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Impacts of water depth increase on offshore floating wind turbine dynamics

Zi Lin¹, Xiaolei Liu^{2*}, Saeid Lotfian³

¹Department of Mechanical & Construction Engineering, Northumbria University, Newcastle upon Tyne NE1 8ST, UK

²James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, UK

³Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde, Glasgow G4 0LZ

*Corresponding author, E-mail: Xiaolei.Liu@glasgow.ac.uk

Abstract

This paper aims at investigating the effect of water depth increase on the global performance of a floating offshore wind turbine, with a special focus on the environmental loading effects and turbine operating status. An integrated aero-hydro-servo-elastic (AHSE) analysis was simulated in the time domain. The model was first validated against published results in terms of mooring system restoring force and platform natural frequencies. The considered water depth is between 200 and 300 m, which is the deep-water range used in the current floating offshore wind turbine (FOWT) industry. In this study, both normal operating and failure conditions were considered. Key conclusions from case studies indicated that, based on the current water depth range, platform heave motion with slack mooring configurations and mooring line top tension are more sensitive to water depth. Water depth increase influences the tower base bending force when the turbine has a high-speed shaft brake due to grid loss, but the effects are restricted to the high-frequency response range (>2 Hz) and less obvious than the influences on mooring lines.

Keywords

FOWT; failure condition; water depths effects; slack mooring; taut mooring

Nomenclature

Abbreviations

AHSE	Aero-hydro-servo-elastic
BEM	Blade Element Momentum
BVP	Boundary Value Problem
DEL	Damage Equivalent Load
DFT	Discrete Fourier Transform
DOF	Degree of Freedom
FOWT	Floating Offshore Wind Turbine
FPSO	Floating Production Storage and Offloading

33	HSS	High-speed Shaft
34	IEC	International Electrotechnical Commission
35	JONSWAP	Joint North Sea Wave Project
36	LC	Load Case
37	NREL	National Renewable Energy Laboratory
38	NTM	Normal Turbulence Model
39	PSD	Power Spectral Density
40	QTF	Quadratic Transfer Function
41	SWL	Still Water Level
42	<i>Symbols</i>	
43	ω	Circular Frequency
44	φ	Local inflow angle
45	$b(\omega)$	Radiation Damping
46	ρ	Water Density
47	A_k and A_l	Complex wave amplitude
48	$F_{mooring}$	Mooring force
49	F_{seabed}	Forces due to seabed and mooring line interaction
50	F_v	Viscous force
51	F_{wave}	Wave force
52	F_{wind}	Wind force
53	L_{ji}^{RF}	Load range about a fixed load-mean value
54	M^a	Added mass
55	U_0	Current velocities
56	$U_{sub_surface}$	Sub-surface velocity
57	V_{total}	Total wind velocity

58	n_j^{STeq}	Total equivalent fatigue counts for the j^{th} time series
59	z_d	Vertical position of the water particle
60	Φ_w	Incident wave potential
61	γ^r	Peak enhancement factor
62	ζ_a	Wave amplitude
63	c_b	Damping coefficients
64	h, d	Water depth
65	k	Wavenumber
66	K	Stiffness matrix
67	k_b	Stiffness coefficients
68	M	Mass
69	N	Number of waves
70	n, l, m, j	Number index
71	r	Local radius
72	R	Retardation function
73	t	Time
74	ε	Random phase

75

76 1. Introduction

77 The UK government's new vision of power every home through offshore wind by 2030 necessitates a substantial
78 advancement of innovative offshore wind technologies (Durakovic, 2020). This goal can be achieved by significant growth in
79 the offshore wind sector, with larger turbines to be developed in deeper water depths. In addition, the EU offshore wind industry
80 has boosted since last few years, reaching to 3,627 MW new capacity installations in 2019, with a trend of continues expansion
81 of wind farm size and moving to deeper water depths (Walsh, 2020). Worldwide, the majority of the seawater depth, for
82 example, over two-thirds of US coastal areas and European locations, suitable for wind turbine installations is floating solutions
83 (Simos et al., 2018), which has triggered the offshore wind industry gradually moving to deeper water depths.

84 Offshore wind turbines are sited on fixed or floating platforms. Fixed foundations, such as gravity and monopile types, are
85 restricted to a maximum water depth of 15 and 30 m, respectively (Nagababu et al., 2017). However, from an economic prospect
86 of view, a fixed base starts to lose its advantage for water depths larger than 60 m (Goupee et al., 2014). Water depth is one of
87 the key factors in identifying foundation technology (Nagababu et al., 2017). More specifically, for floating structures with
88 mooring lines, water depth is well known to be a critical parameter in system design, as illustrated by Luo and Baudic (Luo
89 and Baudic, 2003): mooring line length, material and configuration are required to satisfy strict criteria. Currently, fewer
90 studies have focused on mooring system design & analysis with increased water depths. It is widely agreed that a large number
91 of parameters related to the design & analysis of floating offshore wind turbines (FOWTs) need to consider the variety of water
92 depths. The corresponding trend and analysis methods have been learnt from the offshore oil & gas industry. More specifically,
93 when water depth increases, the length and type of mooring lines are adjusted to provide the most effective stiffness for station-
94 keeping purpose. With the growth of water depths, the dynamics of mooring lines are becoming more vital than relative
95 shallower water depth scenarios, which has an emphasis on relying on the coupled system analysis rather than an un-coupled
96 analysis. Generally speaking, water depth effects for moored structures could be divided into two categories:

- 97 • One stems from the wave forces in the wave-structure interaction problems, showing a water depth-dependent
98 character, especially in shallow water range.
- 99 • The other comes from the interaction between the floating support structure, showing a different level of coupling
100 effects and the dynamic motion responses of the whole system. For most of the moored offshore structures, these
101 coupling effects are stronger in deeper water depth.

102 For the first category, a widely accepted numerical simulation framework is under the potential flow theory and focuses
103 on the floating body only. Moreover, the adopted assumption is the evaluation of wave forces are not strongly coupled with
104 mooring line dynamics, and therefore the system global performance is often calculated by an un-coupled way in the frequency
105 domain. Both water wave theories and wave forces are depth-dependent. A number of relevant studies have been investigated
106 intensively and are of great significance for the design & optimization of offshore floating structures. The amplitude of second-
107 order forces are much smaller than that of the first-order counterparts, but the difference and sum-frequency components of
108 second-order forces are essential as they are of the potential for trigger slowly varying responses or high-frequency oscillations,
109 respectively (Roald et al., 2013). More specifically, ship-shaped floating support structures like floating production storage and
110 offloading (FPSOs) are sensitive to surge excitation due to their low damping in surge direction (Bayati et al., 2015). In terms
111 of FOWTs, the types of support structures have seen a large variety, but the water-plane area has a much smaller dimension
112 compared to FPSOs. Nonetheless, nonlinear wave forces remain significant for the support structure design & optimization of

113 FOWTs. To this end, Roald *et al.* (Roald et al., 2013) compared the level of significance of different loading sources applied
114 on FOWTs, showing that, for a Spar-type FOWT, the second-order forces are likely to excite eigenfrequencies, although the
115 level of magnitude of the mean drift force is much smaller than that of mean turbine thrust force. In another example, Duarte
116 *et al.* (Duarte et al., 2014) analysed the effects of second-order wave forces on a Spar-type 5 MW offshore wind turbine. It is
117 concluded that using Newman's approximation (Newman, 1974) underestimated pitch response of the FOWT, regardless of
118 normal of extreme sea states.

119 Another consideration has focused on the subsequent effect from the interaction between the mooring lines and the floating
120 body, which is also considered as the coupling effects. For shallower water depth, tradition mooring materials include heavy
121 mooring chains and usually formed in a spread mooring configuration. The weight of mooring chains, compared to the floating
122 body, results in a weak coupling effect between the floating body and the mooring lines. Therefore, motion responses and
123 global performance are often carried out in a non-coupled method. With the upsurge of water depths, the coupling effects
124 between floating bodies and mooring lines are becoming increasingly central. Moreover, the components of low-frequency
125 responses out surge the other motion components in deep water depths. For example, Bayati et al. (2015) analysed the effects
126 of water depths for a semisubmersible type FOWT. The water depth ranges from 30 to 200 m. It is claimed that water depths
127 have a greater influence on heave motion than surge motion when water depth decreases from 200m to 30m. Chen et al.
128 (2019) analysed the motion response of the wind turbine support platform considering water depth effects. It is claimed that the
129 effects of water depth mainly happened in shallower water depths. From a structural safety point of view, water depths effects
130 need to be considered during the design process and the motion analysis of floating wind turbines. It needs to be pointed out
131 that Chen et al. (2019)'s investigations were based on an un-coupled analysis, without considering the coupling effects between
132 wind turbine aero-hydro-servo-elastic (AHSE) and mooring line dynamic responses. Wen et al.(2018) designed a short new
133 spar floating vertical axis offshore wind turbine, aiming at operating in a moderate water depth range, based on the feasibility
134 of fully coupled time-domain numerical simulation. It is demonstrated that the new spar outperformance the original design in
135 terms of platform horizontal motion responses and tower side-side bending moments. (Le et al. (2019) proposed a new
136 submerged offshore wind turbine aiming at operating in intermediate water depths between 20 and 200 m. Feasibility studies
137 were put forward concerning different environmental conditions, tether length, tether pretension and tether failure scenarios. It
138 is claimed that tether length contributes to the surge, heave pitch and yaw motion responses.

139 As a result of more stable wind resources in offshore locations, this paper contributes to investigating the effects of water
140 depth increases for deepwater FOWTs using an integrated AHSE analysis and considers the nonlinear hydrodynamics of the
141 support structures. To sum up, this paper aims at bridging the following knowledge gaps:

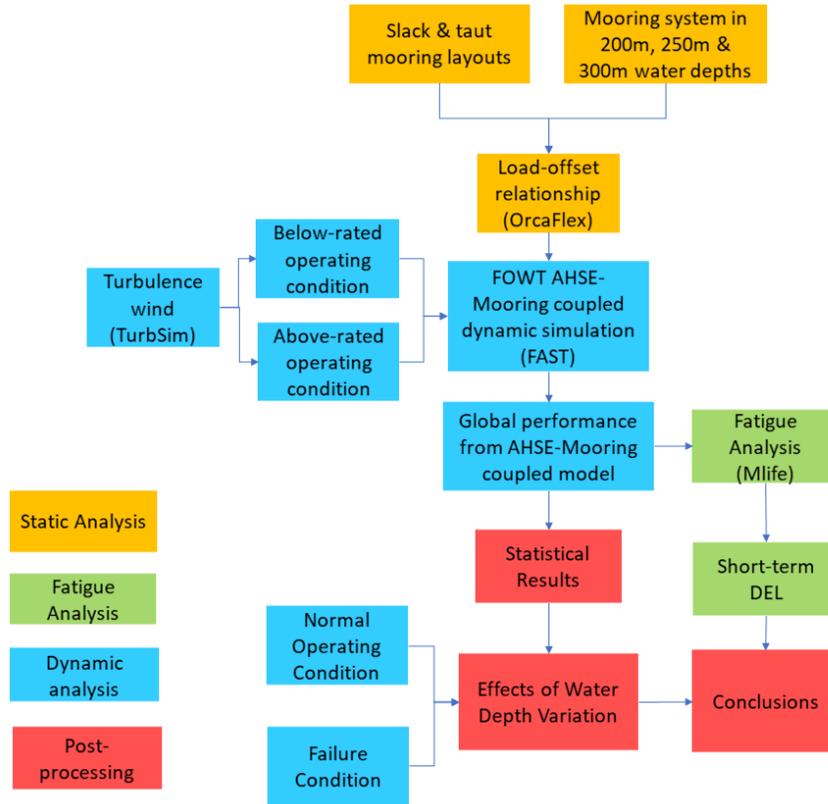
- 142 • Currently, wind turbines operating in water depth for larger than 50 m are being developed (Nagababu et al., 2017).
143 Worldwide, the majority of offshore areas, such as the west coast of the US and Japan are of the range of deep water
144 and suitable for FOWTs. Moreover, many countries have set up the carbon footprint reduction goals, with the offshore
145 floating wind industry to be contributed significantly to achieving these aims. However, the effects of an increased
146 water depth for FOWTs have not been precisely studied in previous studies. Hence, this paper aims to investigate the
147 effects of water depth increases on the global motion responses and mooring dynamics, offering recommendations for
148 wind turbine designer on developing a new wind farm in deep water areas.
- 149 • The progress of mooring materials for station keeping purpose has seen a significant improvement since the past few
150 decades. In the oil & gas sector, the definition of deepwater refers to the level of thousands of meters, which is
151 significantly different from the current deep-water range for FOWTs (~ 300 m). As the length and the cost of mooring
152 lines are proportional to water depths, the suitability of mooring configurations in terms of deep water for oil & gas
153 platforms needs to be re-accessed when it comes to FOWTs. Besides, even though the theory, design and method of
154 analysis for FOWTs originated from offshore oil & gas platforms, the present of the wind turbine and the aerodynamics
155 from wind-structure interactions play a significant role in determining the global performance of the FOWT platform.
156 Nowadays, one of the major difficulties in preventing the offshore wind industry moving to deeper water is the high
157 costs. Tradition catenary mooring configurations with chains will result in a surge in expenses, while a taut mooring
158 configuration could potentially reduce the charges in larger water depth. Therefore, both spread and taut mooring
159 configurations are considered in this study, together with water depth effects.
- 160 • Failure analysis is extremely significant for wind turbine safe operations, which will support in preventing
161 malfunctions and further reduce the costs in daily maintenance. Previous studies have focused on the failure conditions
162 with one mooring line broken (Bae et al., 2017), blade pitch actuator failure (Jiang et al., 2014) and blade structure
163 failure (Ozturk et al., 2018). It should be noted that these failure conditions are focused on one water depth only,
164 although water depth is considered as a non-ignorable design factor. On this account, the case studies carried out in
165 this study include both normal operating and wind turbine failure conditions under a variety of water depths.

