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A comparative study of load estimation methods for offshore wind turbines using a simplified and a high fidelity methods

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Abstract

This paper compares the critical loads calculated for offshore wind turbines (OWTs) at mudline level using a simplified approach and a high-fidelity approach. Three OWTs, NREL 5MW, DTU 10MW and IEA 15MW are used as reference models. Extreme Turbulence Model wind load at rated wind speed combined with the 50-year Extreme Wave Height (EWH) and Extreme Operating Gust (EOG) wind load combined with the 1-year maximum wave height are used as the load combinations in this study. OpenFAST simulations are used as the high-fidelity approach, where the results are then compared with a simplified load estimation approach previously proposed. It is shown that the simplified method provides conservative results for the estimated loads compared to the OpenFAST results. This means that the simplified approach can be effectively used during initial phases of the monopile foundation design by using factor as 1.5 and 2 for shear force and bending moment, respectively.

1. Introduction

The wind energy sector has been growing rapidly in the last years as it has been proved to be one of the most efficient and reliable sources of renewable energy. Offshore Wind Turbines (OWTs) are considered to be more effective than onshore wind turbines, where the wind speed and its direction are more consistent. European offshore industry has installed around 25 GW capacity at the end of 2020, with further plans to develop around 85 GW over next decade (WindEurope 2021).

Figure 1 shows the cumulative number of foundation types installed by the end of 2020. It shows that the monopile foundation is the most common type of foundation installed (81.2%) by 2020 (WindEurope 2021) (Malekjafarian et al. 2021). Furthermore, monopile foundation is used commonly due to its simple design compared to other designs and its suitability for mass-fabrication and installation of such foundations (Kallehave et al. 2015). Turbine technology and its foundations are evolving constantly as the number of offshore wind farms is increasing. Currently, monopile diameter of 8m to 10m or beyond are being installed as a result of the advancement in turbine technology (Reale et al. 2021). By increasing the size of the OWTs, the hydrodynamic loads on the structure will be higher causing higher deflection and rotation of the monopile at the mudline level (Prendergast et al. 2018).

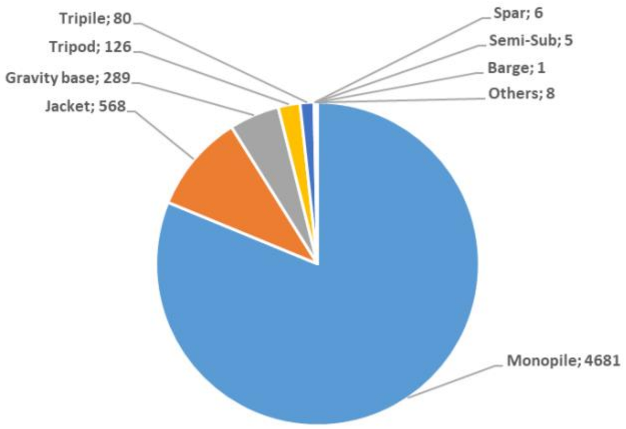


Figure 1: Number of foundation types till 2020 (WindEurope 2021)

In general, it is recommended that the natural frequency of the system should avoid the excitation frequencies such as frequencies caused by wave and wind (1P and 3P). 1P is the frequency referred to operating range wind turbine where 3P is the loads subjected on the tower due to shadowing effect of blades (Bhattacharya 2019). Figure 2 shows the various frequencies and structural design approaches. The natural frequency is dependent on the structural mass and the stiffness where larger monopile diameters increase the self-weight which eventually have impact on the natural frequency.

