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A Study on Lateral Deformation of Monopile of Offshore Wind Turbine due to Environmental Loads

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Abstract

An analytical study is performed to evaluate the displacement behavior of monopile of offshore wind turbine founded in sandy soil. The system consists of pile, turbine tower and soil modeled as 3D finite element model in ANSYS. An explicit dynamic analysis is performed in a time domain considering soil as an explicit material and wind and wave loads act on the turbine tower as static loads. Behavior of monopile in soil is analyzed by considering soil pile interaction. The study shows that pile displacement and pile tilt angle depends on soil properties and pile embedded length and pile diameter.

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Keywords: Deformation, Explicit dynamics; Monopile; Offshore wind turbine; Soil-pile-interaction.

1. Introduction

Wind turbines are power tools to tap nonconventional wind energy. Onshore wind turbine needs plenty of land area for power generation. Thus it was a natural step to take Offshore Wind Turbine (OWT). The wind resources are even more abundant and of better quality at sea as compared to onshore.

The major components of the offshore turbine are turbine blades, Rotor- Nacelle Assembly (RNA), tower transition piece and the foundation. It can provide 2 or 3 blades for turbine, but mostly 3 blades are provided.

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Cumulative Capacity for offshore wind turbine is approximately 9 -10 GW in Europe. Mostly 4 to 11 rpm is approximately taken for a wind turbine.

The design and construction of foundations for offshore turbines are challenging because of the harsh environmental conditions. The support structures for OWT are monopile structure, tripod structure, lattice structure, gravity structure, tripile foundation, and floating structure.

The choice of monopiles results when water depth ranges from 10 m to 30 m. OWT supported on monopile foundations are dynamically sensitive because the overall natural frequencies of these structures are close to the different forcing frequencies imposed upon them. Degradation of soil stiffness due to dynamic and cyclic loading may lead to permanent displacement of the turbine which may jeopardise its performance. Wind turbines typically cannot tolerate more than 0.5 degrees tilt [1].

The overturning moment in jacket super structure supported in multi-piles is transferred as axial loads to opposing foundation piles. For monopile the overturning moment is resisted by horizontal soil reaction along embedded length of monopile. As the pile is not fixed at the top, it is free to rotate and translate. The pile must be long enough to mobilise enough soil over its length to transfer all loads and prevent toe kick. Hence soil pile interaction has an important influence to resist lateral loads. Relation between lateral forces (P) applied to monopile and lateral displacement of pile (y) is the P-y curve shows soil pile interaction of the system is the lateral stiffness of soil.

This study deals with pile displacement behavior by considering soil pile interaction for laterally loaded wind turbine tower.

2. Wind Turbine and Soil Characteristics

About 75% of offshore wind turbine is founded on monopiles foundation. A location at Rameswaram, Tamilnadu has been selected based on environmental data obtained from National Institute of Ocean Technology (NIOT), Chennai. Soil profile mainly consists of sand and a few layers of silt and clay [2]. Soil is behaves as an elasto-plastic material, hence it is modelled as Drucker - Prager model. The Drucker–Prager yield criterion is a pressure-dependent model for determining whether a material has failed or undergone plastic yielding. The criterion was introduced to deal with the plastic deformation of soils.

The material of turbine tower and monopile is steel and the strength properties are modulus of elasticity, Poisons ratio, density. Turbine tower with height 80 m and cross section diameter of 4.5 m is selected as per NIOT, Chennai [2]. Diameter (D) of monopile ranges from 4 m - 6 m and corresponding embedded length is ranges from 7D to 8D.

3. Loads on Turbine Tower

The response of the support structure depending on the loading conditions that the structure likely to experience in ocean environment.

3.1. Wave Load

Compared to the wave load the other loads like current loads are negligible and are not taken into consideration. For slender structures, Morison's equation can be applied to calculate the wave loads [3], [4], [5], [6] and [7].