166 **2. Methodology**

167 This paper applied an integrated AHSE numerical modelling approach for exploring the global performance of FOWT
168 dynamics under different water depths. The numerical outputs generated from the AHSE model are subsequently feeding to
169 the post-processing analysis for carrying out statistical analysis and fatigue analysis. A sketch of the methods applied in this
170 paper is described in **Fig. 1**. The baseline wind turbine was designed to operate in the water depth of 200 m and the other two

171 water depths were developed based on the parameters in this water depth (see section 4.2). Both normal operating and turbine
 172 failure conditions were considered in this paper. All the case studies were carried out in a wind, wave and current loading
 173 environment, with different average wind speeds considering both below-rated and above-rated scenarios, respectively.

174



175

176

Figure 1 Processes of designed numerical simulations and analysis methods

177

2.1. Numerical modelling of FOWT

178

2.1.1. Hydrodynamics

179

For regular waves, the Airy wave theory is applied to evaluate the wave propagation, determined by a sinusoidal wave elevation (Aggarwal et al., 2017):

180

181

$$\zeta = \zeta_a \cos(kx - \omega t) \quad (1)$$

182

where ζ_a is the wave amplitude, k is the wavenumber, ω is the wave frequency, and t is the time. The corresponding incident wave potential Φ_w in finite water depth can be written as (Journée and Massie, 2001):

183

184

$$\Phi_w = \frac{\zeta_a g}{\omega} \cdot \frac{\cosh k(h+z_d)}{\cosh kh} \cdot \sin(kx - \omega t) \quad (2)$$

185

where h is the water depth and z_d is the vertical position of the water particle.

186 For irregular waves, a superposition theory, based on the linear wave theory, is applied to calculate the long-crested random
 187 wave propagation. The approximation to first-order incident wave is sufficient to investigate the second-order wave force
 188 effects, including sum and difference frequency components. For long-crested seas, the incident wave elevation for random
 189 waves can be determined by the summation of a number of regular wave components (Journée and Massie, 2001):

$$190 \quad \zeta(t) = \sum_{n=1}^N \zeta_{a_n} \cos(k_n x - \omega_n t + \varepsilon_n) \quad (3)$$

191 where n describes the number index, N is the number of wave compounds, and ε is the random phase.

192 For wave-structure interaction problems, the added mass, radiation damping and wave exciting forces were calculated in
 193 the frequency domain, before running a time-domain mooring system analysis. In view of the submerged structure dimension,
 194 full Quadratic Transfer Function (QTF) was considered in terms of evaluating the wave structure interaction problems, which
 195 was realised through establishing the boundary value problem (BVP) up to the second-order perturbation expansion. More
 196 specifically, the second-order summation-frequency and difference-frequency are calculated by using the direct method through
 197 WAMIT (“WAMIT® WAMIT, Inc.”).

198 **2.1.2. Aerodynamics**

199 The numerical simulation of wind-structural interaction problems has been divided into two steps. The first step includes
 200 generating the time series of undisturbed inflow turbulence wind. The input parameters for the turbulence wind generation
 201 follow the design standards recommended by IEC-61400-3 (IEC, 2019). More specifically, Kaimal spectrum model together
 202 with a turbulence intensity of the inflow wind was applied in the power spectral density for the turbulence wind. To account
 203 for wind shear effects, mean u-component wind speed across the rotor disk is calculated by the power-law wind profile:

$$204 \quad \bar{u}(z) = \bar{u}_{hub} \left(\frac{z}{H_{hub}} \right)^{PLExp} \quad (4)$$

205 where z denotes the height above ground level, H_{hub} is hub height, \bar{u}_{hub} is the wind speed at hub height, and the value of
 206 $PLExp$ is 0.14 for Normal Turbulence Model (NTM), following the recommendations by the International Electrotechnical
 207 Commission (IEC).

208 The second step includes evaluating the wind loading on wind turbine blades using the blade element momentum (BEM)
 209 theory. The total forces and moments acting on the blade span can be evaluated by an integration of the discrete elements (Deo
 210 et al., 2018).

211

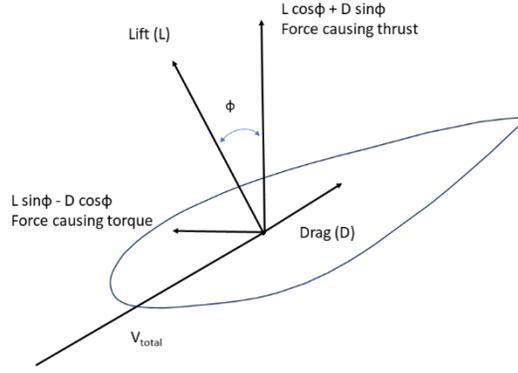


Figure 2 Local element forces

212
213
214 **Fig. 2** shows a sketch of the definition of local element sectional forces and their components. The forces are divided into
215 two parts. One is parallel to the rotor plane, which is the torque of the rotor, and the other one is perpendicular to the rotor
216 plane, which is the thrust force.

2.1.3. Structure and mooring models

218 Dynamic motion responses of the FOWT were evaluated in the time domain. A combined mode shape representation and
219 multi-body analysis were applied for the FOWT dynamic responses. Before running time-domain FOWT dynamic analysis
220 under sea environments, the mode shapes for the tower and the blade were calculated using the BModes (Bir,
221 2007)computational tool built by National Renewable Energy Laboratory (NREL). Based on Cummins's impulse response
222 function theory (Cummins, 1962), the frequency-dependent wave exciting force, added mass, and radiation damping was
223 converted into time-domain exciting force, infinite added mass matrix and retardation function, respectively. The floating body
224 equation of motion can be written as:

$$[M + M^a(\infty)]\ddot{x} + Kx + \int_{-\infty}^t R(t - \tau)\dot{x}(\tau) d\tau = F_{wave} + F_{wind} + F_{mooring} + F_v \quad (5)$$

226 where M and M^a are mass and added mass; K is the stiffness matrix; F_{wave} , F_{wind} and $F_{mooring}$ are the wave, wind and
227 mooring forces, respectively; F_v is viscous force. The retardation function (R) can be evaluated by:

$$R(t) = \frac{2}{\pi} \int_0^{\infty} b(\omega) \cos(\omega t) d\omega \quad (6)$$

229 where $b(\omega)$ is radiation damping. F_{wave} includes first and second-order wave exciting forces, which were evaluated in the
230 frequency domain without mooring lines and transferred into the time domain using Discrete Fourier Transform (DFT). As a
231 consequence of the water depth effects carried out in the time domain and focused on the global performance of the FOWT,

232 the wave forces for different water depth assumed unchanged. The first and second components of wave exciting forces can be
 233 evaluated as (Roald et al., 2013):

234 First-order forces ($F_{ex_i}^{(1)}$, $i=1, 2, \dots, 6$):

$$235 \quad F_{ex_i}^{(1)} = Re \left(\sum_{m=1}^N A_m F_i(\omega_k) e^{j\omega_k t} \right) \quad (7)$$

236 Second-order forces:

$$237 \quad F_{ex_i}^{(2)} = Re \left(\sum_{m=1}^N \sum_{l=1}^N [A_m A_l F_i^+ e^{j(\omega^+)t} + A_m A_l^* F_i^- e^{j(\omega^-)t}] \right) \quad (8)$$

238 where $\omega^+ = \omega_m + \omega_l$ and $\omega^- = \omega_m - \omega_l$; k and l are member index; A_m and A_l are complex wave amplitude; The asterisk
 239 (*) indicated the complex conjugate. Apart from wave loadings, water particle movements due to sea currents effects were also
 240 taken into consideration in the present study. The modelling approach of current-structure interaction follows the standard
 241 method as refined in IEC 61400-3 (IEC, 2019):

$$242 \quad U_{sub_surface} = U_0 \left(\frac{z+d}{d} \right)^{\frac{1}{7}} \quad (9)$$

243 where d is the water depth, z is the vertical coornidate, and U_0 denotes the current velocity.

244 As the above wave-structure interaction modelling is based on potential flow theory, the augmented viscous damping
 245 from potential flow loads is realised through the viscous drag term from Morison's equation (Morison et al., 1950).

246 By using the coupled time-domain simulation method, the effect of mooring line damping and the interaction between the
 247 mooring line and the floating body are accounted for automatically. A lumped-mass model (Hall and Goupee, 2015) is used
 248 for the dynamic response of the mooring line and realised through the MoorDyn Module of FAST (Hall, 2017). Numerical
 249 modelling of mooring line considered hydrodynamic loadings (Morison et al., 1950) and a linear stiffness representation (Bach-
 250 Gansmo et al., 2020). For slack mooring chains with a certain component on the seabed, it is important to model the dynamic
 251 interactions between the horizontal mooring line and the seabed. To this end, a linear spring-damper model was applied to
 252 model the vertical force from the seabed. For a node in the lumped-mass model, the force related to mooring line-seabed
 253 interaction (F_{seabed}) can be written as (Hall and Goupee, 2015):

$$254 \quad F_{seabed} = (z_{bottom} - z)k_b - zc_b \quad (10)$$

255 where k_b and c_b are the stiffness and the damping coefficients, respectively. The equation is only active when z is lesser than or
 256 equals to z_{bottom} .