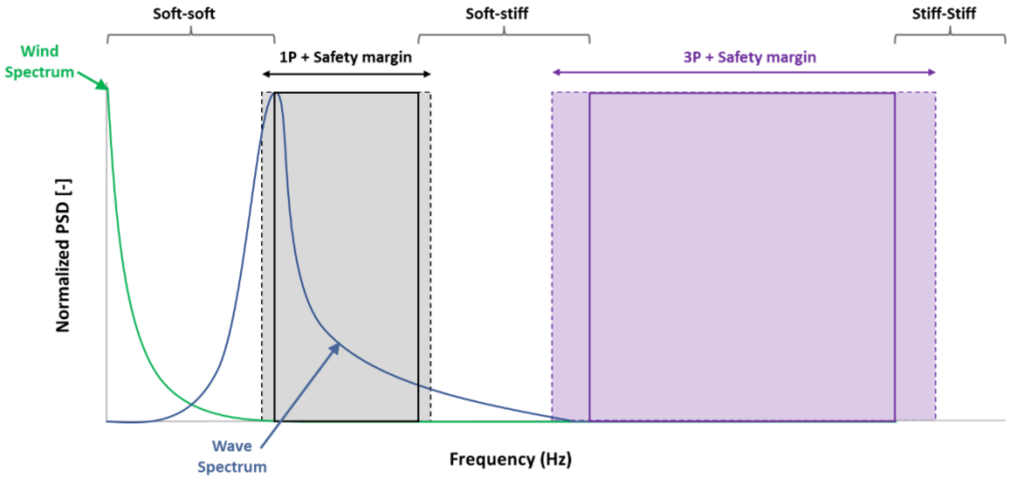


Figure 2: Various ranges of wind turbine frequencies (Modified after Bhattacharya (2019))

The design of offshore substructures must be optimized to be cost effective in order to make power from offshore wind to be a feasible solution (Chew et al. 2015). This may be achieved by reducing the uncertainties in the calculation of environmental loads acting on it . The maximum load i.e., ultimate loads subjected to the OWT structure must be assessed in order to make sure the OWT is safe throughout the lifetime of the structure (Wang et al. 2021). The main role of the foundation of OWTs is to transfer all the loads during its design life from top the structure to the mudline safely and to resist the allowable deformations. The design load calculations should ensure that the capacity of chosen foundation should resist the maximum loads acting on the structure (Bhattacharya 2019). There are many design load combinations (DLCs) are provided in the standards (IEC (2020); DNVGL (2016)) in order to assess the OWT in different conditions.

Arany et al. (2017) proposes two load combinations which are more conservative to calculate the ultimate loads for simplified approach, namely, (i) Extreme Turbulence Model (ETM) wind load at rated wind speed combined with the 50-year Extreme Wave Height (EWH) and (ii) Extreme Operating Gust (EOG) wind load combined with the 1-year maximum wave height. However, the combination of hydrodynamic, aerodynamic, non-linear interaction of soil structure and effect of controller makes the design of OWTs a very challenging process (Bhattacharya 2014). However, in recent years, detailed mathematical models including hydrodynamics, aerodynamics, servo dynamics and its influence on the dynamics of the structure are developed. These ensures the accuracy and reliable approach to design the offshore wind structures, but computational time for these types of analysis will be expensive (Schløer et al. 2016).

It is important to have the simplified approach for preliminary design of OWTs in order to get the final geometry of the structure to use it in the high-fidelity software (Ishwarya et al. 2017). In general, OWTs are designed for a lifetime of 25-30 years. OWT foundations are designed using a complex process based on the site characteristics and turbine size which will result in the dimensions/geometry of the foundation. The detail and accuracy of the design needed for the model will differ from the conceptual design stage to the detailed designed stage. However, the foundation designers normally change the turbine type and also the dimension/geometry several times during the development phase of a project. This means that the design process needs to be repeated several times which will be extremely time consuming if a high-fidelity approach is used. Therefore, having a simplified design approach during the preliminary design of monopile foundation is vital. Arany et al. (2017) introduces a simplified design approach for designing monopiles in 10 steps. However, it is necessary to validate the results of this approach with a more reliable approach to ensure that the results can be used during the primary design stage. For this purpose, this paper aims at comparing the loads calculated for three different wind turbines using the simplified approach to the results obtained from OpenFAST software which is considered as the high-fidelity approach. The results are compared to ensure the reliability of the simplified approach.

2. Loads acting on OWTs

This section introduces various external loads acting on the OWTs. In addition to the self-weight of the structure, there are four primary loads acting on OWTs, namely, (a) wind (aerodynamic load), (b) wave (hydrodynamic load), (c) 1P load (rotor frequency) and (d) 3P load (blade-passing frequency) (Bhattacharya 2019). Figure 3 shows the various loads experienced by the wind turbine during the service time of structure.

