Simulation and numerical analysis of offshore wind turbine with monopile foundation

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Abstract: Static Analysis and Harmonic response analysis using Finite Element Analysis (FEA) is performed to evaluate the deformation, stresses and strain energy of monopile and tower of offshore wind turbine (OWT) in dense sand. In this study monopile, tower and soil along with water layer modelled as 3 dimension solid model in ANSYS workbench. Considering the soil as explicit material with environmental loads like wind and wave loads on turbine as static loads static analysis is done. From the analysis it is concluded that the structures behaviour changes with accordance to the change of parameters, turbines response towards the excitation frequency is investigated.

Keywords: Numerical analysis, offshore wind turbine, Finite element software

1. INTRODUCTION

Wind energy is accepted together as the foremost developed, foreseen efficient and verified renewable energy technologies to fulfill rise of electricity requirements in a very appropriate manner. Enormous scale preparation of onshore wind energy have reached a stage and became competitive with fuel based mostly electricity generation across the planet, exploitation of offshore wind energy is nonetheless to succeed in a comparable scale. Asian countries mostly achieved important success within the onshore alternative energy development with concerning 24 GW of wind energy already put in and generating power [8]. The government is trying to transpose the success of offshore alternative energy development. Almost 8.7 GW offshore wind capability has already been put in across the globe associate degreed just about an equal capability is beneath construction. There are offshore wind farms existing and underdevelopment within the UK (4494MW), Scandinavian country (1271MW), Federal Republic of Germany (1049MW), Belgium (712MW), China (670MW), European nation (247MW) and Scandinavian nation (212MW) [15]. The study of behaviour of offshore wind turbine thus will provide us a brief idea and knowledge about its simulation over extreme operational conditions. In India there’s a scarcity of sensible demonstration expertise of offshore wind generation projects but, it’s the coastline of 7,600 kilometers used for the development of offshore wind power generation. Almost 8.7 GW offshore wind capability has already been put in across the globe associate degreed just about an equal capability is beneath construction. There are offshore wind farms existing and underdevelopment within the UK (4494MW), Scandinavian country (1271MW), Federal Republic of Germany (1049MW), Belgium (712MW), China (670MW), European nation (247MW) and Scandinavian nation (212MW) [15]. The study of behaviour of offshore wind turbine thus will provide us a brief idea and knowledge about its simulation over extreme operational conditions. In India there’s a scarcity of sensible demonstration expertise of offshore wind generation projects but, it’s the coastline of 7,600 kilometers used for the development of offshore wind power generation. Almost 8.7 GW offshore wind capability has already been put in across the globe associate degreed just about an equal capability is beneath construction. There are offshore wind farms existing and underdevelopment within the UK (4494MW), Scandinavian country (1271MW), Federal Republic of Germany (1049MW), Belgium (712MW), China (670MW), European nation (247MW) and Scandinavian nation (212MW) [15]. The study of behaviour of offshore wind turbine thus will provide us a brief idea and knowledge about its simulation over extreme operational conditions. In India there’s a scarcity of sensible demonstration expertise of offshore wind generation projects but, it’s the coastline of 7,600 kilometers used for the development of offshore wind power generation. Almost 8.7 GW offshore wind capability has already been put in across the globe associate degreed just about an equal capability is beneath construction. There are offshore wind farms existing and underdevelopment within the UK (4494MW), Scandinavian country (1271MW), Federal Republic of Germany (1049MW), Belgium (712MW), China (670MW), European nation (247MW) and Scandinavian nation (212MW) [15]. The study of behaviour of offshore wind turbine thus will provide us a brief idea and knowledge about its simulation over extreme operational conditions. In India there’s a scarcity of sensible demonstration expertise of offshore wind generation projects but, it’s the coastline of 7,600 kilometers used for the development of offshore wind power generation. Almost 8.7 GW offshore wind capability has already been put in across the globe associate degreed just about an equal capability is beneath construction. There are offshore wind farms existing and underdevelopment within the UK (4494MW), Scandinavian country (1271MW), Federal Republic of Germany (1049MW), Belgium (712MW), China (670MW), European nation (247MW) and Scandinavian nation (212MW) [15]. The study of behaviour of offshore wind turbine thus will provide us a brief idea and knowledge about its simulation over extreme operational conditions. In India there’s a scarcity of sensible demonstration expertise of offshore wind generation projects but, it’s the coastline of 7,600 kilometers used for the development of offshore wind power generation. Almost 8.7 GW offshore wind capability has already been put in across the globe associate degreed just about an equal capability is beneath construction. There are offshore wind farms existing and underdevelopment within the UK (4494MW), Scandinavian country (1271MW), Federal Republic of Germany (1049MW), Belgium (712MW), China (670MW), European nation (247MW) and Scandinavian nation (212MW) [15].
turbine foundation selection plays a vital role in greater choices made over financial implications. Typically, foundations cost 15–35% of the overall costs, depending on the wind farms location and size. The design of offshore oil and gas (O&G) structures is being followed for the design of foundation. The OWT structures are unique in their features. The most important difference in OWT with respect to O&G installation structure is dynamic sensitivity [3] – i.e. the forcing frequencies from wave, rotor Frequency (1P), and blade frequency (2P/3P) is nearer to natural frequencies of OWT structures [18]. The large hollow steel-driven pile of diameter 3 to 6 m is the most commonly used foundation system for offshore wind turbines, and has been reported with a length-to-diameter ratio of less than 8. Monopiles has become an efficient solution for offshore wind turbine foundations in water depths nearing 30-35 m.

