A Study on Lateral Deformation of Monopile Foundation of Offshore Wind Turbine

Neenu Maria Jose
PG Student
Department of Structural Engineering and Construction Management & Civil Engineering
Mar Athanasius College of Engineering

Dr. Alice Mathai
Associate Professor
Department of Civil Engineering
Mar Athanasius College of Engineering

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 structure interaction effect.
Keywords: Deformation, Explicit dynamics, Monopile, Offshore wind turbine, Soil pile interaction

I. INTRODUCTION

Wind turbines are power tools to tap nonconventional wind energy. Onshore wind turbine needs plenty of land area for power generation. Thus it is 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.

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. Selection of support structure depends on water depth.

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].

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

II. WIND TURBINE AND SOIL CHARACTERISTICS

About 75% of offshore wind turbine is founded on monopiles foundation. A location at Rameswaram, Tamil Nadu 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 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 material of turbine tower and monopile is steel and the strength properties are modulus of elasticity, Poisons ratio and 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 is 4.2 m and corresponding embedded length is 30 m [2].

III. LOADS ON TURBINE TOWER

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

A. Wave Load

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

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

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

B. Wind Load

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];

$$F_t = \frac{1}{2} \cdot \rho \cdot \mu^2 \cdot C_s \cdot A \quad (2)$$

F_t = Wind force in kN
ρ = Air density in kg/m^3
μ = Wind speed in m/s
C_s = Shape coefficient or force coefficient depend on shape of structure
A = Projected area in m^2

IV. 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. 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. 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 [6].

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 [6]. The lateral stiffness of soil at 15 m depth is calculated. P-y curve varies depends on depth of soil from sea bed as shown in Fig. 1.

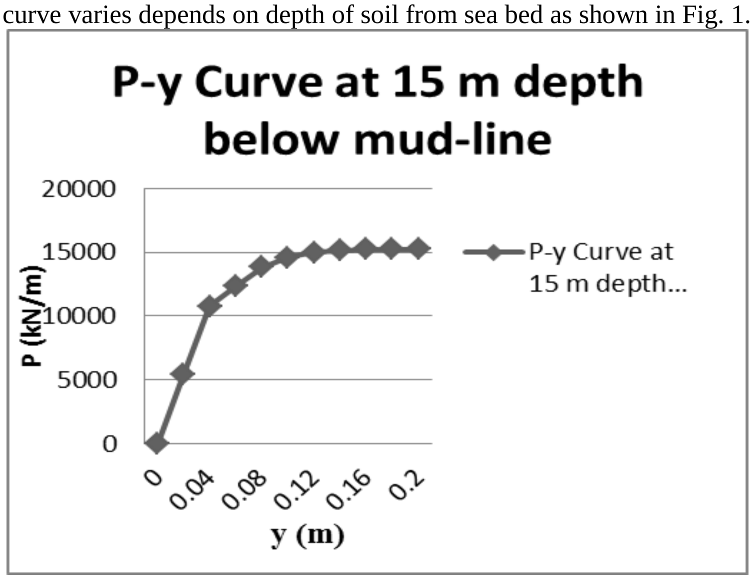

Fig. 1: P-y curve at 15m depth below sea bed

V. 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 modelled in Ansys. Material property of tower and monopile are structural steel. Soil is modelled as an explicit material with strength material properties like modulus of elasticity, Poison ratio of 0.25 and density of 18kN/m3. Friction between pile and soil is provided by contact-target pairs in Ansys. Soil is modelled 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 and wave load are provided along turbine tower as concentrated load is shown in Fig. 2.

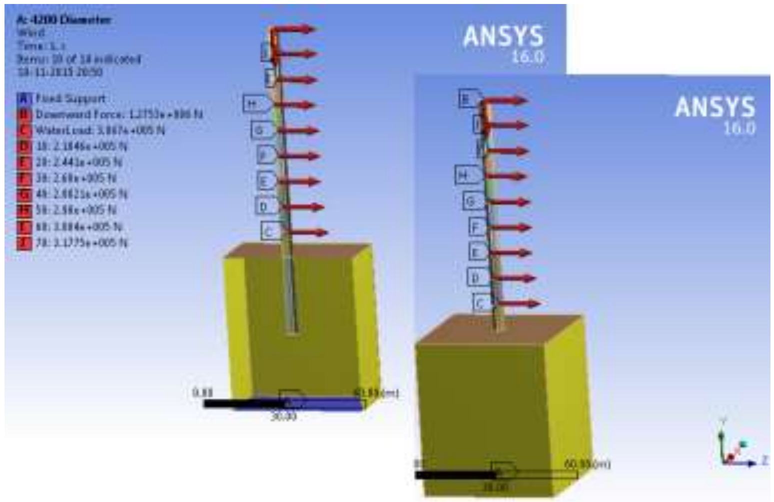

Fig. 2: Model of monopile, tower and soil in Ansys.