257 2.1.4. Fatigue analysis

258 For a better comparison and understanding of the water depths effects for FOWTs, one of the post-processing procedures
259 cover the fatigue analysis of the FOWT mooring line dynamic time histories. More specifically, the short-term damage
260 equivalent load (DEL) was applied to analyse each output time series. The DEL about a fixed mean is based on an open-source
261 simulation code Mlife (Hayman, 2012), and can be evaluated as follows:

$$262 \quad DEL_j^{STF} = \left(\frac{\sum_i (n_{ji} (L_{ji}^{RF})^m)}{n_j^{STeq}} \right)^{\frac{1}{m}} \quad (11)$$

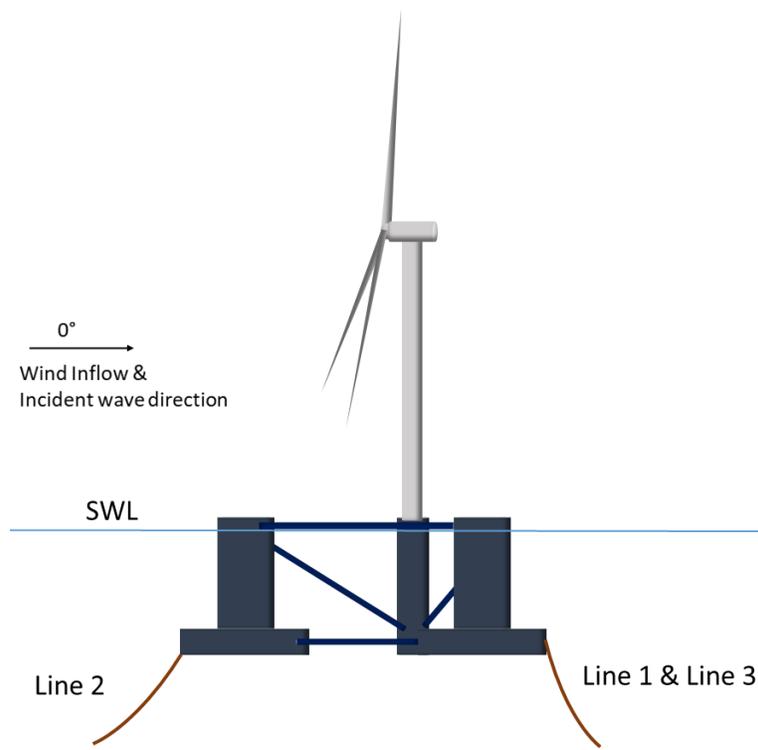
263 where j denotes the time series number, n_j^{STeq} is the total equivalent fatigue counts for the j^{th} time series, and L_{ji}^{RF} is the corrected
264 load range about a fixed mean cor cycle i , time series j . The damage accumulates follow a linear assumption, as recommended
265 by the Miner's Rule (Miner, 1945).

266 3. Model Descriptions and Validations

267 3.1. Description of the target wind turbine

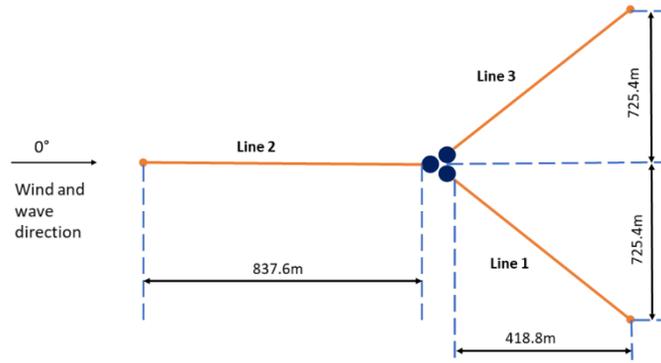
268 The present study selected a baseline offshore wind turbine designed by NREL - the 5MW OC-4 DeepWind FOWT
269 (Robertson et al., 2014). The wind turbine is supported by a Semisubmersible-type platform, moored by three symmetrically
270 oriented catenary chains, operating in a water depth of 200 m. Detailed characteristics of the target wind turbine are shown in
271 Robertson et al.(2014), while the layout of the wind turbine mooring system and the definition of environmental conditions
272 are shown in **Fig. 3 and Fig. 4**. For mooring arrangements in **Fig. 4**, the horizontal and the vertical distances between fairlead
273 and anchor indicate the FOWT in 200m water depth. For the remaining water depth (250m and 300m) the arrangement follows
274 the same configuration as **Fig. 4** (three symmetrically oriented lines), but with different horizontal and vertical distances. The
275 detailed anchor positions are described in **Table 3**.

276



277
278

Figure 3 Sketch of the FOWT along with mooring system



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280
281

Figure 4 Sketch of the mooring system arrangement (200 m water depth)

282 The top of the tower has an elevation of 87.6 m above the still water level (SWL), which is consistent with the NREL 5
 283 MW baseline wind turbine for a land-based design. There is a 10 m length elevation between the tower base and the SWL. The
 284 main column of the supporting platform has a diameter of 6.5 m, which matches the tower base diameter. The submerged
 285 section of the semisubmersible consists of the main column, connecting to the tower and three offset columns with 12 m
 286 diameters. The depths between platform base and SWL is 20 m. The ballast water effects in the numerical simulation were
 287 converted into two additional stiffness values. Further details are given by (Robertson et al., 2014).

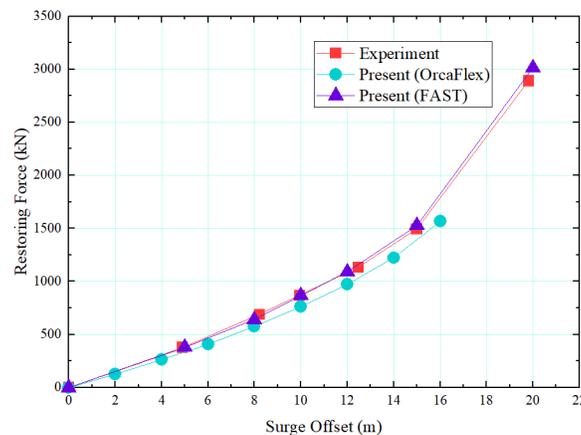
288 **3.2. Validation load cases & results**

289 Before running dynamic analysis, a static validation process, focusing on the horizontal restoring forces provided by the
290 mooring lines, were carried out and compared with model tests data. Two validation processes were carried out. One has
291 focuses on the static restoring performance, which is significant for setting up mooring line configurations for different water
292 depths. The other focused on the free decay simulations and the natural frequencies in terms of supporting the platform’s six
293 degrees of freedom (DOFs).

294 **3.2.1. Restoring forces**

295 The load-offset graph in 200m water depth in the surge direction is shown in **Fig. 5**. The numerical tests were realised
296 through setting different initial surge motions, ranging from zero to around 20 m. In **Fig. 5**, “Experiment” denotes the model
297 test results from Dagher et al. (2017); Present (OrcaFlex) and Present (FAST) indicated the numerical simulation results based
298 on OrcaFlex (“Orcina Ltd,”) and FAST (Jonkman and Jonkman, 2016), respectively. As can be seen, there is an excellent
299 agreement between model test results and present results based on FAST, showing the validity of the present method in the
300 forthcoming dynamic analysis regarding water depth effects. There is a minor difference for horizontal offsets larger than 10
301 m when compared to numerical simulation using OrcaFlex and model test results, but the overall agreement has reached a
302 satisfying match, showing a good preparation for the subsequent case studies.

303



304

305

Figure 5 Static validation

306 **3.2.2. Natural Frequencies**

307 The second validation step has focused on the structure’s natural frequencies. Six numerical free decay simulations were
308 carried out based on each DOF’s pre-subscribed initial positions. More specifically, for horizontal (surge and sway) motion
309 DOFs, the initial offset was fixed at 10 m, while, for vertical DOF (heave), it had an initial offset of 3 m above the SWL. For

310 rotational DOFs (roll, pitch and yaw), the initial angle was selected as 10 degrees. The free decay simulation was realised and
 311 carried out by disabling all the control capabilities and on a non-rotating turbine condition. To this end, the turbine generator
 312 DOF was also excluded during the simulation. All the free decay calculations were carried out in a no wind, wave or sea current
 313 condition. **Table 1** describes the comparison between the present numerical results and the model tests. All the comparisons
 314 have presented excellent agreements, except for the minor difference in roll and pitch DOFs. Nonetheless, the discrepancies
 315 are less than 3%, showing a great agreement between the present results and the model tests.

316 **Table 1** Platform natural frequencies (present results and experimental results)

	Surge (Hz)	Sway (Hz)	Heave (Hz)	Roll (Hz)	Pitch (Hz)	Yaw (Hz)
Present	0.009	0.009	0.057	0.038	0.036	0.012
Experiment (Dagher et al., 2017)	0.009	0.009	0.057	0.037	0.037	0.012

317 4. Results & discussions

318 In this section, a list of load cases (LCs) for the analysis of water depth effects is described, followed by explanations of
 319 how the environmental conditions are calculated. All the LCs were simulated under a variety of water depths ranging from 200
 320 to 300 m for both slack and taut mooring configurations. The total simulation time is one hour. Due to the application of a time-
 321 domain analysis, the initial 400s generate unstable results and this transient period was removed before carrying out post-
 322 processing investigations.

323 4.1. Load cases

324 As stated in section 1, it is valuable to investigate water depth effects under both healthy and failure conditions. Therefore,
 325 the proposed LCs are shown in **Table 2**. Two normal operating conditions are considered, where one LC's average wind speed
 326 locates in the below-rated wind range while the other LC has an average wind speed of the above-rated condition. Both wave
 327 heights and wave periods are selected in accordance with the average wind speed. For the failure LC, this paper has focused
 328 on a grid loss condition and the forthcoming outcome of HSS brake, which is an important event to investigate the safe
 329 operating of FOWTs. During LC3, all the three blades are feathered after the failure happened (Jiang et al., 2014), the
 330 considered sea states include an average wind speed of 22 m/s (above-rated) and the same wave conditions as LC2.

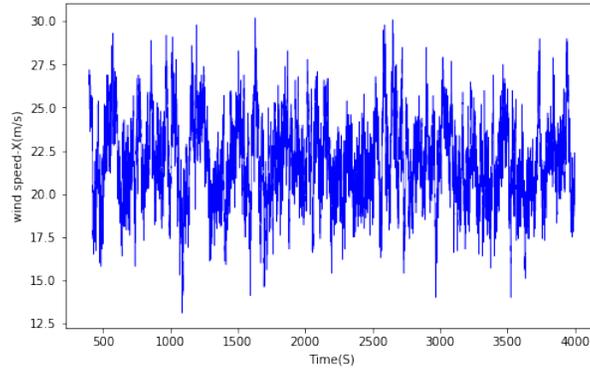
331 **Table 2.** Environmental conditions and turbine operating status in the case studies (sea stated conditions from Qu et
 332 al. (2020))

LC	Wind speed (m/s)	Sea states			Turbine status
		Wave height (m)	Wave Period (s)	Current speed (m/s)	
1	8	1.67	8	0.5	Normal Operating

2	22	6.2	12.5	0.5	Normal Operating
3	22	6.2	12.5	0.5	HSS Brake due to grid loss

333 In the numerical simulation, the turbulence wind profile was pre-generated by an open-source tool TurbSim(Jonkman,
334 2009). The wind speeds in space were calculated based on Kaimal spectrum, with a standard turbulence intensity of the
335 recommendation from IEC type A. An example of the undisturbed wind speed time history in the horizontal X-direction under
336 LC2 (see **Table 2**) is described in **Fig. 6** for a total duration of one hour.

337



338

339 Figure 6 Horizontal undisturbed wind speed in the X direction (LC2 in Table 2)

340

340 The wave kinematics model was based on the Joint North Sea Wave Project (JONSWAP) spectrum with mono incident
341 wave direction (Hasselmann et al., 1973):

342

$$S(\omega) = \frac{\alpha g^2}{\omega^5} \exp \left[-\frac{5}{4} \left(\frac{\omega_p}{\omega} \right)^4 \right] \gamma^r \quad (15)$$

343

$$r = \exp \left[-\frac{(\omega - \omega_p)^2}{2\sigma^2 \omega_p^2} \right] \quad (16)$$

344

where γ is the peak enhancement factor; $\gamma=3.3$.

345

346

Fig. 7 shows the incident wave spectrum for the first LC in **Table 2**. It has a significant wave height of 6.2 m and a peak period of 12.5s. The power spectrum was generated by the incident wave time series and normalised by the mean square value. The adjacent-averaging algorithm was applied to remove the noise of the spectrum with a moving window.

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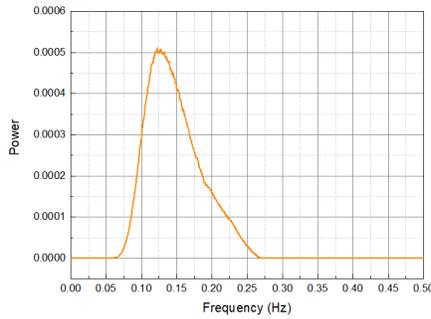


Figure 7 Incident wave spectrum (generated from wave elevation at platform centre of LC2)

4.2. Mooring configurations & load-offset relationships

Due to the large number of parameters related to water depth variations, it is necessary to limit the number of parameters, while at the same making responses results in different water depth more comparable. Based on the surge restoring force under different offsets for 200 m water depths in a slack mooring configuration (see Fig. 5), the principle of developing the mooring properties is to measure the surge load-offset relationship as accurate as possible (Ahmed Ali et al., 2019) (Fig. 8). Table 3 shows the mooring positions (anchor) and line lengths for different water depths and configurations. The fairlead positions for different water depths remain the same as the original design of the OC4 semi-submersible type FOWT (Robertson et al., 2014) (200 m water depth, slack mooring configuration). Mooring line material for all the slack configurations utilized the same chain as in 200m water depth (Robertson et al., 2014). It has a mooring line length of 835.5m and an equivalent mooring line mass in water of 108.63 kg. The material for the taut mooring line is polyester. The nominal diameter for the polyester (0.2m) line is obtained from Azcon et al.(2017), and the remaining parameters based on the diameter is derived in OrcaFlex. More details of the properties for the two types of lines can be seen in Table 4.

