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Static actions evaluations on offshore wind tower on the coast of Maranhão

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Abstract

Clean and renewable energy sources are fundamental to the development and restructuration of the energy matrix of many countries, which is one of the UN's sustainable development goals. Hence, engineering professionals are expected to be able to develop solutions to generate clean and renewable energy. Wind energy stands out as one of the alternatives of energy source, since it has zero emissions of pollutants and low environmental impact. Wind turbines can be built on land or in marine environment, the offshore alternative has as advantage a greater energy potential. However, offshore wind turbines are subject to more complex loads, in comparison to their onshore counterpart, due to the environment it is built. The assessment of these actions is a fundamental task in the design process of such structures. In Brazil, the studies of the subject are still scarce, despite the large energy potential of the country. The objective of this study is to obtain the main actions that should be considered in the static structural analysis of an monopile offshore wind tower. Among those actions, the environmental loads depend mainly on the local environmental. In this analysis, a standardized turbine of 5 MW was considered. The considered deployment location is on the Bay of São Marcos about 27 km from the Maranhão State shore. The actions evaluated are: self-weight from the structure and additional marine growth; wind pressure acting on the blades, turbines and the tower; buoyancy loads throughout the submerged structure; loads due to sea waves and currents and other actions such accidental or maintenance loads. The obtained actions could be used to obtain both stresses and strain fields on the structure, which is a crucial information to the design of the offshore wind structures.

Key-words

Offshore structures; static analysis; wind energy.

Introduction

Clean and renewable energy sources are fundamental to the development of countries and are fundamental to the restructuring of the countries' energy matrix, which is one of the UN's sustainable development goals [1]. Therefore, a growing demand in the world for green energy sources is expected.

Wind energy stands out as one of the solutions to meet this demand, since it is a source with zero emissions of pollutants and has a low environmental impact [2].

Wind turbines can be built on land or in the maritime region, the offshore alternative has as advantage a greater energy potential, since it is operated in a place with more constant wind regime and with higher speeds. In addition to being away from urban centers avoiding noise pollution, a common issue in onshore wind towers.

Despite the advantages over onshore wind towers, the offshore system has a cost up to 150% higher [3]. The higher cost occurs because the offshore turbines are generally bigger and are subjected to higher and more complex loads, due to the marine environment. The correct analysis of these actions is crucial to the design of this type of wind turbines. The evaluation of the marine loads is a challenge since it depends on data of waves, sea currents, boats that transit nearby, wind regime and seismic activity at the local. These data are necessary to correct evaluate aerodynamic loads; wind-generated drag loads; hydrodynamic loads generated by waves, sea current and ice; maintenance and accidental loads due to vessel collision [4].

The offshore turbines have another challenge that is the constructions aspects of the structure, because its implementation is more complex than implementing an onshore turbine. The implementation depends on the type of foundation chosen, vessel availability and environmental conditions. The foundation can be fixed or floating, at depths of up to 50 meters the fixed foundations are more economical and also the most used. Fixed solutions include monopile foundations, gravity base, suction bucket, tripod, tri-pile, jacket and high-rise pile cap. The monopile foundation consists in a pile fixed on the seabed that will support the tower and the turbine, the monopile is also the most widely used type [5].

Despite the technical difficulties of this type of structure, its implementation is feasible and has already been carried out in the world, in Brazil the studies of the subject are still scarce, despite the large energy potential of the country [3].

In this study will be developed the calculation of the static loads working in an offshore wind tower, and this process is part of the dimensioning of the structure. The structure analyzed consists of a tower with monopile foundation, which will support the a NREL 5 MW reference wind turbine. It will be considered that the tower will be located near the São Marcos Bay in São Luís do Maranhão. The location was chosen due to good wind energy potential and availability of the majority of environmental data [6-8].

Characterization

Deployment area

In the structural analysis of the offshore wind tower, parameters are used that depend on the environment in which the structure is situated.

