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A COMPARATIVE STUDY OF JACKET FOUNDATIONS FOR OFFSHORE WIND TURBINES

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Abstract. The increasing use of wind energy comes from the need to ensure diversity and energy supply, as well as the search for renewable energy sources, reducing the environmental impacts accentuated by the use of fossil fuels. In this context, the worldwide trend in the development of technologies associated with the production of wind energy has become more present in several countries. In Brazil, the first wind turbines were installed in the northeast region, that suffers most from the critical levels of water reservoirs and is well known for its great wind potential, which contributes to the success obtained in the production of onshore wind farms. Aiming at the constant increase of the production of this type of energy, the studies for offshore turbine installations have started. This work aims to study the installation of wind turbines in a water depth of 40m using jackets as foundations. The natural frequencies and stresses in a jacket structure used to support 5MW and 10MW wind turbines are evaluated. The analyses were performed considering static and environmental loads of wind, wave and current. It was possible to verify that the structural set related to the 10MW turbine has greater periods of vibration, besides greater efforts, becoming necessary to adapt the jacket, as base enlargement. In addition, an adjustment of structures geometries was also necessary in order to obtain greater cost-benefit.

keywords: Offshore Wind Turbine, Jacket, Geometry

1 Introduction

The growth in energy demand is directly related to the economic development of a country. Based on the world energy matrix mainly composed of oil derivatives, many countries have invested in researches and projects to ensure the diversity in energy supply. Furthermore, international requirements to reduce fossil fuels emission, such as oil and coal, also contributed to investment in renewable energy.

Although the use of oil and coal is still prevailing, renewables energies sources achieved high visibility and showed considerable growth in the last decade, assuming large participation in the energy matrix of many countries around the world. In addition to collaborating with global climate target, the use of these new sources contributed to the development of new technologies for energy exploration and new skilled jobs creation.

The Brazilian energy matrix is mainly composed of clean energy, due to the large natural resources availability and favorable environmental conditions for their exploration. This matrix is mostly composed of hydroelectric, wind and biomass power plants (Fig. 1). According to ABEEólica [1], the current installed wind capacity in Brazil (about 15 GW) is greater than Itaipu's power plant capacity (about 14 GW) [2].

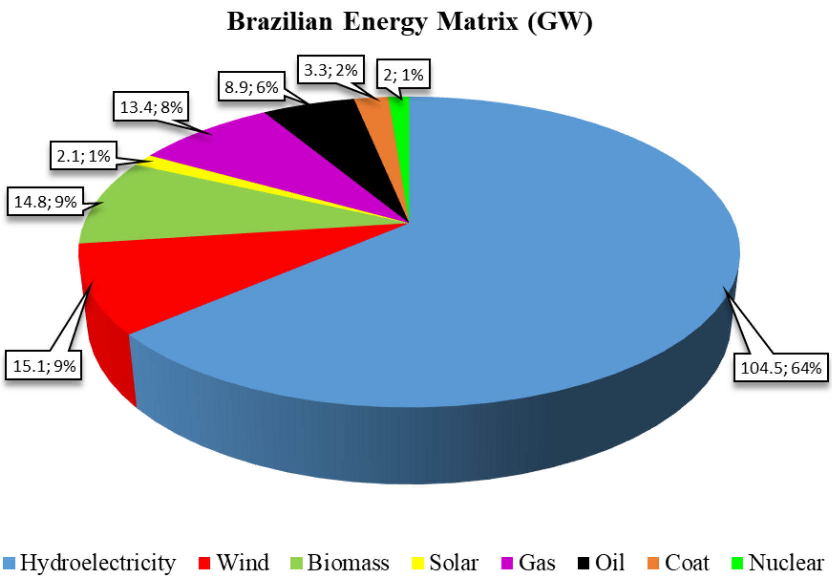


Figure 1. Brazilian energy sources (2018).

Investments towards expanding wind farms in Brazil follows a global trend, which has leading the country to the eighth position in the world ranking of installed wind power capacity in 2017, according to the GWEC [3]. The Northeast represents the region with the highest wind power generation in Brazil, and Rio Grande do Norte the state with the largest production when it comes to this source of electricity generation [3]

Determining the wind electricity generation potential in a region is extremely complex. It requires studies and monitoring for wind behavior, for a minimum period of one to two years, using different methodologies. The wind speed, for example, is directly influenced by the blades height to the reference level - soil or water, depending on whether the farm is located onshore or offshore, respectively - the presence of obstacles and the wind turbulence. The offshore wind power extraction has been increasingly growing in order to reduce the influence of limiting factors of wind speed and explore the best use of wind potential.

Offshore wind turbine design is quite complex. It should take into account several factors such as location, distance to the shore, water depth, interference with shipping routes and marine life. The support structure needs to be adjusted to the installed location environmental conditions as well as to provide to the structural assembly strength and stability presenting, therefore, a further challenge to their installation.

With that in concern, this study aims to provide the analysis of offshore wind turbines installed on a jacket type foundation, under the action of the Northeast environmental conditions. Natural frequencies of the assembly and stresses acting on the structural elements (for extreme loads) are some of the results aimed by the analyzes presented along this paper.

2 Offshore Wind Turbines

The offshore wind turbine installation requires the optimization of support structures with rigidity and stability necessary to resist to wind loads, wave and current.

Although monopiles have proved to be a widely satisfactory solution for wind farms in shallow water, its use becomes less viable in deeper water projects, with turbines of larger sizes. In addition to the challenges related to bathymetry, the soil parameters (regarding soil types of lower resistance) and extreme sea states make monopiles less attractive economically. Furthermore, monopiles also require large structural mass to ensure the modal performance of the system. Figure 2 shows the relation between the cost of support structure of offshore wind turbine and the water depth in which can be seen that greater depths requires greater structure complexity. Thus, the jackets may provide the necessary stiffness and stability due to their larger bases and truss geometry.

Still according to Fig. 2, the truss structures and jackets are the most suitable types of foundations for wind turbines installed in intermediate water (30 to 60m).