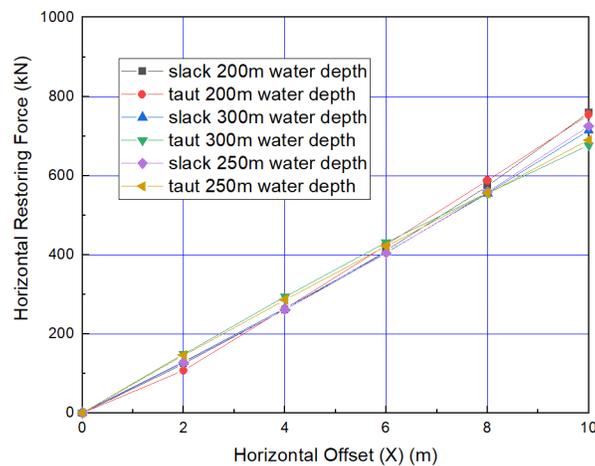


Figure 8. Horizontal (surge) offset for all the water depths

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Table 3. Mooring line properties (Anchor)

Water depth (m)	Slack Mooring					Taut Mooring				
	length (m)	Line No.	X	Y	Z	length (m)	Line No.	X	Y	Z
200	835.5	1	418.8	725.4	-200.0	245.0	1	100.0	173.2	-200.0
		2	-837.6	0.0	-200.0		2	-200.0	0.0	-200.0
		3	418.8	-725.4	-200.0		3	100.0	-173.2	-200.0
250	1054.5	1	523.5	906.7	-250.0	314.5	1	125.0	216.5	-250.0
		2	-1047.0	0.0	-250.0		2	-250.0	0.0	-250.0
		3	523.5	-906.7	-250.0		3	125.0	-216.5	-250.0
300	1273	1	628.2	1088.0	-300.0	383.5	1	150.0	259.8	-300.0
		2	-1256.4	0.0	-300.0		2	-300.0	0.0	-300.0
		3	628.2	-1088.0	-300.0		3	150.0	-259.8	-300.0

367

368

Table 4 Parameters of slack and taut lines

Configuration	Material	Mass in water (kg/m)	EA (kN)
Slack	Studlink Chain	108.63	753600
Taut	Polyester	31.91	43600

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370

371 4.3. Normal operating condition

372 4.3.1. Time-history results

- 373 • Statistics of motion responses

374 Compared with platform pitch responses, surge and heave motion responses are more affected by water depth (**Fig.9**).

375 The static surge responses for different water depth and mooring configurations have been matched statically without

376 environmental loadings (see **Fig.8**), resulting in the mean surge less dependent on the water depth. When considering a sever

377 sea state (above-rated in **Fig.8**), water depth effects become important for the evaluation of maximum surge values, especially

378 for taut lines. This is probably due to the different restoring forces levels provided between slack and taut lines. With the

379 increasing of surge offset, the nonlinearity in the mooring stiffness is significant. Besides, the dynamic coupling effects could

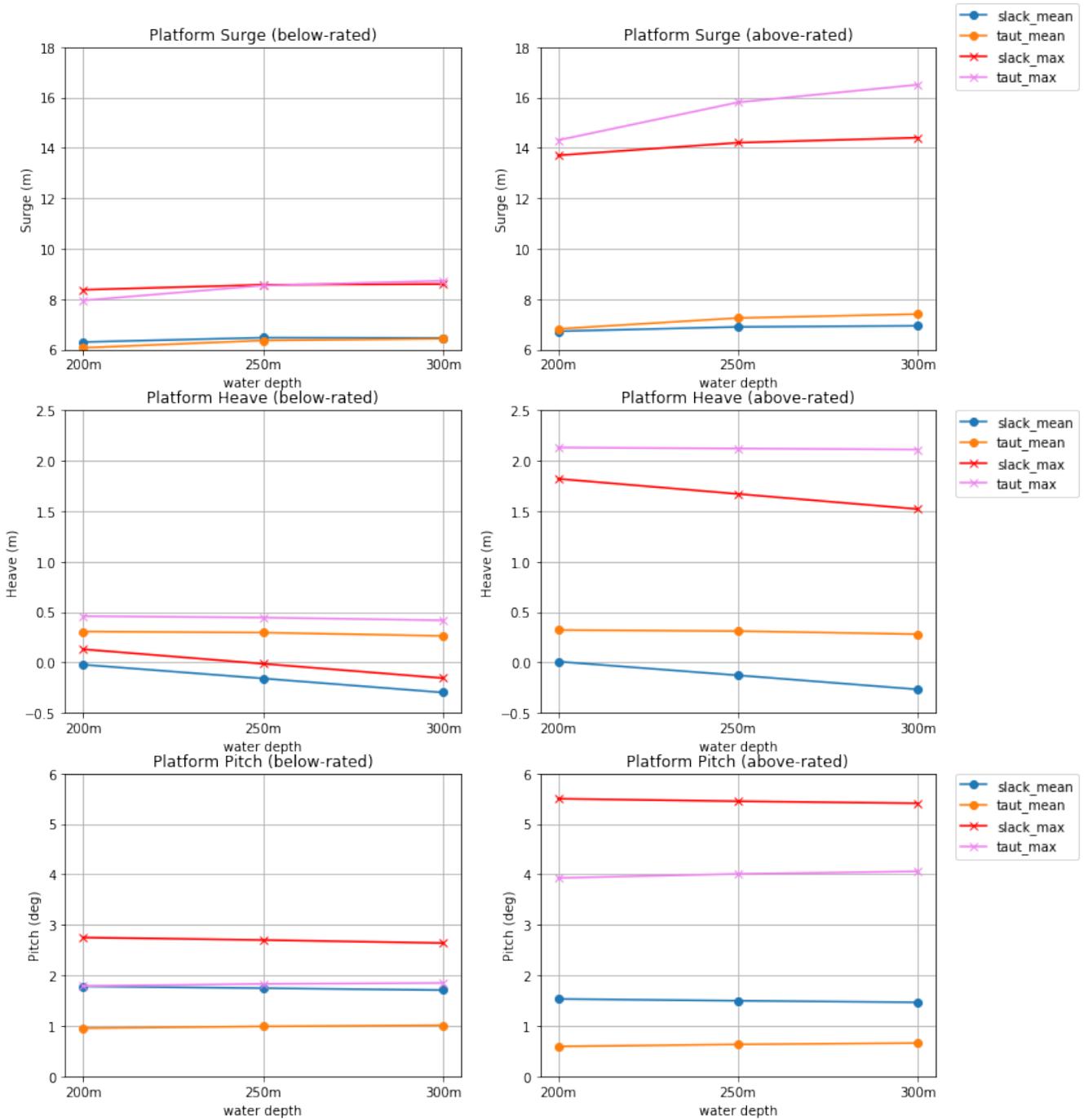
380 contribute to the discrepancy, as the matching Fig. 8 was carried out statically. The increased water depth has resulted in an

381 apparent effect on the heave motion with slack mooring lines, while for taut lines the differences on heave motions between

382 200m and 300m water depths are almost ignorable (**Fig.9**). One reason for it is due to the different vertical components provided

383 by slack and taut lines. For slack moorings, the steeper fairlead angle contributes to a higher vertical force component than the

384 taut counterpart (Bach-Gansmo et al., 2020).



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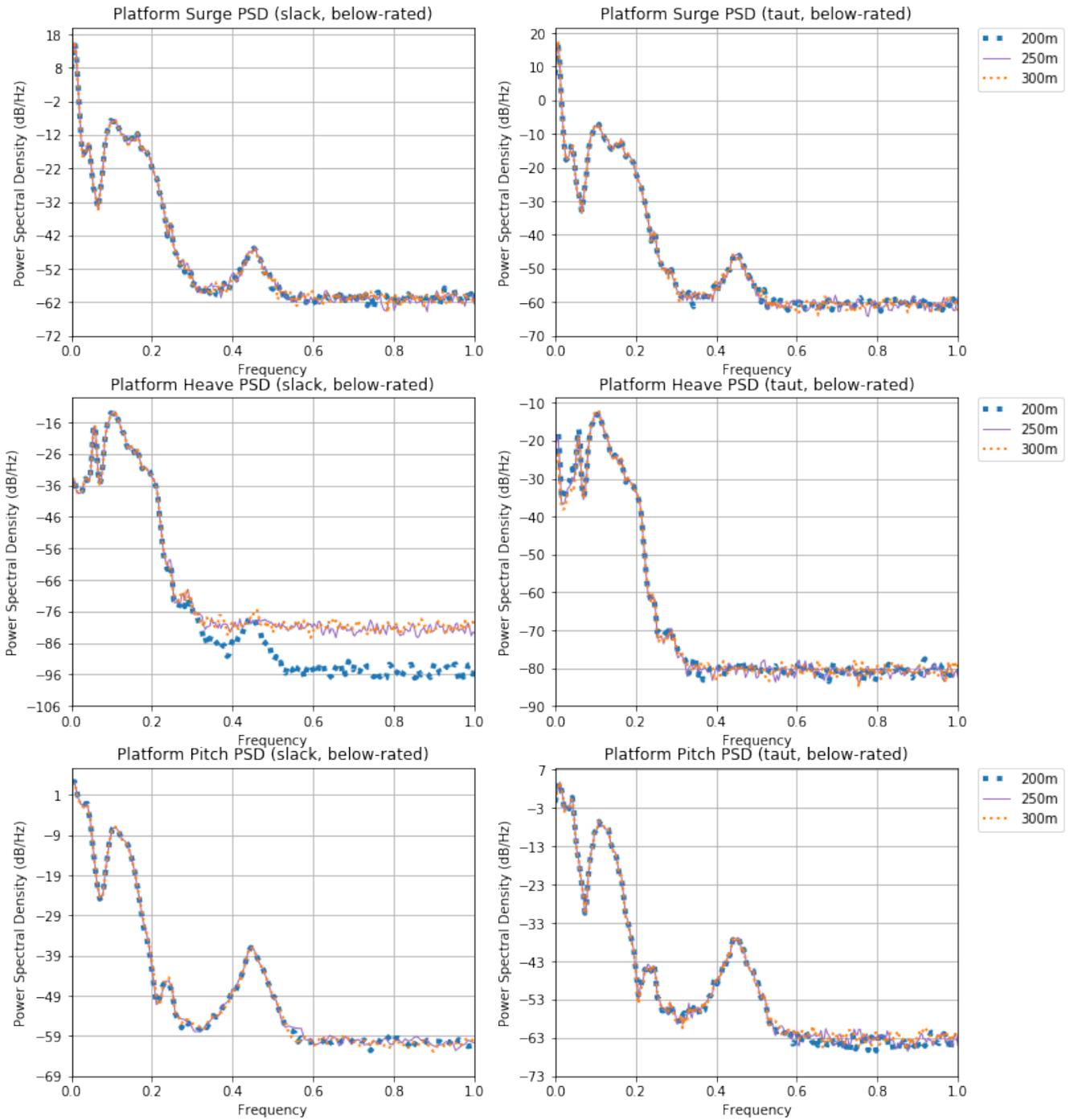
386 Figure 9 Statistical results of platform motions for slack & taut moorings (LC1: below-rated; LC2: above-rated)

- 387 • Spectra of motion responses

388 To further examine the reason for the discrepancies in statistical results, the power spectral density (PSD) of the motion
 389 time history is shown in **Fig. 10** and **Fig. 11**. The PSD was evaluated by Welch's average periodogram method (Welch, 1967).

