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Seismic Analysis of Offshore Wind Turbine Foundations

Aparna M Nair[1], M.V Varkey[2]

[1]*Mtech Student, Dept. of Civil Engineering, Amal Jyothi College of Engineering, Koovapally*
[2]*Assistant Professor, Dept. of Civil Engineering, Amal Jyothi College of Engineering, Koovapally*

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Abstract - *Renewable source of energy have gained more and more importance in recent days in behalf of large emission of greenhouse gases by conventional energy sources. Offshore wind energy is a highly potent alternative which can immensely reduce impact of energy production to environment. Several researches are ongoing on both structural aspects and foundations of offshore wind generation structures. Due to the difference between the marine environment and onshore environment, the research methods and achievements about the onshore wind power foundation cannot be applied to offshore wind power foundation. Therefore, it is important to study the bearing capacity of offshore wind power foundation under combined horizontal and vertical loadings. This paper analyzes the wind turbine as per Indian offshore condition. A comparative study on deformation and stress of monopile, tripod and group pile foundations was done. Later, seismic analysis as all these foundations were done and compared.*

***Key Words*: Offshore Wind Turbine, Foundations, Height, Analysis, ANSYS**

1. INTRODUCTION

Wind farms are constructed in bodies of water to convert wind energy into electricity. Wind speed is high at offshore compared to that on land, thus making offshore electricity generation more productive. Though offshore wind farms are expensive they reduce greenhouse gas emission. Offshore wind farms are 50%more expensive than onshore. Offshore wind turbine s are 20% more expensive, tower and foundations are 350%more costly than that on onshore [15]. The overall cost of offshore wind unit is double or triple than that of onshore wind unit [8]. Since the location of offshore wind farms are far from populated areas it reduce noise and visual impacts. Offshore wind farms are more common in Europe, United Kingdom and Germany. The world's first offshore wind farms was constructed near Shanghai. Offshore wind farms are expected to grow over the next decades. Offshore wind farms of 5 Giga watts have been installed in northern Europe and United States of America has many offshore development projects. China has started pilot projects which plan to build 30 Giga watts by 2020.

Offshore wind production is more complicated because of the difficulty in design and construction of the turbine system. Offshore wind turbines are often located above the crest level of the highest waves. The offshore wind turbine structures are supported by different types of foundations mainly gravity base, monopile, tripod, suction bucket and jacket foundation. These foundations are subjected to different types of loading such as axial force from the turbine structure and varying loads from the water body [18]. These foundations mass resist wind force and hydrodynamic load in varying direction, frequency. These structures also vulnerable to earth quake loads especially in areas of active seismicity. Thus it is important to studies the response of offshore wind turbine when subjected to combination of all these three loading [2].

1.1 Types of Foundations

There are several types of foundations use for offshore wind turbine structure. They are mainly monopile, tripod, suction bucket and gravity base. Selection of foundation depends on water depth and soil condition. Different types of foundation shall be discussed below.

Monopile foundations are the most widely used foundation because of their simplicity in its installation. They are preferred in locations having a shallow depth. Monopile is a soil pile tower system usually 20-40m in length and having a 3-6m diameter [22]

Tripod foundations are used in waters deep up to 35m. It's made of diff pieces welded together and it's fixed to the ground with three steel piles of diameter 2m. The spatial steel frame transfers the forces from tower to seabed [12]

Gravity base foundations are constructed using the precast unit and are ballasted with gravel, stone or sand. These are adopted regions having depth up to 10mand are appropriate for seabed composed of sand, soil, compacted clay and rock [12]

The suction bucket foundation is a type of offshore foundation with a skirt around the lid. The bearing capacity is mainly from the interaction between the soil and bucket skirt as well as the top lid bearing [22]

Floating tension leg platforms are structures that are floated to the site and submerged by means of tensioned vertical anchor legs. The base structure helps dampen the motion of the system. Installation is simple because the structure can be floated to the site and connected to anchor or suction caissons. The structure can be lowered by use of ballast tanks or tension system[12]

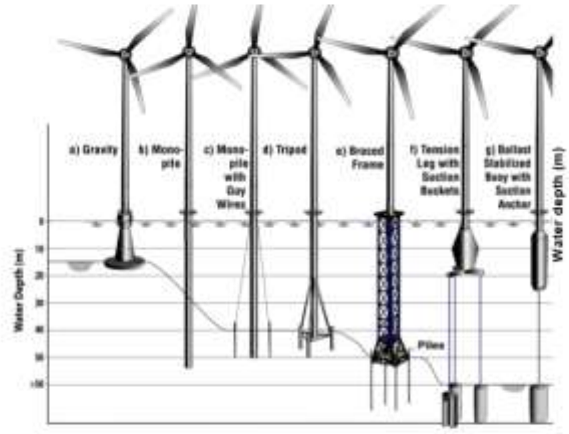

Fig-1: Various Types of Support Structures (Source: Malhotra et al., 2007)