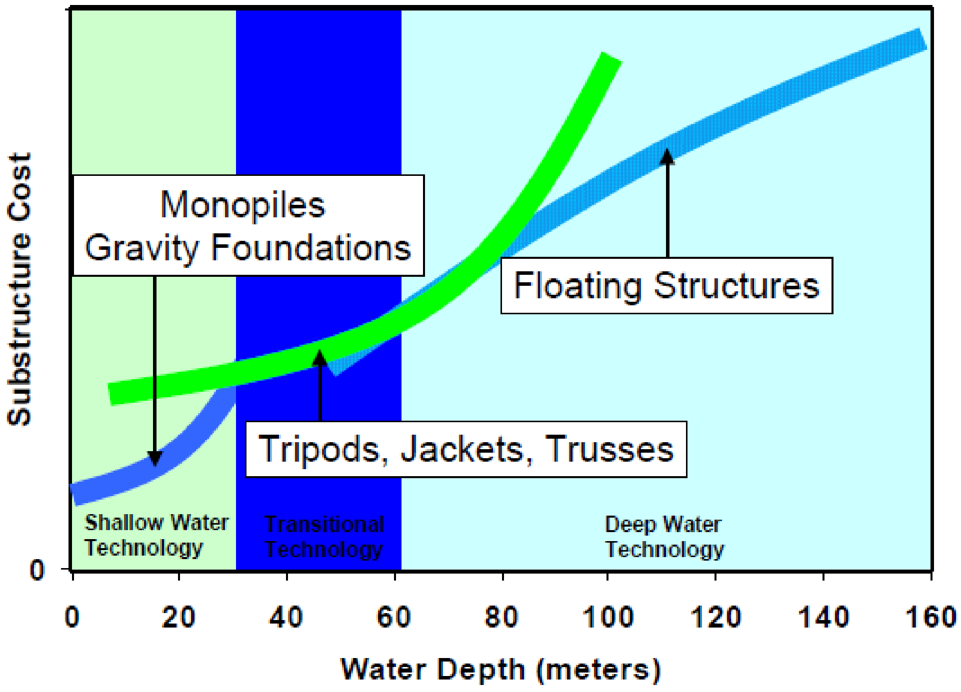


Figure 2. Relationship between the value OWT support structures and water depth [4].

2.1 Wind Turbine Structure

The term turbine comprises the control equipment, responsible for transforming the wind kinetic energy into mechanical rotational energy (in the rotor) and subsequently into electricity (in the nacelle), and the tower. The turbine in its turn is supported by the lattice structure, as shown in Fig. 3.

Rotor includes the blades, responsible for capturing and converting wind energy into rotational energy, and the hub which connects the blades to the shaft. The nacelle is the compartment that houses the engine and other gears that controls the rotational speed of the blades, as well as the generators for converting mechanical energy into electrical energy.

The tower provides support for the assembly rotor-nacelle and the necessary height in order to obtain better usage of the onsite wind, while the lattice support structure properly transfers the environmental loads to the soil.

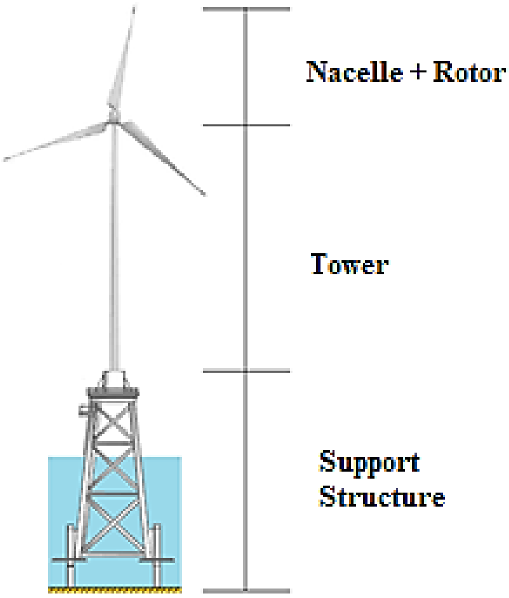


Figure 3. Structure of Offshore Wind Turbine.

The substructure geometry, that englobes the transition part and the foundation structure, is determined by Serviceability Limit State, Fatigue Limit State and Ultimate Limit State (SLS, FLS, ULS, respectively), while being subjected to combination of aerodynamic and hydrodynamic loads.

Since changes in the design impacts directly on the system dynamics and integrity of the structure, it is necessary a constant optimization process of the structure geometry. This process involves the following steps:

1. Initial model proposal
2. Modal analysis and modal mass estimation of the system
3. Geometry adjustment
4. Static and dynamic structural analysis
5. Choice of the type of foundation adopted
6. Final structure geometry definition

For jacket support, the geometry optimization consists an even more complex process due to the complexity of the lattice structures and its higher cost of execution and installation than other types of foundations.

2.2 Modes of Vibration

The first analysis to be performed on the structural system is the determination of its vibration modes. It is important that its first natural frequency do not approach neither the Rotor rotational frequency (1P) nor the vibration frequencies caused by the passage of the three blades through the tower (3P) according to the analyzed type of turbine. The latter phenomenon is usually known as shadow effect. Thus, Letcher [5] and DNV-OS-J101 [6] recommend that the structural system must be ± 10% apart of the major excitation forces, there being included frequency 1P and 3P.

