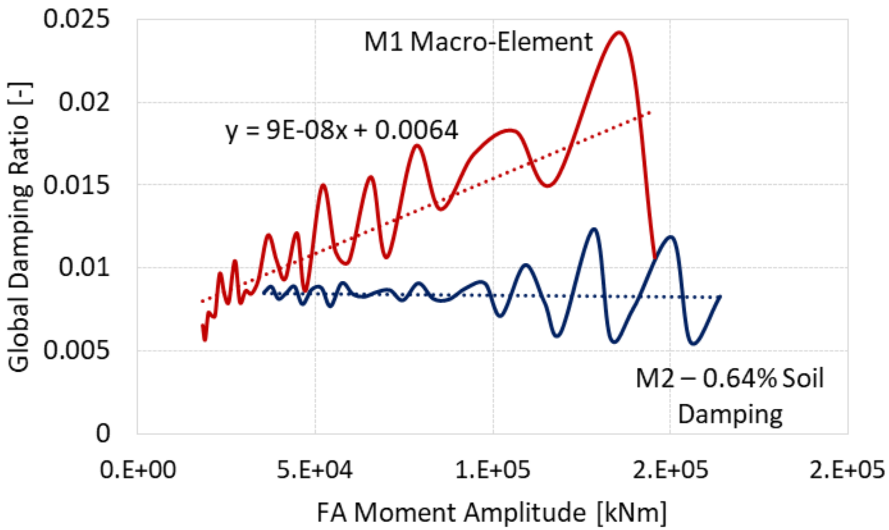


Decay test for M1: Contribution of foundation damping to global damping

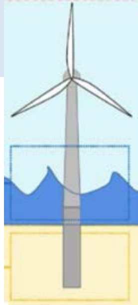


$$\delta = \ln\left(\frac{A_i}{A_{i+1}}\right) = 2\pi\frac{\xi}{\sqrt{1-\xi^2}} \approx 2\pi\xi$$

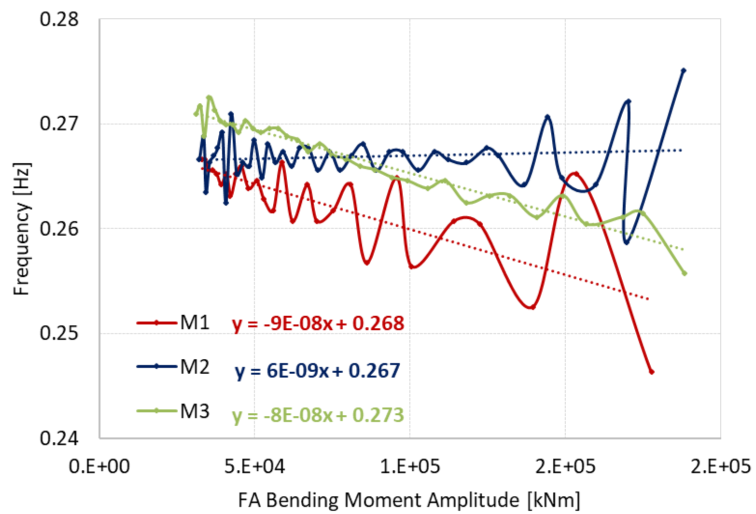
M2 & M3: Soil Damping 0.64% applied as Rayleigh structural damping based on M1.



Nonlinear damping in M1. Increases with respect to the response amplitude

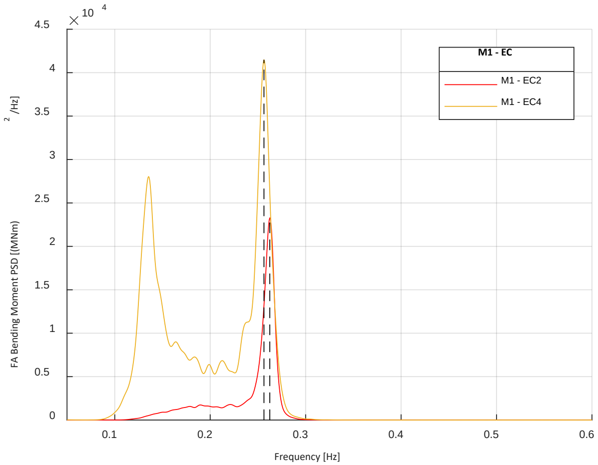


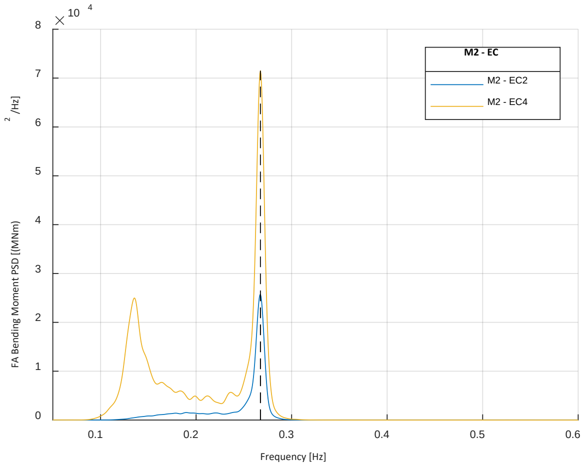
Natural frequency dependency on load levels

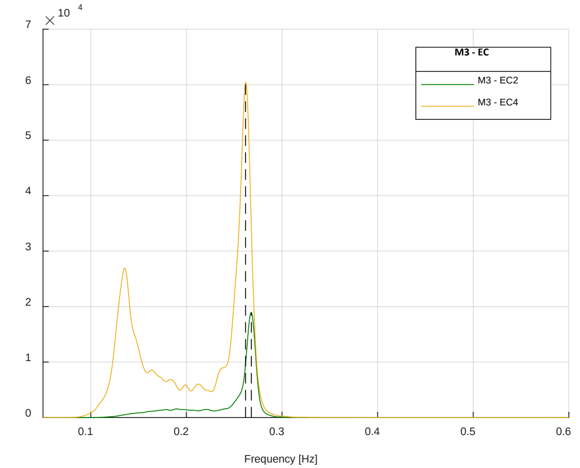


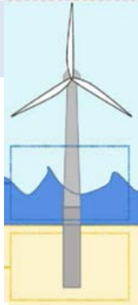
M1, M3 : For higher load levels → lower foundation stiffness → lower natural frequencies

