International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 08 | Aug 2020 www.irjet.net p-ISSN: 2395-0072

Offshore Wind Turbine Monopile Response to the Dynamic and Earthquake Loading in Indian Conditions

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***Abstract** -. A major challenge in Offshore Wind Turbine (OWT) mono pile design is accounting for soil-structure interaction under the influence of dynamic loading from waves, currents, and winds. The present work deals with the monopile OWT foundation behavior in the Indian offshore environmental conditions. The structure used in this study is NREL 5MW OWT monopile foundation supporting the self-weight, dynamic loads coming from wind and waves; also, the El Centro record earthquake load to find the response of the pile foundation. The ground profile is similar to west coast of India, which are alternate sand and soil layers of varying depths. A water depth of 20 m is considered.*

***Key Words*: Offshore Wind Turbine, monopile foundation, Soil structure Interaction, Earthquake Load, dynamic response, layered soil profile.**

1. INTRODUCTION

Offshore wind turbines (OWT) offer an attractive, sustainable, Eco-friendly solution to the increasing global energy demand. India has the world's4th largest onshore wind market with total installed capacity of about 33 GW, but India need to build the large scale clean, green and indigenous energy generation to fulfill its rapidly growing economy. Offshore wind energy has a great potential to provide the considerable part of energy. India is blessed with the long coastline of about 7500 km, and has the large wind power density potential (W/m^2) throughout the year indicate the bright future of offshore wind energy market in India. The Ministry of New & Renewable Energy has declared medium- and long-term target which are 5 GW by year 2022 and 30 GW by year 2030. The proposed 1000 MW wind turbine farm off the Coast of Gujrat and Tamil Nadu is the major step towards the clean and green energy. Since this technology is relatively new for India, though it has been using since year 1978. Further, there are not a common design code acceptable worldwide and different companies and institute developed the design code based on their experience. Therefore, it is very necessary to study the different aspect of design for different specific conditions.

From the point of view of investment per megawatt (MW), offshore wind is almost 50% more expensive than onshore wind. Overall construction of an offshore wind turbines are 20% more expensive than onshore wind turbine. The most expensive part of OWT is foundation, since the foundation has erected in very harsh conditions, and as the depth of water changes, the type of foundation changes. Data shows the investment in foundations accounts for 20–30% of the total cost of a typical offshore wind farm. Therefore, the selection of proper OWT foundation type is the key factor in the utilization of OWT energy efficiently.

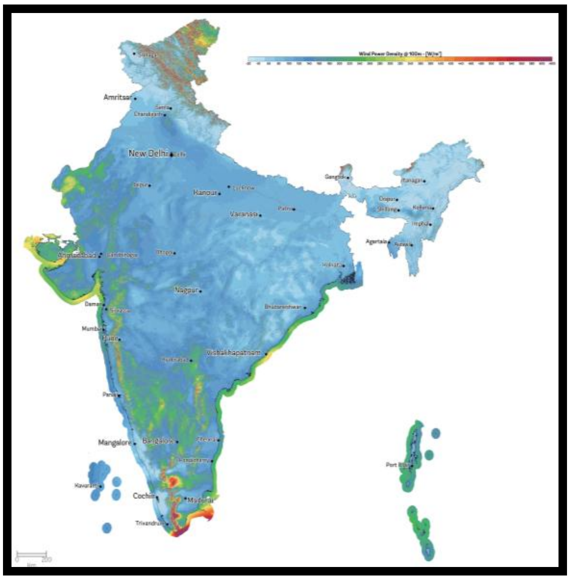


Fig -1: Wind power density potential at 100 m height in India (W/m^2)

