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SEISMIC RESPONSE STUDY OF MONOPILE AND SUCTION PILE FOUNDATION FOR OFFSHORE WIND TURBINES

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Abstract - *Soil-foundation-structure interaction can affect the seismic response of wind turbines. In this paper, the effects of soil-foundation-structure interaction on the seismic response of offshore wind turbines are investigated. Two types of foundations (Suction pile and mono pile) with frequency-based design are analyzed for an offshore wind turbine system (OWTS). Finite element modeling of the OWTS with different foundation condition is done to obtain the natural frequency and mode shapes. The variation in frequencies and mode shapes due to different foundation conditions are analyzed. Results shows that wind turbines with monopile foundation and suction pile reduced the natural frequency. Peak acceleration response has reduced by 40 -60% for structure with foundation.*

Key Words: Wind turbine, Seismic response, Finite element, Monopile, Suctionpile.

1. INTRODUCTION

Wind turbines are one of the fastest growing sources of renewable energy resources. Wind turbines form the main energy source in most of the European countries where wind is available in plenty. In areas having fewer winds, there is a need to provide taller towers with longer blades because of higher output demand. In seismic areas, taller wind turbines may not last long. So there is a need to properly analyse seismic response of the structures which in turn leads to cost reduction and increase in fatigue life of the structure. Traditionally modal analysis used for buildings is used for the design of wind turbines but for wind turbines in seismic areas must be analysed by time history analysis.

Offshore Wind turbines have been widely used for last few years but the cost of construction make its usage limited. Deep water wind turbines are proved to be more profitable in terms of energy produced but the cost of construction and installation of the structures make its emergence limited. So research works in this field is necessary in order to reduce the total cost of construction. Wind turbines are designed such that it can resist the dynamic load like wind, wave, earthquake etc. Now, large number of wind turbines are installed in areas prone to earthquake. Hence a proper analysis method is required to determine the response of the wind turbine to seismic and other dynamic forces. So during dynamic forces, damping is an important parameter that can bring change to structural dimensions of wind turbine. Correct prediction of response of wind turbine to all dynamic forces can bring a reduction in the cost of offshore wind turbines.

2. METHODOLOGY

In design and analysis of wind turbine, tower design is governed by the frequency limits. The ratio of natural frequency to operational frequency must be greater than 1 with 10% safety margin otherwise resonance occurs. If the safety margin is not big enough, the effect of soil structure interaction can shift the natural frequency close to operational frequency. Therefore frequency based design with fixed wind turbine may not be conservative. So there is a need to properly analyse the wind turbine under seismic forces.

Methodology can be summarised as below:

- Validation of 65 kW wind turbine is done based on an experimental results obtained from journal.
- Wind turbine is model in FEM based software Ansys for two foundation conditions.
- Natural frequencies and peak acceleration response is obtained for Landers earth- quake time history for two conditions.
- Values are compared with experimental values.

2.1 Validation of Numerical Method

Validation of the finite element model is necessary in order to ensure the accuracy of material model, element formulation and mathematical calculations. In this study, experimental data obtained from testing a full-scale 65 KW wind turbine on a shaking table is used to validate the model[5]. This wind turbine with its rotor parked is subjected to east west component of Landers earthquake 1992 by applying the component on the base of shaking table. The uniaxial horizontal motion is applied in the direction perpendicular to the rotor's axis. An accelerometer is placed on the top of Nacelle to record the peak acceleration response at the top of Nacelle. Experimental research provided results in the form of mode shape and acceleration response. Mode shapes are constructed using an average amplitude and phase transfer function. First and second natural frequency obtained are 1.7 Hz and 12 Hz respectively and acceleration response due to earthquake vibration is 0.28g at t = 30.48 s, for 0.86% damping and 0.38 g for 0.5% damping.