1.2 Literature Review

Dynamic responses of monopile supported offshore wind turbine (OWT) in clay subjected to wind, wave and earthquake load was studied (Wang et.al., 2018) [20] The three-dimensional finite element model of the structure is developed. The tower and monopile is modeled as a beam element, nonlinear Winkler foundation approach is used to model the pile-soil interface, and the pile water interface modeled as a hydrodynamic added mass. The wind, wave and earthquake are applied as loadings on the structure. The wind velocity, induction factor, wave period, peak ground acceleration, and soil parameters on the dynamic responses of the structure are studied. The result shows that it is necessary to consider the combination of wind, wave and earthquake actions in the design of offshore wind turbine structure.

Another study (Zuo et.al., 2018)[23] was the dynamic responses of the 5MW wind turbine tower subjected to the combined wind and wave loadings are numerically investigated by using the finite element model in ABAQUS. The result shows that the responses of the wind turbine in the operating condition are much larger than those in the parked condition. Soil structure interaction can affect the tower vibrations substantially, while it has a less effect on the in-plane vibrations of the blades.

Another study (Risi et al.,2018)[17] investigates the structural performance of an offshore wind turbine tower subjected to strong ground motions. The monopile supported offshore wind turbine towers are vulnerable to stronger earthquakes, and the vulnerability increases when the structure is laid on a soft soils. The structural modeling is generally necessary to avoid over estimation of the seismic capacity of offshore wind turbines. That it is necessary to consider the combination of wind, wave and earthquake actions in the design of offshore wind turbine structure (Wang et.al.,2018)[19].

Another study (Jiang et.al.,2018)[10].The challenge is to analyze the responses of the multimode system (catamaran-spar-wind turbine) Subjected to wind and wave loads. Time-domain simulations were conducted for the coupled catamaran-spar system with mechanical coupling, dynamic positioning control for the catamaran ans passive mooring system for the spar. This study focus on the steady-state stage mating process between one turbine unit and the spar, and also discuss the effects of wind loads and wave conditions on motion responses of the catamaran and the spar, relative motions at the mating point, gripper forces and mooring forces.

The aim of this is to analyze the behavior of offshore wind turbine tower subjected to wind, wave, current and seismic load. This study intends to find optimized tower heights for monopile, tripod and group pile foundations as per Indian offshore condition. Seismic analysis on all these optimized tower height is also done for all three foundations.

2. LOAD ON STRUCTURE

Wind, wave, current and seismic loads are applied to the offshore wind turbine tower. Each of these loads is introduced as follows.

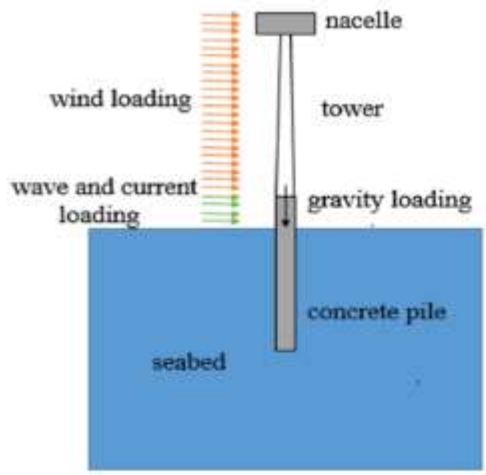

Fig-2: Loadings on the offshore wind turbine (Source: Xiao et al., 2018)

2.1 Wind Load

For the calculation of wind load basic wind speed is used. Wind load on the wind turbine is divided into two parts. Those are wind load on tower and wind load on hub. The equations for wind load calculations are obtained from DNV-OS-J101 [6].

The wind load acting on the hub called thrust force can be calculated using the following equation [15].

$F_{hub} = 0.5\rho\pi RT^2V^2 (1+2v/V) C_D$

Where F_{hub} is the wind load acting on the tower in N/m, ρ is air density, RT is the rotor diameter, C_D is drag coefficient, V is the mean wind velocity and v is the fluctuating wind velocity.

The tower is divided into 8 segments and the wind load act as a concentrated load at each segment. In this analysis, towers of different heights have been modeled and corresponding values are calculated. The wind load acting on the tower can be calculated using following equation. The equation for wind load is obtained from DNV-OS-J101 [6].