Wave force = Drag force + Inertia force

$$F = C_D \ \tfrac{1}{2} \rho D |U| U + \rho C_I \ \pi D^2/4 \ a_x \quad (1)$$

C_D - Drag coefficient

ρ - Mass density of sea water = weight density of water / acceleration due to gravity in kg/m^3

D - Projected area normal to cylinder axis / unit length in m

C_I - Inertia coefficient for smooth circular cylinder

U - Component of velocity vector of water due to wave normal to axis of thee member in m/s

The expression for velocity and acceleration are;

$$U = \{h_w \pi \cosh(k (z_2 + d_w)) \ \cos(kx - \omega_w t)\} / \{T_w \ \sinh (kd_w)\} \quad (2)$$

$a_x = \{h_w \pi^2 \cosh(k (z_2 + d_w)) \ \sin(kx - \omega_w t)\} / \{T_w^2 \ \sinh(kd_w)\}$ (3)

h_w - Wave height in m
k - Wave number in m^{-1}
w_w - Wave frequency in rad/sec
T_w - Wave period in sec
d_w - Water depth in m

3.2. Wind Load

Wind force exerted on turbine structure depends on size and shape of structural member in wind path and speed of wind blowing.

Wind load acting on the turbine blades (F_b) is [3];

$F_b = 0.5\ \rho_a\ \pi\ R_T^2\ V^2\ C_T\ (\lambda_S)$ (4)

Fb - Wind load acting on the hub in N
V - Wind speed at the hub height in m/s
R_T - Rotor radius in m
ρa - Air density which equals to1.23kg/m3 at 15.1^{0}C at1atm

Tip speed ratio $\lambda_s = V_r\ R_T/V$ (5)

V_r - Rotor speed in rad/sec
R_T - Rotor diameter in m

$V(z) = u^*/\ k_a \ln(z_1/z_0)$ (6)

ka - Von Karman's constant
z_1 - Tower height in m
z_0 - Terrain roughness parameter = 0.0001 min the open sea without waves.
u* - Wind friction velocity calculated from 10min mean wind speed at the height Ht equals to10m

$u^* = \sqrt{(k)}\ U_{10}$ (7)

Where the Surface friction coefficient $k = \{k_a/ \ln(H_t/z_0)\}^2$

Wind load acting on turbine tower depend on wind velocity along the tower. Tower is divided into different segment and wind load act as concentrated load at each segment. Wind load acting on turbine tower (F_t) is [6];

$F_t = ½ . \rho . \mu^2 . C_s . A$ (8)

F - Wind force in kN
ρ - Air density in kg/m^3
μ - Wind speed in m/s
A - Projected area in m^2

Velocity translation to another height is;

$V = V_{ref} \times \ln(Z/0.002) / \ln(Z_{ref}/0.002)$ (9)

V_{ref} - Basic wind speed at height 10 m Reference

Z_{ref} - Reference height

4. Soil Pile Interaction

Monopile supported wind turbine resists both axial loads and lateral loads by soil reaction around the monopile. The axial resistance of the soil is provided by a combination of axial soil-pile adhesion and end bearing resistance at the pile tip is shown in Fig. 1. The relationship between mobilized soil-pile shear transfer and local pile deflection at any depth is described using a t-z curve. The relationship between mobilized end bearing resistance and axial tip deflection is described using a Q-z curve. The lateral resistance of the soil is provided by lateral soil reaction is shown in Fig 2. Pile under lateral loading the response of the soil is described in terms of P–y curve which relates the soil resistance to the pile deflection. A P-y curve describes the nonlinear relationship between the soil resistance acting against the pile wall, P, and the lateral deflection of the pile, y [6].