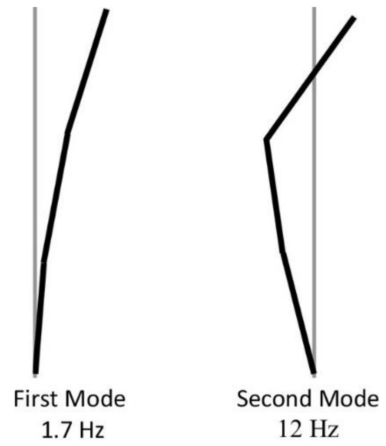


Fig -1: Experimental Values

Model for wind turbine comprises of Tower, Nacelle, and hub and rotor blade. These components are modeled in Ansys for the purpose of validation. Properties of the components of wind turbines are given in the table below.

Table -1: Materials used

Part	**Structural Steel**
Tower	Structural Steel
Nacelle	Structural Steel
Rotor Blades	Fiberglass and Carbon Fibres
Hub	Structural Steel

Table -2: Properties of materials

Property	**Fiberglass And Carbon Fibers**	**Structural Steel**
Density	648 kg/m3	7860 kg/m3
Young's modulus	235,000 MPa	200,000 MPa
Poisson's ratio	0.3	0.3
Tensile yield strength	3920 MPa	250 MPa

Real nacelle is lighter compared to a solid nacelle model with the dimensions specified, equivalent lower density is used to model the nacelle. Material used is structural steel and a composite material - fibreglass and carbon fibre. Composite material is used for rotor blade since lighter material usage can produce more power and also this material has more fatigue life.

Table -3: Dimensions of wind turbine

Property	**Element**
Hub diameter, length	0.4, 0.25 m 1.31, 0.82 (ft)
Hub height	22.6 m (74.1 ft)
Rotor blades diameter	16 m (105 ft)
Rotor blades mass	6400 kg
Rotor blades thickness	60 mm (2.36 in.)
Nacelle width, height, length	1.45, 1.4, 3.28 m 4.76, 4.59, 10.76 (ft)
Nacelle mass	2400 kg
Tower diameter outer, bottom	2.02 m (6.6 ft)
Tower diameter outer, top	1.06 m (3.5 ft)
Tower length	21.9 m (71.8 ft)
Tower mass	1900 kg
Tower thickness	5.3 mm (0.21 in.)

2.1.1 Seismic load

Seismic load selected should have frequency close to natural frequency of wind turbines so that they can excite natural modes of wind turbine. East west component of landers earthquake 1992 has been selected which has recorded peak ground acceleration (PGA) as 0.15 g at desert hot springs station (DHS). Magnitude moment of the earthquake was 7.3. Desert hot springs station is 23 km far from landers earthquake fault.

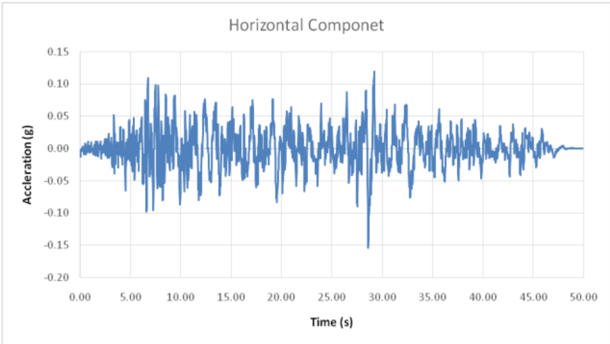


Fig -2: Horizontal component of Landers Earthquake 1992

2.1.2 Assumptions

- Modeling of wind turbine is done such that x axis is parallel to rotor axis and y axis is perpendicular to tower axis.
- Wind turbine is assumed to be parked which means blades are rested to prevent excessive force on other mechanical parts.
- All connections made a bonded in all degrees of freedom.
- Global and local buckling modes of tower are ignored since it can resist buckling.
- In practical condition this is achieved by providing stiffeners along the length of tower.
- Wind turbine with no foundation is modeled with fixed base so that all translational and rotational motions are prevented.
- Acceleration response is obtained in terms of acceleration due to gravity.
- Water depth is assumed to be 20m.

