Response of Laterally Loaded Monopile Using Three Dimensional Finite Element Analysis

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Abstract. The increase in need for energy in the developing world boosted the search for efficient energy sources. Most of the current energy sources in the past decades were not sustainable. The growing concern on the existence of earth leads to find an alternative sustainable energy source. The right proportion of energy need in many developed countries is obtained using offshore wind energy. Offshore wind turbine (OWT) produces renewable and efficient energy in this era, which is supported on large diameter monopiles. These monopiles are subjected to very high lateral and moment loads. This paper deals with the response of a bottom fixed monopile under lateral loads taking into account varying soil strata and pile diameter. The analysis was performed using a three-dimensional finite element approach for the pile embedded in three types of soils, that is, clay, sand, and layered soil. By varying the diameter of the monopile, it is observed that large diameter monopile in any soil tends to behave like a rigid system having a minor deflection. However, the soil profile influences the behavior of monopile considerably with considerable length to diameter ratios.

Keywords: Finite Elements; Lateral Load; Monopile; Offshore; Soil Types

1 Introduction

Wind energy, a renewable source of energy, is expected to satisfy the right proportion of electricity demand in the coming generation. In comparison with onshore wind, offshore wind is more steady and robust (Bilgili et al., 2011). In shallow waters, offshore wind turbines are supported on monopiles, which are connected through transition piece (Abhinav and Saha, 2017). Monopiles are tubular piles with large diameter which carry lateral loads and moment loads from ocean waves and wind energy. It also gives the weight of the tower and turbine in the form of axial loads. (Dhertyand Gavin, 2011).

Generally, monopiles have a diameter of 4m to 6mhaving a slenderness ratio of less than 10. However, monopiles with diameter 7.5m are also used for more giant wind turbines (Achmus et al. 2009, LeBlanc et al. 2010, Tomlinson, 2001). The lateral load acting on the monopiles are transferred to the soil by way of bending action (Schaumann and Boker, 2005). An overturning moment is applied to the monopile foundation by the effect on wind force. In calculating the overturning moment acting on the monopile, the wind load has a higher lever arm, which results in more significant loading condition. For instance, in the northern sea environment, about 75% of the overturning moment is caused by a horizontal force developed by wind force (Byrne and Houlsby 2003). Torsional moments acting on monopiles are negligible, and the lateral loads cause high bending moment and control the design of monopile. The wind and wave loading causes horizontal forces and bending moments, which are transferred to the earth by cantilever action (Malhotra, 2011).

The design parameters of a monopile depend on the amount of energy to be produced from that windmill. However, it also depends on the environmental conditions and soil profile. As a design criterion, the limiting value for maximum horizontal deflection of a monopile under field condition is 120mm (Arshad and O'Kelly, 2016, Zachariah et al., 2019). The p-y design methodology is currently used for the design of monopiles using American Petroleum Institute (API 2000) and DNV 2011 codes. The method deals with the non-linear relationship between soil reaction (p) and the lateral deflection (y) of the monopile. The monopile is considered as a Winkler beam resting on soil represented as uncoupled non-linear elastic springs (Brodbaek et al., 2009*)*.

The presence of different types of soil in the sea basins has been reported in various locations around the globe. This makes the importance of the study on the behavior of monopile in different soil conditions. The effect of change in length and diameter were also considered in the present study. Keeping the length to diameter ratio constant, the diameter and length of the monopile is changed to obtain the response of monopile on extreme static loading conditions.

In this paper, the response of a bottom fixed monopile supporting an offshore wind turbine subjected to extreme static loading conditions has been studied. The loads on the monopile are in the form of horizontal force by the action of ocean waves and currents and moment by the action of massive wind force on the tower. The response was obtained in the form of lateral deflection of the monopile from the initial position and bending moment, along with the depth of the monopile. A comparison has been made by changing the soil profile (soft clay, medium dense sand, layered soil) and properties. Also, the lateral response has been studied by varying the penetration depth and diameter of the monopile keeping the slenderness ratio (length to diameter ratio) within a range of 4-6.