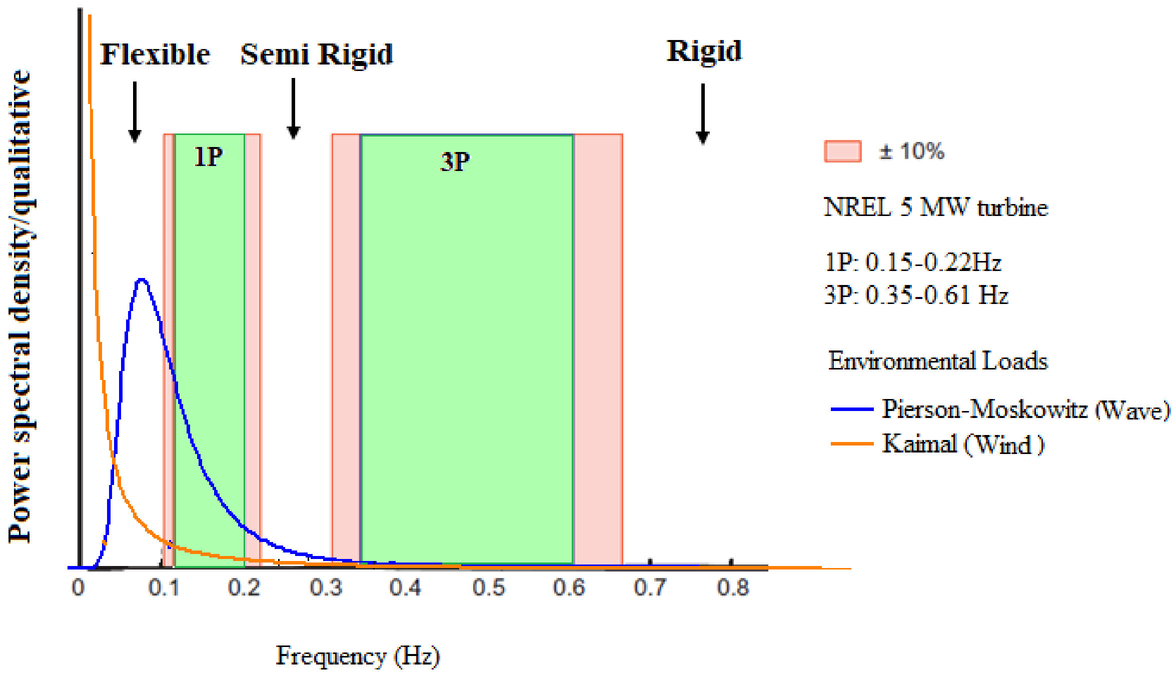
Offshore wind turbines are subjected to specific dynamic loading action, acting on the system elements, such as aerodynamic loads, generated by wind turbulence incident on the rotor, depending on the wind speed, and the mass imbalances generated by the rotational frequency of the engine (1P); loads generated by the vibrations coming from the shadow effect of the blades (3P); and hydrodynamic loads generated by waves impact on the subframe, according to time and period of the waves.

The structures are classified according to their natural frequency as:

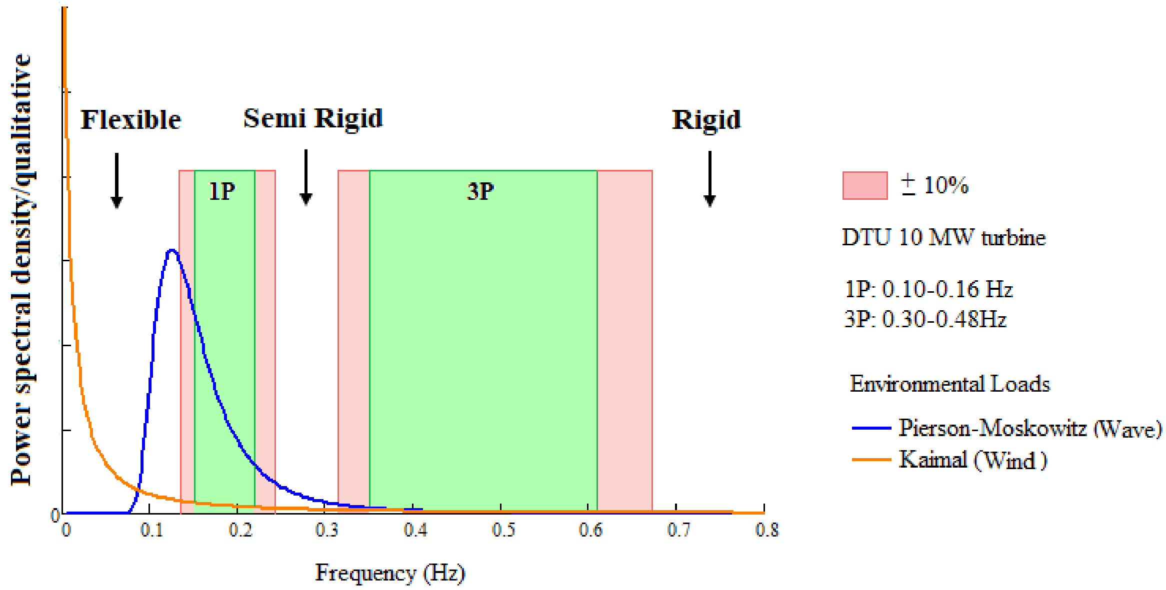
- Flexible structures: natural frequency below 1P, which usually covers floating foundations;
- Semi-rigid structures: natural frequencies in the range of 1P and 3P, comprising foundations fixed at its base, but with certain mobility; and
- Rigid structures: Natural frequencies above 3P.

Figure 4 shows the qualitative power spectra of the main frequencies considering a wind turbine of 5 MW, proposed by NREL [7], and another of 10MW, proposed by DTU [8]. It also indicates the possible frequency bands for each type of system being used. Since very flexible structures would overlap the frequency range of the wave and of the wind; and rigid structures are not very profitable, because they would depend on having large mass in order to obtain such a degree of stiffness, Letcher[5] suggests choosing a semi-rigid support structure.

Thus, although according to Fig. 4, the frequency range would be adopted in 0.22Hz 0.35Hz, for 5MW turbine and the 0,16Hz 0,30Hz to 10MW turbine.



(a)



(b)

Figure 4. Spectrum qualitative power of the main frequencies, considering a 5MW wind turbine (a) and 10MW (b).

3 Structural Model

In this paper jacket type support structures were studied for two types of turbine: a 5MW (based on the model presented by Vorpahl [9]) and a 10MW (based on the model presented by STOLPE [10]). For both jackets, with smaller diameters hollow sections, so as to reduce material costs, geometry suitability tests were performed in order to obtain a structure able to withstand the aerodynamic and hydrodynamic loads. All diameters and thicknesses of the jacket profiles as well as the pile, were determined based on the ASME [11].

3.1 Tower

The turbine model studied in this paper was defined from the tower data of 5MW presented in references [7] and [9] and of the 10MW presented in [8]. The properties main regarding the materials and geometry of the tower are shown respectively in Tables 1 and 2.

Table 1. Material Properties

Properties	Value
Steel specific mass[1]	8500 kg / m³
Modulus of elasticity	210 GPa
Shear modulus	80.8 GPa

[1] The density corresponds to the density of the steel (7850kg / m³) plus 10%, based on the weight paint, welds and screws.

Table 2. Tower Data

	5 MW turbine	10MW turbine
Tower length²	78.65 m	102.13 m
Rotor radius	63.0 m	89.15 m
Hub height to the WL[3, 4]	90.55 m	119.0 m
Tilt rotor shaft angle	5 °	5 °
Outside diameter at the top of the tower	3.87 m	5.5 m
Thickness at tower top	0.0247 m	0.020 m
Outside diameter in the tower base	6.00 m	8.3 m
Thickness in the base of the tower	0.0351 m	0.038 m
Number of blades	3	3

[2]The tower height corresponding to the length from the base to the top of the tower, based on Vorphal[9] and BAK [8].
[3]WL = average level of water.
[4]Hub heights defined in Vorphal[9] and BAK [8].