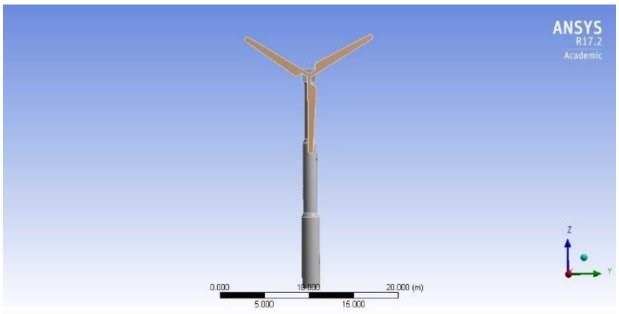


Fig -3: Wind turbine modeled with fixed base

2.1.3 Modal Analysis

In order to find the natural frequency of wind turbine, modal analysis is used in Ansys. Modal analysis is performed using Block Lancoz method. This method is adopted to find many modes of large models and can handle poorly shaped elements. Analysis includes first 50 modes. For analysis, the bottom of wind turbine is made fixed. The results obtained for 1st and 2nd natural frequencies are 1.67 Hz and 9.13 Hz respectively. First two modes have greater effect, whereas others have much smaller effect.

Table -4: Mesh summary

PARTS	ELEMENTS	NODES
TOWER	1805	12730
NACELLE	588	3079
HUB	28	199
BLADES	265	726
TOTAL	2686	16734

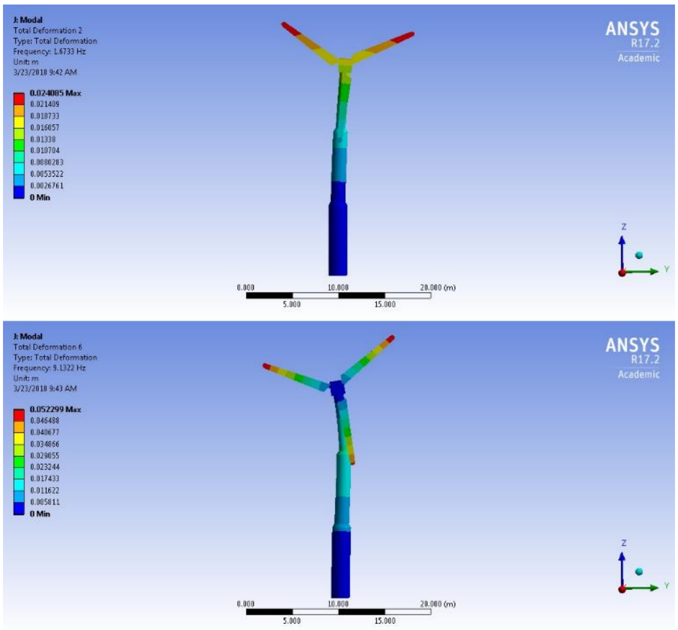


Fig -4: First and second natural frequencies of wind turbine with fixed base

2.1.4 Transient Analysis

To obtain the peak acceleration in response at the top of Nacelle when subjected to seismic forces a transient analysis is to be done. East west component of landers earthquake is applied as base acceleration to the bottom of wind turbine and transient analysis is performed. A time step of 0.02 is found to be efficient. It is obtained that peak acceleration at the top of Nacelle is 0.38g for 0.5% damping.