390 As can be seen from the figures, the spectra are all dominated by a frequency range of less than 0.2 Hz. All the major

391 discrepancies are observed for the frequency range above 0.4 Hz (Fig. 10 and Fig. 11). In addition, the variation of water depth
392 has an influence on the low-frequency range of heave responses (below 0.1 Hz).



393
394 Figure 10 PSD of platform motions (LC1, slack & taut moorings)
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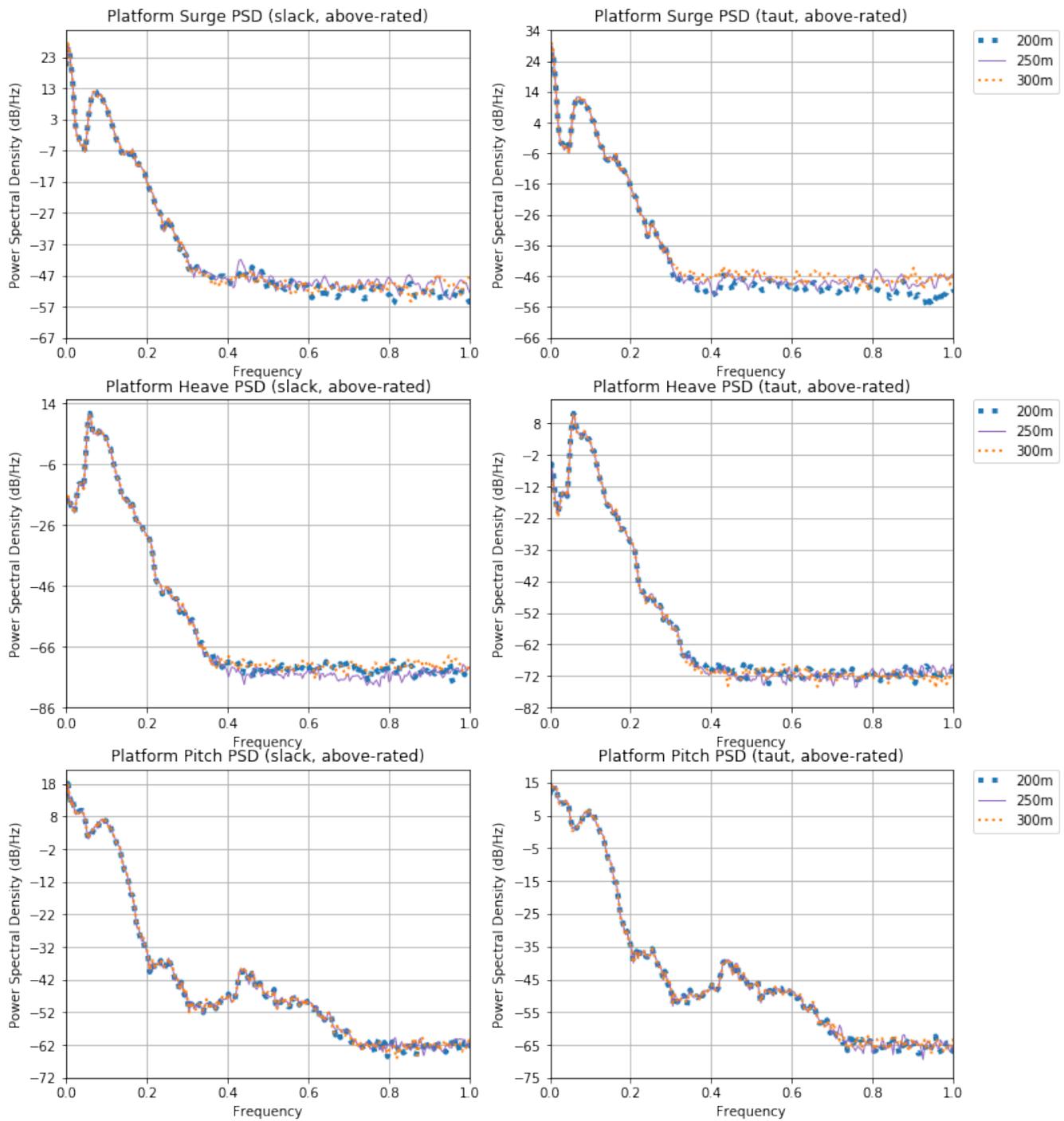


Figure 11 PSD of platform motions (LC2, slack & taut moorings)

- Mooring line tensions

For slack moorings, both mean and maximum values increase with the growth of water depths, while taut moorings are less sensitive to water depth variations (Fig.12). Slack mooring configuration tends to significantly enlarge its maximum mooring line tension with the increasing of water depths. This trend showed an agreement with the corresponding power spectra as shown in Fig.13. All the mooring line tension PSD are in consistence with platform surge motion, caused by the incident

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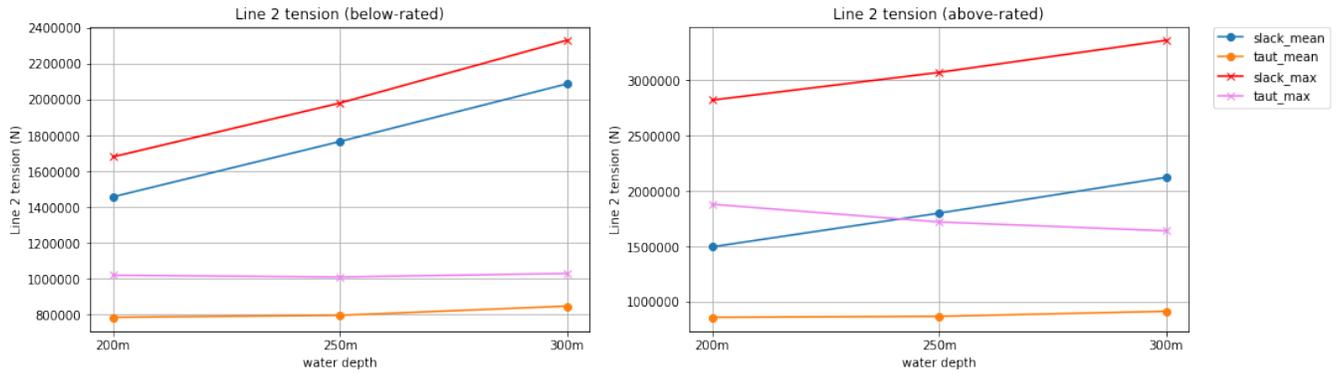
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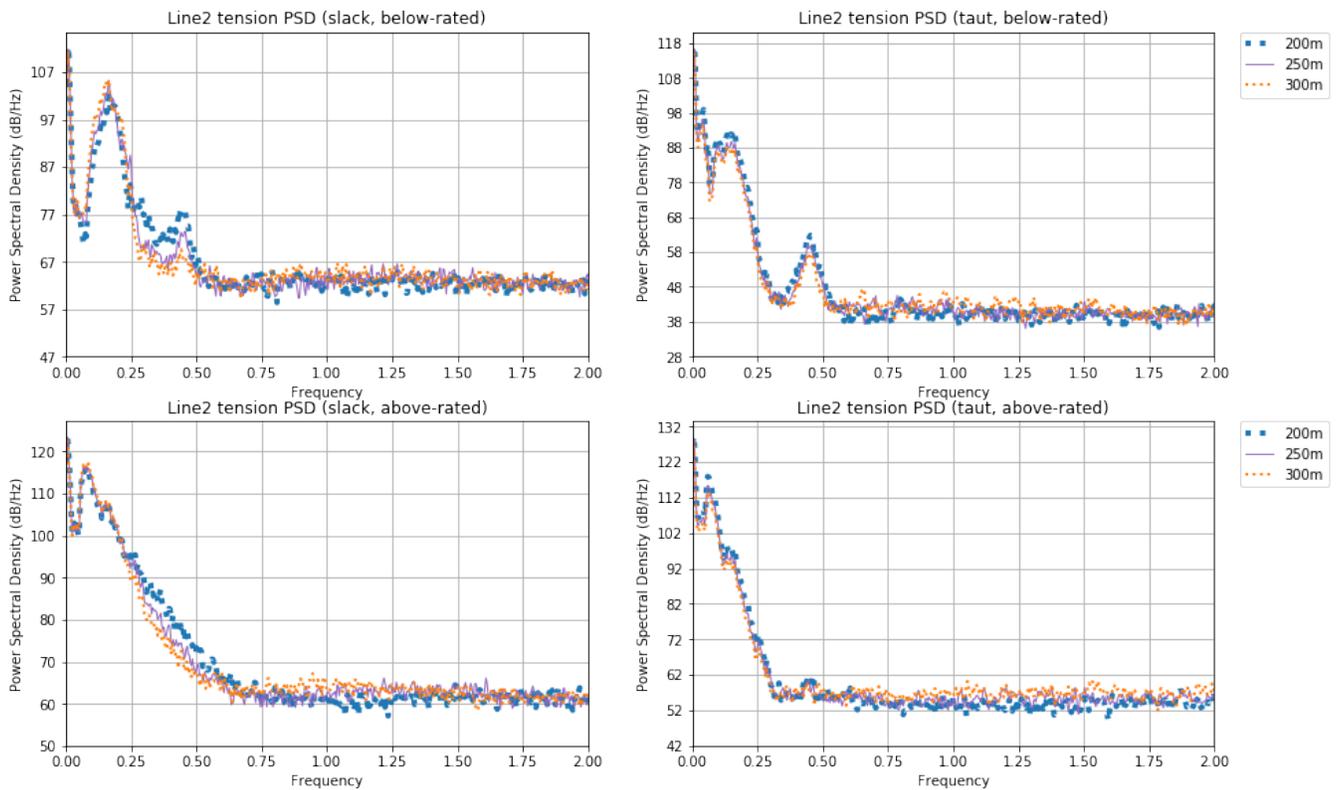
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403 wave spectra, regardless of below or above wind conditions. These phenomena show that the mooring line top tension is mainly
 404 driven by the surge motion. With the increase of water depth, the discrepancies regarding PSD are more significant on the slack
 405 mooring configuration than the taut configuration (see **Fig. 13**). For slack moorings, this discrepancy is mainly centred at a
 406 frequency range of below 0.25 Hz. While for taut moorings, the differences are more significant for a frequency range below
 407 0.1 Hz in above-rated condition (see **Fig. 13**).



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Figure 12 statistical results of line 2 top tension (LC1, LC2, slack & taut)