3.2 Jacket

The jacket was modeled using tubular sections for all elements with the properties of materials presented in Table 3The geometry data of the two jackets are shown in Table 4.

Table 3. Properties and materials

Properties	Value
Steel density	7850 kg / m³
Young Modulus	210 GPa
Shear modulus	80.8 GPa

Table 4. Geometry of the jacket

	5 MW turbine	10MW turbine
Jacket Height[5]	45.5 m	45.5 m
Transition piece height	4 m	8 m
Transition piece mass	400 t	400 t
Jacket levels	3	3
Number of jacket legs	4	4
Width of the top of the jacket	8 m	16 m
Base width	11 meters	28 m

[5]Height to deck jacket excluding the transition piece.

Figure 4 shows the structural models, with the help of the GeniE, component of the DNVGL software package SESAM. The dimensions and geometry of the structures shown were obtained from models found in the bibliographies and minimally optimized to give less weight and jackets that could withstand the extreme loads applied. As the optimization process is not part of the scope of work presented, we have chosen to present only the final dimensions found (Table 5).

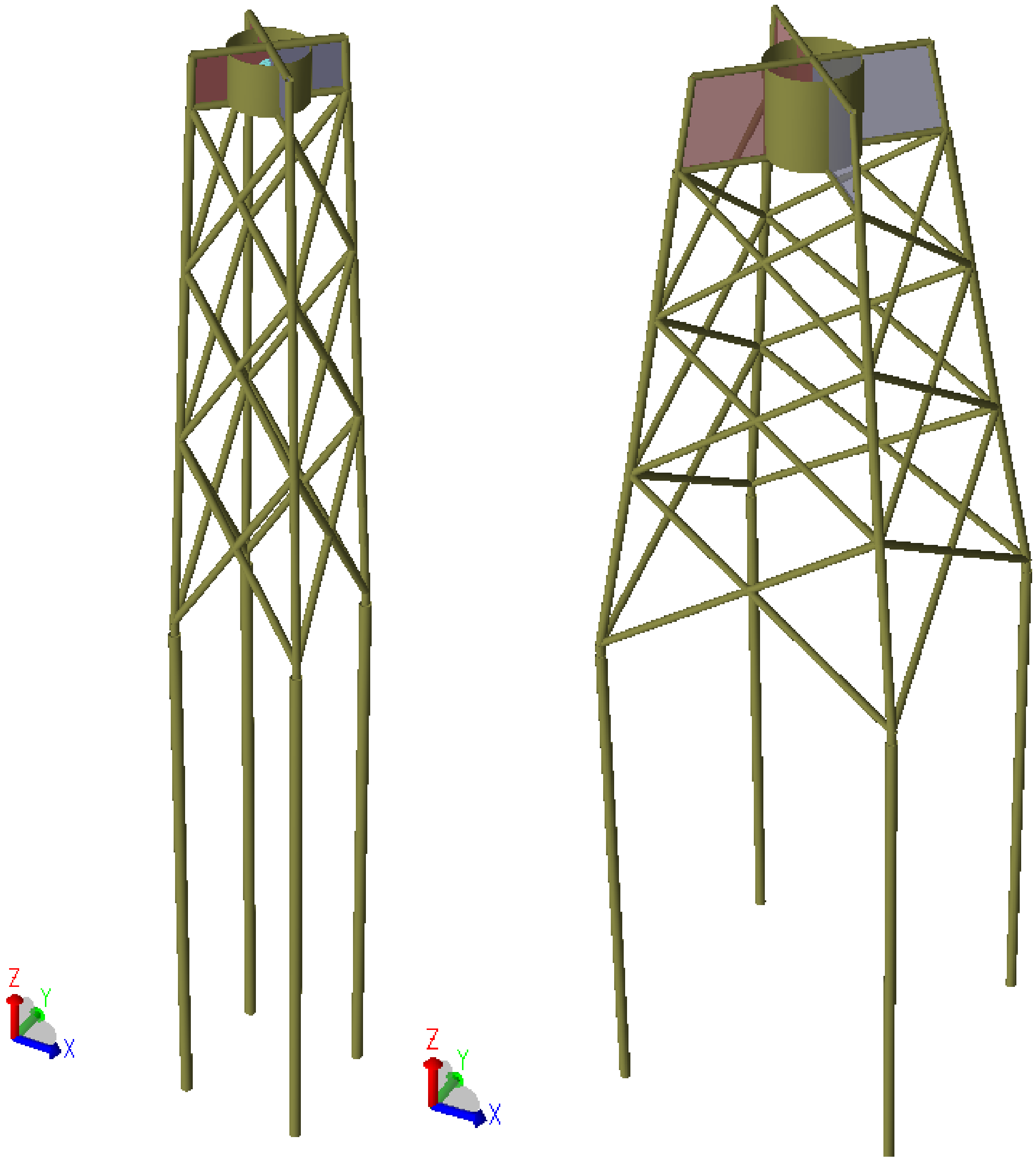
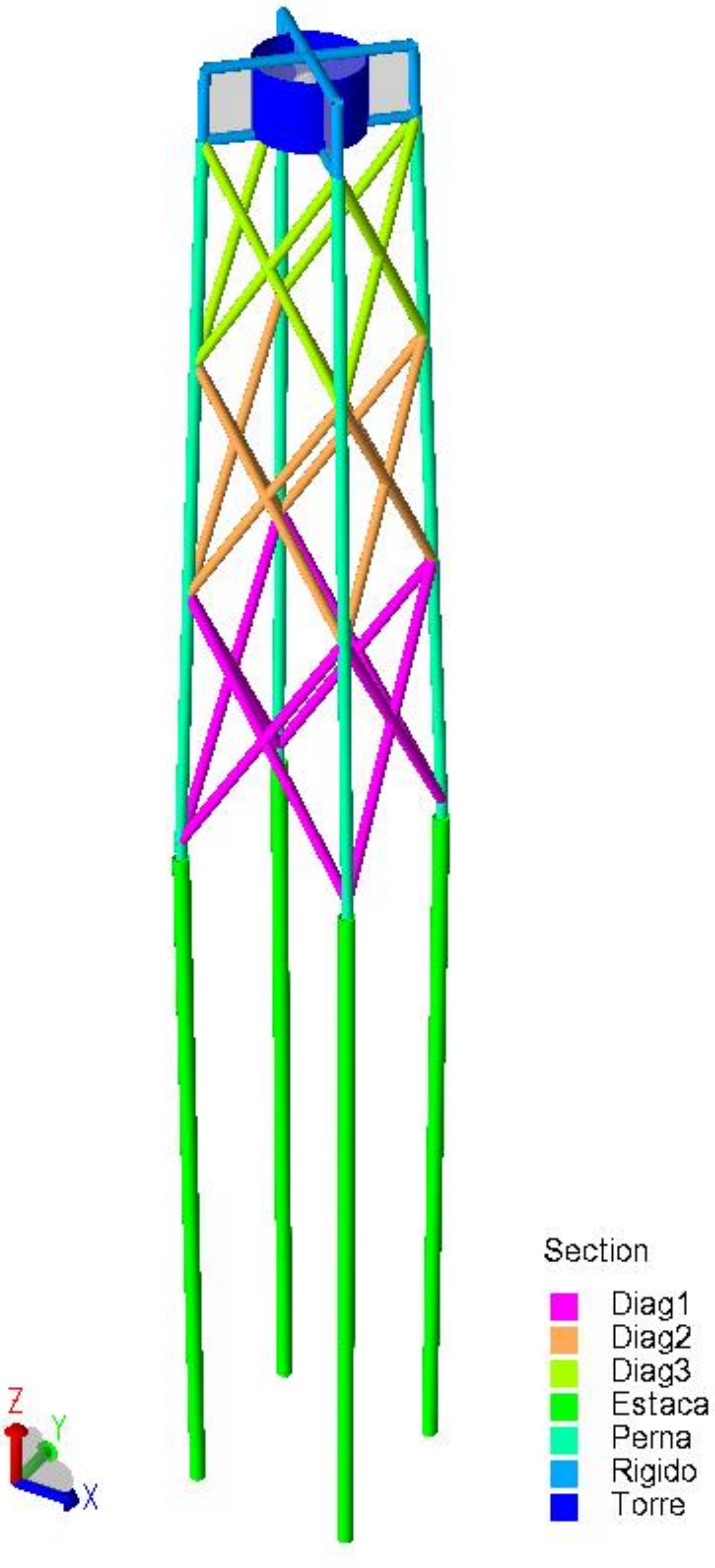