For this analysis, the region near the city of São Luís in the state of Maranhão, northeast of Brazil, was adopted. The region is in an area with good potential for offshore wind power [6] and is close to the Port of Itaqui, which could be an appropriated facility in construction period, its deployment and in future maintenance actions. The chosen region, 27 km away from the shore located approximately at the coordinates 2°3'8.50"S 44°13'44.43"W, is adopted as shown in Figure 1.

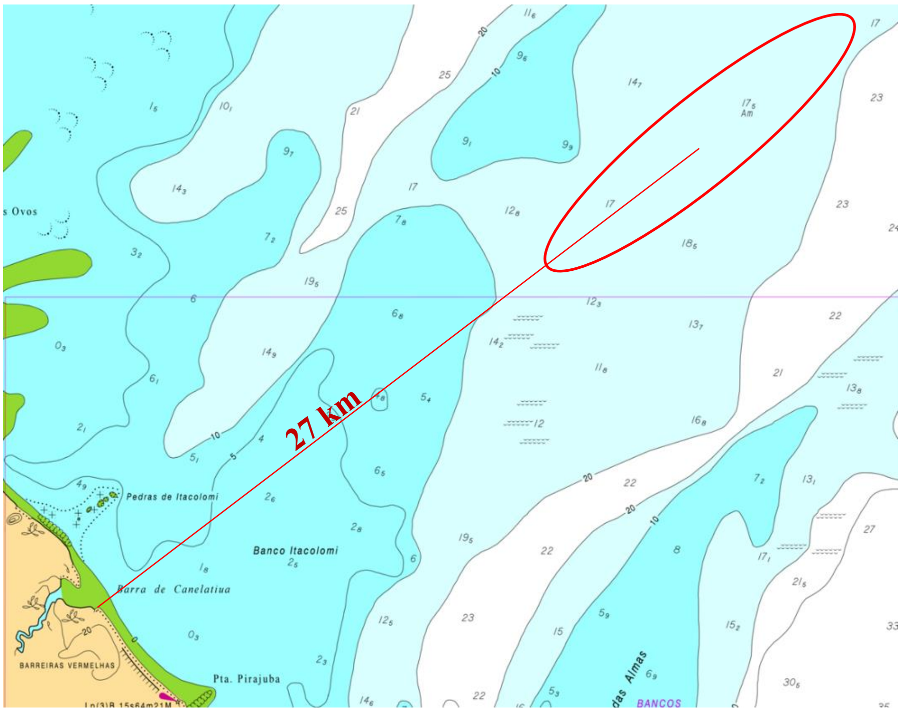

Figure 1 - Deployment area [7].

The data required to obtain the loads are described below.

The depth of the chosen region reaches up to 17 meters at average low-sea level of spring tide [7], and the tide variation for the region is 6.5 meters [8]. Therefore, the depth will range from 17 meters to 23.5 meters, which is suitable to monopile foundation [9].

Sea currents are caused by tidal movement and exert pressure on submerged structures. The currents vary in direction throughout the day, for the analysis were selected the highest speeds in the sea direction and in the land direction. The highest speed towards land is 1.6 knots (0.82 m/s) and in the sea direction is 3.7 knots (1.90 m/s).

As the region has large tidal amplitudes, an increase factor should be used to determine the design current velocities. According to the Brazilian Navy's Tidal Current Charter, the largest amplitude is 6.5 meters and the corresponding increase factor in current velocity is 1.4. Using this factor the resulted increased speeds are 2.24 knots (1.15 m/s) in the land direction and 5.18 knots (2.67 m/s) in the sea direction [8].

The significant wave height, the maximum wave height and the peak period were not found for the region, so in order to sequence the work, it was used the data obtained by the meta oceanographic buoy of Fortaleza, since it is the closest buoy made available by the Brazilian Navy. The data provided show values from November 2016 to May 2018. The maximum wave height is 5.87 meters with a corresponding peak period of 7.7 seconds. The wave measurements were carried out at a depth of 1.5 meters [10].