2 Finite Element Modelling

Three-dimensional finite element analysis (3D FEA) has been attempted to study the response of laterally loaded monopile in different soil conditions (clay, medium dense sand, and layered profile). Mohr-Coulomb failure criterion is employed to simulate the soil profiles. The analysis was carried out using the finite element tool Abaqus CAE.

2.1 Monopile modeling

Monopiles are open-ended tubular piles with large diameter subjected to the combined action of lateral and moment loads. The presence of heavy wind load and wave load contributes to the bending of monopile as a flexible pile. However, in some cases, monopiles are considered as rigid, which results in rotation and translation action.

A monopile of 4.5 m diameter and an overall length of 22 m is chosen for the numerical study. The monopile is composed of a steel (linearly elastic material) with Young's Modulus (E) of 210 GPA and Poisson's ratio (υ) 0.3. The density of steel is taken as 7850 kg/m^3. The tubular pile is replaced with a solid cylinder with the same diameter in such a way that the bending stiffness of the two monopiles is kept unchanged. The bottom of the monopile is kept fixed and restricted to any deflection.

The effect of change in diameter and length of the monopile was also considered in the numerical study. The response was obtained by changing the length and diameter of the monopile, keeping the length to diameter (*l/d*) ratio constant. The length and diameter of the monopile corresponding to *l/d* ratio is shown in Table 1. The monopile was constructed using eight noded linear brick element with reduced integration and hourglass control and six noded linear triangular wedge prism towards the center. A global mesh size of 0.5 was adopted for modeling.

Table 1. Size of monopiles for different conditions

l/d ratio	*d*(when *l* is unchanged)
4	5.5 m
5	4.4 m
6	3.6 m

2.2 Soil Modelling

Three different soil conditions were taken for the study. The overall diameter of the model was considered to be 20D, where D is the diameter of the monopile. The bottom of the soil mass is restricted to translate in all directions. A mesh sensitivity analysis has been carried out to fix the mesh density.

During the load application, clay exhibits an undrained behavior due to its low permeability. Clayey soil with an undrained shear strength (C_u) of 75 kPa and plasticity index (P.I.) of 40 %, which represents the actual clay obtained from sea bed is considered for the study. The soil is defined by Young’s Modulus (E_c), Poisson’s Ratio (υ_c) and undrained shear strength. The homogeneous and isotropic clay is assumed to be normally consolidated with an unchanged C_u and E_c throughout its depth. The value of E_c is calculated using the relation,

$$E_c = K_c . C_u \tag{1}$$

Where K_c is the correlation factor depending on the Plasticity Index and Over Consolidation Ratio of the clay. Fig. 1 shows the value of K_c of clay with C_u 75 kPa and OCR 1.

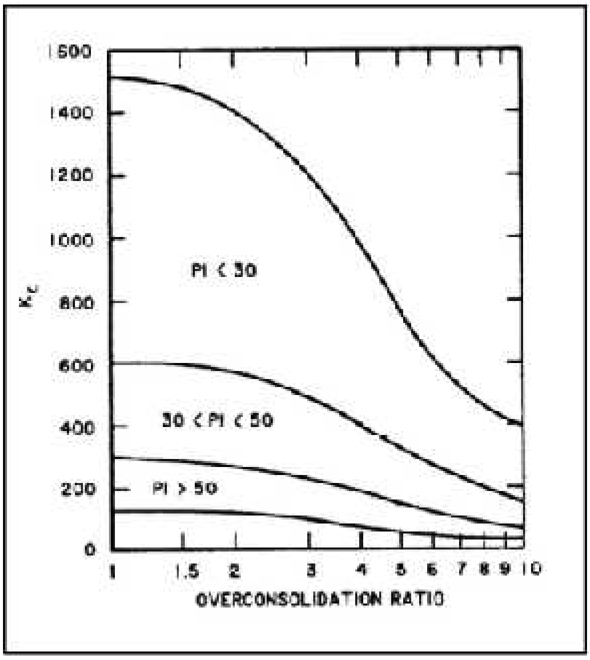

Fig. 1. Kc for Clays (USAC, 1998)

The second soil profile is a dense sand medium with an effective unit weight (γ′) of 11 kN/m^3.