Figure 5. Structural model of jackets 5MW (left) and 10MW (right).

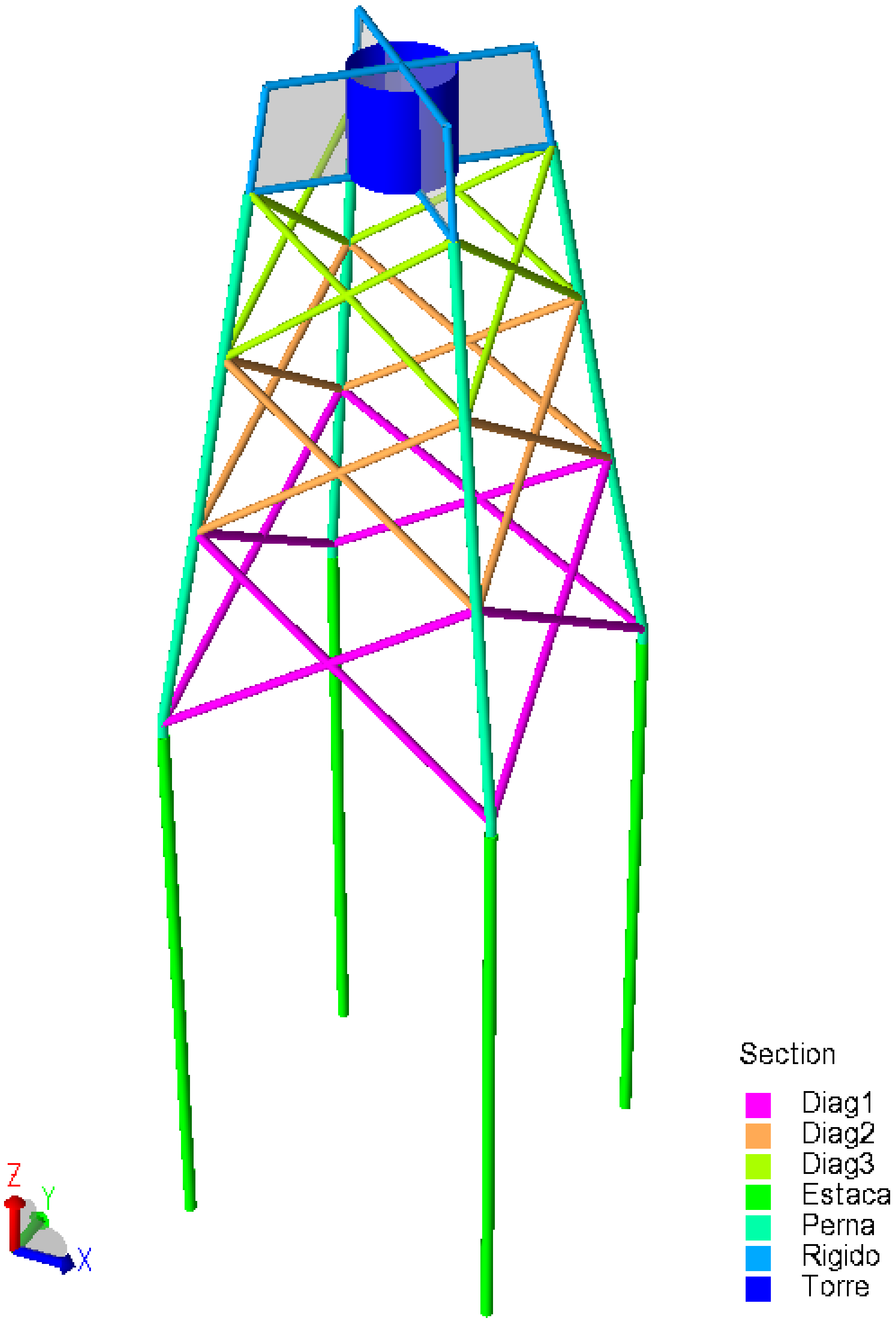
Table 5. Cross sections of tubular profiles

5MW and 10MW turbine		
Section	Outer diameter	Thickness
Leg	0.711 m	0.01748 m
Diagonal 1st level	0.660 m	0.0127 m
Diagonal 2nd level	0.610 m	0.0127 m
Diagonal 3rd level	0.610 m	0.0127 m

Figure 6 shows the structural model with respective sections.