$F_{tower} = c\ q\ s\ \sin\alpha$

F_{tower} is the distributed force acting on the tower, q is the wind pressure, C is the shape coefficient and S is the projected area.

2.2 Wave Load

For the calculation of the wave loads, the Morison formula for slender structure is used, as proposed in the DNV offshore standard. The wave force acting on the structure consists of two parts. One is the inertia force which is proportional to wave acceleration, and the other is the drag force which is proportional to the square of wave velocity. The wave load acting on the structure can be calculated using the following equation [12].

$F_{wave} = 1/2.\ \rho.\ Cd.\ D.U^2 + 1/4\ .\ Cm.\ \rho.\ D^2.\ \pi.\ (du/dt)$

ρ is the water density, C_D is the drag coefficient, C_m is the Mass coefficient, U is the wave velocity and du/dt is the wave acceleration.

2.3 Current Load

The current velocity will cause a load on the pile under water. The load is not constant under water, but will be highest at the surface level and zero at the seabed due to friction. The equation for current load calculation is obtained from DNV-OS-J101 [6]. The current load acting on the structure can be calculated using the following equation

$F_C = ½.\ \rho.\ U.\ C_D.\ A$

ρ Is water density, C_D is drag coefficient, U is current velocity and A is projected area.

2.4 Seismic Load

In this study, response spectrum method is used for calculating seismic load. The seismic load calculation is based on IS-1893 (Part 1):2002. Response spectrum method requires only natural period, mode shape and mass distribution of the structure to calculate maximum seismic loads.

3. METHODOLOGY

This study aims on the effect of wind, wave, current and seismic on offshore wind turbine tower. It also aims to analyze the wind turbine as per Indian offshore condition. For this study, turbine tower is modeled and analyzed using the finite element method. For this analysis the geometry is prepared and then various analyses were carried out and results are compared after providing proper meshing and properties. Equal volume of steel is used for all three foundations. The wind and wave data collected from ESSO - Indian National Centre for Ocean Information Services records. The structure is to be modeled and analysed in ANSYS 16 software. As wind velocity varies with height, the power that can be obtained at different heights will be different. ANSYS models for various tower heights starting from 60m to 100m are analyzed and maximum deformation is obtained. Power obtained at each of these heights is then calculated. Further, power obtained per unit deformation is calculated and compared for all these power heights. The one that yields maximum power per unit deformation is chosen as optimum height.

Two types of analysis were carried out in this project, Static load analysis and seismic load analysis. Wind, wave and current loads are input for static load analysis. Seismic load input for seismic analysis. The seismic analysis will carried out at this optimum height. Response spectrum method is used for seismic analysis. The turbine tower supported by various foundations such as monopile, tripod and group pile were analyzed and monitoring their responses by checking the deformation and stress.

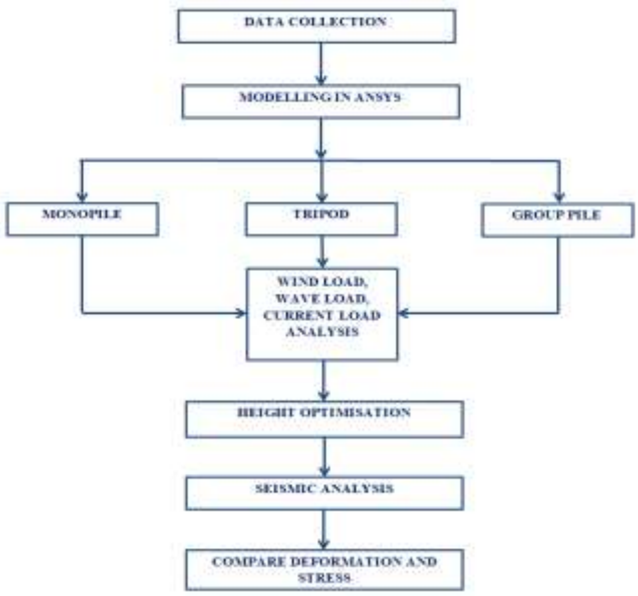

Fig-3: Methodology

4. MODELING

The aim of finite element analysis is to recreate mathematically the behavior of an actual engineering system. This model consist of all the nodes, elements, material properties, real constants, boundary conditions and the other features that are used to represent the physical system.in this study, ANSYS 16 was used for the linear static analysis. Monopile, tripod and group pile supported wind turbines were modeled in ANSYS. The material of tower and pile is steel and the properties are modulus of elasticity, poisons ratio and density.