VI. LATERAL PILE DEFORMATION

An explicit dynamic analysis with static loading is performed since soil is an explicit material. All the dynamic loads like wind load, wave loads are applied as static load in the model.

A. *Result and Discussion*

Pile has a positive deformation at mud-line and negative deformation at pile toe. Due to the lateral loads pile has a tendency to tilt about a pivot point. Maximum permissible tilt of monopile in sandy soil is 0.5^0 [3]. As per calculation for a 30 m embedded length pivot point lies at 22 m depth from mud-line [8] as shown in Fig. 3. All the wind loads and wave load are acting in z direction. Hence lateral deformation of pile is in z direction as shown in Fig. 4.

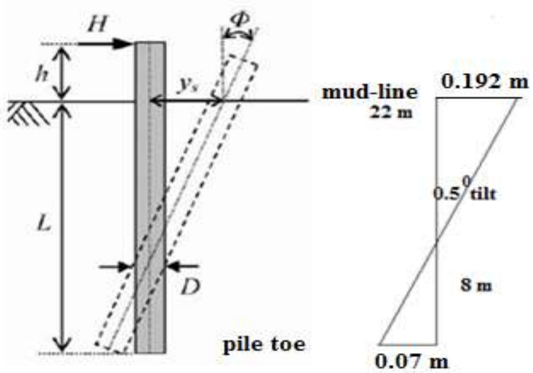

Fig. 3: Tilt of rigid monopile at pivot point and Maximum displacements at 0.5^0 tilts.

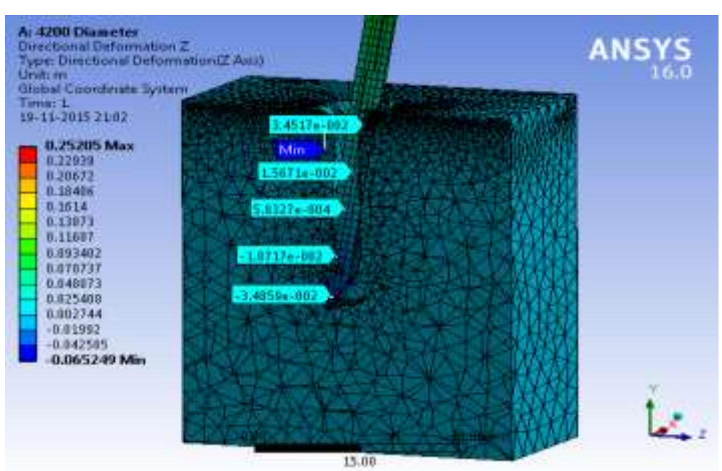

Fig. 4: Displacement at mud-line and pile toe of 4.2 m diameter pile.

As when depth increases from sea bed along pile, deformation of pile decreases as tabulated in Table - 1. Pile has a zero displacement at pivot point. A positive deformation takes place at the top of pivot point and a negative deformation at the bottom of the pivot point.

Table - 1
Soil depth along pile embedded depth and corresponding lateral deformation.

Soil depth from sea bed	*Pile lateral deformation*
0	3.45×10^{-2}
7	1.56×10^{-2}
15	5.83×10^{-4}
23	-1.87×10^{-2}
30	-3.48×10^{-2}

The tilt angle obtained is 0.13 degree is less than 0.5 degree which is in safe limit.

VII. CONCLUSION

An explicit dynamic analysis with static load is performed by numerical modelling. From the analysis result, the obtained displacement at mud-line is positive and the pile toe is negative, because laterally loaded pile tilt at the pivot point. Obtained tilt angle is less than permissible tilt angle which is in safe limit. So when the depth of the soil along the pile increases from the sea bed, deformation of the pile decreases.

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