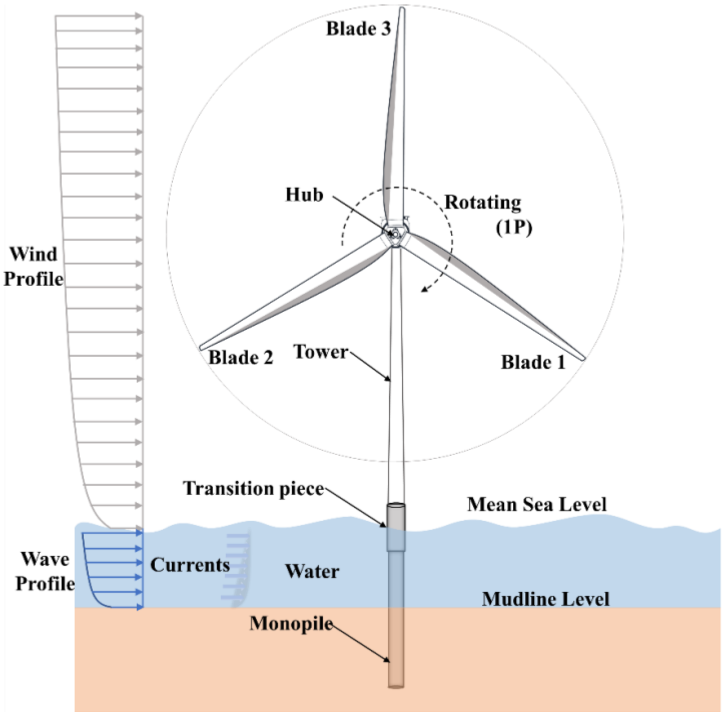


Figure 3: Loading on fixed offshore wind turbine atop monopile

Aerodynamic loads are caused due to the wind acting on the structure. These loads are produced by the thrust of the wind subjected to tower and blades. These loads are calculated based on the wind characteristics at the site and wind turbine generator (WTG) characteristics. The loads at the interface level will be higher if the hub height of the turbine is higher and consequently, wind speed at higher elevations is higher.

Hydrodynamic loads are caused due to the water waves acting on the substructure of OWTs (i.e., part of the structure submerged in water). These wave loads depend on the site-specific characteristics such as, wave height and wave period along with the water depth. In addition, the magnitude of wave loads depends on the diameter of the substructure i.e., higher the diameter higher will be the magnitude of load at the mudline level.

1P load is a load caused due to the vibration of rotor at hub height level because of mass and aerodynamic imbalance of the rotor while this corresponds to the rotational frequency of the rotor. This frequency varies according to the turbine characteristics i.e., cut-in and rated rpm (revolutions per minute). Hence, 1P will result in the range between highest and lowest rpm. However, design of the structure should not be in these range frequencies in order to avoid the resonance.

3P loads also referred as blade-passing load where the loads on the tower due to the vibration caused by the shadowing effect of blades i.e., there will be change in load (reduces the thrust on the tower) acting the tower when the blade passes through the front of the tower. This effect depends on the number of blades and this frequency can be obtained by multiplying the number of blades with the rotor frequency (1P).

3. Simplified approach

This section introduces the simplified method to calculate the ultimate loads at the mudline for OWT including wind and wave loads as proposed by Arany et al. (2017). Two load combinations are chosen for finding out ultimate loads.

3.1. Wind Loads

Wind loads are calculated for Extreme Turbulence Model (ETM) at rated wind speed and the 50-year Extreme Operating Gust (EOG) which are used in the ULS load combinations. Wind loads corresponding to ETM at rated wind speed uses the standard deviation of wind speed at the rated wind speed while the EOG uses long term distribution of 10-minutes mean wind speeds.

3.1.1 Extreme Turbulence (ETM) at Rated Wind Speed

The standard deviation of wind speed in ETM ($\sigma_{U,ETM}$) is given in IEC (2005) as,

$$\sigma_{U,ETM} = cI_{\mathrm{ref}}\left[0.072\left(\frac{\mathrm{U_{avg}}}{c}+3\right)\left(\frac{\mathrm{U_R}}{c}-4\right)+10\right] \tag{1}$$

where $\mathrm{I_{ref}}$ represents the reference turbulence intensity depends on the turbine class, $\mathrm{U_{avg}}$ is the long term average wind speed at the site and $\mathrm{U_R}$ is the rated wind speed.