Monopile supported wind turbine were modeled in ANSYS having 50mm thickness. Tower heights starting from 60m to 100m are modeled. Diameter of the monopile is 6m, water depth is 25m and pile length is 25m. Tripod consists of three legs. The pile is connected to the tower by legs. Tower heights starting from 60m to 100m are modeled. Thickness of pile and tower is 50cm, length of pile is 25m and diameter of each pile is 4m. Group pile consists of four legs pile having 3m diameter each were modeled in ANSYS. Tower heights starting from 60m to 100m were modeled. The Length of pile is 25m and thickness 50cm.

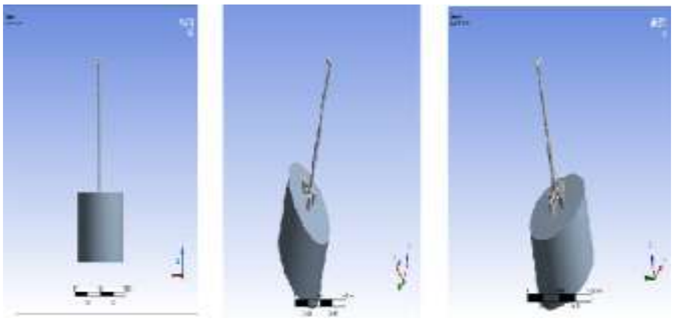

Fig-4: Model of Wind Turbine Tower

5. ANALYSIS AND RESULT

Two types of analysis were carried out in this project, Static load analysis and seismic load analysis. Wind, wave and current loads are input for static load analysis. Response spectrum method requires only natural period, mode shape and mass distribution of the structure to calculate maximum seismic loads. Response spectrum analysis method is used in this study.

5.1 Height Optimization

As wind velocity varies with height, the power that can be obtained at different heights will be different. ANSYS models for various tower heights starting from 60m to 100m are analyzed and maximum deformation is obtained. Power obtained at each of these heights is then calculated. Further, power obtained per unit deformation is calculated and compared for all these power heights. The one that yields maximum power per unit deformation is chosen as optimum height.

Table-1: Height Optimization of Monopile Supported Turbine Tower

Tower Height (m)	Deformation (cm)	Power (KW)	Power per Deformation
60	53.718	621.27	11.56
65	54.809	637.43	11.63
70	55.64	656.62	11.80
75	56.56	673.398	11.91
80	59.234	687.685	11.60
85	63.431	704.870	11.11
90	66.815	719.493	10.76
95	70.213	731.336	10.41
100	76.479	746.322	9.75

The optimum height of monopile supported wind turbine tower is 75m.

Table-2: Height Optimization of Tripod Supported Wind Turbine Tower

Tower Height (m)	Deformation (cm)	Power (KW)	Power per Deformation
60	42.97	621.27	14.45
65	44.39	637.43	14.51
70	46.43	656.62	14.14
75	48.23	673.398	13.96
80	51.34	687.685	13.39
85	53.46	704.870	13.18
90	56.31	719.493	12.77
95	60.13	731.336	12.16
100	64.0.2	746.322	11.65

The optimum height of tripod supported wind turbine tower is 65m.

Table-3: Height Optimization of Group Pile Supported Turbine Tower

Tower Height (m)	Deformation (cm)	Power (KW)	Power per Deformation
60	48.94	621.27	12.69
65	50.15	637.43	12.71
70	51.41	656.62	12.77
75	53.22	673.398	12.65
80	57.13	687.685	12.04
85	60.15	704.870	11.71
90	62.36	719.493	11.54
95	64.22	731.336	11.39
100	67.66	746.322	11.03

Power obtained per unit deformation is calculated and compared for all these power height. The one that yields maximum power per unit deformation is chosen as optimum height. The maximum power per unit deformation is obtained at 70m height. So the optimum height of group pile supported wind turbine tower is 70m.

Optimum heights for monopile, tripod and group pile supported wind turbine are 75m, 65m, 70m respectively

5.2 Wind, Wave and Current Load Response of Wind Turbine Tower

The wind, wave and current load response of a monopile, tripod and group pile supported wind turbine tower is analyzed at optimum height. The optimum height of monopile, tripod and group pile supported wind turbine tower is 75m, 65m and 70m respectively. The results from the analysis can be comparable and it was described in the table below. Table describes the comparison of total deformation and stress.

Table-4: Result Comparison

Foundations	Monopile	Tripod	Group Pile
Deformation (cm)	56.556	44.399	51.412
Stress (MPa)	15.189	14.223	14.627

From the results it is observed that, the deformation of tripod is less when compared with that of monopile and group pile. From the obtained results of pile head it is clear that deformation of pile head is more in monopile than tripod and group pile in same water depth. Deformation is found to be maximum at the top of the tower, this is because the wind was striking with a maximum velocity. In the case of monopile, Stress is found to be maximum at the bottom of the tower. The soil pressure was acting at the bottom of the tower. Thus the stress concentration at the bottom level is higher.

