A STUDY ON NATURAL FREQUENCY OF OFFSHORE WIND TURBINE IN A LAYERED SOIL

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Abstract - *A Modal Analysis using Finite Element Method is performed to evaluate natural frequency of monopile and tower of Offshore Wind Turbine (OWT) in medium dense sand. In this study monopile, tower and soil modeled as 3 Dimension solid model in ANSYS workbench. Soil modeled as layers with different depth and material properties in each layer. An explicit dynamic analysis is conducted, considering soil as an explicit material with environmental loads like wind and wave loads on turbine as static loads. From the analysis it is concluded that the natural frequency of the offshore wind turbine is far away from forced frequency.*

Key Words: Monopile, turbine tower, soil pile interaction, explicit dynamic analysis, natural frequency, Modal analysis

1. INTRODUCTION

Wind energy are more abundant and of better quality at offshore as compared to onshore. Wind conditions at offshore sites are stronger and more stable and soil condition is sandy and silty in nature. Design and construction of foundations for offshore turbines are very challenging because of the harsh environmental conditions [1]. Most of the Offshore Wind Turbine (OWT) founded on monopile due to their simplicity in installation and construction. This type of foundation is opted when water depth ranges from 10 m to 30 m.

For monopile the lateral loads like wind and wave loads acting on turbine tower and the overturning moment due to these loads are resisted by horizontal soil reactions on monopile. Alternate degradation and stiffening of soil will be more due to dynamic and cyclic loading, which may affect soil stiffness [1]. This may leads to permanent deformation of tower and monopile and wind turbine cannot tolerate more than 0.5 degree tilt.

Offshore wind turbines supported on monopile foundations are dynamically sensitive because the overall natural frequencies of these structures are close to the forcing frequencies imposed upon them due to lateral loads [1]. Change of soil stiffness due to dynamic loading leads to changes in the natural frequency of the system, this may cause unplanned system resonances and excessive cyclic displacements. Hence a modal analysis of tower and monopile of OWT is taken under consideration [1].

2. SITE AND SOIL CHARACTERISTICS

A location at Rameswaram, Tamil Nadu has been selected based on environmental data obtained. All the wind data, wave data and soil data were obtained from National Institute of Ocean Technology (NIOT) Chennai [2]. The actual water depth of the selected location is approximately 10 m, hence monopile foundation is selected. The Basic wind and wave data depend on the site conditions is collected by NIOT [2]. The soil condition for the selected location is obtained from NIOT, Chennai [2]. Soil material properties depend upon soil type and soil depth shown in Table 1 [2].

Table -1: Soil Characteristics

Soil description	Depth(m)	Internal friction(^{0})
Grey fine sand	0 – 3	32-33
Grey silty fine sand	3- 7.5	33-39
Grey silty clay with calcareous sand stone	7.5-10.5	33-34
Crushed pieces of rock and calcareous sand stone	10.5-12	34-44
Silty fine sand	12- 13.5	31-44
Fine sand with white color small stone	13.5-16.5	31-41
Fine silty sand	16.5-30	34-42

3. TURBINE TOWER AND MONOPILE CHARACTERISTICS

Steel turbine tower with height 80 m and diameter 4.5 m is selected as per NIOT Chennai [2]. Steel monopile diameter ranges from 4 to 6 m and corresponding embedded length ranges from 7D to 8D [2].

4. LATERAL LOADS ON MONOPILE

4.1 Wave Load

For slender structures, Morison's equation can be applied to calculate the wave loads [3], [4], [5], [6], [7] which is the sum of drag and inertia forces shown in equation (1).

Wave force = Drag force + inertia force

$F = C_D \,.\, ½ \,.\, \rho \,.\, D \,.\, |U| \,.\, U + \rho \,.\, C_I \,.\, \pi D^2/4 \,.\, a_x$ (1)

C_D = Drag coefficient

ρ = mass density of sea water

D = projected area normal to cylinder axis/unit length

C_I = inertia coefficient for smooth circular cylinder

U = component of velocity vector of water due to wave normal to axis of the member in m/s

|U| = absolute value of U in m/s

4.2 Wind Load

Wind load on turbine blades is shown in equation (2).

$F_b = 0.5\ \rho_a.\ R_T^2.V^2.C_T.(\lambda_S)$ (2)

F_b = the wind load acting on the hub in N

V = the wind speed at the hub height in m/s

R_T = the rotor radius in m

ρ_a = the air density

C_T = force coefficient depend on shape of structure

C_T (λ_S) = is the thrust coefficient which is a function of the tip speed ratio (λ_S)

5. SOIL MONOPILE INTERACTION

Monopile under lateral external loading the response of soil is described in terms of p – y curve which relates the soil resistance to the pile deformation at various depths below the ground surfaces. These curves are Non-linear in nature and depend on several parameters, including depth and soil material properties [6]. For different soil material properties and soil depth the p-y curve vary shown in Figure 1 based on the equation below (3),(4),(5).

