Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Behavior of Monopile Founded Offshore Wind Turbine under Static Load – A Parametric Study

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Abstract: A parametric study has been covered for the performance of monopile founded offshore wind turbine (OWT) in clay. The change in deflection of monopile head is considered for this study to verify the behavior of monopile founded OWT. Diameter of the pile, the load applied on the wind turbine and the height of the tower are varying to verify the response of the monopile. The change in displacement due to different soil properties also considered in this study. A numerical model is considered in this study where the monopile is modeled based on American Petroleum Institute (API) based static p-y and t-z curves. The base of the monopile is considered to be fixed for this study to fulfil the 'zero-toe-kick' criteria.

Keywords: Monopile; Offshore Wind Turbine; Clay; Soil Stiffness; Loading Condition.

1 Introduction

As the time progresses the amount of non-renewable energy sources are decreasing day by day and this type of energy is unhealthy for the environment. The process of producing non-renewable energy, high amount of greenhouse gases are emitted and these greenhouse gases are very harmful for the environment (Li et al. 2012). As time progresses the value and importance of renewable energy is increasing day-by-day that is good for the environment. A major part of the renewable energy is wind energy and the rate of growth of wind energy is increasing gradually. Over the last 10 years, offshore wind farms have grown rapidly, becoming a new field of development in the wind power industry (Kwon et al. 2012). Foundation types currently in use include monopile, gravity, tripod, jacket, and floating foundations. Of all the foundation types, the monopile foundation accounts for more than 65% of those currently used. The monopile foundation is a simple construction (API 2005). The foundation consists of a steel pile with a diameter of between 3.5 m and 4.5 m. The pile is driven up to 10 m to 20 m into the seabed depending on the type of soil properties. The monopile foundation is effectively extending the turbine tower under water and into the seabed (Kuo et al. 2012).

Many studies have been performed on monopile foundation. Several methods have been proposed to estimate the deformation of pile under cyclic lateral load. Achmus et al. (2009) came to the conclusion that degradation stiffness model is able to account for cyclic lateral loading of piles in the determination of pile deformations. They also presented how some important factors like pile length, diameter and loading state effects the deformation and gave the design chart, in which they considered a normalized ultimate lateral resistance of pile. According to their studies horizontally loaded offshore pile often needs the suitability of the 'zero-toe-kick' or vertical tangent criterion for its design when diameter of the monopile is large. Nowadays the needs of offshore wind turbine are increasing due to demand for renewable energy and lack of fossil fuel supplies. Although wind turbine creates geotechnical challenges especially in the design section. Doherty et al. (2011) consider some aspects related to the reliability of methods of designing monopile foundation and jacket structure foundations so that next generation pile design can be beneficiated. They concluded that the large diameter monopiles with low slenderness ratios are commonly used in intermediate water depths while jacket/tripod structures are used in deeper waters. They also discussed about the limitations of these designs both for monopile foundations subjected to lateral loading and for jacket piles subjected to axial forces. In last few year, large-diameter monopile foundation is usually used for wind turbines to increase its bearing capacity though there is no any mature method existed that can define how the diameter affects the bearing characteristics of large-diameter steel-pipe pile. Liu et al. (2015) investigated the differences between the stress and deformation characteristics of the pile body and the soil around it between large-diameter and small-diameter steel-pipe piles subjected to vertical loads and horizontal loads in sands, on the basis of numerical simulation. For large-diameter steel-pipe piles, a calculation method for the vertical bearing capacity considering both the soil-arching effect and a calculation method for the lateral displacement based on shell theory are proposed by them. The vertical ultimate bearing capacity calculated by the method considering the soil-arching effect is significantly higher than that predicted by the API (2005) code method, and the lateral displacement at the pile top using the method based on the shell theory is 5–45% greater than that predicted by the p–y curve method in the API code. Lada et al. (2014) describes the behavior of monopile in sand subjected to a lateral loading condition and investigate the effects of pile diameter, length and load eccentricity on the results. This article is mainly focused on the analysis of large-diameter monopile based on numerical model results. Meanwhile cyclic loading is also taken under consideration and they came to this conclusion that the cyclic loading leads to an accumulated rotation, thus by using the SLS (serviceability limit state) design the maximum permanent rotation must not exceed the limit value for a given wind turbine.