![Figure 1. Location of wind farm in southern India](image1.png)

![Figure 2. Model representing offshore wind turbine](image2.png)
2. Finite Element Modeling & Analysis

The Modeling of offshore wind turbine shown in Figure 2 needs to be reliable, and should be precise as much as possible, here the finite element package ANSYS Workbench software is used for the analysis of deformation, stresses, strain values over the tower and monopile and also energy dissipated on the soil layer where the monopile is embedded is also obtained [12].

![Figure 3. Geometry (a).Tower (b).Transition Piece (c).Monopile Foundation.](image)

The Engineering parameters from Figure. 3 and other parameters considered for the modeling of wind turbine tower, monopile, soil layer and water layer is given below [13],

A. **Soil parameters**
   - Density – 1100 Kg/m³
   - Young’s Modulus – 60 MPa
   - Poisson’s Ratio – 0.25
   - Initial Inner Friction Angle – 35°
   - Initial Cohesion – 10 Pa
   - Dilatancy Angle – 5°
   - Soil Depth – 20 m

B. **Structural steel parameters**
   - Density – 7850 Kg/m³
   - Young’s Modulus – 2 x10^5 MPa
   - Poisson’s Ratio – 0.3
   - Tensile yield strength – 250 MPa
   - Tensile ultimate Strength – 460 MPa

C. **Water data**
   - Density – 1030 Kg/m³
   - Bulk Modulus – 2200 MPa
   - Water Depth – 10 m

D. **Properties of Wind turbine Model**
   - Rating (MW) – 3.0
Wind Class – IEC IA
Hub Height – 90 m
Rotor Position, rotor type – Upwind, 3-bladed
Rotor Weight – 41 ton
Nacelle Mass – 143 ton
Blade Weight – 8.4 ton

The Figure. 2 full scale model Computational time for the meshing and analyzing takes more time so scale down of model is done by means of scale down laws.

The models are based on Froude number in Froude’s model law which means, the Froude number for dynamic similarity between the model and the prototype should be equal. If gravity force is only predominant force which controls the flow in addition to the force of inertia (i.e.,) wave is generated on surface. Froude’s number (dimensionless number is used) is defined as the square root of the ratio of inertia force of a fluid to the gravity force mathematically,

\[ F_e = \sqrt{\frac{F_i}{F_g}} \]  \hspace{1cm} (1)

Here,
F\(_e\) = Froude number  \hspace{0.5cm} F\(_i\) = Inertial force
F\(_g\) = Force due to gravity  \hspace{0.5cm} L\(_r\) = scale ratio for length
F\(_r\) = scale ratio for force  \hspace{0.5cm} P\(_r\) = scale ratio for pressure

According to Froude model law Scale ratio for Force is 
F\(_r\) = L\(_r\)^3; and Moment M\(_r\)=L\(_r\)^4.

**Loads on wind turbine**
The wind turbine manufacturer provide us the Wind Load on the hub height, [1] the wave load based on linear Airy wave theory and the wheeler stretching method using the Morison’s equation is calculated. The DNV (DNV-OS-J101, 2014) helps in appraisal of serviceability load cases. Other load combinations were not likely considered in the study. The loads under serviceability limit state are,

Vertical force – 2092.0 KN
Horizontal shear force – 492.5 KN
Moment – 1142.6 kNm
Torque – 721.7 kNm
Standard Earth Gravity – 9.8 m/s\(^2\)
The Vertical load of RNA is applied on the top of tower and the horizontal shear force, the total moment and torque is also applied at the top of the tower as shown in Figure 4 [2, 11]. Meshing of model is done in ANSYS Workbench software where the Minimum Edge length of mesh is 106.12m, and the target quality is 0.05 with inflation of smooth transition and the transition ratio is 0.272, here the number of nodes generated is 236012 and total number of elements formed is 272184.

The solid elements are created by SOLID186 & SOLID 187 the contact between the soil layer and the water layer as shown in Figure 5 is done by CONTA174 &TARG170. The Multiple contacts are done by MPC 184 and the number of contact elements created is 157719 [14]. The soil boundary layer created is of 10 times the diameter of the monopile which will give us the stiffness to the foundation [4, 7]. The bottom of the soil layer and the monopile is fixed to the ground to assess the long term performance of the wind turbine the loading condition should be of time stepping but in our we have only applied the loading as static loading which will produce the initial analysis report and behavior of monopile and tower structure on soil layer [20, 21].
3. RESULTS AND DISCUSSION

The effect of long-term cyclic loading increase the deflection and rotation of monopile head, the current design codes quotes that the maximum deflection on top of the tower and the deflection and rotation of pile head are usually subjected to constraints to meet the serviceability requirement (DNV-OS-J101, 2014) [6]. For example, DNV clarifies that the installation leeway at the mud line and permanent rotation is 0.25°. The maximum deflection at pile head is considered as 30 mm (Wang and Yang, 2012) [22], and (DNV-OS-J101, 2014) provoke towers maximum deflection is to be set about $\frac{L_W}{200}$ [6].