Ultimate bearing capacity;

$P_{us} = [C_1 \,.\, H + C_2 \,.\, D] \,.\, \gamma.\, H$ (3)

$P_{ud} = C_3 \,.\, D \,.\gamma.\, H$ (4)

where,

P_u = ultimate resistance (kN/m)

γ= effective soil weight (KN/m³)

H = depth (m)

ϕ= angle of internal friction of sand

D = average pile diameter from surface to depth (m)

Soil resistance;

$P = A \,.\, P_u \,.\, \tan h[\{(k \,.\, H)/(A \,.\, P_u)\}.y]$ (5)

A = factor to account for cyclic or static loading condition.

P_u = ultimate bearing capacity at depth H (kN/m)

k = initial modulus of subgrade reaction (kN/m³)

y = lateral deflection (m)

H = soil depth (m)

p-y curve at different soil depth is shown in Chart 1 below.

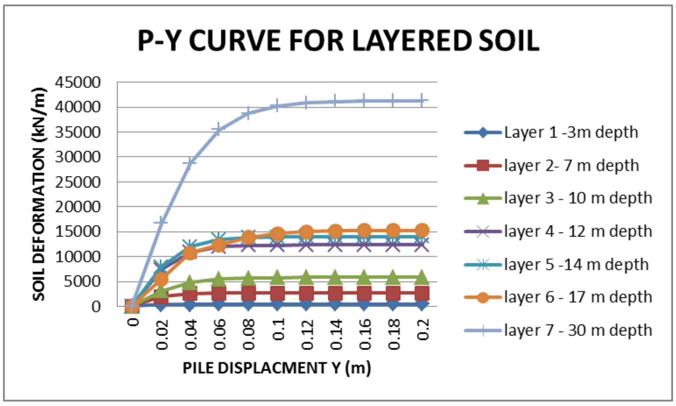

Chart -1: p-y curve at different soil depth

6. FINITE ELELMENT MODELLING IN ANSYS WORKBENCH

A 3 dimension finite element model of tower, monopile and surrounding soil is modeled in Ansys. Soil modeled as layers of different depth and different material properties like modulus of elasticity, poisons ratio and density. Modulus of elasticity is increases with increase in depth. Structural steel material property is assigned to both tower and monopile. Soil is behaved as nature of a non-linear inelastic material hence soil is modeled as Drucker-Prager model. Soil is modeled as a rectangular solid cube of 20 m around the pile. A fixed boundary condition is provided at the bottom of soil solid cube and at the lateral sides of soil solid cube, soil free to move in the corresponding direction. Contact friction is provided at pile-soil interface [8]. Soil is modeled as an explicit material, since soil behavior is elasto plastic in nature. All the dynamic loads wind loads, wave loads are applied as static load in the model shown in Fig 1.

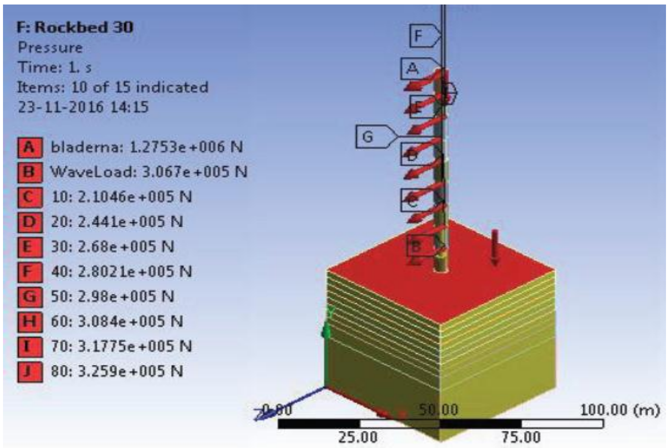

Fig -1: Model of soil, tower and monopile in Ansys

Embedment length depends upon soil properties and for sand soil it lies between 7D-8D is the safe limit where D is the diameter of pile [9]. Various pile diameter and corresponding embedded length is shown in Table 2.

Table -2: Various pile diameter and pile embedded length

Diameter of pile (d) (m)	Embedded length of pile (l) (m)	l/d ratio
4.2	30	7.14
4.5	32.14	
5	35.7	
5.3	37.84	

7. MODAL ANALYSIS

The first natural frequency of the foundation structure is a very important parameter as it determines the dynamic behaviour of the offshore wind turbine [10]. If the frequency of excitation is near the natural frequency, resonance occurs and it will lead to higher stresses in the monopile structures [10].