M2 linear elastic model → Constant natural frequency for all load levels

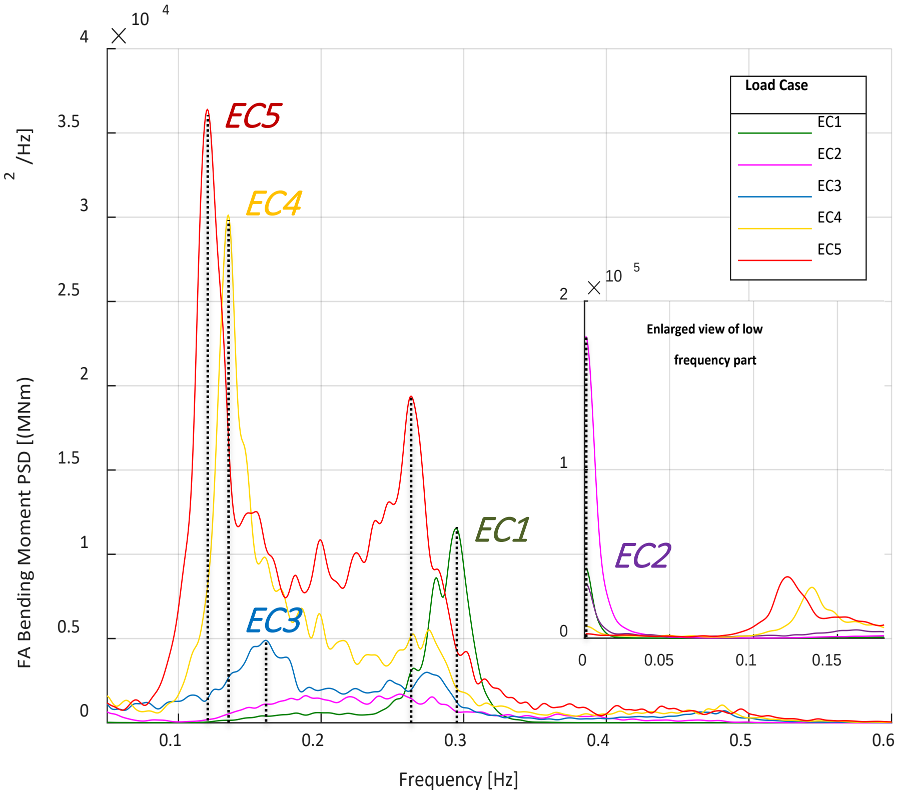








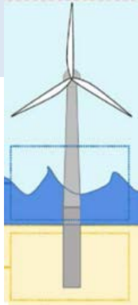
Operational state: Different processes dominate per EC



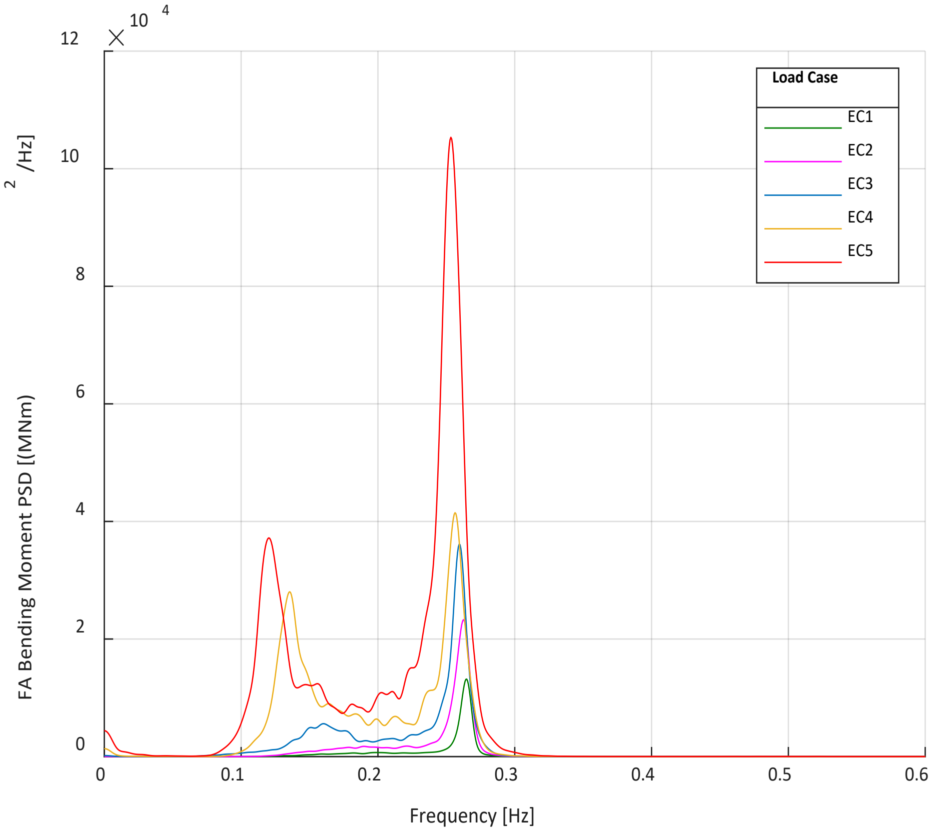
EC1	3P component
EC2	Slowly varying wind component
EC3	Wide range – Mainly waves
EC4	Waves – Aerodynamic damping effect at natural frequency range
EC5	Waves – Large loads at natural frequency range

EC	U_w [m/s]	H_s [m]	T_p [s]
1	5.06	0.75	5.50
2	9.06	1.25	5.50
3	14.94	2.25	6.50
4	20.90	3.75	7.50
5	26.74	5.25	8.50

Combination of stiffness and damping dominance per EC



Parked State: Responses close to natural frequency dominate for all ECs



EC	U_w [m/s]	H_s [m]	T_p [s]
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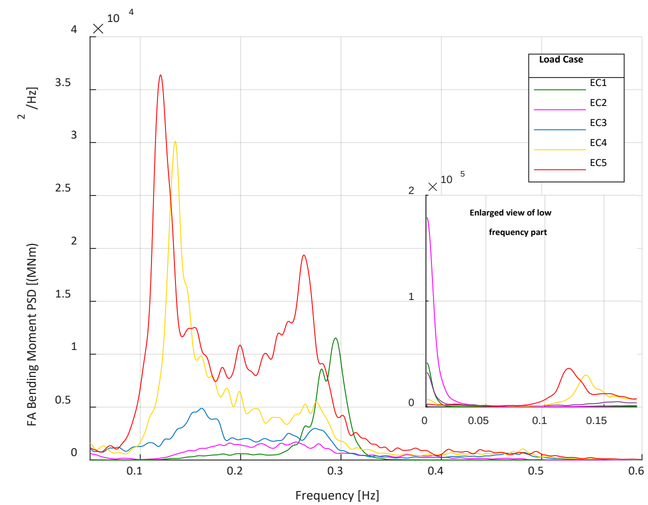
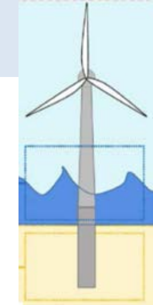


Figure of previous slide

(Operation)