The basic design wind of the region is 30 m/s according to NBR 6123 [11]. To determine the characteristic speed, a topographic factor (S1), a factor of the roughness of the terrain and the dimensions of the structure (S2), and a statistical factor (S3) are used. The factors are described below:

- Factor S1 = 1.0 (flat terrain);
- Factor S2 = 1.24 (considering tower 90 m high);
- Factor S3 = 0.95 (low occupancy factor).

The design speed is obtained by multiplying the basic speed by the factors, resulting in a speed of 35.34 m/s.

The Geological Charter [12], indicates that the soil of the site is part of the Itapecuru formation, composed of sandstone, siltstone and shale. For more information about local soil, it is necessary to conduct surveys on site.

Turbine

The chosen turbine for this study is the NREL 5 Megawatts reference wind turbine [13]. The turbine will impact in the self-weight of the structure, since the tower has to support the system, thus the weight of all parts of the wind system is important to the load calculation.

The system is composed by three blades, HUB, nacelle and tower, as shown in Figure 2.

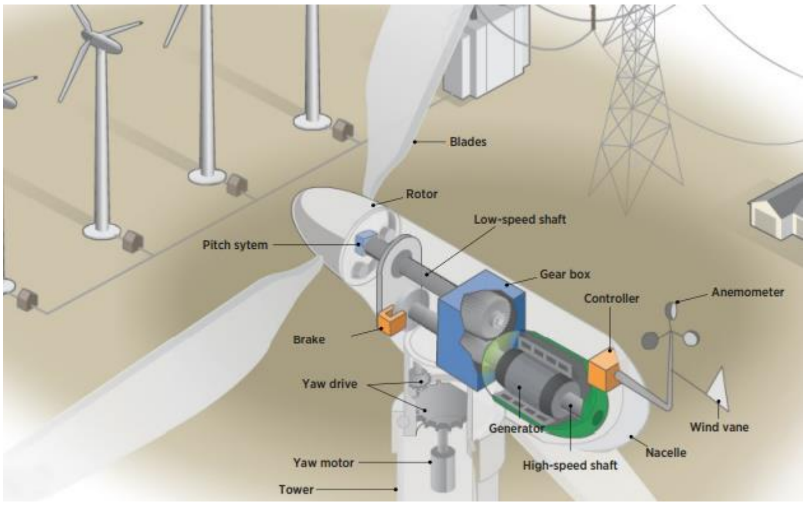

Figure 2 - Wind turbine main parts [14].

The blades are responsible for conduct the kinect energy from the wind to the HUB and the gearbox, where the energy will be converted in electric energy; the nacelle supports all the mechanical parts responsible for generating energy; the tower supports the nacelle, the HUB and the blades. The reference tower has a base diameter of 6.0 meters and a thickness of 27 millimeters.
The top of the tower has a diameter of 3.87 meters and a thickness of 19 millimeters. For the tower it is considered an ASTM 572 Gr. 50 steel with a specific weight of 8,500 kg/m³, this consideration of density is used to cover all the components not included in the calculation, as paint, flanges, bolts and other constructive elements [13].
The monopile will be submerged and will have a diameter of 10.0 meters and a thickness of 106.35 millimeters [15].
The Table 1 shows the dimensions and mass of the turbine parts.

Table 1 - NREL 5 Megawatts reference wind turbine and monopile.

Component	Dimensions (m)	Mass (kg)
Blade (x3)	61.5 (length)	17,740 (each)
HUB	3.0 (diameter)	56,780
Nacelle	-	240,000
Tower	87.6 (length)	347,460
Monopile	56 (length)	730,465

Loadings formulation

Direct wind loads

Despite being the power of the turbine, the wind also generates loads that needs to be supported by the structure. The wind loads occur in the tower and in the rotor.
To calculate the wind acting in the tower it is necessary to obtain the wind speed, that can be calculated with the following equation [4].

$$|U(z)| = |U_{hub}| \left(\frac{z}{z_{hub}}\right)^{\alpha_s} \qquad \text{(Eq. 1)}$$

Where U is the wind speed at altitude z, and U_{hub} is the known wind speed at altitude z_{hub}, and α_s is the wind power-law exponent (= 0.11 for open sea applications [16]).