As the offshore wind turbine rotates, creating vibrations to which the offshore wind turbine is sensitive due to the reason that it is a slender structure. When a three bladed rotor encounters a turbulent eddy it resists peak forces at frequencies of 1P and 3P, where P is the blade passing frequency [11]. For a typical variable speed turbine, the blade passing frequency is in between an approximate range of 0.15 Hz and 0.3 Hz, and rotation frequency, which is between about 0.44 Hz and 0.92 Hz [11]. The cyclic loading from sea waves typically occurs at a frequency between 0.04 Hz and 0.29 Hz [11].

Therefore, to avoid resonance, the offshore wind turbine (turbine, tower, monopile) have to be designed with a natural frequency that is different from the forced frequencies like blade passing frequency, rotor frequencies and wave frequencies. Forced frequencies on offshore wind turbine are shown in the Fig 2.

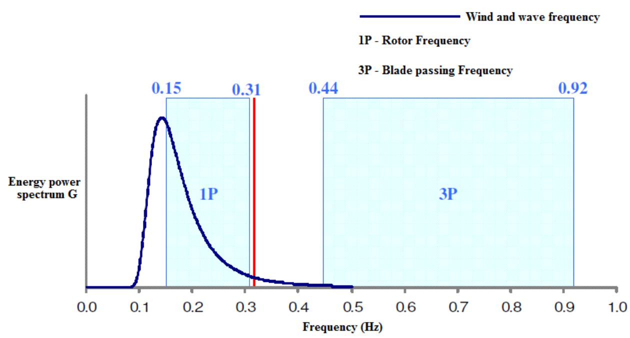

Fig -2: Forced frequencies on offshore wind turbine

8. RESULT AND DISCUSSIONS

From Fig 3 to Fig 8 shows the 1st to 6th frequencies and the mode shape of vibration of the model and are tabulated in Table 3.