A parametric study has been carried out in this study considering the parameters such as diameter of the pile, soil stiffness, load amplitude and tower height. The API (2005) based static *p-y*, *t-z* curve considered to model the monopile. The tower is not considered in this study. However the tower and rotor-nacelle assemble (RNA) mass applied as a point mass on the top of the monopile has been considered in this study. The objective of the study is to verify the deflection of the monopile head for the variation of the several parameters such as diameter of the pile, load amplitude and tower height under static horizontal load. The effect of soil stiffness on the behavior of offshore wind turbine under static load has also been considered in the present study. The loading condition on offshore wind turbine is dynamic in nature due to wind and wave frequency in the field. However, the response due to dynamic load is insignificant as compared to static load when the fundamental frequency is away from resonance condition (Bisoi and Haldar 2014). Therefore, the present study considered the static load without considering any resonance condition.

2 Method Of Analysis

API (2005) based static *p-y* curve and *t-z* curve have been considered in the present study to verify the behavior of the monopile founded OWT. The vertical load in terms of tower mass and RNA mass has been considered as point mass and applied at the top of the pile (Fig. 1). Lateral laod is considered from wind load and applied as static load. The moment is applied at 5 m above the top of monopile due to tower.

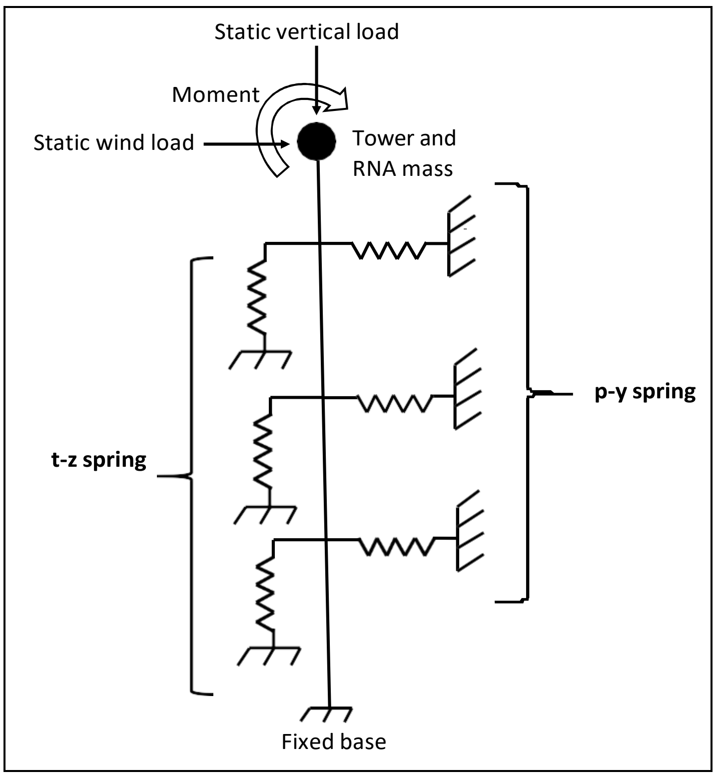

Fig 1: A monopile supported offshore wind turbine in clay.