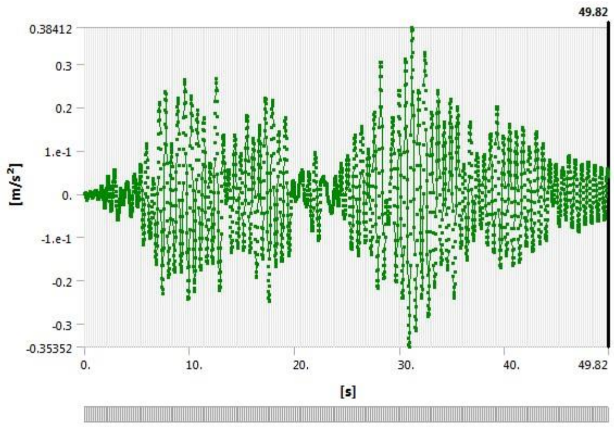


Fig -5: Peak acceleration response at top of nacelle

The numerical results obtained shows first and second mode shapes are similar to experimental mode shapes. Also peak acceleration is much closer.

2.2 Finite element analysis of wind turbine – ANSYS

65 KW wind turbine with different foundation conditions are analysed so that the variation in natural frequency and acceleration response can be found out. Foundations used in this study are mono pile foundation and suction pile foundation. Dimensions are adopted from Offshore Code Comparison Collaboration (OC3) for IEA Task 23 Offshore Wind Technology and Deployment [7].

2.2.1 Monopile

Mono pile is the most commonly adopted foundation for wind turbine. They are usually adopted for water depth ranging 0-30 m. The installation of mono pile becomes difficult when water depth is greater than 30m, also the cost increases. Mono pile is mainly made of steel or concrete. Mono pile transfers load through bearing or frictional resistance. Embedding length of 50% of total length and thickness of 1% of diameter of pile is usually adopted. Dimensions for pile adopted are given in table 5.

2.2.2 Suction pile

Limitation mono pile usage in deep water paved the way for the development other foundation types like suction pipe. Suction pipe can be adopted for water depth greater than 50 m. Suction piles are provided with jacket structure so that its load carrying capacity can be increased. Force action pile with jacket structure L/D ratio should be between 1 and 4. Thickness of pile is usually 1% of diameter. Dimensions of pile and jacket adopted are given in table 5 and 6.

Table -5: Dimensions of foundations

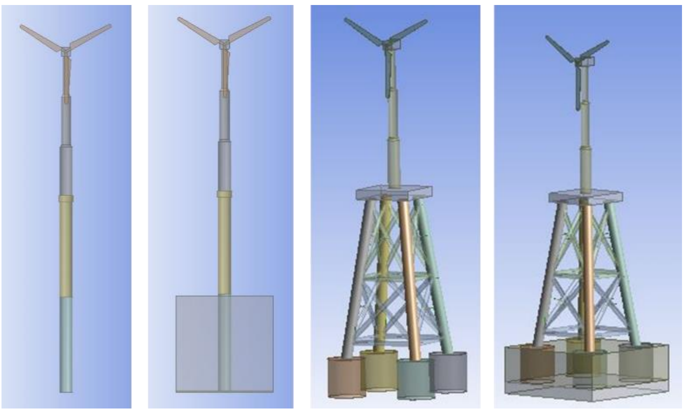
Foundation	Diameter (m)	Length (m)	Thickness (mm)	Material	Remark	Foundation
Mono pile	2.02	30	20	Structural Steel	Embedment length = 15 m	Monopile
Suction Pile	6	6	60	Structural Steel	L/D ratio between 1 and 4	Suction Pile

Table -6: Dimensions of Jacket structure for suction pile

Transition piece	9 m x 9 m
Thickness of Brace	0.03 m
Thickness of Leg	0.04 m
Diameter of Brace	0.09 m
Diameter of Leg	1.8 m
Height of Jacket structure	20 m

Table -7: Soil parameters used

Foundation type	Unit weight (K N/m3)	Modulus of elasticity (MPa)	Poisson's ratio	Soil cube
Monopile	20	100	0.3	15 m x 15 m x 16 m
Suction pile	20	100	0.3	20 m x 20 m x 8 m



(a) Monopile (b) Monopile + soil (c) Suction pile (d) Suction pile + soil

Fig -6: Finite element model of 65 KW wind turbine with different foundation types

3. RESULTS AND DISCUSSION

Case 1:

Wind turbine of 65 KW capacity is attached to mono pile of Steel and analysis is carried out with its base as fixed. Natural frequency for 1st and 2nd modes are obtained as 1.23 Hz and 5.11 Hz. Transient analysis for the model has given the value of peak acceleration response as 0.194g.