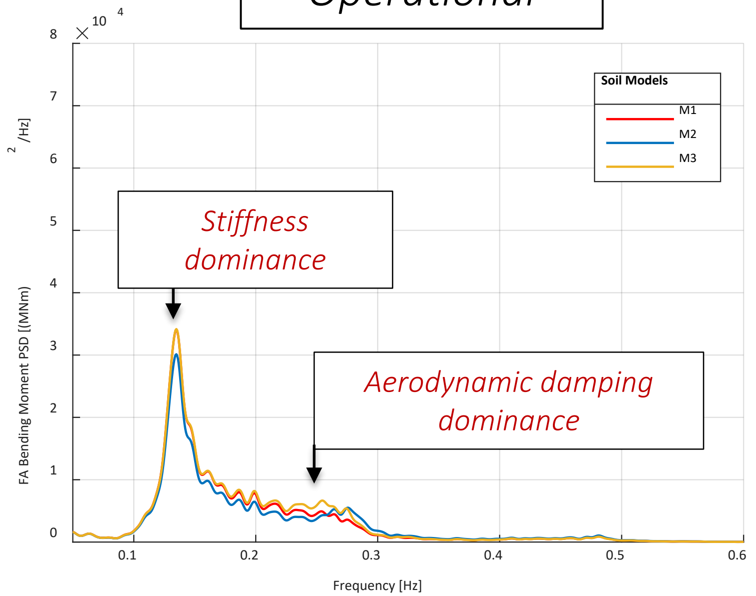
Soil Damping dominance for all ECs

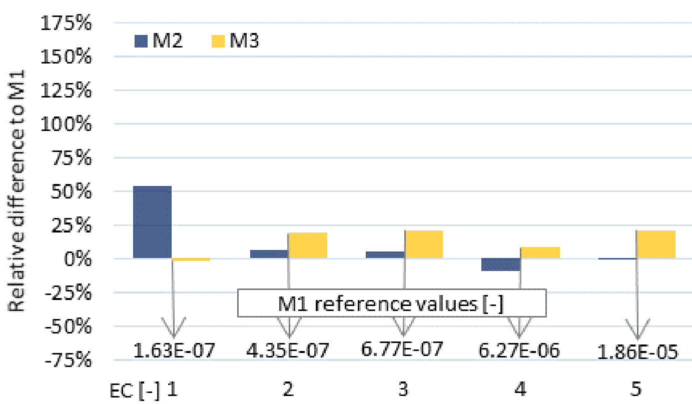


Comparison of the different soil models (Example - EC4)

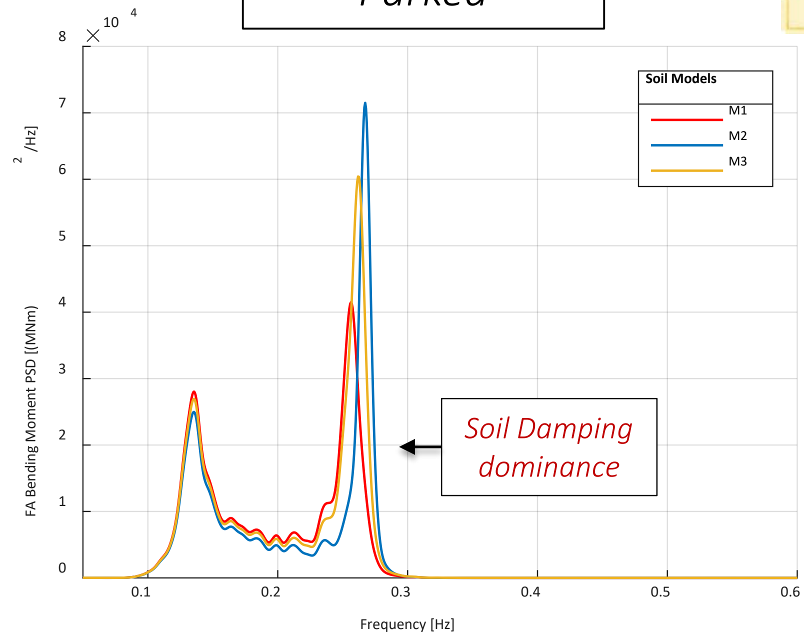
U_w [m/s]	H_s [m]	T_p [s]
20.90	3.75	7.50