1.1. Literature survey

T. K. Deb & B. Singh (2019) studied the drained behavior of monopod bucket foundation under monotonic eccentric lateral loads using finite element analysis. They also studied the influence of bucket dimensions and wind turbine self-weight on the lateral load response of the foundation system. They observed that the ultimate lateral load capacity of the bucket foundation has decrease with the increase of load eccentricity, but it increases marginally with self-weight and noticeably with the foundation size. S. Bhattacharya and M. Giblin (2017) investigated the behavior of piled foundations for different soils profiles susceptible to liquefaction by using numerical analysis in Abaqus software. A single pile as a beam–column element carrying both axial and El Centro record earthquake loading has modeled and found the displacement and deformation and results has used to demonstrate the pile capacity and discussed the damage patterns and location of plastic hinges. Abhinav and Saha (2015) studied the dynamic analysis of the NREL 5MW OWT on a monopile foundation in Indian waters with parametric studies on various clayey soil profiles in the FEM based coupled hydrodynamic - geotechnical software, DNV-GL - USFOS and shows the SSI effect in OWT studies and Variation in response due to change in pile penetration depth and pile diameter. S. Jung and S. Kim (2015) presented the study to compare different foundation modeling approaches, mainly focusing on their effects on the structural response of the wind turbine tower. They integrated the wind turbine aerodynamic simulation with different models of the foundation and found that ignoring the flexibility of the foundation caused significant error in the wind turbine tower behavior. Abhinav and saha (2015) compares the response of a jacket-supported offshore wind turbine OWT under wave loadingwith and without soil–structure interaction. They found that ignoring SSI tends to over-estimate the ultimate strength characteristics of the OWT by 3–60% in various modes or exceeds the displacement serviceable limit of tower top. Masoud S. and S. Bhattacharya (2016) carried out a theoretical study utilizing Hamiltonian principle to analyze deep foundations ($L/\ 2\ D\geq$) embedded in three types of ground profiles. they concluded that the conventional Winkler-based approach (such as p–y curves or Beanon-Dynamic Winkler Foundations) may not be applicable for piles or caissons having aspect ratio less than about 10 to 15. The results also show that, for the same dimensionless frequency, damping ratio of large diameter rigid piles is higher than long flexible piles and is approximately 1.2–1.5 times the material damping. Rupam Mahanta (2019) presented a case study of deployment of a jack-up at a site off the east coast of India where the jack-up had a 'punch-through' during preloading. Punch-through is a sudden and uncontrolled penetration of the spudcan often causing structural damage of the unit. The deployment of the rig was carried out on the basis of preliminary soil investigation report from the consultant on-board the geotechnical vessel deployed for soil investigation. Author analysed and discussed the case. Computer program 'MAHAJACK' developed by the author for carrying out leg-penetration and punch-through analysis for foundation of jack-up rigs has been used for the analysis. E. N. Hearn *at. El.* describes some analyses of a large diameter monopile in dense sand. They take the soil characteristics that encountered at wind farm sites in the southern North Sea and offshore the Northeast United States. The pile was modeled by the p-y method and also by 3D finite element analysis (FEA). They concluded that the API method over predicts soil resistance and under predicts pile deflection for large diameter monopiles subjected to lateral load and in stiff soils Aleksandra L. *at. el*. (2014) performed the analysis of a large-diameter monopile foundation for offshore wind turbine based on the numerical model results. The case describes the behavior of a monopile in sand subjected to lateral loading conditions. They investigate the effects of the pile diameter, the length and the load eccentricity. L-Z Wang (2015) experimented on the scaled wind turbine model that were supported on monopile, subjected to different types of dynamic loading using an innovative out of balance mass system to apply cyclic/dynamic loads. In the test results, they found that the natural frequency of the wind turbine structure increases with the number of cycles, but with a reduced rate of increase with the accumulation of soil strain level. The change were found to be dependent on the shear strain level in the soil next to the pile which matches with the expectations from the element tests of the soil. Abhinav, and Saha (2015) investigate the effect of soil-structure interaction (SSI) on a jacket-offshore wind turbine (OWT) in a water depth of 70 m using JONSWAP spectrum. Stochastic responses of the OWT under varying soil profiles and met-ocean conditions studied, by coupling the aerodynamic and hydrodynamic forces. They concluded that the SSI have significant influence in soft clay and layered soils at and rated wind speeds whereas the dense sand have negligible influence. M. Damgaard (2014) studied the dynamic soil–structure interaction into aeroelastic codes with focus on monopile foundations. Semi-analytical frequency-domain solutions are applied to evaluate the dynamic impedance functions of the soil–pile system at a number of discrete frequencies. The aeroelastic response has evaluated for three different foundation conditions, i.e. apparent fixity length, the consistent lumped-parameter model and fixed support at the seabed.hey observed the significant loss of accuracy of the modal parameters related to the second tower modes.