The maximum turbulent wind speed component u_{ETM} is determined as (Aranya et al. (2017)),

$$\sigma_{U,ETM,f>f_{1P}} = \sigma_{U,ETM}\sqrt{\frac{1}{\left(\frac{6L_k}{U_R}f_{1P,max}+1\right)^{\frac{2}{3}}}} \tag{2}$$

where L_k is the integral length scale, $f_{1P,max}$ is the rotational speed of the turbine.

The turbulent wind speed is calculated as,

$$\mathrm{U}_{ETM} = 2\sigma_{U,ETM,f>f_{1P}} \tag{3}$$

The ultimate loads corresponding to ETM is as follows,

$$F_{wind,ETM} = \frac{1}{2}\rho_a A_R C_T (U_R + u_{ETM})^2 \tag{4}$$

$$M_{wind,ETM} = F_{wind,ETM}\,(S + z_{hub}) \tag{5}$$

whereas $F_{wind,ETM}$ and $M_{wind,ETM}$ are the lateral force and moment at the mudline level, ρ_a is the density of air, A_R is the rotor swept area, C_T is the thrust coefficient, S represents the water depth and z_{hub} is the hub height above sea level

3.1.2 Extreme Operating Gust (EOG) at Rated Wind Speed

The maximum force is assumed to occur when the maximum mean thrust force acts and the 50-year Extreme Operating Gust (EOG) hits the rotor. Due to this sudden gust, the wind speed is assumed to change so fast that the pitch control doesn't have time to adjust the blade pitch angles. This assumption is very conservative as the pitch control in reality has a time constant which would allow for some adjustment of the blade pitch.

Wind load corresponding to the EOG is calculated as,

$$F_{wind,EOG} = \frac{1}{2}\rho_a A_R C_T (U_R + u_{EOG})^2 \tag{6}$$

$$M_{wind,EOG} = F_{wind,EOG}\,(S + z_{hub}) \tag{7}$$

whereas $F_{wind,EOG}$ and $M_{wind,EOG}$ are the lateral force and moment at the mudline level corresponding to EOG condition, u_{EOG} is the wind speed component of EOG condition.

3.2. Wave Loads

The simplified approach uses the Morison's equation in order to calculate the wave loads on the structure. It uses 50-year wave period and wave height to calculate the load. Extreme wave height corresponding to return period of 1yr ($H_{S,1}$) is calculated using the below formula (Arany et al. 2017),

$$H_{S,1} = 0.8 H_{S,50} \tag{8}$$

$$T_{S,1} = 1.11 \sqrt{\frac{H_{S,1}}{g}} \tag{9}$$

$$H_1 = H_{S,1} \sqrt{\frac{1}{2} ln\left(\frac{10800}{T_{S,1}}\right)} \tag{10}$$

$$T_1 = 1.11 \sqrt{\frac{H_1}{g}} \tag{11}$$

where $H_{S,50}$ is the extreme wave height corresponding to the return period of 50-year, $T_{S,1}$ is time period corresponding to the return period of the 1-year, H_1 and T_1 are the wave height and wave period with the 1-year return period.

In the simplified method, for obtaining foundation loads, it can be conservatively assumed that the sum of the maxima of drag and inertia loads is the design wave load. This assumption is conservative, because the maxima of the drag load and inertia load occur at different time instants. Therefore, wave loads are calculated based on the above calculated values as follows (Arany et al. 2017),

$$F_{D,max} = \frac{1}{2} \rho_w D_s C_D \frac{\pi^2 \mathrm{H}^2}{T^2 \sinh^2(kS)} \, P_D(k,S,\eta) \tag{12}$$

$$M_{D,max} = \frac{1}{2} \rho_w D_s C_D \frac{\pi^2 \mathrm{H}^2}{T^2 \sinh(kS)} \, Q_D(k,S,\eta) \tag{13}$$

where,

$$P_D(k,s,\eta) = \frac{\mathrm{e}^{2\mathrm{k}(\mathrm{S}+\eta)} - e^{-2k(S+\eta)}}{8k} + \frac{S+\eta}{2} \text{ and} \tag{14}$$