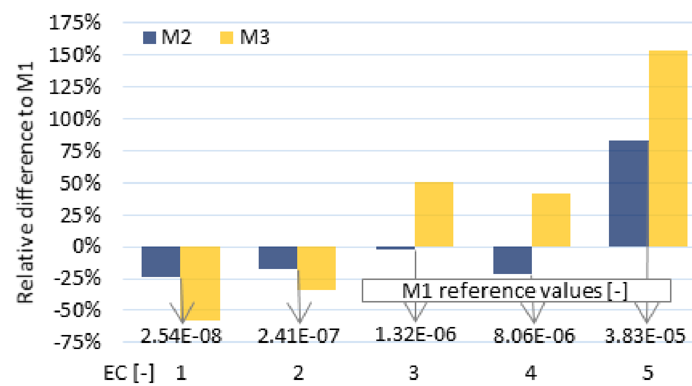
Operational

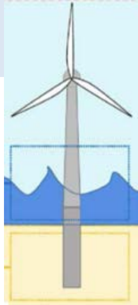




Parked

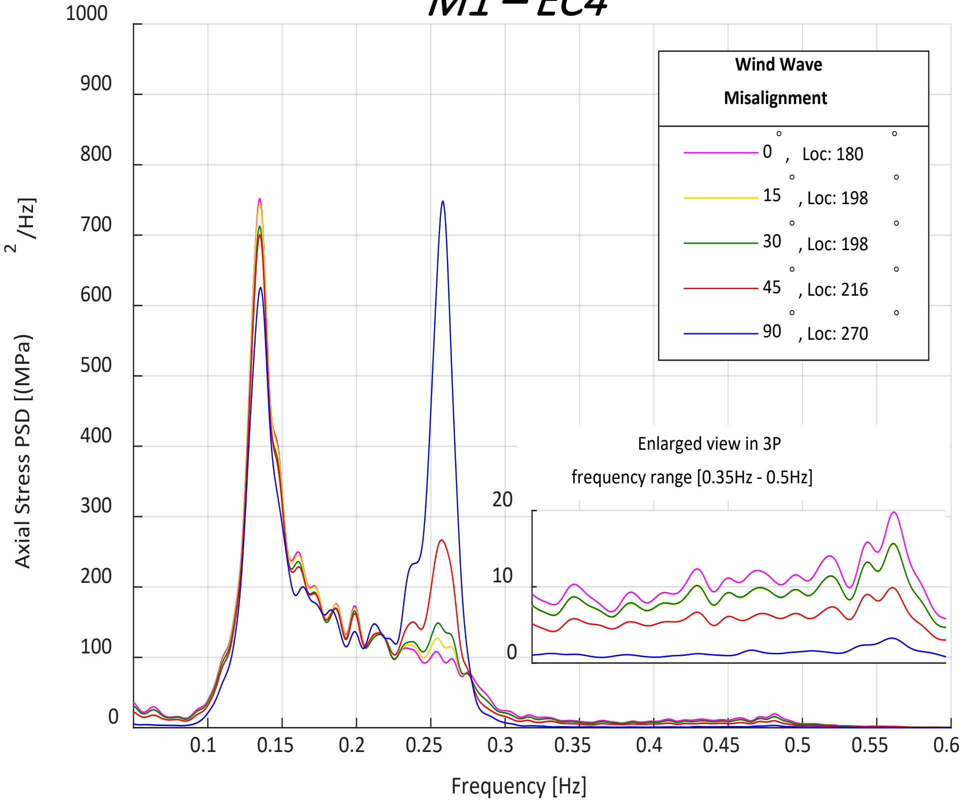


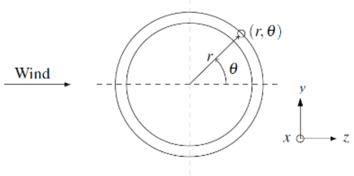




Operational State - Various angles of misalignment

M1 – EC4





EC	U_w [m/s]	H_s [m]	T_p [s]
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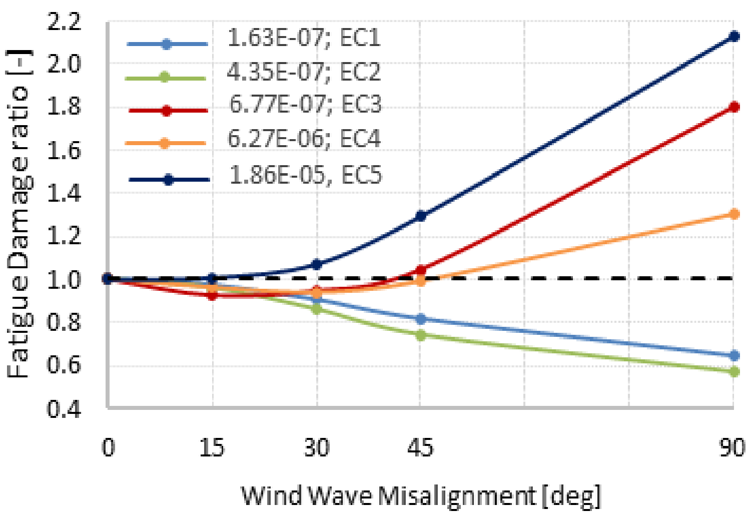
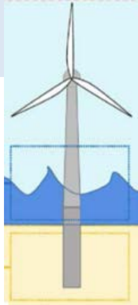


Soil Damping dominates for misalignment angles over 30 degrees



Operational State

EC	U_w [m/s]	H_s [m]	T_p [s]
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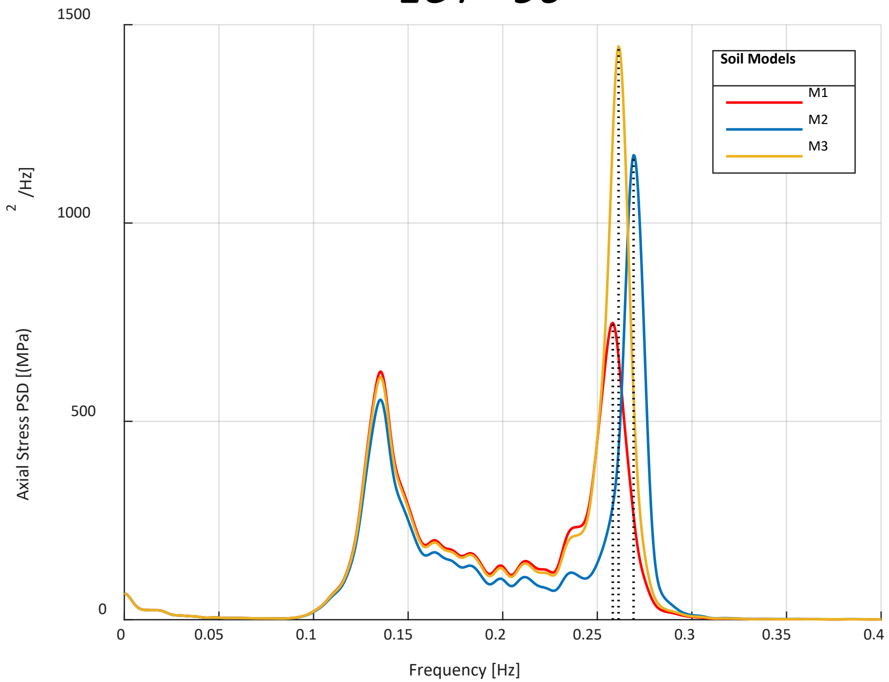
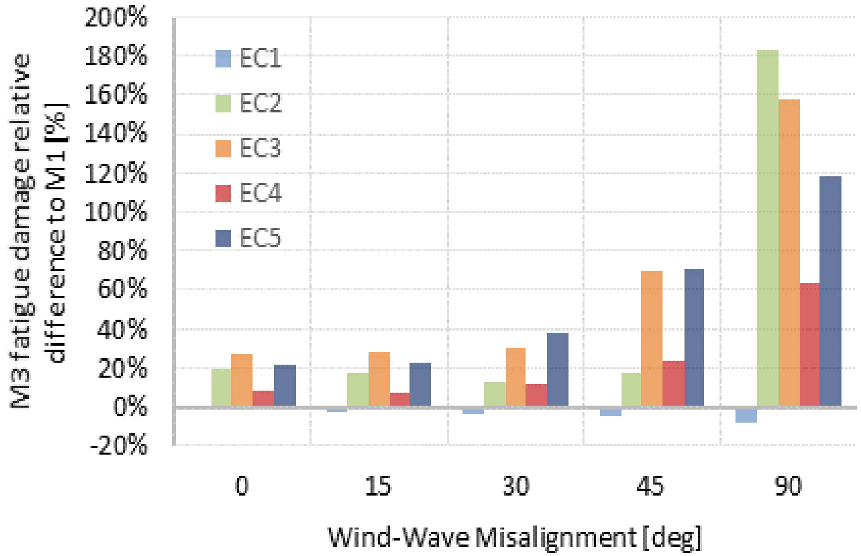
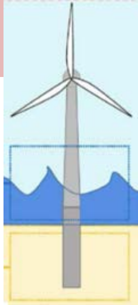
3	14.94	2.25	6.50
4	20.90	3.75	7.50
5	26.74	5.25	8.50

EC4 – 90°





Soil Damping dominates for misalignment angles over 30 degrees



Conclusions

1. Different processes dominate the dynamic processes depending on the environmental state.

2. Both foundation stiffness and damping formulation affect the behavior in different frequency regimes.

3. Considerably higher fatigue differences in parked state (-60% to 154%) compared to operational state (-10% to 50%).

4. Large differences (up to 183%) for misalignment angles larger than 30 degrees.

Relatively high importance of foundation modelling and hysteretic effects for fatigue damage in cases where aerodynamic damping is negligible.