(a)



(b)

Figure 6. Sections of jackets 5MW (left) and 10MW (right).

Considering the same height for the jackets and in order to that the force applied to the turbine rotor, due to the aerodynamic load, and that the length of the tower are higher in the turbine of 10MW than in the one of 5MW, it became necessary jacket with larger dimensions (width about twice as larger). However, the same tubular sections were maintained for both support structures, in order to perform a sensitivity study on the utilization factor of the structure.

3.3 Piles

The load capacity of a foundation is directly related to the properties and soil resistance. In the case of the jacket-type supported structures, piles are used for attachment. It requires the analyses of the soil reaction to the movement thereof. Thus, the answer to this displacement is given in the loading direction, through axial and shear stresses at pile section.

The soil representation was based on non-linear spring, so as to represent the lateral and tip resistance of the pile. Non-linear spring stiffness varies with depth and is represented by the following curves:

- P-y curves: represents resistance to lateral displacement of the soil;
- T-z curves: characterize the load transfer between the shaft and the ground;
- Q-z curve: featuring the pile tip resistance.

Such curves are related to soil parameters and have different formulations for sandy and clay soils, found in API RP 2A WSD [12]. This work considered a soil mainly composed by sand with a 35° angle and friction resistance curves determined for each meter.

The length and diameter of the pile section were initially estimated based on the dimensions shown in [8] and [9]. Based on the length of the pile, the dimensions of the tubular section and the chosen soil parameters, it was possible to calculate the load capacity of the soil by the formula:

$$Q_d = Q_f + Q_p = \pi \cdot D \int_0^L f \, dl + qA_p. \tag{1}$$

where:
Q_f is the lateral frictional resistance (kN);
Q_p is the tip load (kN);
f is the lateral friction capacity (kPa);
D is the outer pile diameter (m);
L is the length of the pile (m);
q is the tip capacity (kPa);
A_p is the pile tip area (m²).

Determined the pile bearing capacity and obtaining the axial forces acting on top of it, the pile may be resized, for the sake of optimizing the structure. Thus, it was decided to adopt piles of 40 and 50m length, with external diameter of 1.016m and thickness of 0.01588m, according to the established in ASTME[11]. To estimate the design ultimate bearing capacity, however, a safety factor should be applied to the value found in Eq. (1), suggested by API RP 2A WSD[12].

Table 6 lists the lateral resistance of the tip and the soil ultimate load for the lengths and soil parameters chosen.

Table 6. Cross sections of tubular profiles

Pile Length	40m	50 m
Lateral resistance	10 342 kN	12 927 kN
Tip resistance	4 054 kN	4 054 kN
Ultimate bearing capacity	14 395 kN	16 981 kN
Safety factor	2	2
Design ultimate bearing capacity	7 198 kN	8 490 kN

4 Loads

For stress analysis and determination of factors used in the jacket members were considered extreme loads applied to the structure. The loads were obtained based on the environmental survey data set of the Northeast and the wave and current parameters were considered for a period of 100 years. The wind case was considered a 11.4 m/s speed, the turbine rated speed (maximum speed power generation), according to the extracted data of BAK[8] and Vorpahl[9].

5 Results

5.1 Ultimate Bearing Capacity

The maximum axial loads encountered at the top of the pile was 7068 kN for the 5MW jacket support and 8200kN for 10MW turbine. Figures 7 and 8 show the normal force diagram for the most requested pile of each model and the absorption of this effort along the pile due to nonlinear soil resistance curves calculated following the method explained in item 3.3.

Given that the values found for the axial forces at the top of the pile are lower than the ultimate soil strength, it can be concluded that the length of the piles and dimensions of the cross section, established to computer models, meet the design criteria.

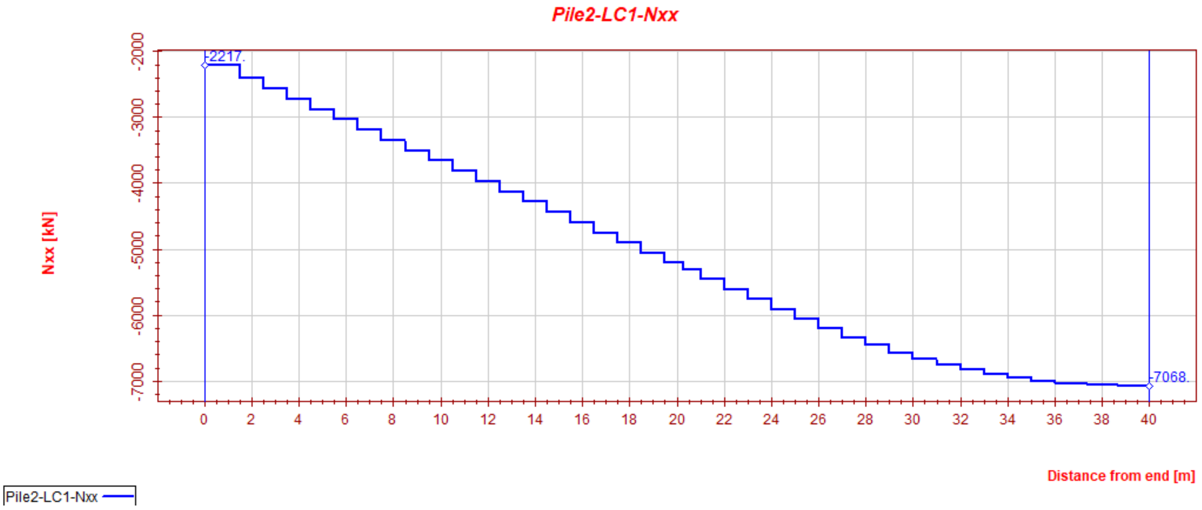


Figure 7. Axial force diagram for the most requested pile - 5MW turbine.