With the wind speed obtained, the pseudo static load can be determined by the equation below [4].

$$f_a = 0{,}5\rho_a \pi D_{sh} C_d G_f U|U| \qquad \text{(Eq. 2)}$$

Where f_a is the force per unit length due to wind aerodynamic drag, ρ_a the air density, D_{sh} the outer diameter of the tower, U the wind speed, C_d the drag coefficient (= 0.6 – 0.7 [4]), and G_f the gust factor (= 1.6 [17]).

Hydrodynamic loads

The monopile structure is affected by the hydrodynamic loads generated by the sea current and waves, thus it is important to obtain these actions.
Given the wave dynamic behavior, the effects on the structure due wave action are described with more accuracy with a dynamic analysis. However, the static analysis can describe the wave loads adequately, since the dynamic effects are more significant in deeper waters [18].
The wave and sea current loadings on the monopile can be calculated with the Morison equation for slender members [4], as shown below.

$$f_w = 0{,}25\rho_w \pi {D_{sh}}^2 C_m U_w + 0{,}5\rho_w \pi D_{sh} C_d U_w |U_w| \qquad \text{(Eq. 3)}$$

where f_w is the force per unit length due to wave and sea current; ρ_w is the sea water density; D_{sh} is the tower outside diameter; U_w is the wave and current speed; and C_d and C_m are the drag coefficient and the added mass coefficient, respectively. The API recommended values for a rough surface are C_d=1.05 and C_m=1.2 [18].

Self-weight loads

The monopile shall support the weight of the turbine and tower structure, and the local soil also shall support the total weight of the structure.
The weight of the structure can be calculated with Newton's second law.

$$F = ma \qquad \text{(Eq. 4)}$$

Where F is the weight of the structure, m is the mass of each part, and a is the acceleration (in this case, the force is caused by gravitational force of Earth, thus a = gravity acceleration = 9.81 m/s²).

It is important to consider the additional marine growth in the monopile structure. The additional thickness recommended by API is equivalent to 3.81 centimeters [18] and the common density for marine growth is 1325 kg/m³ [19]. Conservatively, the marine growth is considered along the monopile above seabed, which corresponds to 18,670 kg over 23.5 m.

Accidental loads

The accidental loads due to boats collisions should be considered and the turbine shall have dedicated fenders for boat landing. These fenders are designed to absorb the impact generated in the collision, but the structure shall withstand the impact energy.
For the calculation of the impact loads, the following equation can be used [4].

$$F_{si} = v_{si}\sqrt{c_{si} a_{si} m_{si}} \qquad \text{(Eq. 5)}$$

where m_{si} is the mass of impact vessel; v_{si} is the vessel impact speed; c_{si} is the stiffness of the vessel part that made contact; and a_{si} is the added mass coefficient during collision (1.4 – 1.6 sideway impact, 1.1 bow or stern collision [4]).

In this study the accidental loads will not be considered since the information about boat traffic is not available.

Seismic loads

The seismic events can generate significant forces on the wind turbine structure and the loads shall be considered in the design process. However, in this study it is considered that any seismic event will not occur, since the structure is located in the Zone 0 of the NBR 15421:2006 [20], therefore there is not any seismic resistance requirement.

Results

The environmental loads acting on the wind turbine installed near the coast of São Luis do Maranhão can be calculated used the formulation described and the characterization data.
To obtain the environmental loads, it was considered the scenario with the highest sea level (23,5 meters above seabed).

Direct wind loads

For the wind action, the tower length above sea will be divided in 4 segments, each one with 21.9 meters. The tower division is illustrated in Figure 3.