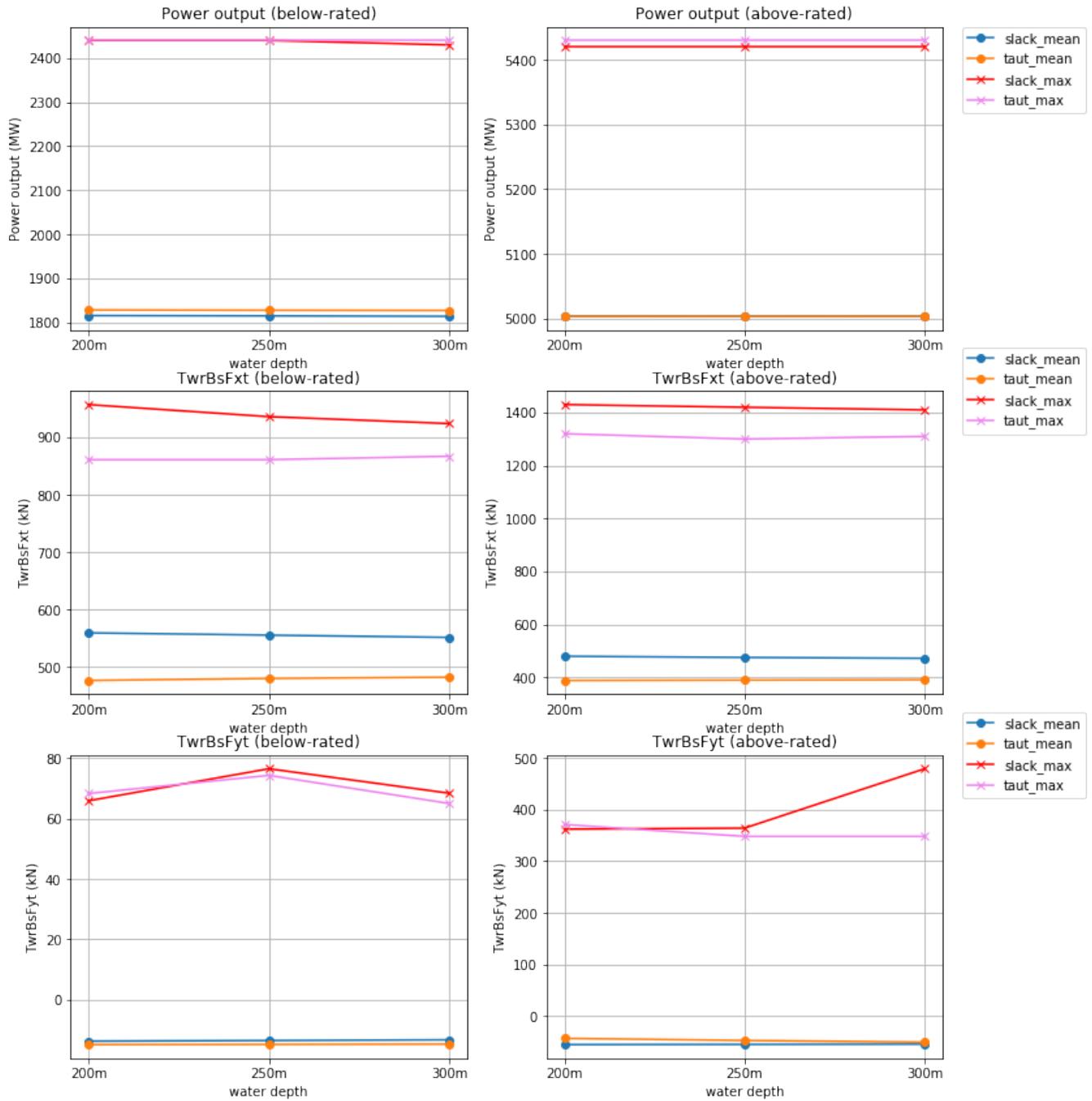


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Figure 13 PSD of line 2 top tension (LC1, LC2, slack & taut)

412 On the contrary to the significant effects from platform motions and most loaded line (line 2) top tensions, wind turbine
 413 power output and tower base forces are almost independent of water depths (see **Fig. 14~15**). Compared with the fore-aft force

414 (TwrBsFxt), tower base side-side force (TwrBsFyt) performed differently with the increasing of water depth, but the
 415 discrepancies are less significant, which can be further proved from the PSD as shown in Fig.15.



416
 417 Figure 14 statistical results of wind turbine power output and tower base forces (LC1 &LC2, slack & taut moorings)

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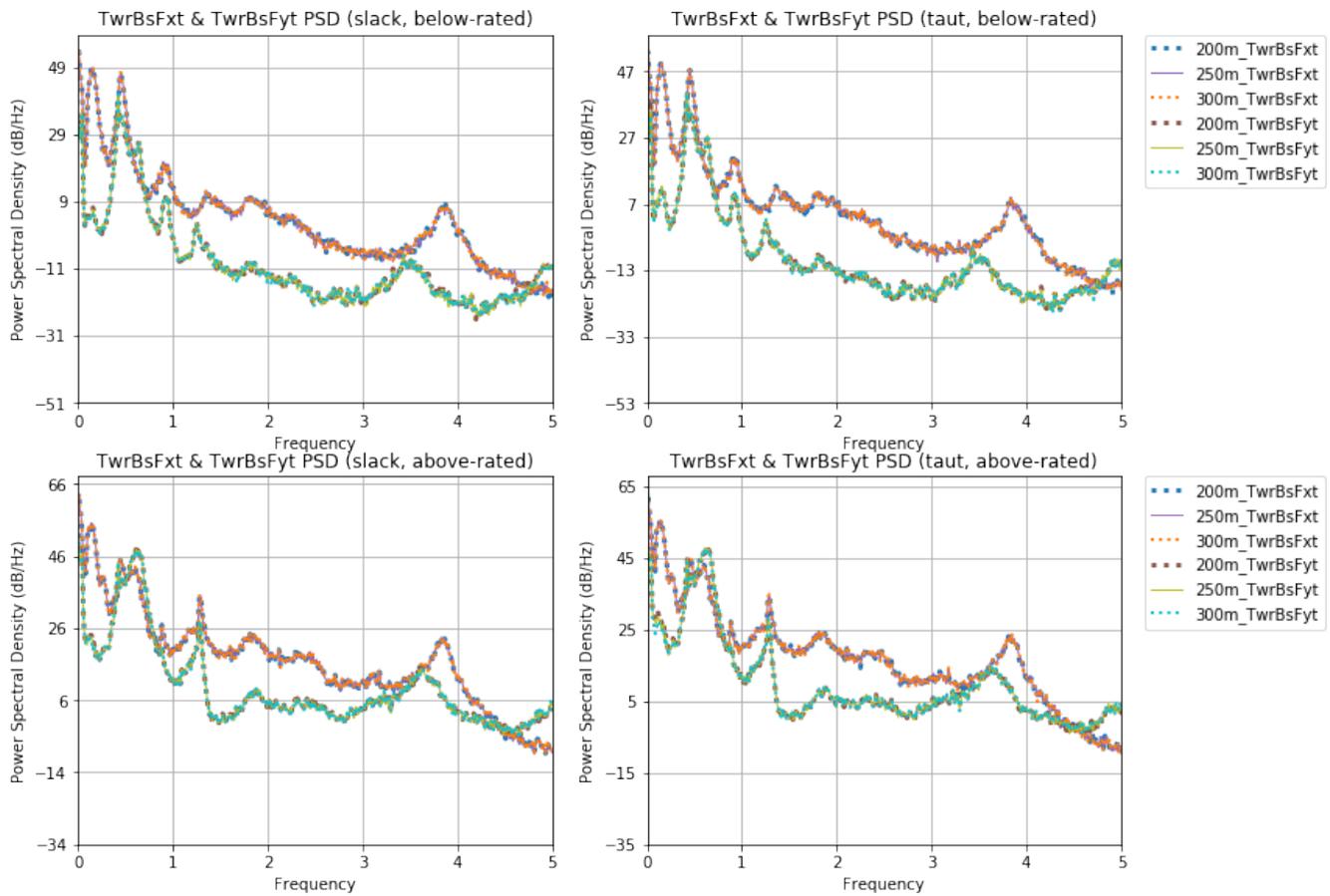


Figure 15 PSD of tower base bending forces (LC1 & LC2, slack & taut moorings)

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422 4.3.2. Fatigue results

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Section 4.3.1 has discussed the dynamic response characteristics in terms of statistical results and spectra. In this section, responses and performances of the FOWT under a variety of water depth are compared and discussed based on short-term DELs. The calculation methods for generating the DELs have been introduced in section 2.1.5, which include a computation using a fixed mean value and the Goodman correction. **Fig.16** and **Fig.17** show a description of calculated DELs under different environmental (below-rated and above-rated) and mooring conditions. As can be seen, compared with tower DELs, mooring line DELs performed differently with the increase of water depth. Comparing against different mooring configurations, taut moorings are expected to have larger DELs, which are almost double of that of slack mooring lines with catenary chains. As for the tower DELs, there are almost no significant differences under different environmental (below-rated and above-rated conditions) conditions and mooring configurations. There are only minor differences for tower base DEL (side-side bending force) under slack mooring configuration, showing a slight rise of DEL with the growth of water depth.

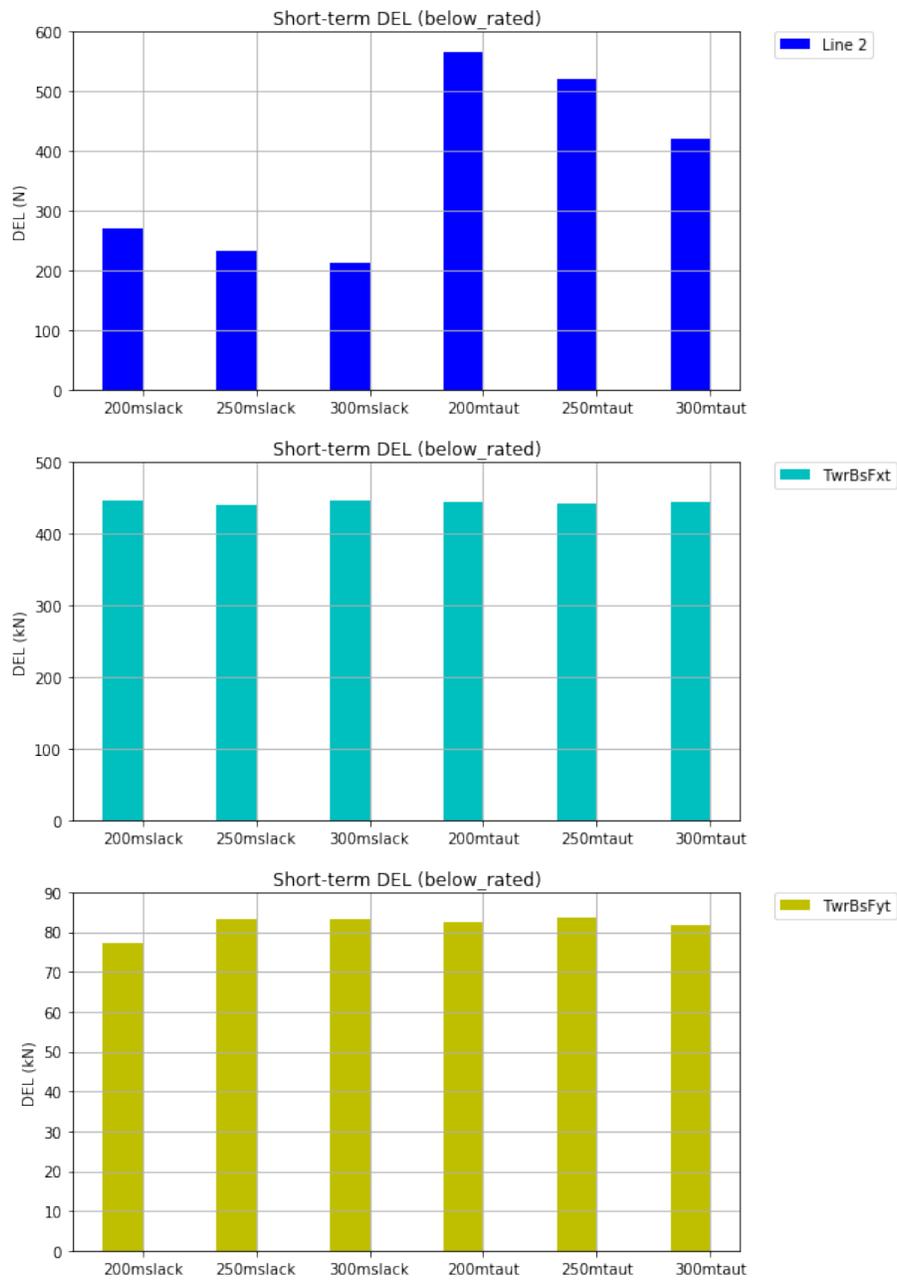


Figure 16 DEL of line 2 top tension and tower base forces (LC1)