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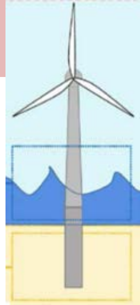
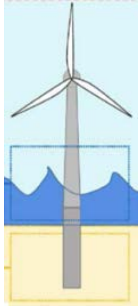


Acknowledgements

- Erin Bachynski (NTNU)
- Ana Page (NGI)
- Sverre Haver (UiS)



Thank you for your attention!

Questions?

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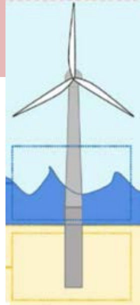
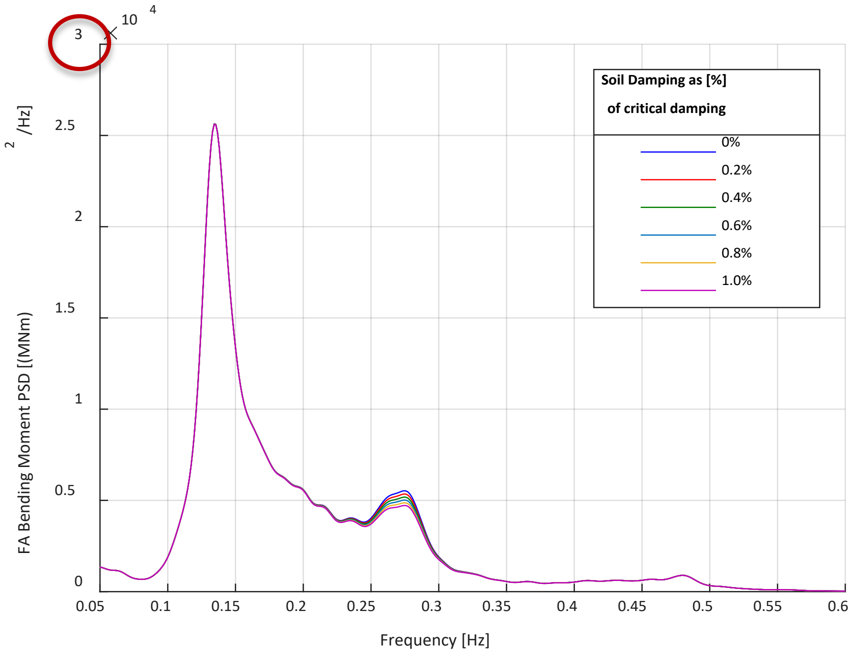
Science and Technology



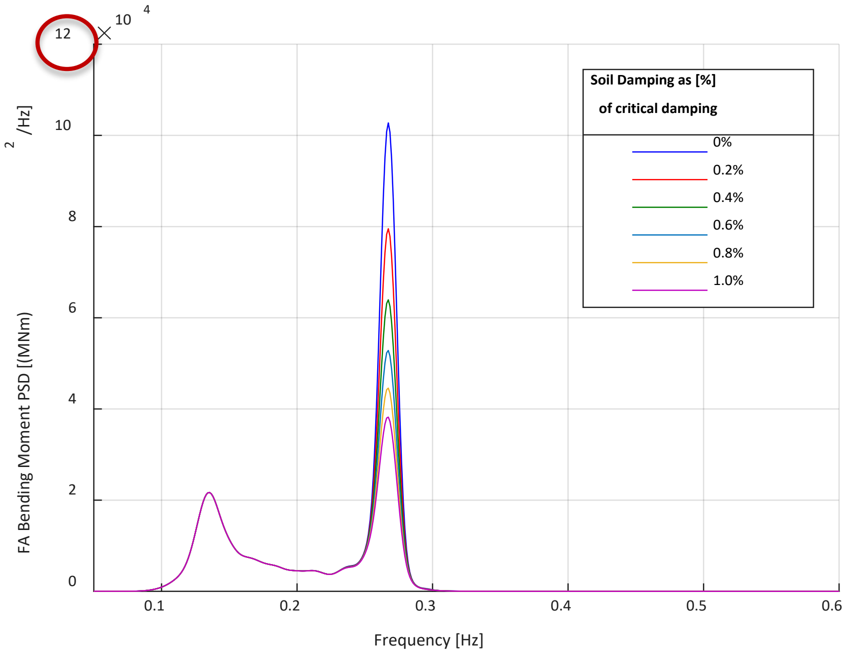
BACK-UP SLIDES

Fore-Aft Bending Moment PSD for M2 with varying of soil damping [%]