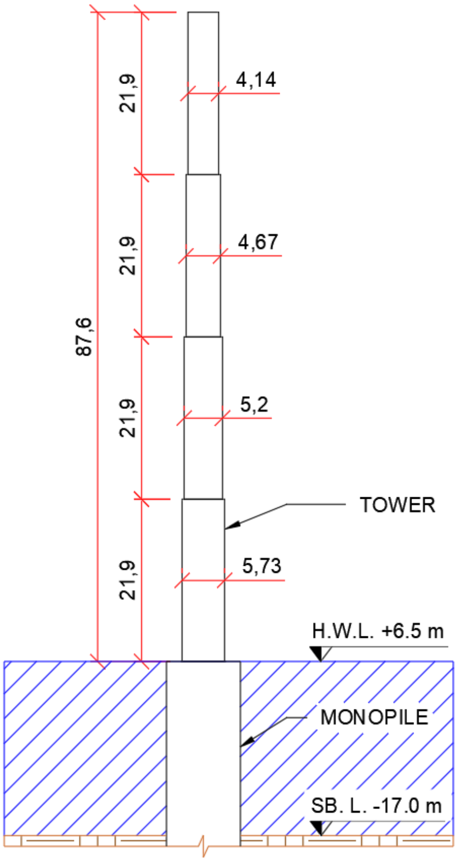

Figure 3 - Tower scheme [Author].

The wind speed considered is the wind speed at the average height of the segment. The outside diameter of each segment is necessary for the load calculation. It will be considered the average diameter of the segment. Both average height and diameter are shown in Table 2.

Table 2 – Segments dimensions.

Segment	Average diameter (m)	Average height (m)
1	5.73	10.95
2	5.20	32.85
3	4.67	54.75
4	4.14	76.65

With Equation 1, the wind speed for each segment is obtained as shown:

$$|U(10.95m)| = 28.03\ m/s;$$
$$|U(32.85m)| = 31.63\ m/s;$$
$$|U(54.75m)| = 33.46\ m/s;$$

$$|U(76.65m)| = 34.72\ m/s.$$

With the wind speed obtained, the pseudo static load can be determined with Equation 2.

$$f_{a,1} = 9{,}379.67\ N/m;$$
$$f_{a,2} = 10{,}838.98\ N/m;$$
$$f_{a,3} = 10{,}893.20\ N/m;$$
$$f_{a,4} = 10{,}397.92\ N/m.$$

Hydrodynamic loads

To obtain the hydrodynamic loads, will be adopted the current and wave speed at the same direction, thus the current speed towards land is 1.15 m/s.
Considering regular waves for deep waters, the wave speed calculated is 7.07 m/s. The velocity used in Equation 3 is the sum of current and wave speed, therefore 8.22 m/s.

$$f_w = 1{,}945{,}763.81\ N/m$$

Self-weight loads

The weight of the turbine structure (rotor, nacelle and tower); marine growth; and monopile can be calculated with Equation 4. The weight of each structure and the total weight is shown below.

$$W_{turbine} = 6{,}842{,}082.60\ N$$
$$W_{marine\ growth} = 183{,}152.70\ N$$
$$W_{monopile} = 7{,}165{,}861.65\ N$$
$$W_{total} = 14{,}191{,}096.95\ N$$

Conclusion

Wind energy is a great alternative to produce renewable energy, standing out because it does not depend on scarce raw materials or produce greenhouse gases during operation.
The application of offshore wind turbines has as main advantage a greater generating potential in relation to onshore wind turbines. However, due to the marine environment this type of solution is subject to greater and more complex loads that need to be properly evaluated to ensure proper design of the structure.
The present study raised the loads acting on a NREL 5 MW reference wind turbine located 27 km off the coast of Maranhão. The calculation of loads is complex and is very dependent on the availability of local environmental data. As the data are available, it was possible to calculate the loads in the structure. The wind and hydrodynamic loads were quite significant for the structure, being the main loads to be considered in the structural design of an offshore wind turbine.

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