$$Q_D(k,s,\eta) = \left(\frac{S+\eta}{8k} - \frac{1}{16k^2}\right) \mathrm{e}^{2\mathrm{k}(\mathrm{S}+\eta)} - \left(\frac{S+\eta}{8k} + \frac{1}{16k^2}\right) \mathrm{e}^{-2\mathrm{k}(\mathrm{S}+\eta)} + \left(\frac{S+\eta}{2}\right)^2 + \frac{1}{8k^2} \tag{15}$$

$$F_{I,max} = \frac{1}{2} \rho_w C_m {D_s}^2 \frac{\pi^3 H}{T^2 \sinh(kS)} \, P_I(k,S,\eta) \tag{16}$$

$$M_{I,max} = \frac{1}{2} \rho_w C_m {D_s}^2 \frac{\pi^3 H}{T^2 \sinh(kS)} \, Q_I(k,S,\eta) \tag{17}$$

where,

$$P_I(k,s,\eta) = \frac{\sinh(k(S+\eta))}{k} \text{ and} \tag{18}$$

$$Q_I(k,s,\eta) = \left(\frac{S+\eta}{2k} - \frac{1}{2k^2}\right)\mathrm{e}^{\mathrm{k(S+}\eta)} - \left(\frac{S+\eta}{2k} + \frac{1}{2k^2}\right)\mathrm{e}^{-\mathrm{k(S+}\eta)} + \frac{1}{k^2} \tag{19}$$

where $F_{D,max}$ and $F_{I,max}$ are the maximum drag and inertia force, where $M_{D,max}$ and $M_{I,max}$ are the maximum drag and inertia moments, ρ_w density of water, D_s is the diameter of the substructure, C_D and C_m are the drag and inertia coefficients, H and T are the wave height and period, k is the wave number, S is the water depth, $\eta$is the surface elevation.

The total wave load is calculated as,

$$F_{\text{wave}} = F_{\text{D,max}} + F_{\text{I,max}} \tag{20}$$

$$M_{\text{wave}} = M_{\text{D,max}} + M_{\text{I,max}} \tag{21}$$

4. High fidelity approach

This section illustrates the methodology behind OpenFAST software, and its various modules involved. OpenFAST is an open source aero-hydro-servo-elastic software. The main modules in OpenFAST are SubDyn and Elasto-Dyn for the structural dynamics, ServoDyn for the power generation, and InflowWind, HydroDyn and AeroDyn for external conditions and applied loads.

4.1. Wind Loads

The wind loads acting on the structure is the dominant load during the operation of OWTs. The turbine tower and blades are subjected to the wind loads acting on the wind turbines. OpenFAST uses the blade element momentum (BEM) theory (Moriarty and Hansen 2005) to calculate the aerodynamic loadings on the location along the blades. BEM theory is the combination of blade element theory (or propeller theory) and momentum theory. Blade element theory calculates the forces by dividing the blade into number of segments along the length and then the force is calculated on each segment. Momentum theory incurs the reduction in velocity when wind passes through the rotor. BEM uses these two concepts to find the axial forces and torque acting on the rotor blades.

In addition, the power law is used to calculate the wind load along the turbine tower as wind speed along the vertical height changes (DNVGL 2014):

$$V(z) = V_{hub}\left(\frac{z}{z_{hub}}\right)^{\beta} \tag{22}$$

where $V(z)$ and V_{hub} are the mean wind speed at the height z above the MSL and hub height, z_{hub}, respectively, and the power law coefficient, β of 0.143 has been considered in this study (Bhattacharya 2019).

4.2. Wave Loads

Hydrodyn is a module in the OpenFAST which is used to calculate the hydrodynamic loads. Figure 4 shows the overview of wave parameters involved in the calculation of wave loads on the structure. Regular wave has been considered for the calculation of hydrodynamic loads on the structure in this study. The hydrodynamic loads on the structure are calculated based on strip theory using Morison's equation (Morison et al. 1950). Morison's equation is a function of water particle velocity and acceleration along the depth and the force per unit length along the cylinder is given by,

$$dF_h = 0.5\,\rho_w\,C_d\,D\,dz\,|v_r|v_r\;+\;C_m\,\rho_w\,A(z)dz\,a_r \tag{23}$$

where ρ_w represents the density of water, $D\,dz$ is the area of the strip with diameter (D) and $A(z)dz$ is displaced volume, v_r is the relative water velocity with respect to velocity of the body and ar represents the relative fluid acceleration.