A layered soil profile with different properties at different levels is also considered for the study. This layered stratum represents the existing geotechnical conditions of the offshore soil bed. The profile chosen for the study was taken for Windmill Park at Horns Rev, Denmark (Kellezi and Hansen, 2003). The geotechnical properties of soil profiles at different levels are presented in Table 2.

3 Soil- Monopile interaction

. Soil-Monopile interaction defines the modeling of contact behavior of soil and monopile. The interaction surface is defined by the general surface between the contact surfaces. The contact is constrained in normal and tangential directions with reference to Haiderali (2012). The maximum friction angle (δpeak) between the monopile and clay is observed when the monopile is subjected to its maximum capacity. Fig. 2 gives the value of friction coefficient µ between monopile and clay (Haiderali et al., 2013). For sandy strata, the soil monopile interaction is modeled by considering the friction angle (δ) as two-third of the frictional angle φ. The contact stress is deemed to be zero when a gap is produced between soil and monopile in the normal direction.

Table 2. Different properties of the soil profile

Soil Layer	Name	Depth (m)	Young's modulus, E (kN/m^2)	Effective unit weight, γ' (kN/m^3)	Angle of internal friction, Φ(deg.)	Dilitancy angle, Ψ(deg.)	Poisson's ratio, ν
Clayey Soil	Clay	41.8	33525	8	13.87	0.0	.495
Dense Soil	Sand	41.8	32000	11	35	5.0	.25
Layered Profile							
Layer 1	Sand	1.0	31800	10	42.0	12.0	0.3
Layer 2	Sand	3.5	57100	10	43.5	13.5	0.3
Layer 3	Sand	5.5	52534	10	42.5	12.5	0.3
Layer 4	Sand	6.5	44100	10	41.7	11.7	0.3
Layer 5	Sand	7.0	58200	10	43.2	13.2	0.3
Layer 6	Sand	8.5	72170	10	44.3	14.3	0.3
Layer 7	Sand	10.0	52950	10	43.1	13.1	0.3
Layer 8	Sand	11.5	35400	10	40.3	10.3	0.3
Layer 9	Sand	12.5	23530	10	37.2	7.2	0.3
Layer 10	Sand	13.5	13600	10	33.8	3.8	0.3
Layer 11	Org. Sand	20.0	3135	7	21.6	0.0	0.3
Layer 12	Org. Sand	21.04	12950	7	31.2	1.2	0.3
Layer 13	Sand	41.80	36800	10	37.8	7.8	0.3

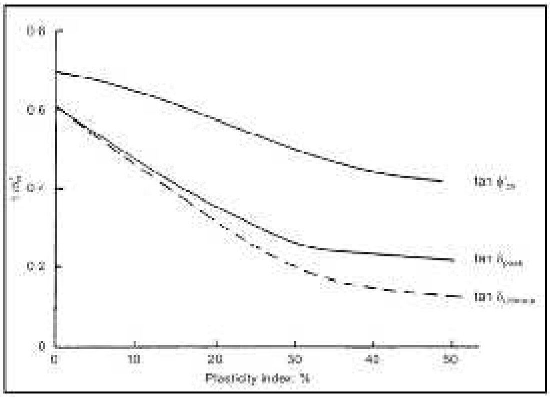

Fig. 2. Pile clay interaction factor (Lehane et al.2000)

4 Loading

An offshore wind turbine, in its lifetime, is subjected to various loading conditions like wind, wave, ice, seismic load, etc. The effect of wind, waves, and currents are the most predominant examples of these loads. These loads are transferred to the monopiles in the form of significant bending moments and lateral loads. A typical loading pattern on an OWT is shown in Fig. 3.