![Figure 6. Total Deformation of the wind turbine](image1)

It is obviously clear that the maximum deformation is at the tower head and the deformation at the pile is lower which is within the specified limits as shown in Figure 6, so it is safe for the wind turbine to operate. The Equivalent elastic stresses and the strain along the tower due to the horizontally applied loads and moments is clearly predicted from the analysis [20]. Due to the applied loading the strain energy produced along the tower is dissipated to the water layer and the soil layer Figure. 10 & Figure. 11 which will clearly enumerate the behavior of monopile along with tower structure in the soil layer. Along the horizontally applied load the stresses are developed, the maximum stress is developed at the top of the tower shown in Figure. 7, when applying the moment at the bottom of the monopile the stress is greater at the mud line where the monopile is embedded and also at the transition piece where geometry changes [19].

![Figure 7. Principle Stress on wind turbine tower and foundation](image2)
Based upon the observations the dissipated strain energy along the supporting tower structure shown in Figure 9 and the strain energy due to the tower over the water layer and soil layer in Figure 8 is mainly happening in and around the pile layer within the distance of 3 times the diameter of pile on the soil layer.
The first natural frequency of any structure is a very crucial parameter in determining the dynamic conduct of the wind turbines in offshore [9]. If the excited frequency is close to the natural frequency, resonance occurs which leads to high stress concentration in the monopile structure. Due to slenderness of the structure when the blade passes it creates vibration of the wind turbine [5].
A rotor having three blades resists the peak forces at frequencies of 1P (Blade passing frequency) and 3P due to turbulent eddy. For a distinctive variable speed turbine, the 1P ranges of 0.15 Hz to 0.3 Hz approx, and rotation frequency 3P which is of 0.44 Hz to 0.92 Hz approx, the sea waves typically creates cyclic loading which is at a frequency rate of 0.04 Hz to 0.29 Hz [16].

The design of offshore wind turbine (turbine, tower, monopile) within a natural frequency between blade passing frequency, rotor frequencies and wave frequencies helps in avoiding the resonance effect is shown in Figure 12 [10]. Figure 13 symbolise the forced frequencies of wind turbine in offshore. The increase in applied lateral wind load decreases the natural frequency in the Mohr-coulomb strain-dependent soil stiffness models. Thus every wind turbine and pile foundation has to be within the allowable frequency range requisite by wind turbine manufacturers.

1P-Rotor Frequency
3p-Blade Passing Frequency

The increase in pile diameter and pile thickness results in drastic decrease over the deflection and rotation upon the pile head region vice versa over tower top and bottom. Using finite element modelling short-term static loading over offshore wind turbine under the serviceability limit state (SLS) is incorporated to examine the performance is attempted here therein a three-dimensional (3D) finite element (FE) model is done with the help of ANSYS Space claim, where the effect of pile-soil interaction due to short-term static loading is neglected. A cogitation carried out over a 3 MW wind turbine supported on a large-diameter monopile in sand using small-scale 3D model. The outlines of main results are:
(a) Under serviceability limit state the deflection and rotation at pile head computed over the short-term cyclic loading are smaller comparing to the effect over long term loading.

(b) Under the serviceability limit state, the deflection ratio and rotation ratio of pile head tends to reduce cut back substantially with an increase in strain energies in and around soil surrounding the pile, the strain energy dissipated also appears to be on the surrounding soil layer. The deflection ratio for tower top tends to be more sensitive towards static type of loading.

(c) The increase in pile wall thickness and pile diameter can lead to a moderate decrease in the deflection of tower top and stresses at maximum over the tower top due to short term loading. Variation over pile diameter causes abrupt change over the strain energies which are dissipated on the water and soil layer.

All the issues relating to offshore wind turbine project is complicated and needs a separate revision which cannot be clubbed in a single project. The numerical model currently used is modelled based on the observations of tests over small scale models which may show limitations of scaling effect. Physical and numerical aspects with high performance computer are needed to develop a better understanding of the problem with full scale modelling.

4. CONCLUSION

In this study of static loading on monopile highlights the initial behaviour of wind turbine. It is suggested to account long-term loading effect for design of foundation. Under its service period of offshore wind turbines supported on monopiles the long-term performance is a major concern to look into. This paper presents an investigation across the effect of static loading on the performance of offshore wind turbine under the limit state by finite element modelling. Three-dimensional (3D) finite element (FE) models were constructed on the platform of ANSYS workbench, in which the effect of soil layer and water layer is taken into account A cogitation carried out on a 3 MW wind turbine supported on a large-diameter monopile in sand using small-scale 3D model conducted to reckon the influence of several design parameters for complete behaviour of offshore wind turbine. Monopile with varied thickness, pile section length and pile with uniform thickness provide us information to design the foundation in an economical way. Currently there are no defined codal provisions for monopile foundation, standardization of design criteria will be helpful in future.

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