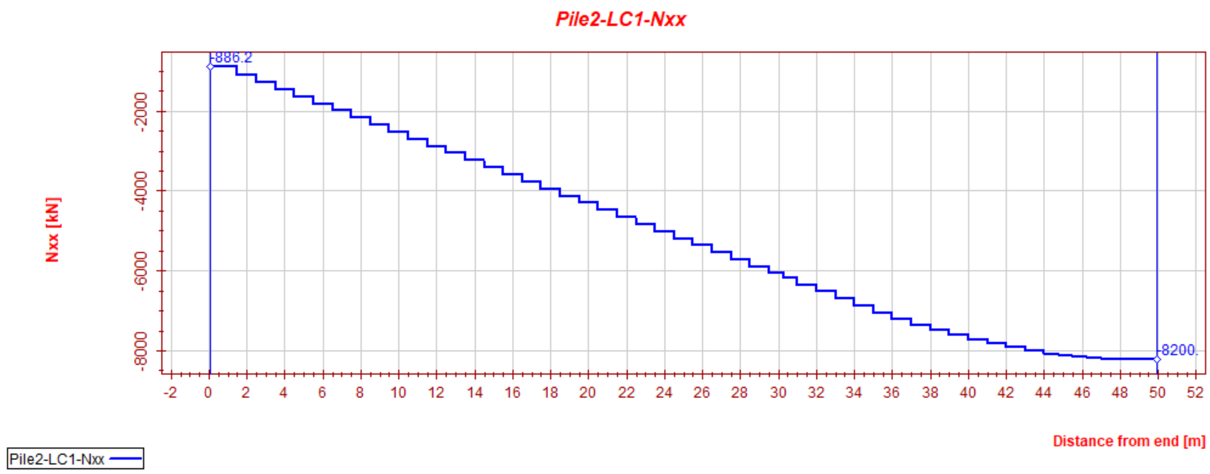
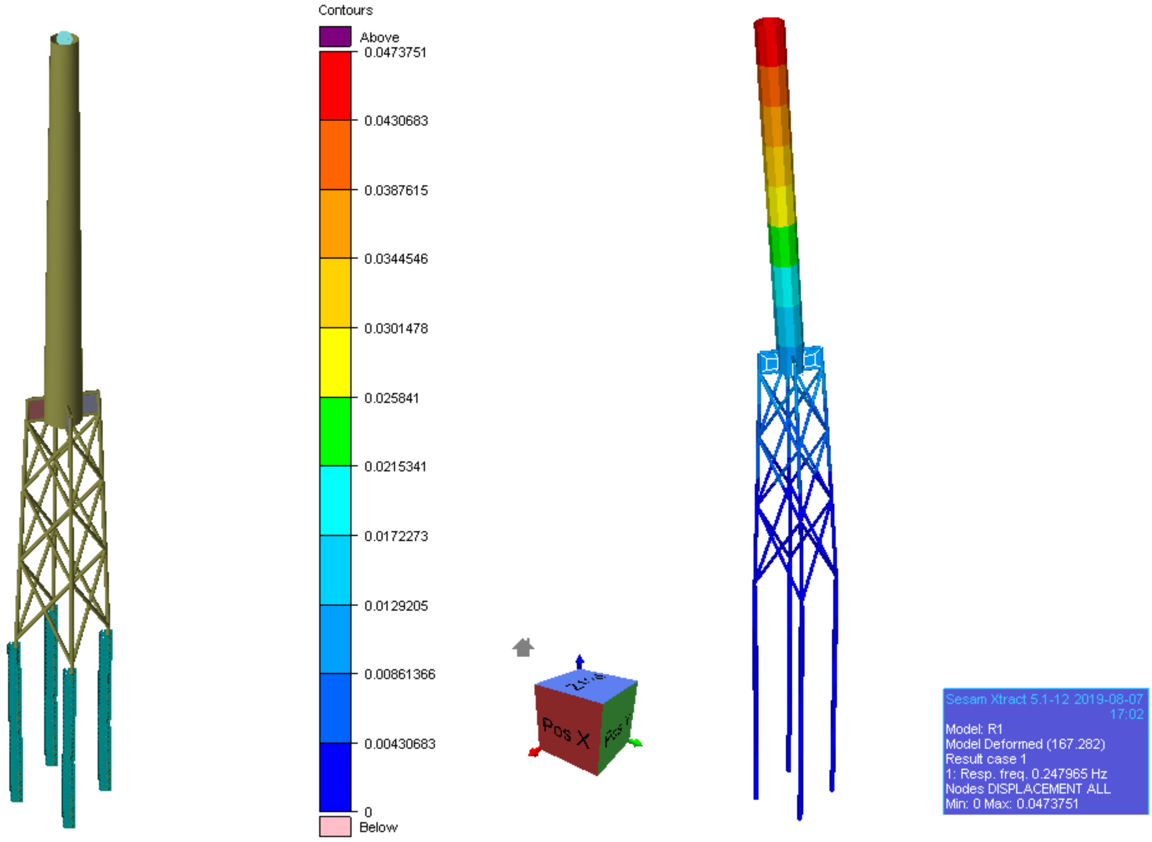


Figure 8. Axial force diagram for the most requested pile - 10 MW turbine.

5.2 Eigenvalues

In eigenvalue analysis of the jackets it was used computational models, with representation of the equivalent mass of the turbine and soil resistance for springs. Figures 9 and 10 present the results obtained for the first mode with its respective displacements.

For 5MW turbine, it was obtained the first natural frequency of 0.248 Hz, while for 10MW it eas obtained a frequency of 0.243Hz. It can be seen that both natural frequencies are within the expected range for a semi-rigid backing structure, according to Fig. 4.



And Figure 9. Structural Model 1 mode vibration - 5 MW turbine.