1.1 *p-y* Curve

p-y curve is generated from the following equations and the Table 1 (API 2005),

$$p_u = 3c + \gamma X + JcX/ D \quad \text{for } X < X_R \tag{1}$$

$$p_u = 9c \quad \text{for } X \geq X_R \tag{2}$$

where,

p_u = ultimate resistance (kPa),
c = undrained shear strength for undisturbed clay soil samples (kPa),
D = pile diameter (mm),
γ = effective unit weight of soil (MN/m^3),
J = dimensionless empirical constant = 0.375
X = depth below soil surface (mm),
X_R = depth below the soil surface to the bottom of reduced resistance zone (mm)
$X_R = 6D/ (\gamma D/c + J)$
p = actual lateral resistance (kPa),
y = actual lateral deflection (mm),
$y_c = 2.5\, \varepsilon_c D$ (mm),
ε_c = strain = 0.01

For the case where equilibrium has been reached under cyclic loading, the static *p-y* curves may be generated from the following table:

Table 1. Lateral resistance vs deflection at different depths (API 2005)

$X > X_R$		$X < X_R$	
P/pu	***y/yc***	***p/pu***	***y/yc***
0.00	0.0	0.00	0.0
0.50	1.0	0.50	1.0
0.72	3.0	0.72	3.0
0.72	6.0	0.72 *X/XR*	15.0
		0.72 *X/XR*	30.0

The p-y curves (Fig. 2) are typically represented at different depth of soil which has been considered for the present study using the Eq. 1, Eq. 2 and Table 1. However, the node of the element and spring interval are considered at 1 m interval (Bisoi and Haldar 2014). It is observed that as the depth increases, lateral resistance (p value) also increases up to X_R and beyond X_R it becomes constant.

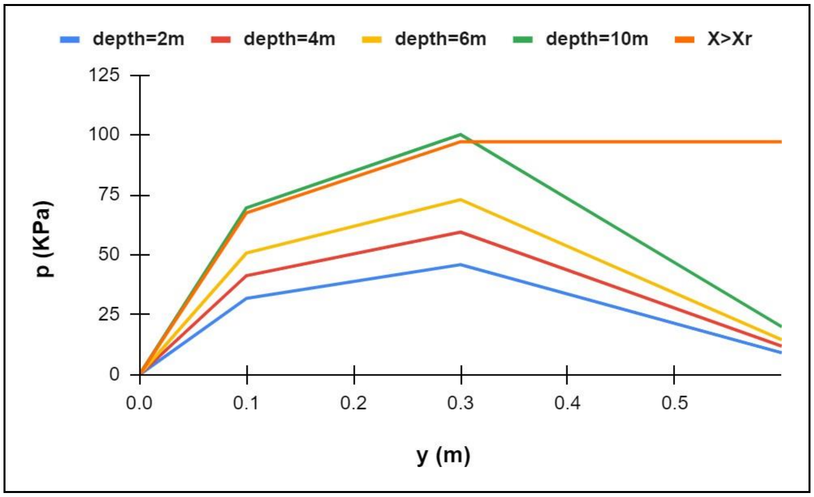

Fig 2: A typical representation of *p*-*y* curve for the variation of depth.

1.2 *t-z* Curve

t-*z* curve is generated as follows

$$t_{max} = \alpha\, c \tag{3}$$

where,

α = a dimensionless factor ($\alpha \leq 1.0$)
c = undrained shear strength of the soil (kPa).

The factor, α, can be computed by the equations:

$$\alpha = 0.5\ \psi^{-0.5}\ \psi \leq 1.0 \tag{4}$$

$$\alpha = 0.5\ \psi^{-0.25}\ \psi > 1.0 \tag{5}$$

where,

$\psi = c/p'_o$,
p'_o = effective overburden pressure (kPa)

Table 2. Frictional resistance vs deflection at different depth (API 2005)

z/D	***t/t***
0.0016	0.30
0.0031	0.50
0.0057	0.75

0.0080	0.90
0.0100	1.00
0.0200	0.80
0.0300	0.80

where

z = local pile deflection (mm),
D = pile diameter (mm),
t = mobilized soil pile adhesion (kPa),
t_{max} = maximum soil pile adhesion or unit skin friction capacity (kPa)

The *p-y* curves (Fig. 3) are typically represented at different depth of soil which has been considered for the present study using the Eq. 3, Eq. 4, Eq. 5 and Table 2. It is observed that as the depth increases, the skin friction is also increases up to the tip of the pile.