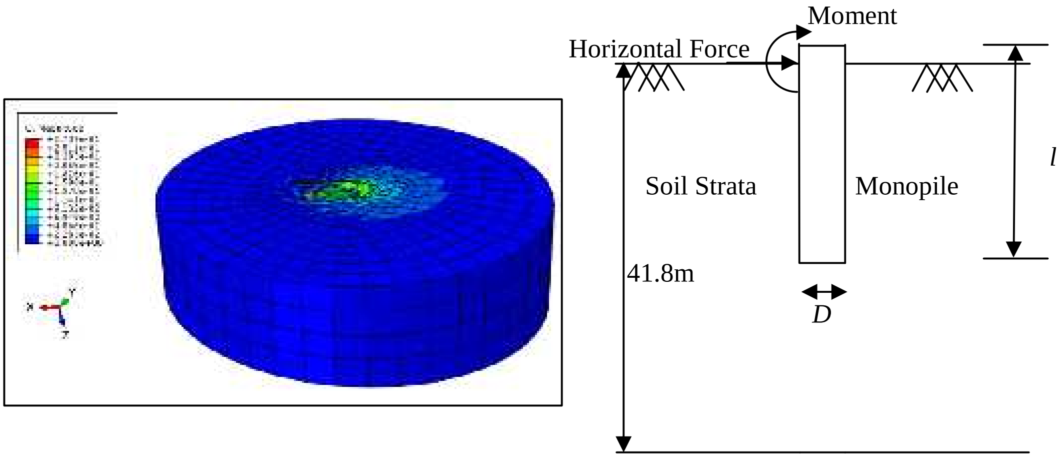

Fig. 3. Meshing and Schematic loading diagram of an OWT supporting monopile

In the present study, the monopiles have been analyzed by applying extreme static loading. The analysis was performed for a static horizontal force of 2503 kN and moment of 89483 kN m as reported by Kallezi and Hansen (2003) for the foundation of a windmill at Horns Rev, Denmark with depth of water varying from 9 – 17m. The windmill was located about 30km away from the shore with a wind speed of 10m/s. This load accounts for the effect of wind load acting on the blades and the ocean waves on the base of the tower.

5 Results and Discussions

The response of monopile subjected to extreme static loading conditions is discussed in this section. Firstly, the monopile is of diameter 4.5m and length 22m (21m embedded length) is analyzed in various soil conditions, i.e., clayey soil, medium dense soil, and a layered stratum. The response is plotted in terms of lateral deflection and a bending moment of the monopile along the length. Further, the effect of length to diameter ratio on the monopile is also studied. The various length to diameter ratio is achieved by two conditions, as discussed in the previous sections.

5.1 Effect of soil profile:

Fig. 4(a) shows the lateral deflection and bending moment of the monopile in various soil conditions. The deflection of the monopile is negligible at the bottom tip and shows a gradual increase to the pile head. The maximum lateral deflection is observed at the pile head. The deflection pattern of the monopile along the length reflects the bending nature of the pile. A similar trend is observed in the case of all three soil types. Moreover, the variation in the magnitude of lateral deflection for monopiles embedded in different soil conditions is negligible.

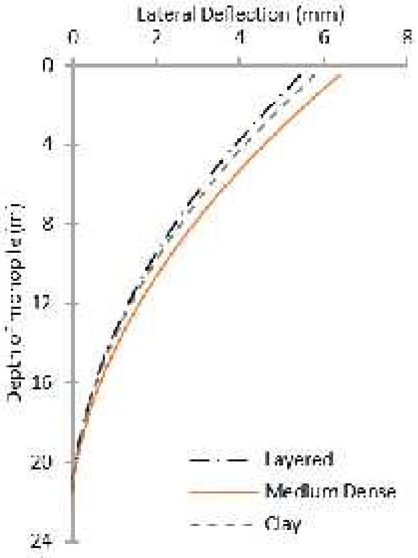

Fig. 4. (a) Lateral deflection of monopile along with depth embedded in different soil

The bending moment induced in the monopile is presented in Fig. 4(b). The maximum bending moment in all the cases is concentrated at the bottom end of the monopile. This is due to the restriction of monopile at the bottom of the pile for any movement. The magnitude of bending moment also follows a similar pattern to deflection. Even though the values of bending moment are very close, the quantity is less in case of layered strata and increased for clay and for medium dense sand. The magnitude of lateral deflection and maximum bending moment in the monopile is tabulated in Table 3.