2. NUMERICAL MODELLING

2.1. Structural model

The reference model for the study is NREL 5MW baseline OWT monopile structure conceptualized by Jonkman *et al.* (2009) is considered. The model of a monopile supporting the NREL 5MW OWT, in a water depth of 20 m is developed in Midas GTS NX. The super structure of turbine consist the rotor-nacelle-assembly (RNA) and steel tower, connected to the monopile through a cylindrical transition piece. The density value considered higher for steel (8500 kg/m^3) to account for the absence of bolts, flanges, and welds in the model. The monopile has a diameter of 6 m and thickness has taken as 0.06m. The piles are modeled using 2-noded beam elements. The wall thickness (*t*) of the monopile is defined by API (2000), on the basis of its diameter (D) given by the equation

$$t = 6.35 + D/100$$

2.2. Soil profile

The study focuses on one soil profile mainly because of soil structure interaction. It is shown in table 1 where γ' is the soil's effective unit weight, Φ' is its angle of internal friction, and *k* is the initial modulus of sub grade reaction. The soil is stratified layered soil, which representative of the off the west coast of India. The scour have not considered in this study though it is not a negligible phenomenon. Scour refers to the removal of soil around the foundation at the seabed; it usually results from turbulence, water particle motion, and currents that displace soil particles. The is constrain all around in the model.

Table -1: Properties of soil layers

Depth (m)	Type	γ' (KN/m³)	Φ	Cohesion (KN/m2)	m
0-1.5	Sand	8.0	20	-	0.3
1.5-5.2	Clay	8.0	-	10.0	0.4
5.2-6.6	Sand	8.5	20	-	0.3
6.6-8.8	Clay	8.5	-	10.0	0.4
8.8-11.7	Sand	9.0	25	-	0.3
11.7-13.1	Sand	9.0	30	-	0.3
13.1-15.6	Clay	8.5	-	17.5	0.4
15.6-16.7	Sand	9.0	25	-	0.3
16.7-37.0	Sand	9.0	30	-	0.3
37.0-49.9	Clay	8.5	-	55.0	0.4

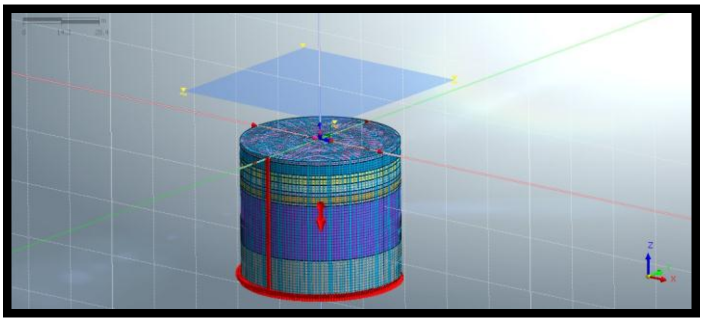


Fig -2: Soil profile model in the Midas GTS NX software

2.3. Loads

OWT are subjected to the action of aerodynamic and hydrodynamic loading computed by the NREL's FAST (Jonkman and Buhl, 2005) code. The loads are taken equivalent to the aerodynamic and hydrodynamic by a single value horizontal point load of H=8MN and the moment M=240 MNm acting at the top portion of pile. Self-weight of tower taken as the downward point load of 3410 KN on the top of pile. The El Centro record earthquake load applied to the model, which is very accurate; represent the non-linear dynamic loads of Earthquake. The graph of the El Centro record earthquake load shown below.