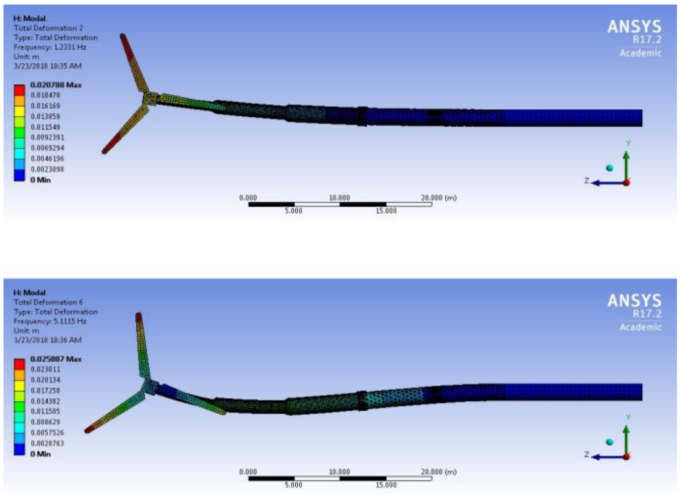


Fig -7: First and Second modes of Wind turbine with mononpile

Case 2:

Mono pile foundation embedded into the soil for an embedment length of 50% of total length. Base of the mono pile is attached to soil volume and analysis is performed. First and second natural modes obtained from modal analysis are 0.77 Hz and 2.31 Hz. Peak acceleration response obtained at the top of the nacelle is 0.17g.

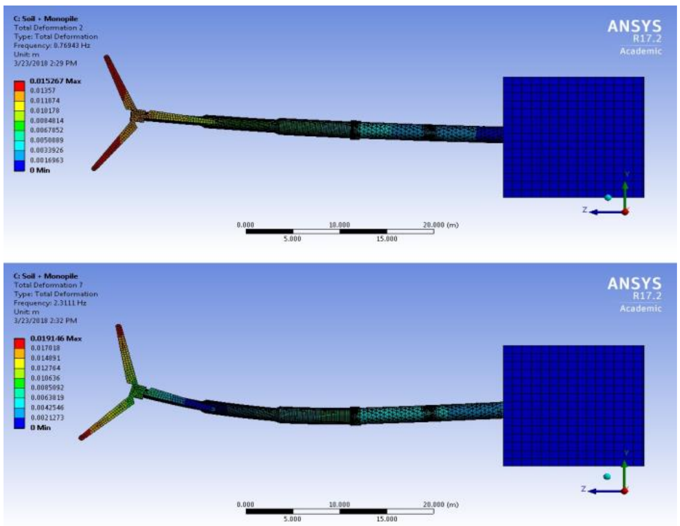


Fig -8: First and Second modes of Wind turbine with mononpile embedded in soil

Case 3:

Four suction pile with the jacket structure attached to the bottom of wind turbine modeled and model analysis and transient analysis are performed. Modal analysis produced first and second natural frequencies of 1.17 Hz and 6.6 Hz. Peak acceleration response obtained at the top of nacelle is 0.16g.

Case 4:

In this, 4 suction piles are embedded in soil, modal analysis and transient analysis are performed. Natural frequencies obtained are 0.88 Hz and 3.15 Hz as first and second modes. Transient analysis produced values of 0.13g at the top of nacelle.