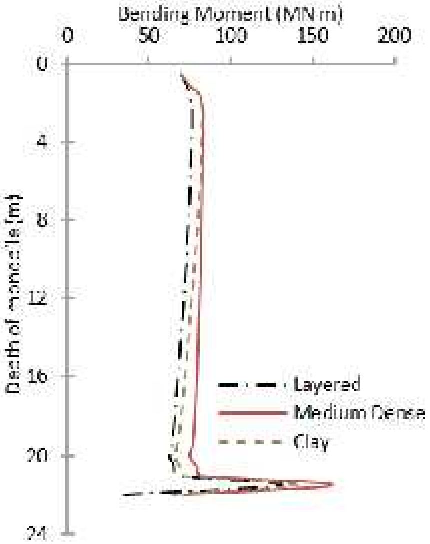

Fig. 4. (b) Bending moment of monopile along with depth embedded in different soil

Table 3. Maximum lateral deflection and bending moment of monopile in different soil profiles

Soil Type	Maximum lateral deflection (mm)	Maximum bending moment(k Nm)
Clay	5.80	140296.542
Medium Dense Sand	6.39	162220.597
Layered profile	5.44	131049.364

5.2 Effect of Pile diameter

The influence of pile diameter on the monopile is studied by changing the *l/D* of the monopile, keeping the constant length 22m. The results were analyzed for *l/D* ratios 4, 5, 6 in terms of lateral deflection and bending moment of the monopile along the length. The diameter of the monopile is reduced with an increase in *the l/D* ratio.

The results show a similar trend in deflection, as shown in Fig. 5 (a, b, c). The lateral deflection of the monopile is observed to be small, with an increase in diameter of the monopile. The lateral deflection is increased 2 to 4 times corresponding to *l/D*=5 and *l/D*=6 when compared to monopile with *l/D*=4. This implies that the monopiles with larger diameter has a tendency to behave like a rigid pile.

Unlike the pattern followed in the primary model, the monopile embedded in clay has a lesser deflection from its initial state. Since the deflection is not much critical in large diameter monopiles, they have a negligible difference in different soil profiles. With the decrease in diameter, the monopile tends to bend more and shows a considerable variation of the maximum lateral deflection. The monopiles with different diameters tend to deflect 10 to 30 percent when embedded in different soil strata. It may be noted that the layered soil is having low stiffness when compared to the other two soil profiles. The deflection pattern reflects a similar trend in the analysis.

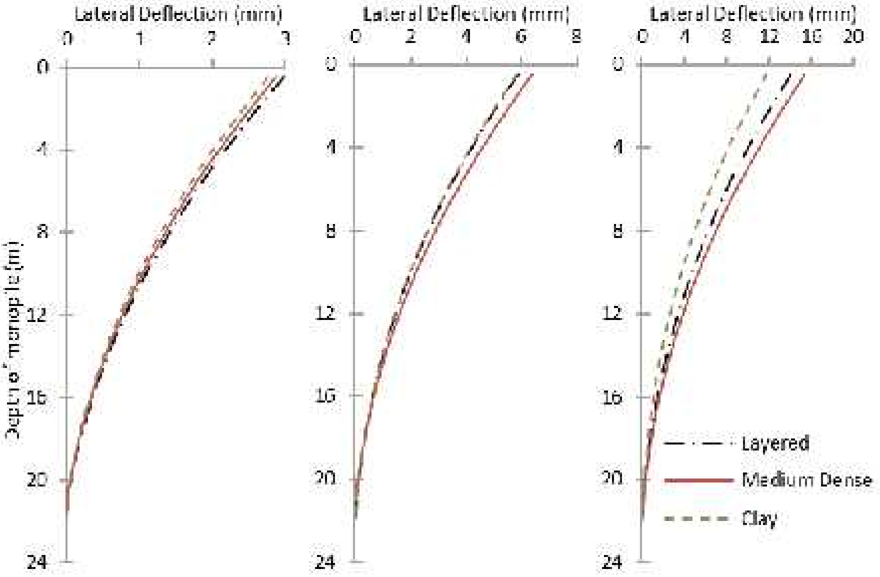

Fig. 5. (a) **Fig. 5(b)** **Fig. 5(c)**

Fig. 5. (a) Lateral deflection of monopile along with depth embedded in different soil for (a) R4, (b) R5, and (c) R6

The bending moment follows a similar trend as the primary model of monopile. The maximum bending moment is concentrated at the bottom of the pile. The results are shown in Fig. 6 (a, b, c). It is observed that the diameter of monopile is not heavily influencing the bending moment because the magnitude of bending moment in various diameter does not show a huge fluctuation. It is thus concluded that the bending stress is the driving factor for bending moment than the moment of inertia (I) and deflection of monopile (y) in the bending equation.