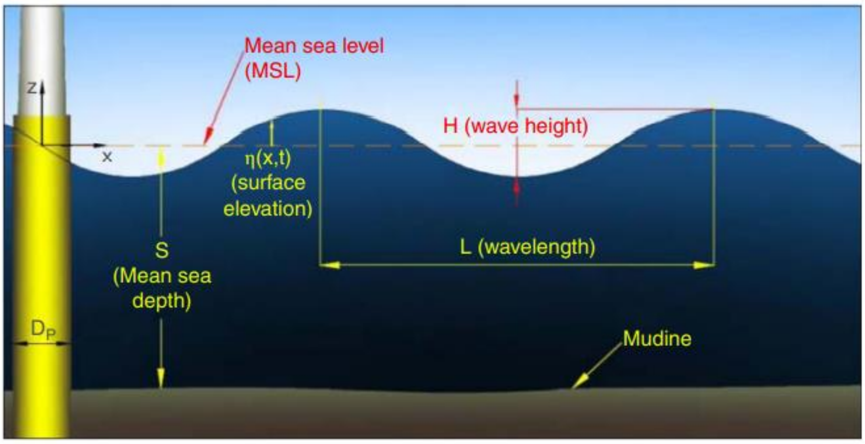


Figure 4: Overview of wave parameters (Bhattacharya 2019)

4.3. Substructure

OpenFAST models substructure, transition piece (TP), tower, and rotor-nacelle assembly (RNA) through various sub-modules. Subdyn is the module which models the structure from the mudline till TP and it allows to model with rigid bottom or option of providing the stiffness matrix at the mudline level. In addition, the parameters related to tower and RNA is modelled in elastodyn module of the OpenFAST where the tower is specified in terms of the mode shapes which are calculated by standalone software BModes (Damiani et al. 2015).

4.4. Servo System

ServoDyn is the control and electrical-drive module. It includes control and electrical-drive models for blade pitch, generator torque, nacelle yaw, high-speed shaft brake and blade-tip brakes. Bladed-style dynamic link library (DLL) is the default blade pitch control mode in OpenFAST. A more detailed description of ServoDyn can be found in (Jonkman and Jonkman 2020).

5. Wind turbine models

This section introduces various Wind Turbine Generators (WTGs) used for the comparison of load estimated by high-fidelity and simplified approach. In this study, three offshore wind turbines namely, NREL 5MW (Jonkman et al. 2009), DTU 10MW (Bak et al. 2013) and IEA 15MW (Gaertner et al. 2020) are considered as the base models. Table 1 shows the various parameters of three WTGs. Hub heights for 5MW, 10MW and 15MW are 90m, 119m and 150m, respectively while rotor diameter of 126m, 178.3m and 240m, respectively.

Table 1: Properties of WTGs

Parameter	Units	Value

Power Rating	MW	5	10	15
Configuration	No.	3	3	3
Rotor, hub diameter	m	126, 3	178.3, 5.6	240, 7.94
Hub height	m	90	119	150
Rated rotor speed	rpm	12.1	9.6	7.56
Rotor mass	kg	110,000	229,000	144,962
Nacelle mass	kg	240,000	446,000	530,888
Tower mass	kg	347,500	605,000	860,000
MP Diameter, wall thicknesses	m	6.0, 0.060	8.3, 0.060	10, 0.055
Tower top diameter, wall thickness	m	3.87, 0.019	5.5, 0.020	6.5, 0.024
Tower base diameter, wall thickness	m	6.0, 0.027	8.3, 0.038	10.0, 0.041

6. Results

This section shows the results for NREL 5MW, DTU 10MW and IEA 15MW turbines. For each turbine size, the loads are calculated using the OpenFAST simulations. The two key parameters, mudline shear force and bending moment are used for the comparison between the methods. The following load combinations are used for the analysis (Arany et al. 2017):

1. Extreme Turbulence Model (ETM) wind load at rated wind speed combined with the 50-year Extreme Wave Height (EWH).
2. Extreme Operating Gust (EOG) wind load combined with the 1-year maximum wave height.