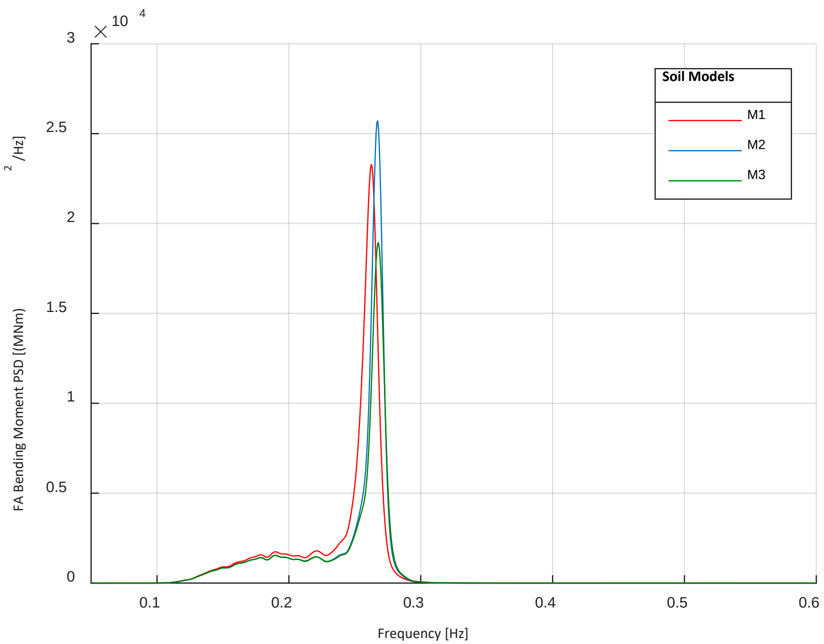
Operational

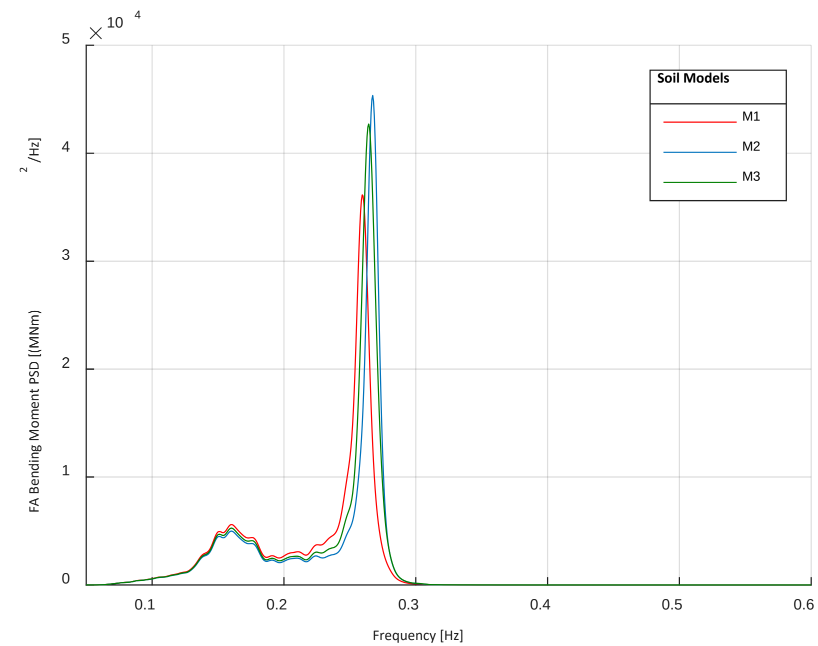


Parked

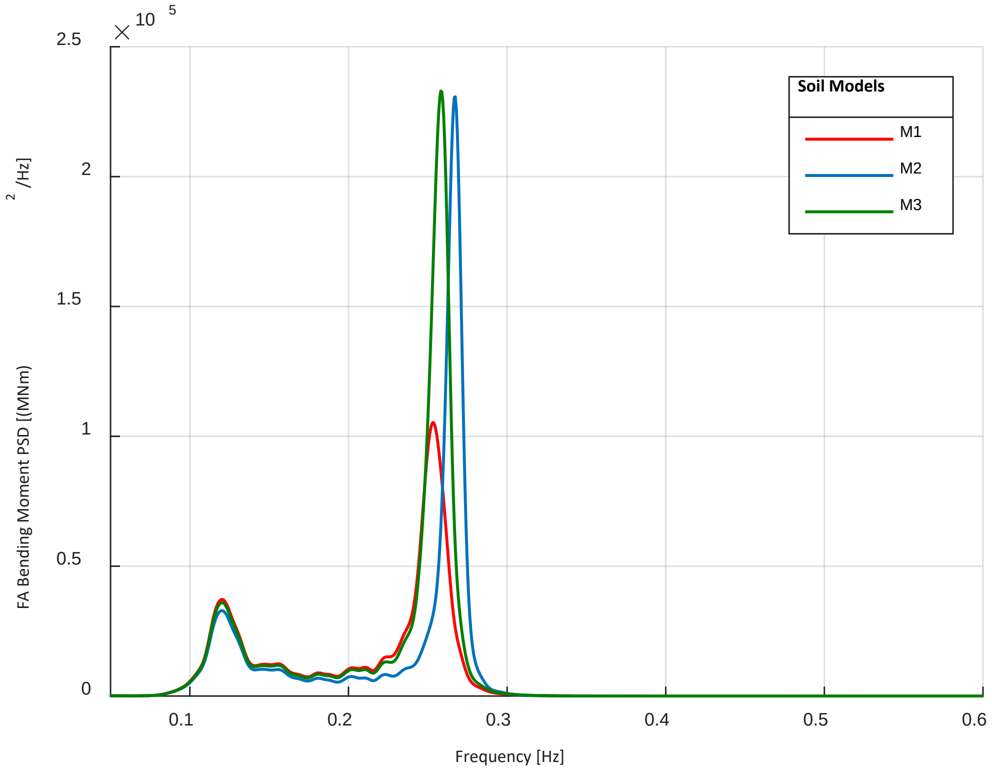


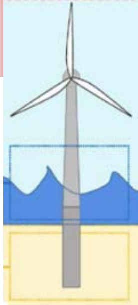
Fore-Aft Bending Moment PSD for EC2 – EC3