It is also seen that the monopile embedded in medium dense sand is subjected to a more bending moment. Like deflection, large-diameter monopiles have lesser fluctuation in bending moment for different types of soil. With the decreasing diameter, the bending moment shows a considerable variation in the results. About 20 Percent of increase in bending moment is observed for monopiles in medium dense than that for clay and layered soil for different diameter of monopiles.

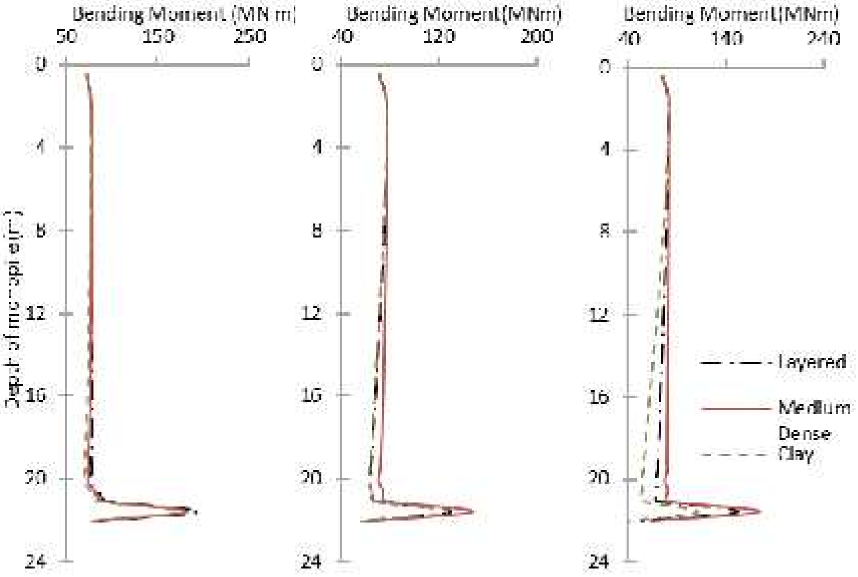

Fig. 6(a) **Fig. 6(b)** **Fig. 6(c)**

Fig. 6. B.M. of monopile along with depth embedded in different soil for (a) R4, (b) R5, and (c) R6

Table 4. Maximum lateral deflection and bending moment of monopile in different soil profiles (for a constant length of monopile)

Soil Type	Maximum lateral deflection (mm)			Maximum bending moment(k Nm)		
	R4	R5	R6	R4	R5	R6
Clay	2.76	5.81	11.73	174769.26	127884.17	111710.63
Medium Dense Sand	2.86	6.40	15.42	183656.72	147784.72	174339.61
Layered profile	2.97	5.86	14.08	193681.85	129707.50	151297.77

6 Conclusions

The response of a monopile under different loading condition has been studied in the present study using finite element based software ABAQUS. The responses were presented in the form of lateral deflection and bending moment of the monopile. The monopile is embedded in three different soil conditions, clay, medium dense sand, and layered profile.

The following conclusions were derived on the basis of the present analysis.

(i) The monopile tends to bend when it is subjected to a combination of lateral and moment load. Also, a maximum lateral deflection is observed at the pile head.

(ii) When a monopile is restrained at the bottom edge, the maximum bending moment is found near the pile bottom.
(iii) The monopile does not show a tendency of bending for higher diameters and deflects a considerable amount with a reduction in diameter.
(iv)The difference in the behavior of monopiles for large and small diameter reflects the importance of pile geometry. A considerable variation in response is observed for small diameter monopiles when embedded in different soil types.

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