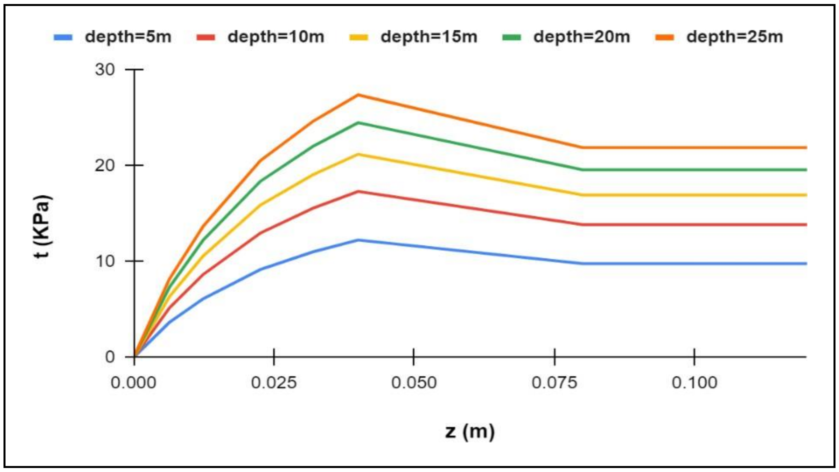

Fig 3: A typical representation of *t-z* curves at different depth.

3 Parameters

A range of parameters has been considered for this parametric study

Table 3. Range of parameters (Lada et al. 2014, Bisoi and Haldar 2014)

Name	Properties	Value
Tower	Tower height	60m, 65m, 70m

Tower	Density of tower material	7850 kg/m^3
	Diameter of tower	4m
	Thickness of the tower	0.04m
	RNA mass	80 ton
Monopile	Diameter of monopile	4m, 5m, 6m
	Length of monopile	20m
Soil	Undrained shear strength of soil	25 KPa, 50KPa, 100KPa
	Unit weight of soil	8 KN/m^3
Static lateral load	Static wind load	15MN, 16MN, 19.3MN

4 Result And Discussion

The tower and RNA mass are applied to the pile head as point mass. A static horizontal load has been applied to the pile head. After applying the load, a typical graph has been generated between the points along the length of the monopile and displacement of monopile (Fig. 4). It is observed that the deflection of the pile head increases due to the static load.

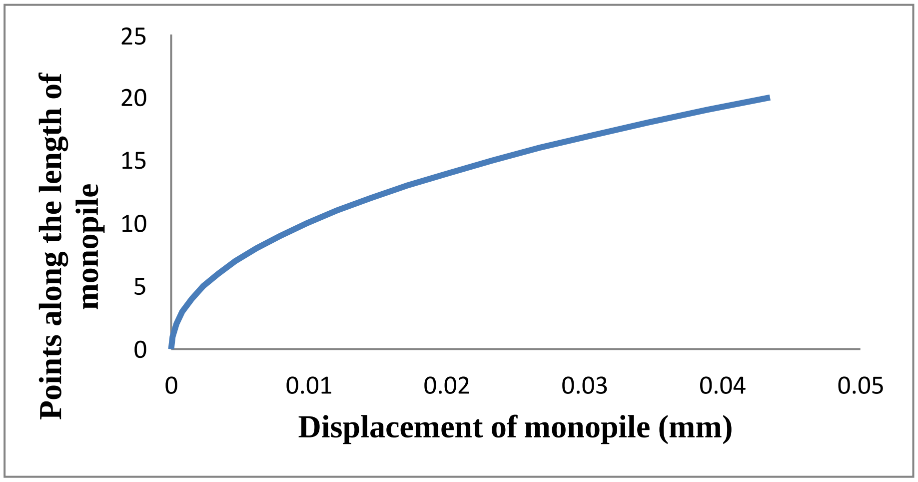

Fig. 4: The response of the monopile head applying a static load.