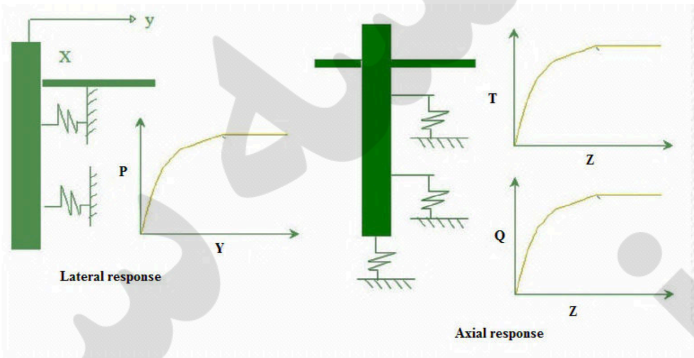

Fig. 1. Pile soil interaction stiffness curves.

The ultimate lateral resistance of soil to lateral loads can be estimated by using the P-y curve method. P-y curve is nonlinear and depend on several parameters, including depth, shearing stress of soil and soil properties.

The development of P-y curve depends on the lateral bearing capacity of pile [6]. The ultimate lateral bearing capacity of sand has been vary depend on shallow depth.

$$Pus = [C1 \times H + C2 \times D] \times \gamma \times H$$
$$Pud = C3 \times D \times \gamma \times H$$

Pu - Ultimate resistance (force/unit length) in kN/m
γ - Effective soil weight in KN/m^3
H - Depth in m
Φ - Angle of internal friction of sand
D - Average pile diameter from surface to depth in m

The following expression shows the soil resistance [6];

$$P = A \times Pu \times \tan h\,[\{ (k \times H) / (A \times Pu)\} \times y]$$

pu - Ultimate bearing capacity at depth *H* in kN/m
k - Initial modulus of subgrade reaction in kN/m^3
y - Lateral deflection in m
H - Soil depth in m

From the above equations lateral stiffness of soil is calculated at each depth. P-y curve varies depends on depth of soil from sea bed as shown in Fig. 2.

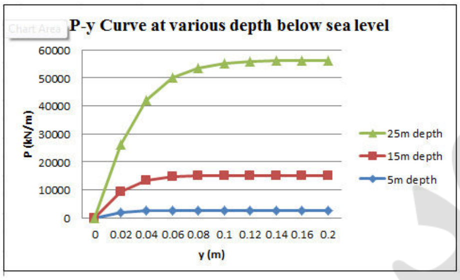

Fig. 2. P-y curve at 5m, 15m 25m depth below sea bed.

5. Displacement and Lateral Soil Reaction

Lateral wind loads on the tower and overturning moment due to lateral load is resisted by lateral soil reaction and resisting moment in soil. Due to the lateral loads pile has a tendency to tilt about a pivot point. Monopile with diameter 4 m – 6 m has a rigid behaviour, hence it has a negative deflection at pile toe [8] as shown in Fig. 3.

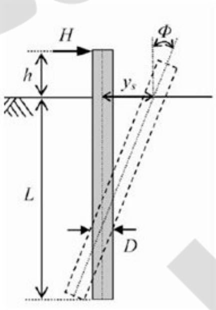

Fig. 3. Tilt of rigid monopile at pivot point.

Maximum permissible tilt of monopile in sandy soil is 0.5^0 [3]. As per calculation for a 30m embedded length pivot point lies at 22m depth from mud-line [9] as shown in Fig. 4. From 0.5^0 tilt angle displacement at each point along pile length is calculated. And from P-y curves corresponding to the displacement value at each point, lateral soil reaction is calculated.

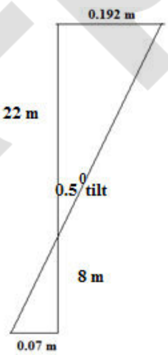

Fig. 4. Maximum displacement at 0.5^0 tilts at pile top and bottom.

6. Finite Element Modeling in Ansys

A 3D finite element model of monopile, tower and surrounding soil at a radius of 20 m around the pile shaft and 30 m below the pile is modeled in Ansys. Material property of tower and monopile are structural steel. Soil is modeled as an explicit material with strength material properties like modulus of elasticity, Poison ratio of 0.25 and density of 18 kN/m^3. Friction between pile and soil provide by contact-target pairs in Ansys. Soil is modeled as a homogeneous layer. Modulus of elasticity of soil is the slope of P-y curve at 15 m depth. Fixed boundary condition provided at bottom of soil and lateral restraints provided at the lateral sides of soil. Wind loads, wave load provided along turbine tower as concentrated load is shown in Fig. 5.