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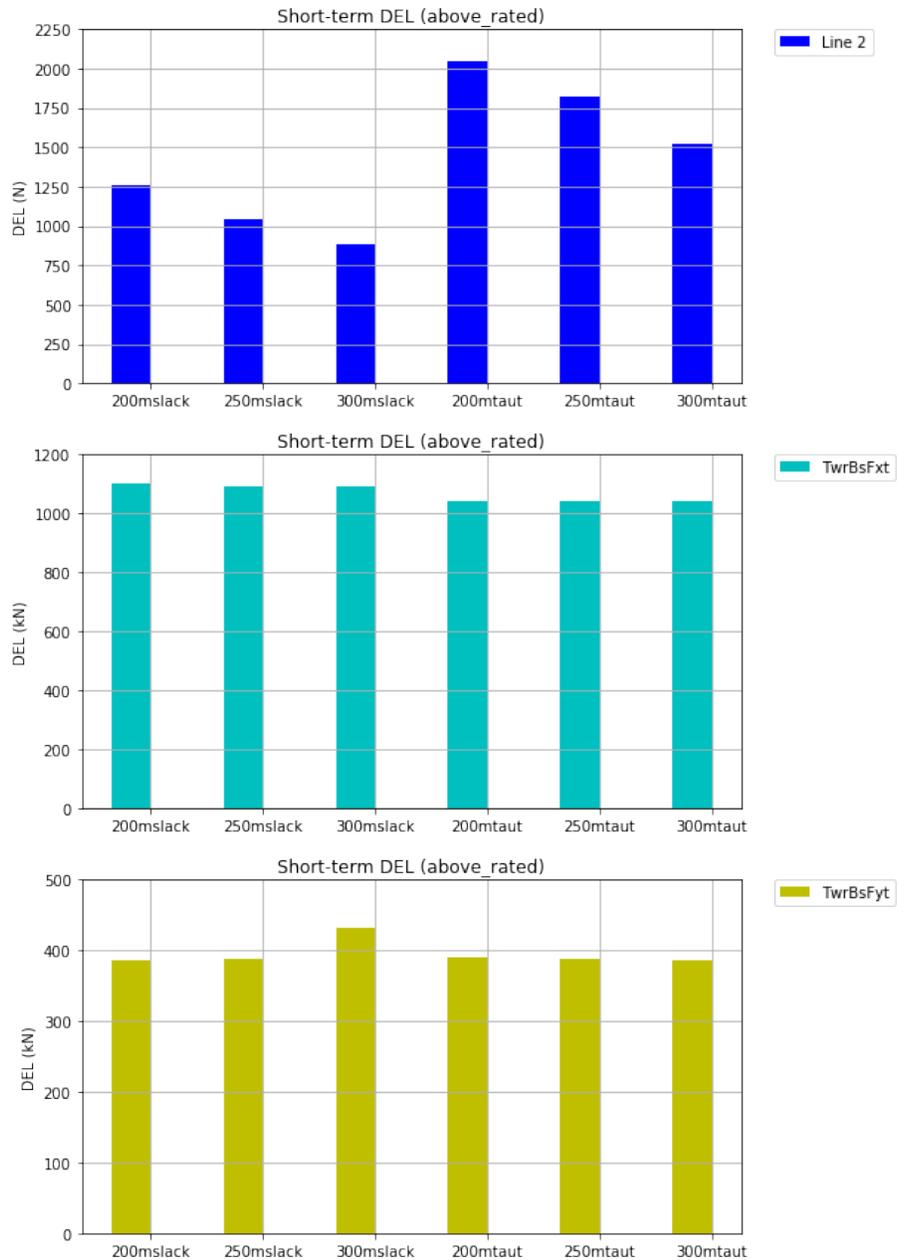


Figure 17 DEL of line 2 top tension and tower base forces (LC2)

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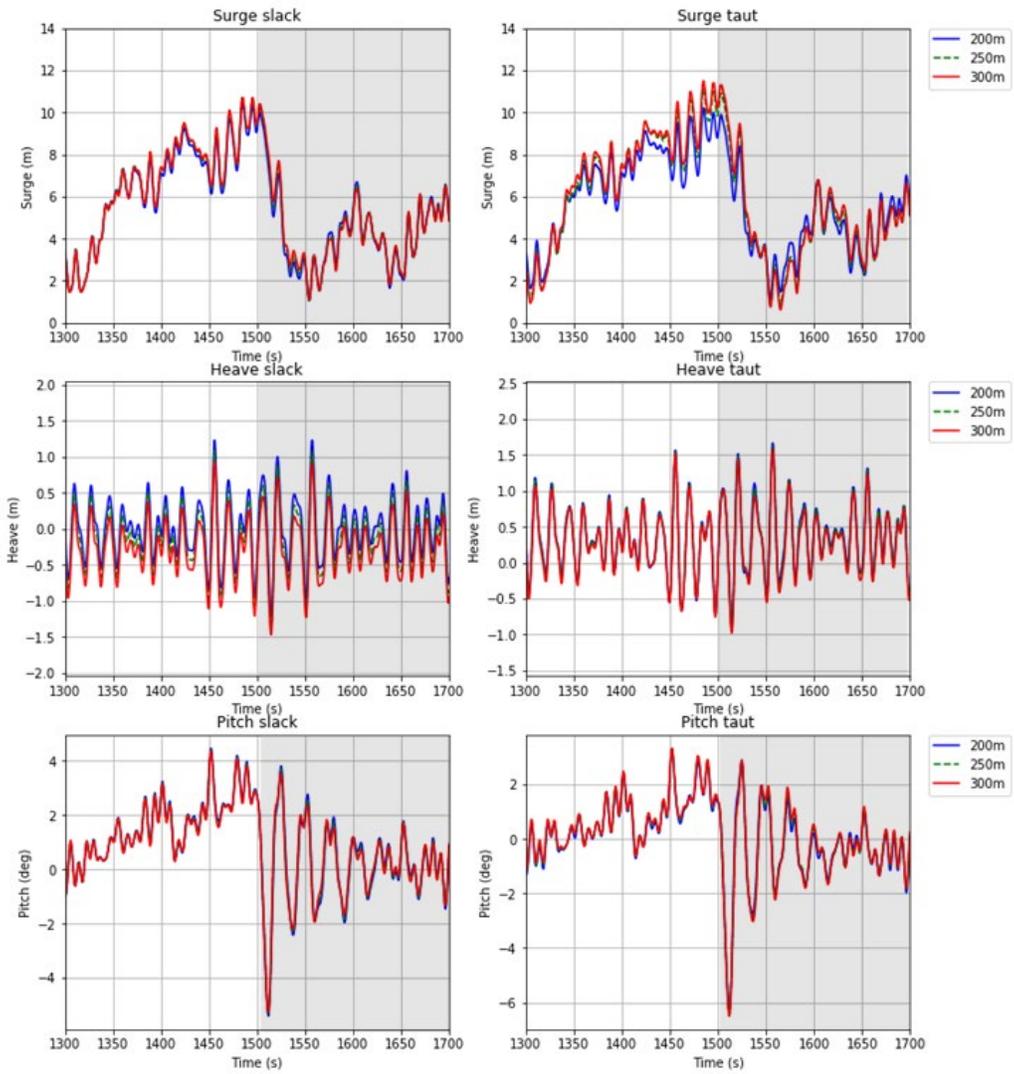
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440 **4.4. Grid loss induced HSS break event**

441 Section 4.3 has focused on analysing water depths effects under normal turbine operating conditions. For safe operation
 442 of the wind turbine, it is significant to explore the global responses with water depth increasing under a certain failure condition.
 443 In this section, the turbine special event with grid loss failure was carried out in a wind, wave and current sea environment.
 444 Only above-rated wind speeds are considered, as the three blades feathered after the failure event happened (Jiang et al., 2014).
 445 The shaft brake torque (28116.2 N·m) follows a linear ramp function from zero to full.

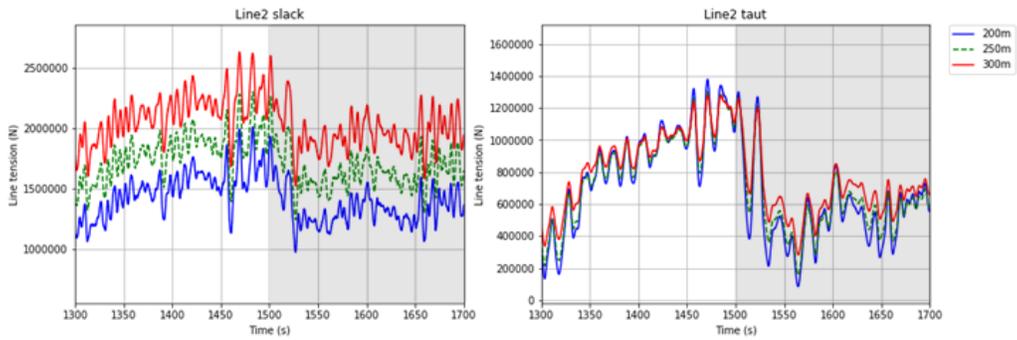
446 Transient behaviour of platform motions, mooring line tension and tower base forces are shown in **Fig. 18**, **Fig.19** and **20**,
447 respectively. The grid loss event and the high-speed shaft (HSS) break started at the 1500 s, where the total simulation time is
448 1 hour. The grey background in **Fig. 18**, **Fig.19** and **20** describes the time history of the failure. As presented, the failure event
449 has a greater influence on the transient surge motion responses and mooring line tensions (**Fig. 18** and **Fig.19**), but less affected
450 the heave motion responses, regardless of mooring system configurations. The response spectra, which was described in **Fig.**
451 **21** and **Fig.22**, only considered the time series after a failure occurred. Compared with turbine healthy conditions, a similar
452 trend has investigated on mooring line tension spectra, for which slack mooring line responses are more water-depth sensitive
453 than the taut lines (**Fig.13** and **Fig.22**).

454 The failure event has a more obvious influence on the tower side-side bending force, compared with the fore-aft bending
455 force. As can be seen in **Fig. 23**, water depth increasing has contributed to the difference in tower base bending forces (above
456 2Hz). In addition, the maximum bending forces are no longer water-independent, especially for the fore-aft direction (see **Fig.**
457 **14** and **Fig.24**), but the overall discrepancies are still less significant compared with the mooring line top tension discrepancies.



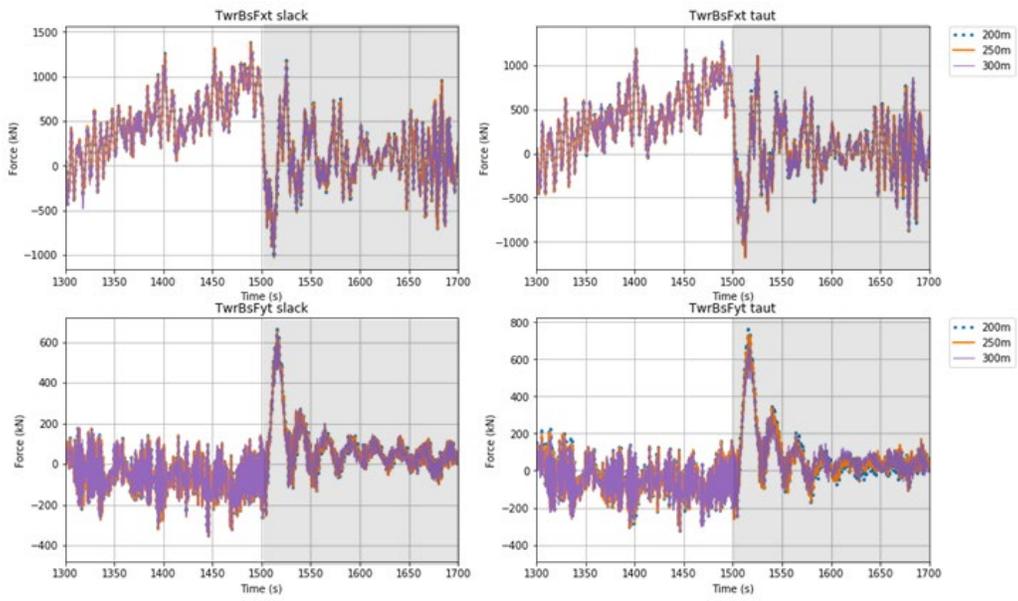
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Figure 18 Transient behaviour of platform motions (LC3)



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Figure 19 Transient behaviour of the most loaded line tension (LC3)