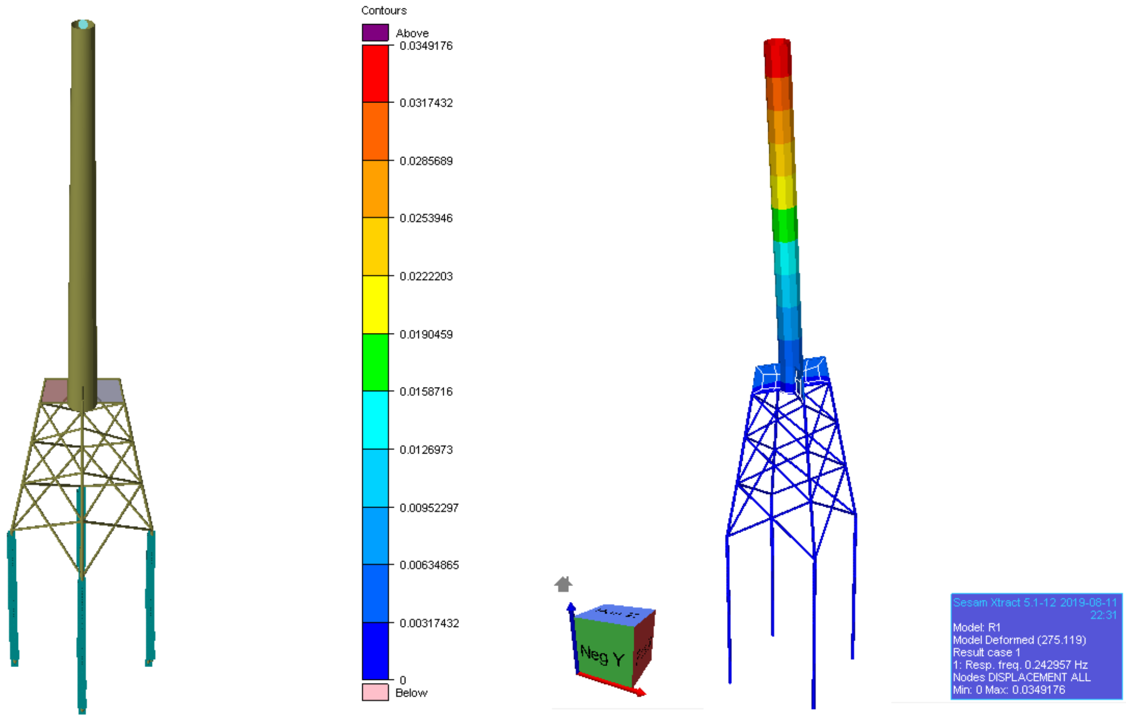


Figure 10. Structural Model 1 and mode vibration - 10 MW turbine.

5.3 Stress analysis

The stress analysis and verification of the utilization factors for jacket members were made in the GeniE software, based on the criteria presented in API RP 2A-WSD [12]. For this, it was considered extreme load cases, acting at the top of the structure, as explained in item 4 . Figure 11 shows the results of stress analysis and members utilization factors of both jackets.

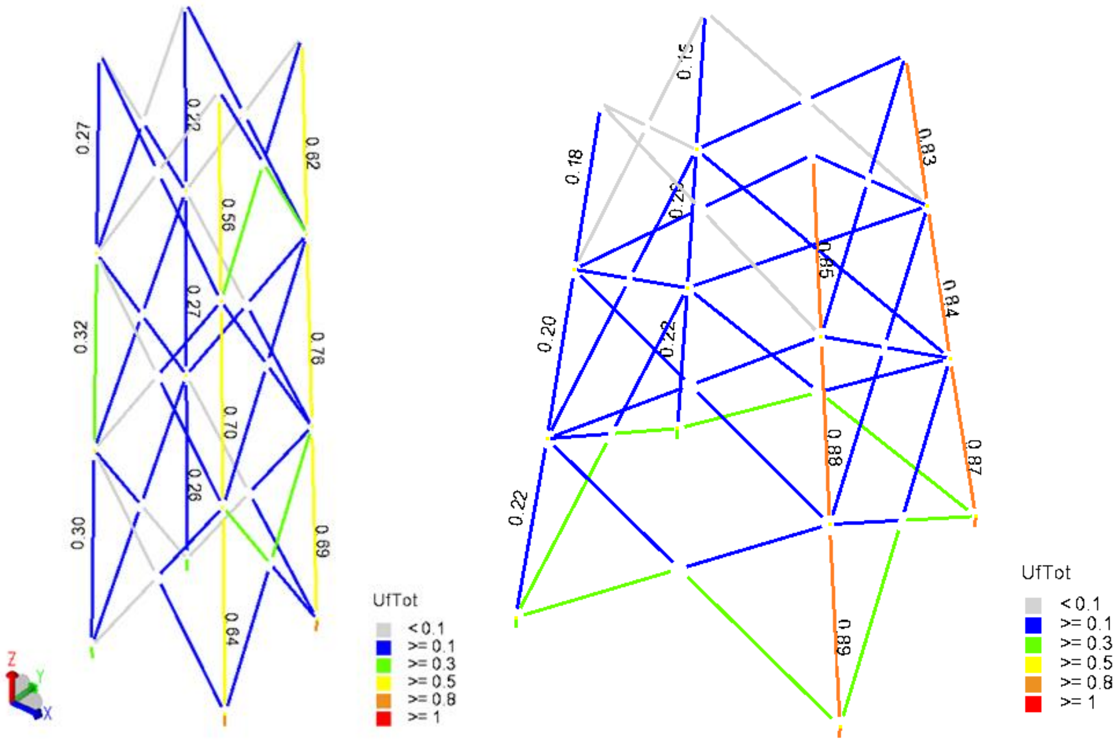


Figure 11. Utilization factor for members of the jacket for the turbine of 5 MW (left) and 10MW (right).

For both jackets, as requested member has a utilization factor of 0.89 and is therefore within acceptable limits proposed by API RP 2A-WSD [12]. It should be noted, however, that the results found were obtained for the final geometry, after making various adjustments in geometry during the scanning process, so as to obtain the smallest cross sections with which the structure of jacket resist to the applied loads. Thus, it is possible to obtain lower utilization factors to other geometries.

6 Conclusions

Since trussed structures have greater stiffness, the jacket has been chosen as a support structure solution for offshore wind turbines of 5 MW and 10 MW. The two structural assemblies were studied at the same water depth and subjected to the same load conditions, in order to obtain a comparative study of the geometry of the jackets. Geometries presented throughout the paper were the result of numerous analyzes, resulting in more optimized structures, aiming to lower material consumption (minimum dimensions) and capable of resisting the efforts.

The dimensions were refereed to confer similar stiffness to the two jackets for each turbine power. This premise has been adopted, for example, to compensate for the greater flexibility of the system composed of the 10MW turbine (greater length of the tower and mass of the turbine) with wider base of the jacket. Thus, there was normal stresses at the top of the pile in the same order of magnitude in the two jackets and factors of use of the most requested and close members.

It was concluded that the presented structures were within the established design criteria for natural frequency and utilization of members of the jacket factors as well as the soil bearing capacity in which the jackets were installed on. The results obtained during the presenting work, with narrow margin of acceptance may be revised due to adjustments in geometry, in order to make it more conservative.

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