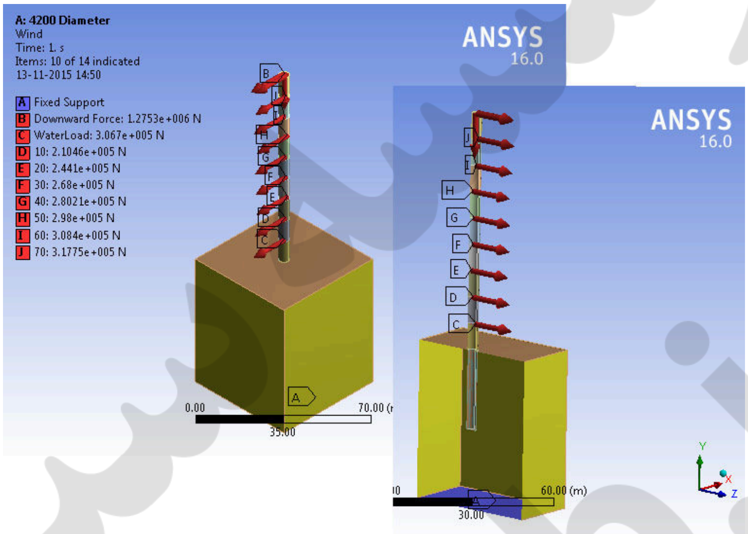

Fig. 5. Model of monopile, tower and soil in Ansys.

7. Lateral Pile Displacement at different Pile Diameter and Depth

An explicit dynamic analysis with static loading is performed since soil is an explicit material. Embedded length of pile is ranges from 7D to 8D, where D is the diameter of monopile. It is decided to maintain L/D ratio as 7.14, hence the diameter and corresponding embedded length is shown in Table 1.

Table 1. Diameter of Pile and Corresponding Embedded Length.

Sl.No.	Diameter of pile (m)	Length of pile(m)	L/D ratio
1	4.2	30	
2	4.5	32	7.14
3	5	35.7	
4	5.3	37.84	

8. Result and discussion

After the dynamic analysis result obtained in Ansys are shown from Fig. 6 to Fig. 9.

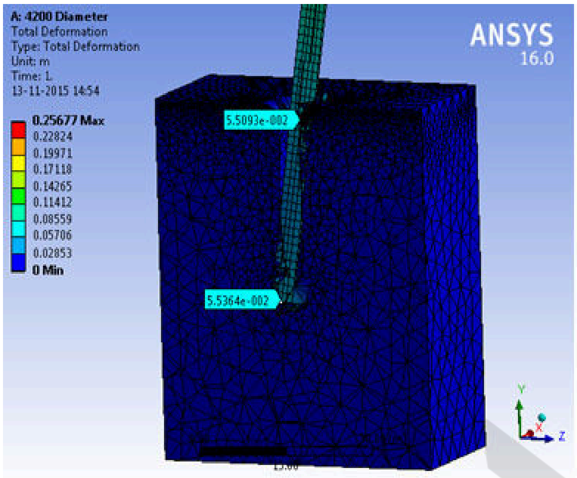

Fig. 6. Displacement at sea bed level of pile and pile toe of 4.2 m diameter pile.