a. The change in deflection due to the variation of static horizontal load

The wind load which is externally acting on the wind turbine has been applied while keeping the other parameters constant. The load is applied as point load at the top of the pile. The load considered for this study are 15 MN, 16 MN and 19.3 MN. The moment is applied on the pile head due to the tower height of OWT. Table 4 shows the change in deflection of the pile head due to the increased loading conditions. It is observed that the deflection of the monopile at ground level, has been increased to 6.6% when the wind load acting on the wind turbine is increased from 15MN to 16MN. The deflection of the monopile at ground level, has been increased to 20.4% when the wind load acting on the wind turbine is increased from 16MN to 19.3MN.

Table 4. Deflection of monopile head due to change in static wind load

Wind load (MN)	Deflection (mm)	Deflection increased (%)
15	0.043446117	-
16	0.046320078	6.6%
19.3	0.055784668	20.4%

b. The change in deflection due to the variation of soil stiffness

The variation in deflection of monopile head due to the change in soil stiffness keeping the other parameters constant which is presented in the Table 5. The stiffness considered for this study are 25 kPa, 50 kPa and 100 kPa. It is observed that the deflection of the monopile at ground level, has been reduced to 0.4% when the soil stiffness is increased from 25kPa to 50kPa. The deflection of the monopile at ground level, has been reduced to 1.2% when the soil stiffness is increased from 50kPa to 100kPa.

Table 5. Deflection of monopile head due to change in soil stiffness

Soil stiffness (kPa)	Deflection (mm)	Deflection reduced (%)
25	0.043446117	-
50	0.043256133	0.4%
100	0.042738263	1.2%

c. The change in deflection due to the variation of monopile diameter

The diameter of the monopile considered for this study are 4 m, 5 m and 6 m to verify the deflection of the pile head (Table 6). The results show that the deflection of the monopile at ground level, has been reduced to 58.8% when the diameter of the monopile is increased from 4m to 5m. The deflection of the monopile at ground level, has been reduced to 51.7% when the diameter of the monopile is increased from 5m to 6m.

Table 6. Deflection of pile head due to change in the diameters of monopile

Diameter of monopile (m)	Deflection (mm)	Deflection reduced (%)
4	0.043446117	-
5	0.017899612	58.8%
6	0.0086436	51.7%

d. The change in deflection due to the variation of tower height

The tower height is considered for this study are 60 m, 65 m and 70 m to verify the deflection of the pile head (Table 7). It is observed that the deflection of the monopile at ground level, has been increased to 13.5% when the tower height is increased from 60m to 65m. The deflection of the monopile at ground level, has been increased to 11.9% when the tower height is increased from 65m to 70m.

Table 7. Deflection of monopile head due to change in tower height

Tower height (m)	Deflection (mm)	Deflection increased (%)
60	0.043446117	-
65	0.049318506	13.5%
70	0.055178652	11.9%

5 Conclusion

A parametric study is carried out for different parameters to investigate the effect of response due to horizontal static load. API (2005) based static *p-y* and *t-z* curves are considered to model the monopile. The horizontal load applied to the pile top and moment is applied at the pile head due to the tower interaction. The mass of tower and RNA is considered as point mass at the pile head. Based on the results, the following conclusions can be drawn:

a. The response of the monopile decreases significantly due to increasing soil stiffness which is important to design the monopile in order to select the monopilediameter.
b. Wind load largely affects the system responses. The monopile response increaseswith an increase in wind load.
c. An increase in tower height marginally affects the monopile response. The lateraldeflection increases with an increase in tower height.
d. The response of the monopile decreases significantly due to increasing the monopile diameter.

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