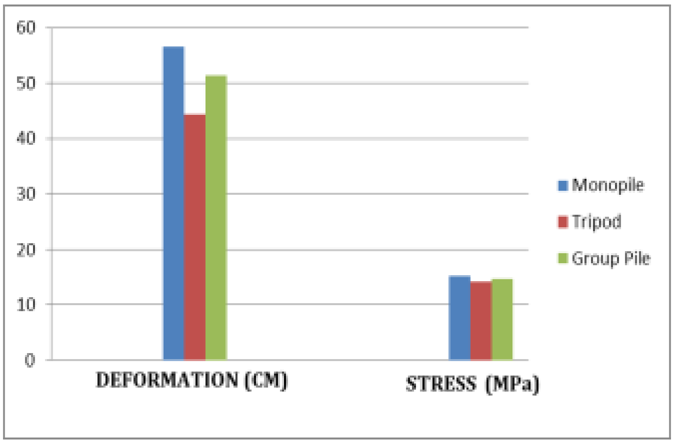

Chart-1: Comparative Graph

The responses of the offshore wind turbine tower system under wind action increases as increasing wind velocity and the responses are mainly caused by thrust force. Wave period has a prominent impact on the wave responses of the offshore wind turbine system. For offshore wind turbine tower, the maximum allowable rotation at tower head is 0.5° (DNV-OS-J101). In this analysis rotation angle satisfies the allowable limit. From this results, also confirmed that the performance of the support structure was satisfactory.

5.3 Seismic Analysis

The wind, wave and current load response of a monopile, tripod and group pile supported wind turbine tower is analysed at optimum height. The optimum height of monopile, tripod and group pile supported wind turbine tower is 75m, 65m and 70m respectively.

The results from the analysis can be comparable and it was described in the table below. Table describes the comparison of total deformation and stress.

Table-5: Result Comparison

Foundations	Monopile	Tripod	Group Pile
Deformation (cm)	68.04	60.508	65.322
Stress (MPa)	180.46	101.62	153.26

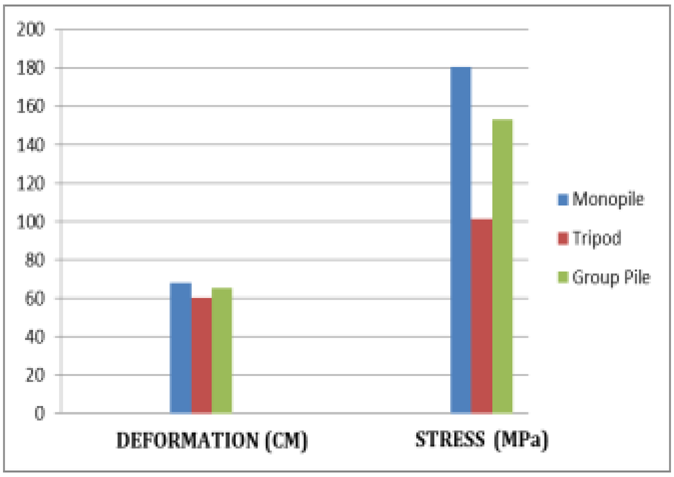

Chart-2: Comparative Graph

From the results it is observed that, the deformation and stress of tripod is less when compared with that of monopile and group pile. Deformation is found to be maximum at the top of the tower, this is because the wind was hitting with a maximum velocity. For offshore wind turbine tower, the maximum allowable rotation at tower head is 0.5° (DNV-OS-J101) [7]. In this analysis rotation angle satisfies the allowable limit. From this results, also confirmed that the performance of the support structure was satisfactory.

6. CONCLUSIONS

The following conclusions are made from the analysis:

- •Power obtained per unit deformation is calculated for monopile, tripod and group pile supported wind turbine tower. The one that yields maximum power per unit deformation is chosen as optimum height.
- •Optimum heights for monopile, tripod and group pile supported wind turbine are 75m, 65m, 70m respectively
- •Deformation is found to be maximum at the top of the tower, this is because the wind was striking with a maximum velocity.
- •In the case of monopile, stress is found to be maximum at bottom of the tower. The soil pressure was acting at the bottom of the tower. Thus the stress concentration at the bottom level is higher.
- •In the case of group pile and tripod the stress is found to be maximum at joints
- •In both static and seismic analysis deformation and stress for wind turbine tower supported by monopile is more than tripod and group pile supported tower.
- •This study concluded that tripod foundation is more stable than monopile and group pile foundations.

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