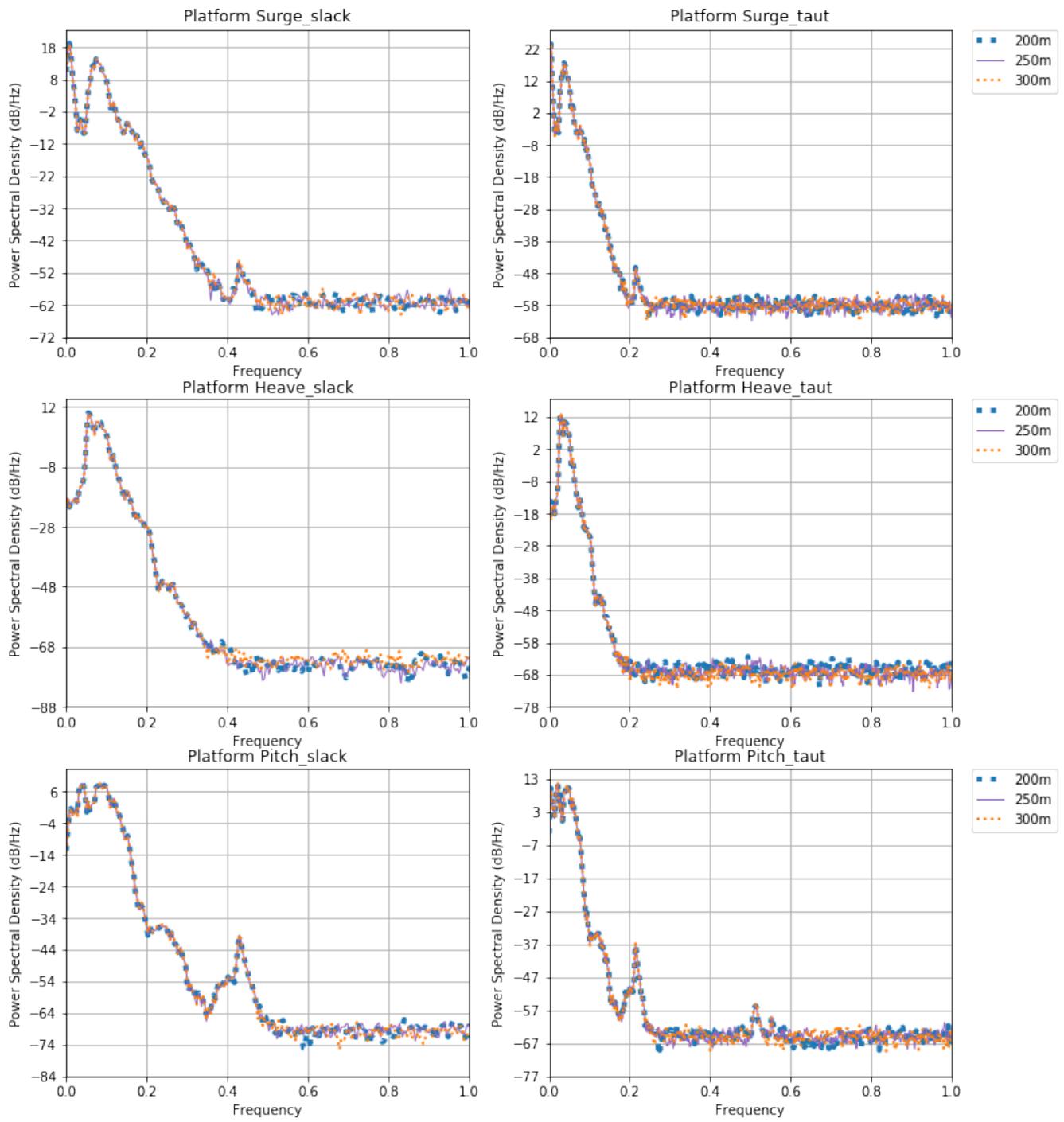
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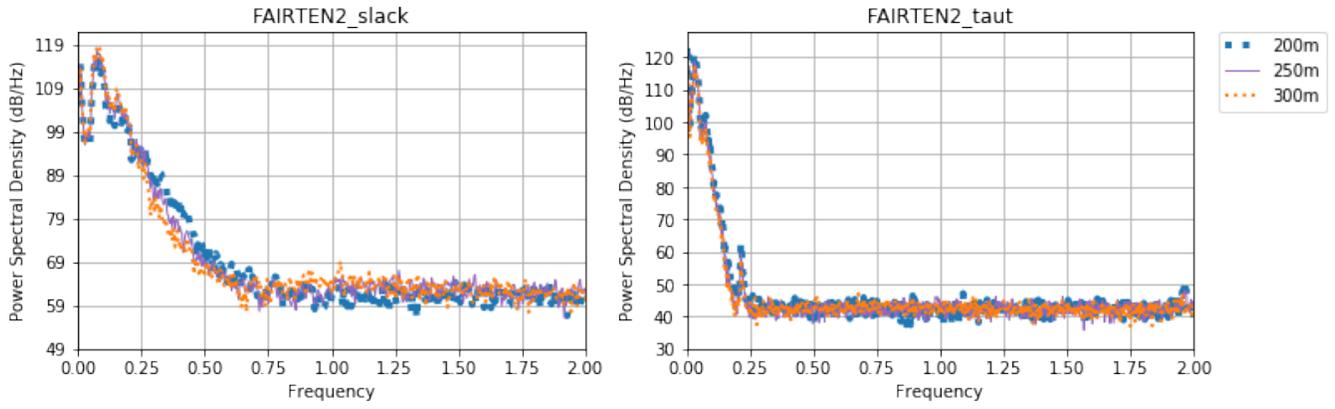
Figure 20 Transient behaviour of tower base forces (LC3)



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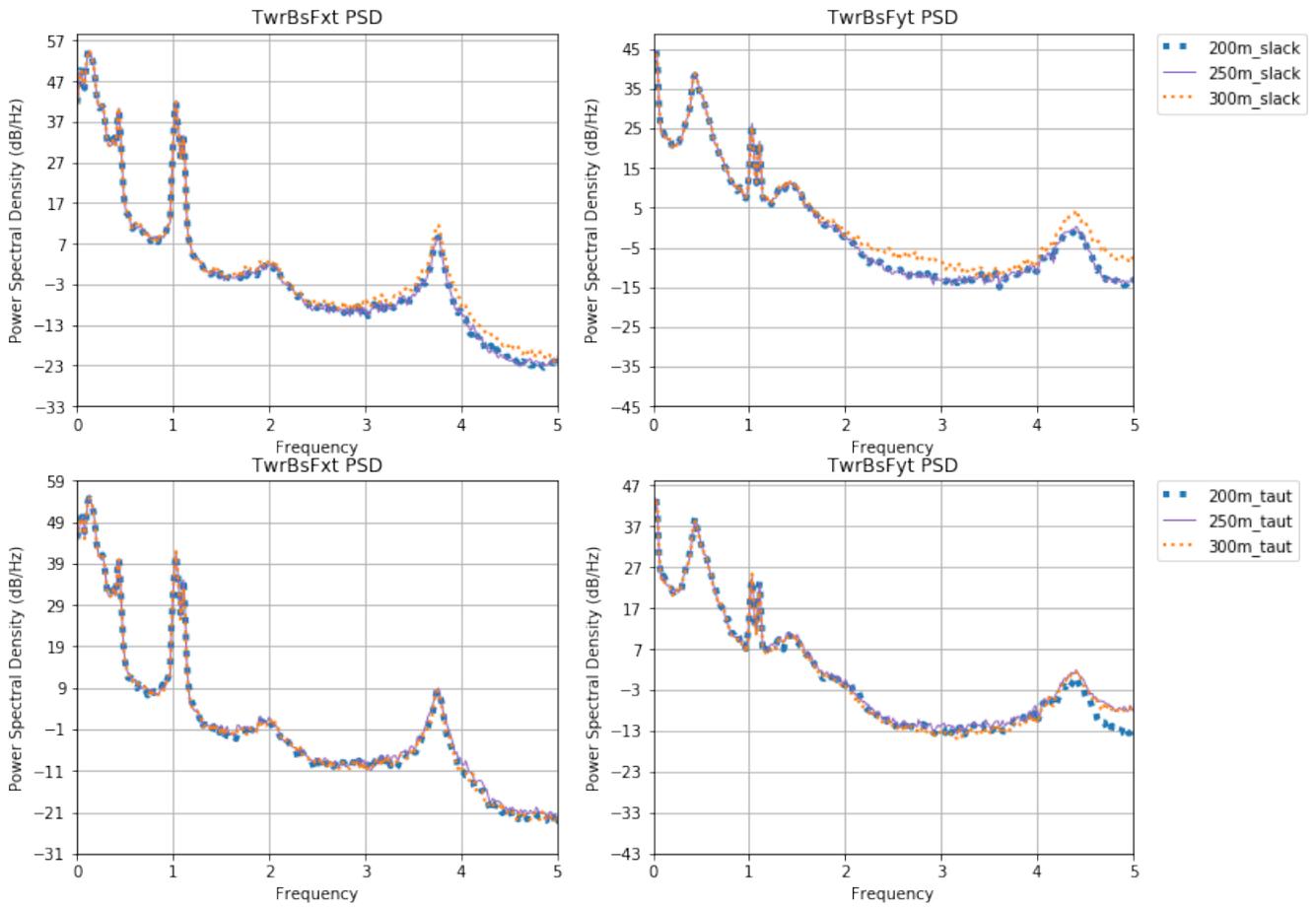
Figure 21 Spectra of platform motions (LC3)



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Figure 22 Spectra of mooring line tension (LC3)



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Figure 23 Spectra of tower base forces (LC3)

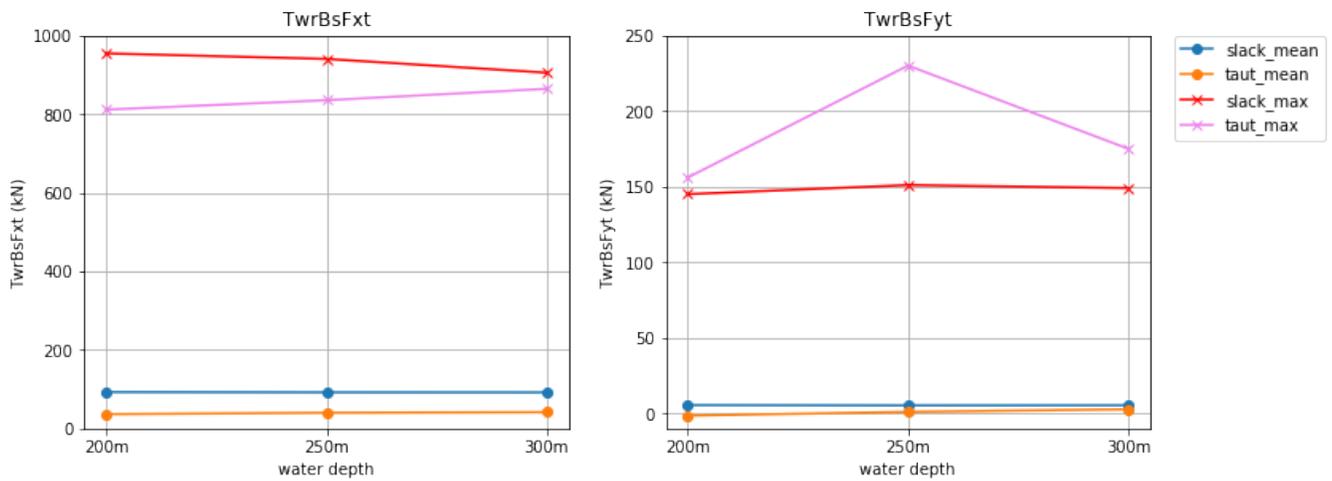


Figure 24 Statistical results of tower base forces (LC3)

5. Conclusions

This study critically analysed the effects of water depth increase on the global performance of FOWTs. The principle of comparison among various water depths lies in keeping the horizontal (surge) static restoring force measured as close as possible. Based on this principle, mooring system properties for both slack and taut configurations were derived based on the original design of the OC4 semi-submersible FOWT. The simulation results were validated against technical data in the public domain, where a great agreement was reached. Before carrying out time-series and fatigue analysis, a number of case studies were put forward in a combined wind, wave and current circumstance under considerations of different turbine operating conditions. Based on the case studies and the post-processing procedure, the following conclusions can be derived:

- For platform motion responses, heave motion with a catenary configuration tends to increase obviously with the growth of water depth, which is because of the steepness of slack moorings in the fairlead and the large vertical force components in larger water depth. For future wind turbines (e.g. 20MW) operated in much deeper water depth (e.g. more than 500 m), taut moorings are expected to outperform slack moorings in terms of vertical motions.
- Compared with surge and pitch motion responses, mooring line top tensions are more sensitive to water depth, regardless of environmental conditions. The increasing of water depth impact the DEL of both slack and taut mooring configurations, but taut moorings are of higher DELs than that of slack moorings.
- Tower base bending forces are almost water-depth independent under normal operating conditions, regardless of below or above wind speeds, but a grid loss event including HSS brake will trigger a discrepancy on the high-frequency (>2Hz) responses of tower base bending forces with an escalation of water depth.

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499

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