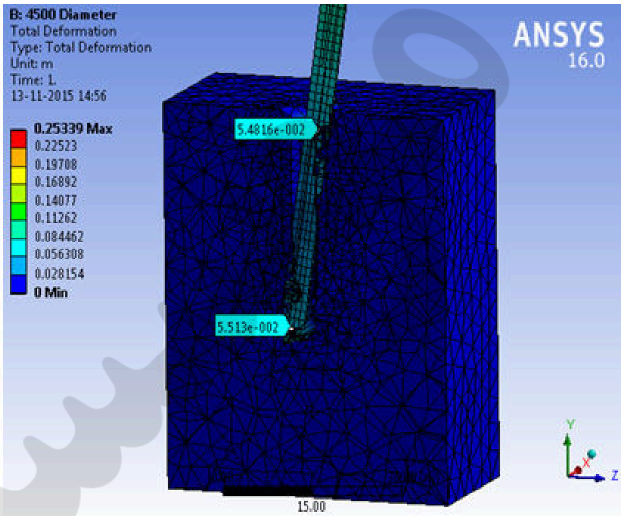

Fig. 7. Displacement at sea bed level of pile and pile toe of 4.5 m diameter pile.

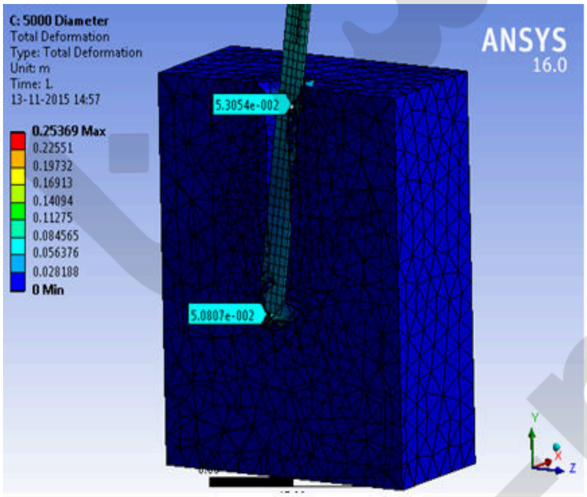

Fig. 8. Displacement at sea bed level of pile and pile toe of 5 m diameter pile.

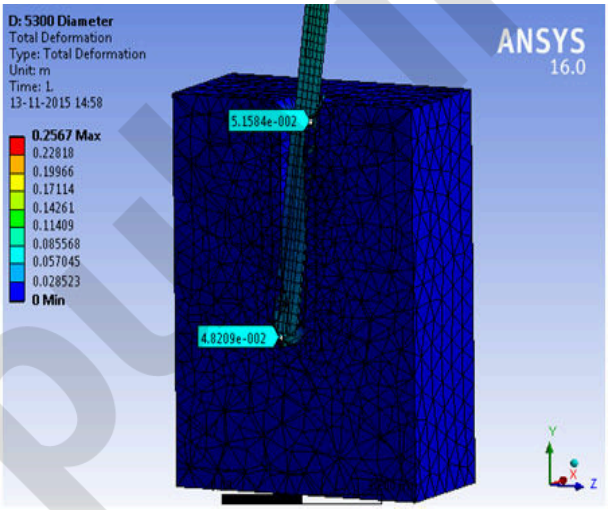

Fig. 9. Displacement at sea bed level of pile and pile toe of 5.3 m diameter pile.

After performing the parametric study by changing diameter and embedded length keeping L/D ratio as 7.14 following results were obtained in Table 2.

Table 2. Tilt angle and deformation obtained for corresponding L/D ratio.

Sl.No.	Diameter / embedded length	Deformation at mud-line (m)	Deformation at Pile toe (m)	Tilt Angle
1	4.2/30	0.0551	0.0553	0.21
2	4.5/32	0.0548	0.05513	0.209
3	5/35.7	0.0531	0.0508	0.198
4	5.3/37.84	0.0516	0.0482	0.19

There is positive deformation at mud line and negative deformation at pile toe. Tilt angle obtained is less than 0.5^0 tilt is in a safe limit.

9. Conclusion

From the above result and discussion it is conclude that;

- As when the diameter and embedded length increases, deformation at mud-line and pile toe decreases.
- Pile tilt angle obtained is decreases with increase in diameter and embedded length and the obtained tilt angle is less than 0.5 degree tilt which is in safe limit.
- Pile rotates about a pivot due to the lateral load and corresponding overturning moment act on tower and there by a positive displacement at mud-line and negative displacement at pile toe.

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