6.1. Comparison between Simplified and high-fidelity approach

Table 1 compares the mudline shear forces and bending moments from the simplified approach and the OpenFAST simulations for NREL 5MW, DTU 10MW and IEA 15MW turbines. It can be seen that shear forces and bending moments increase with increase in turbine size as there is a change in structural geometry. For instance, bending moment obtained from simplified approach corresponding to ETM with 50yr EWH resulted in 215.8 MNm and 1073.1 MNm for NREL 5MW and IEA 15MW turbine, respectively. Furthermore, it can be observed that the simplified method provides larger values for all turbine sizes compared to OpenFAST results. For example, for EOG with 1-year EWH, using the simplified method for NREL 5MW turbine results in 32.9% and 39.2% higher values for the shear force and bending moment compared to OpenFAST, respectively. Similarly, the simplified approach provides 37.9% and 49.5% higher values for the shear force and bending moment for IEA 15 MW compared to OpenFAST for EOG with 1yr EWH.

Table 2: Comparison of mudline loads from Simplified and OpenFAST results.

Turbine	Method	ETM with 50yr EWH		EOG with 1yr EWH	
		Shear Force (MN)	Bending Moment (MN.m)	Shear Force (MN)	Bending Moment (MN.m)
NREL 5 MW	Simplified Method	5.54	215.83	6.45	374.05
	OpenFAST	4.36	165.65	4.33	227.61
	Difference	21.28%	23.25%	32.92%	39.15%
DTU 10 MW	Simplified Method	10.07	507.32	11.65	850.36
	OpenFAST	6.24	154.98	5.39	166.32
	Difference	38.03%	69.45%	53.70%	80.44%
IEA 15 MW	Simplified Method	16.49	1073.14	19.16	1823.80

	OpenFAST	13.74	757.22	11.90	920.43
	Difference	16.66%	29.44%	37.89%	49.53%

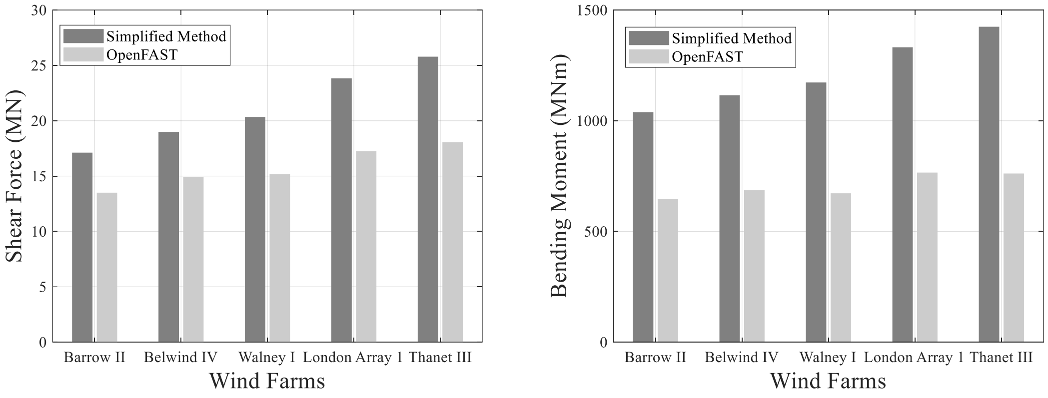
6.2. Site-specific loads using simplified approach

This section introduces the analysis of extreme loads using simplified and high-fidelity method for various metocean data of wind farms. Five wind farms namely, ‘Barrow II’, ‘Belwind IV’, ‘Walney I’, ‘London Array 1’, ‘Thanet III’ have been considered. Table 3 shows the summary of metocean data for various wind farms used for the analysis where the water depth for Barrow II has 18m increases up to 27m for Thanet III wind farm. Barrow II has H_s and T_p with return period of 50 year of 7.5m and 9.7 sec, respectively, whereas 8.4m and 10.3 sec for Belwind IV. Further, Walney I, London Array 1 and Thanet III having wave height of 9m, 10.5m and 11.3m, respectively, and wave period of 10.6 sec, 11.5 sec and 11.9 sec, respectively.