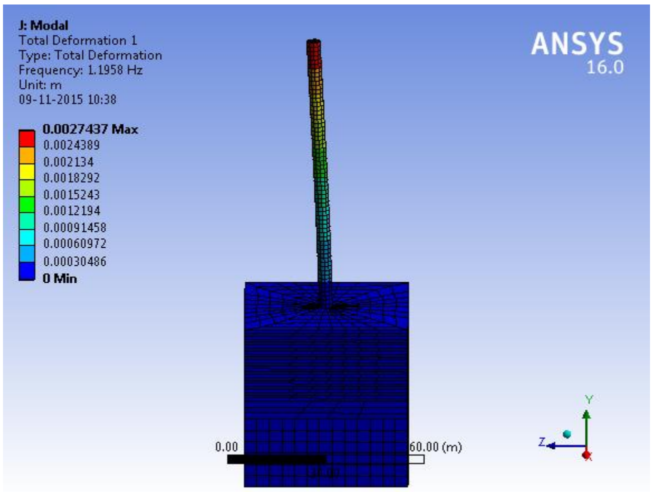

Fig -3: Natural frequency – mode shapes 1

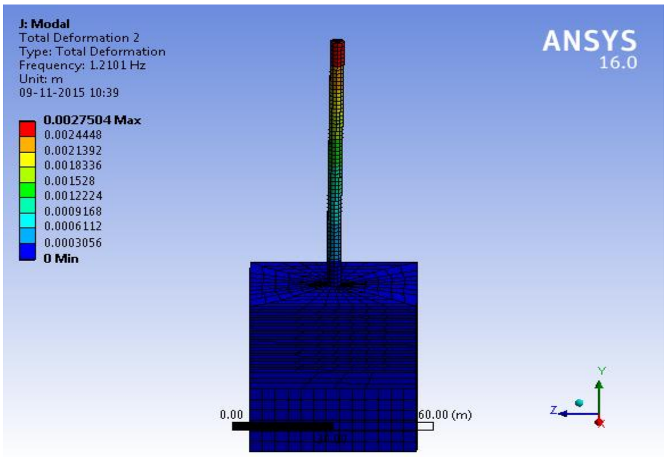

Fig -4: Natural frequency – mode shapes 2

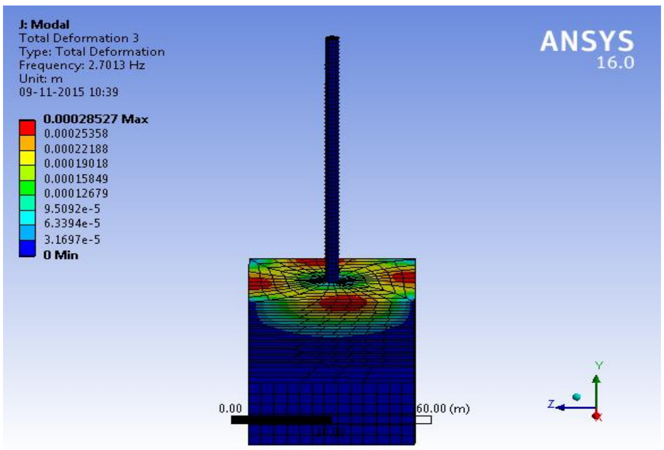

Fig - 5: Natural frequency – mode shapes 3

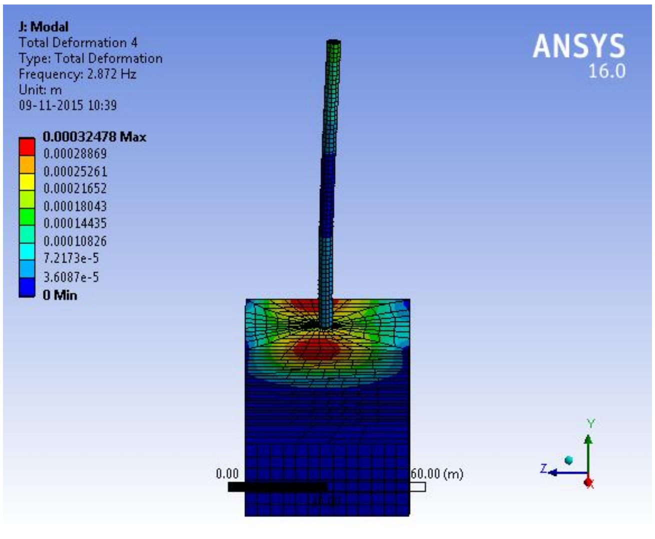

Fig -6: Natural frequency – mode shapes 4

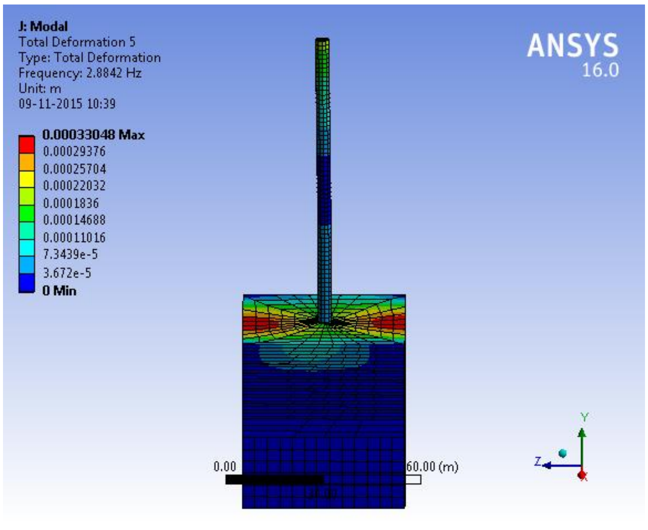

Fig -7: Natural frequency – mode shapes 5

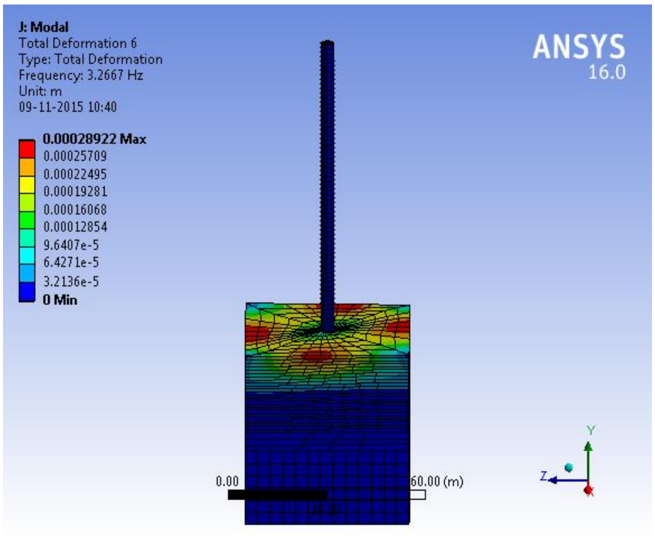

Fig -8: Natural frequency – mode shapes 6

Table -3: Natural Frequency for 6 mode shapes

Mode No:	Natural Frequency (Hz)
1	1.1958
2	1.21
3	2.7013
4	2.873
5	2.884
6	3.267

From the modal analysis in Ansys the calculated natural frequencies are far away from frequency of excitations. Hence all the mode shapes are in the acceptance level. As explained above, 1st mode shape of vibration is the fundamental mode, since about 80% of acceptance belongs to 1st mode shape.

9. CONCLUSIONS

From the free vibration analysis, natural frequencies obtained at various initial modes are far away from forcing frequencies like rotor frequency, blade passing frequency, wind-wave frequency. Thus all mode shapes are in acceptance level and there is no other chance of resonance. 80% of acceptance belongs to first natural frequency and it is the fundamental mode. The fundamental mode is in acceptance level and there is no chance of resonance.

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