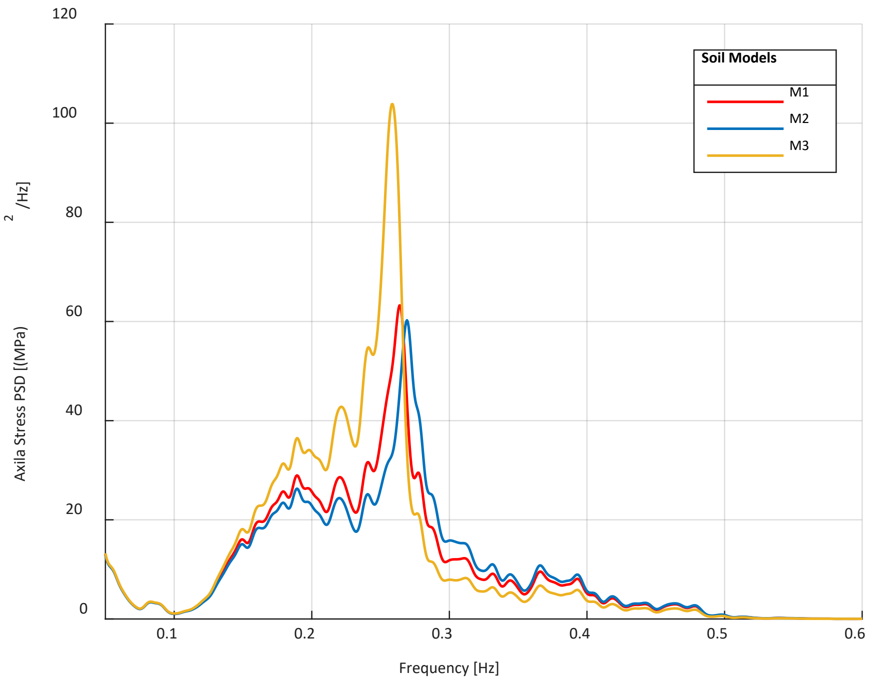
Fore-Aft Bending Moment PSD for EC5



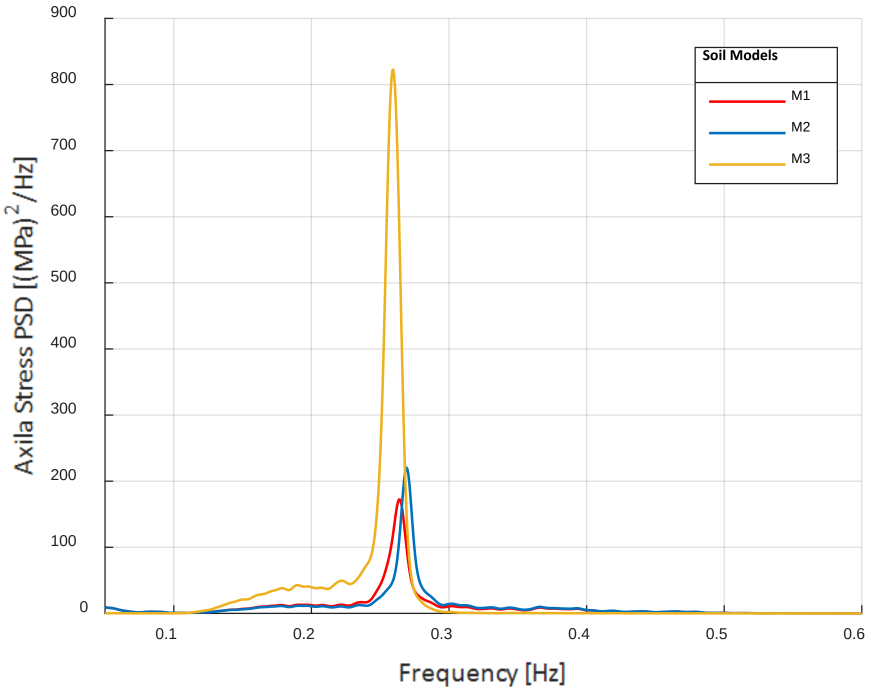


Operational

EC2 45

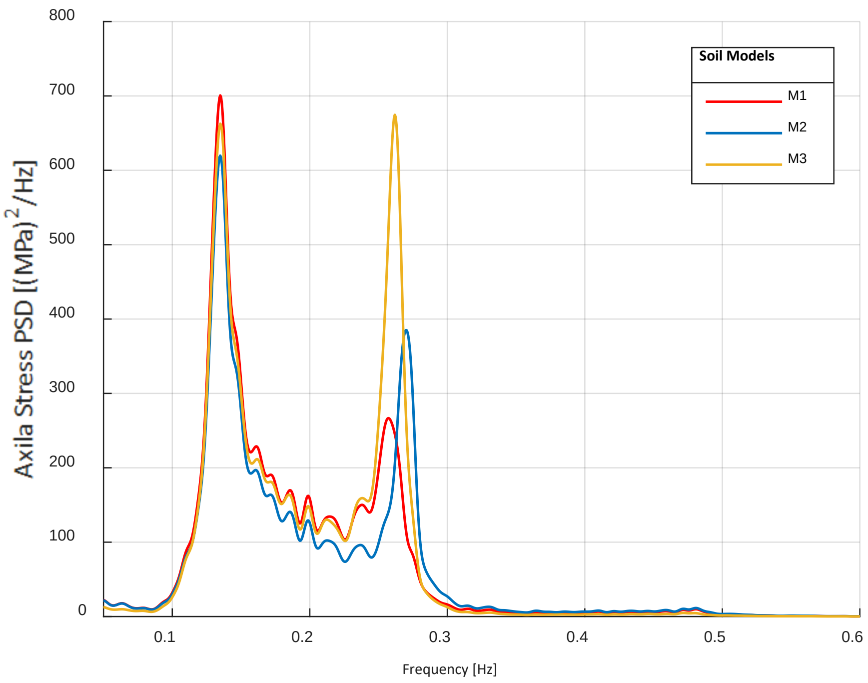


EC2 90

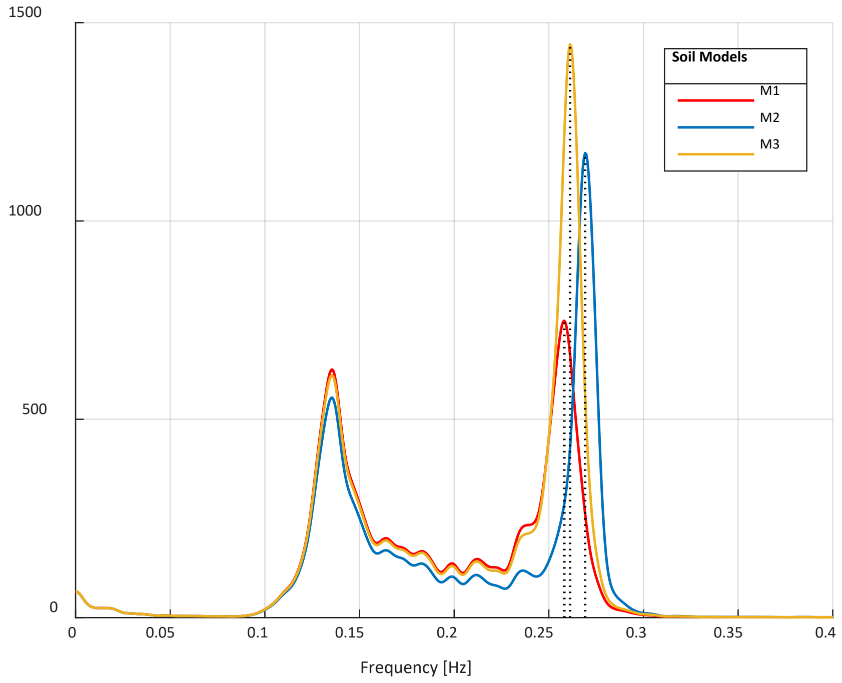


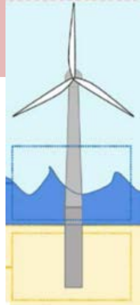
Operational

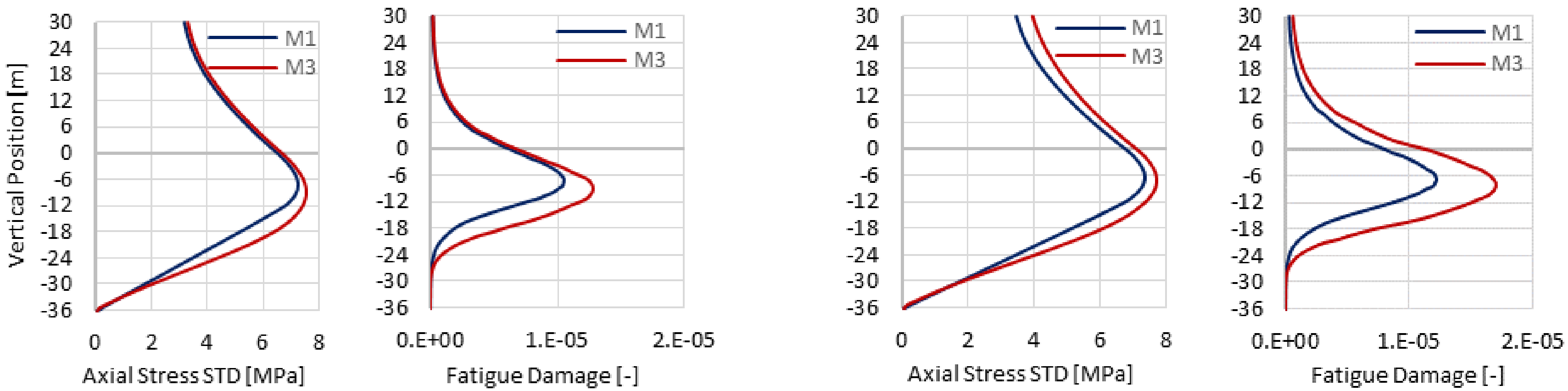
EC4 45



EC4 90







Axial stress STD & fatigue damage along monopile for operational (left) and parked (right) state [EC4]

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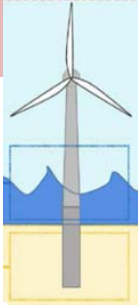
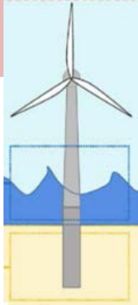
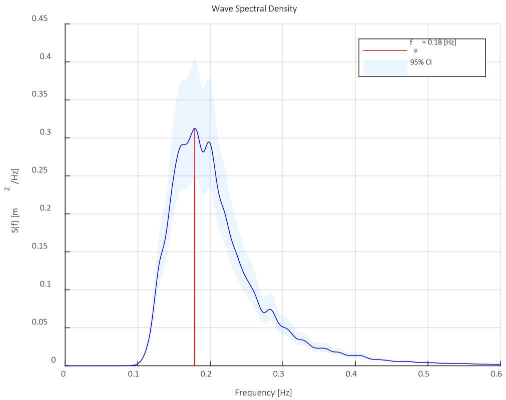
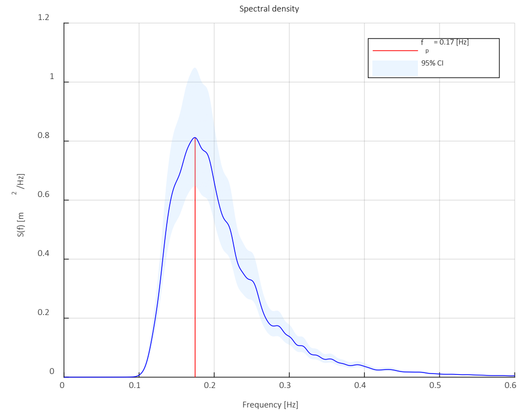
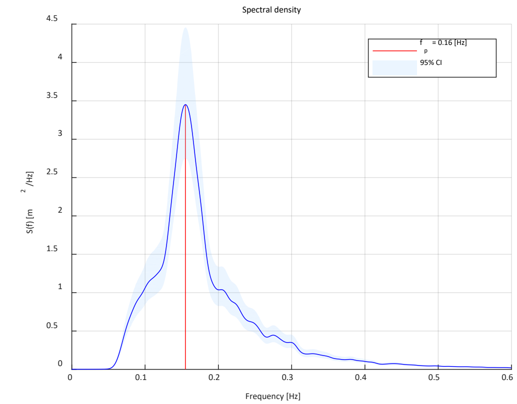


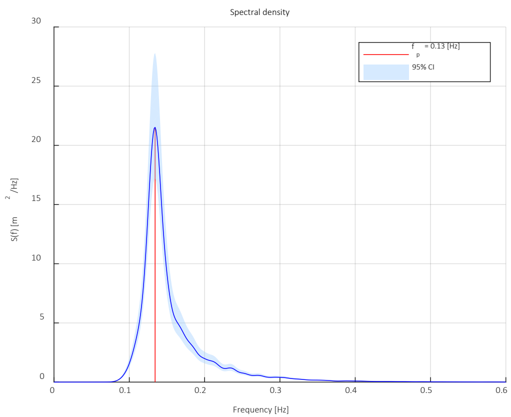
	Fatigue Damage [-] EC1			
	Operational		Parked	
0	1.63E-07	180	2.54E-08	180
15	1.58E-07	180	2.30E-08	198
30	1.47E-07	180	1.88E-08	198
45	1.33E-07	180	1.52E-08	216