Table 3: Metocean data of wind farms

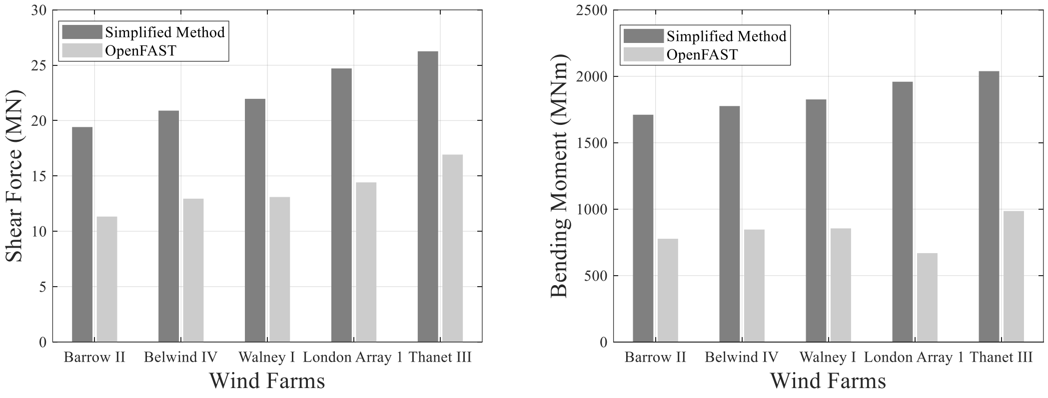
Wind Farm	Water Depth	$H_{s,50}$	$T_{p,50}$
Barrow II	18	7.5	9.7
Belwind IV	20	8.4	10.3
Walney I	21.5	9	10.6
London Array 1	25	10.5	11.5
Thanet III	27	11.3	11.9

As turbine technologies are advancing, it is important to know the extreme loads acting on the larger turbines which might have an impact on the design. In this study, IEA 15MW is considered for sensitivity check. Figure 5 and Figure 6 shows the extreme loads comparison between simplified and OpenFAST method for ETM with 50-year EWH and EOG with 1-year EWH. It can be seen that extreme loads for both loading condition increases with increase in water depth. Further, it can be observed that Simplified method is over conservative with OpenFAST when the water depth is higher compared to lower water depth. Likewise, bending moment results in higher values against shear force in simplified approach when compared to high-fidelity method. For instance, simplified method for Barrow II results in 21.2% and 37.8% higher than high-fidelity approach for shear force and bending moment, respectively, corresponding to ETM with 50yr EWH while for EOG with 1yr EWH showed 41.7% and 54.7% higher. Similarly, for Thanet III, shear force for simplified method resulted in 29.9% and 35.6% while bending moments of 46.6% and 51.7% higher compared to OpenFAST results corresponding to ETM with 50yr EWH and EOG with 1yr EWH, respectively. This suggests that the simplified method is conservative than high-fidelity method. However, factor of 1.5 and 2 may be used for shear force and bending moment, respectively, in order to consider for preliminary design.



(a) (b)

Figure 5: Comparison of extreme loads for ETM with 50yr EWH: (a) Shear Force; (b) Bending Moment



(b) (b)

Figure 6: Comparison of extreme loads for EOG with 1yr EWH: (a) Shear Force; (b) Bending Moment

7. Conclusion

This paper shows a comparison of the loads estimated for OWT foundations using a simplified and a high-fidelity method. The comparison is carried out for loads obtained corresponding to ETM with 50-year EWH and EOG with 1-year EWH scenarios. It is shown that the simplified method results in higher values for load compared to the OpenFAST results. Further, ultimate loads against larger turbine i.e., IEA 15MW resulted in higher loads compared to other turbine size. Sensitivity check against IEA 15MW turbine shown that the higher water depth leads to higher loads at the mudline. In addition, sensitivity check ensures again the simplified method resulted in higher loads than response from OpenFAST. Hence, it can be concluded that the simplified method is a conservative approach. But, factor of 1.5 and 2 may be used for the shear force and bending moment, respectively, in order to account for the early design phase of monopile foundations and during the tendering phase. However, the results from the simplified approach do not imply the detailed design loads.

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