Table -8: Natural frequency and peak acceleration response for different foundation types

	Experimental	Fixed base	Monopile	Monopile + soil	Suction pile	Suction Pile + soil
First Frequency (Hz)	1.7	1.67	1.23	0.77	1.18	0.88
Second Frequency (Hz)	11.7-12.3	9.113	5.115	2.311	6.653	1.87
Peak acceleration response (g)	0.35	0.38	0.194	0.17	0.16	0.13

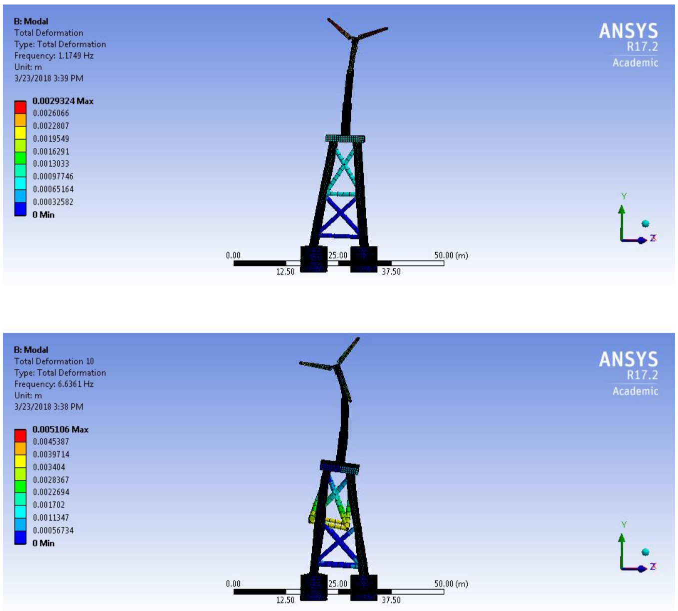


Fig -9: First and Second modes of Wind turbine with suction pile

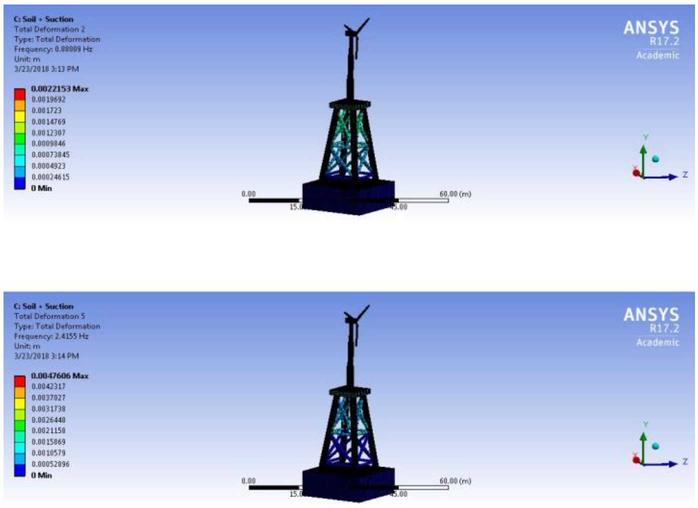


Fig -10: First and Second modes of Wind turbine with suction pile embedded in soil

4. CONCLUSIONS

- Natural frequencies obtained by modal analysis in validation is close to the experimental value obtained from literature for 65 KW wind turbine. Hence numerical analysis is a valid tool for analysis of wind turbine.

- Natural frequencies of the wind turbines has decreased with incorporation of foundation and soil. So from results it is evident that natural frequencies analysis of wind turbine by assuming based as fixed produce inappropriate results.

- Natural frequency value decreased by 20% when foundation alone was used. But the deprecation becomes 50% when soil was added.

- Results of transient analysis shows that peak acceleration response has decreased by 40-50% for monopile and 50-60% for suction pile.

- The decrease in natural frequency is caused by structural damping and soil damping. So proper analysis of these damping can be used to reduce the cost of construction of wind turbine.

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