90	1.06E-07	180	1.02E-08	270
	Fatigue Damage [-] EC2			
	Operational		Parked	
0	4.35E-07	0	2.41E-07	180
15	4.18E-07	0	2.18E-07	198
30	3.74E-07	0	1.74E-07	198
45	3.22E-07	18	1.35E-07	216
90	2.48E-07	324	8.07E-08	270
	Fatigue Damage [-] EC3			
	Operational		Parked	
0	6.77E-07	180	1.32E-06	180
15	6.27E-07	198	1.13E-06	198
30	6.42E-07	198	9.70E-07	198
45	7.08E-07	216	7.83E-07	216
90	1.22E-06	270	6.18E-07	270
	Fatigue Damage [-] EC4			
	Operational		Parked	
0	6.27E-06	180	8.06E-06	180
15	6.05E-06	198	7.20E-06	198
30	5.90E-06	198	6.46E-06	198
45	6.22E-06	216	6.16E-06	216
90	8.16E-06	270	6.56E-06	270
	Fatigue Damage [-] EC4			
	Operational		Parked	
0	1.86E-05	180	3.83E-05	180
15	1.87E-05	198	3.27E-05	0
30	1.99E-05	216	2.88E-05	198
45	2.40E-05	234	2.68E-05	216
90	3.95E-05	270	3.36E-05	270

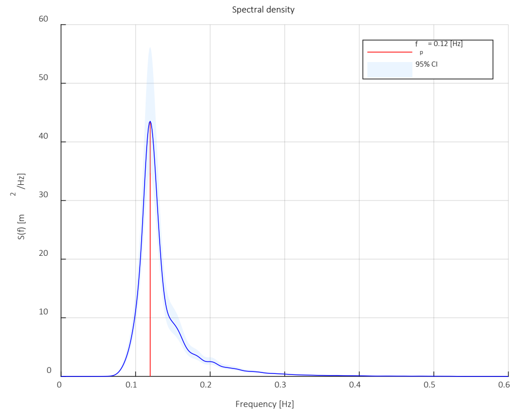












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