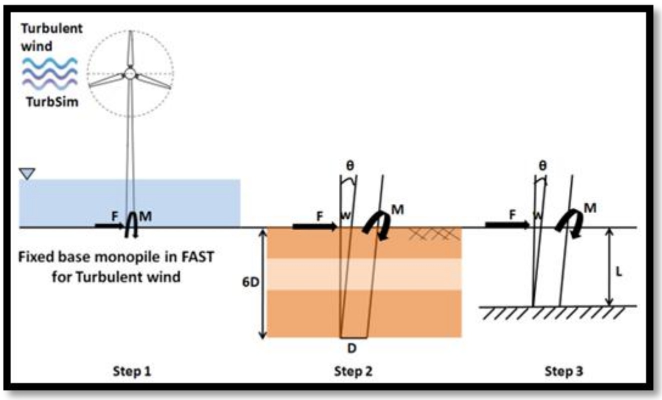


Fig 3-: Loading scheme on monopile foundation

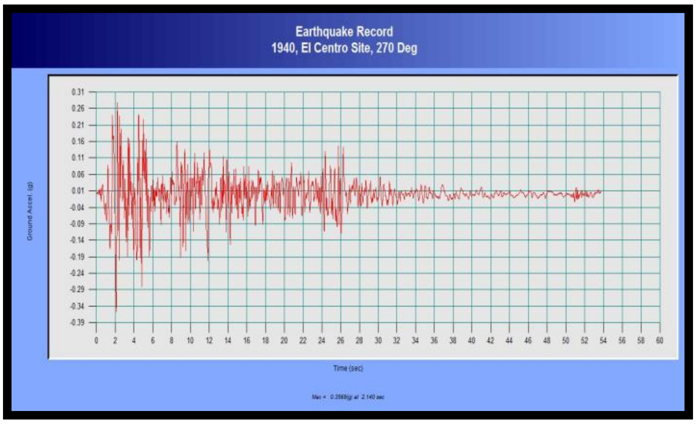
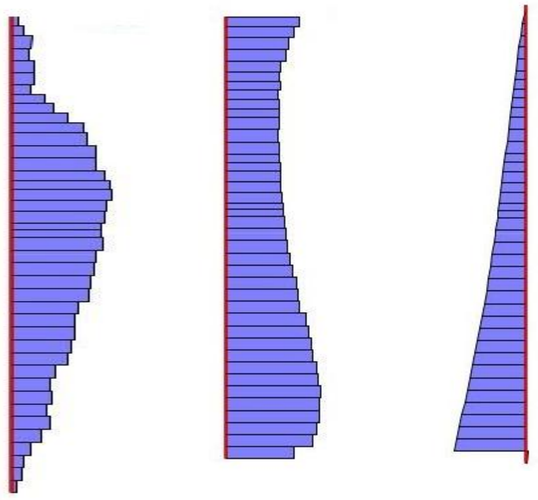


Chart -1: El Centro record earthquake load graph

3. RESULTS

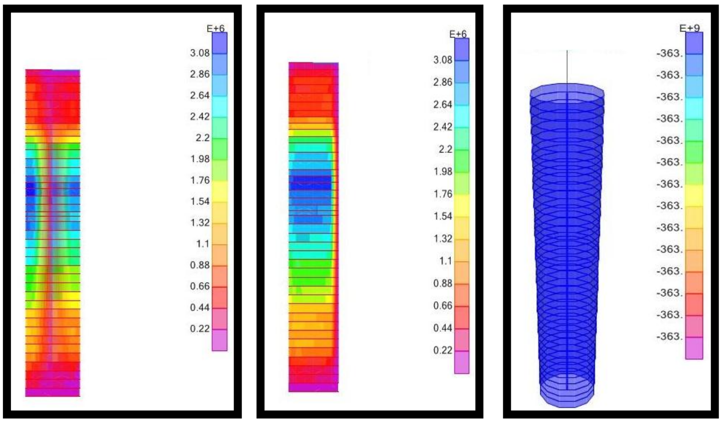
The pile response in the 3D Finite Element Analysis governed by the respective material properties, length, and the surrounding soil. The behavior of pile observed for different loading stage. The stresses of the systems and the interaction between the soil and the pile are shown in Figures, which also illustrates the maximum bending moment, Shear Forces at the different places on the pile and deflections and deformations in the pile.

For the first case with only self weight and aerodynamic loading and hydrodynamic loading without considering the earthquake load. The maximum stress comes out to be 3212596KN/m^2 and maximum resultant axial force 3456514.77KN at a depth of 13.1 m. The maximum shear force of 9769.18 KN at 30.23m and maximum bending moment of 249855 KN-m at depth of 35.07m as shown in the figures.



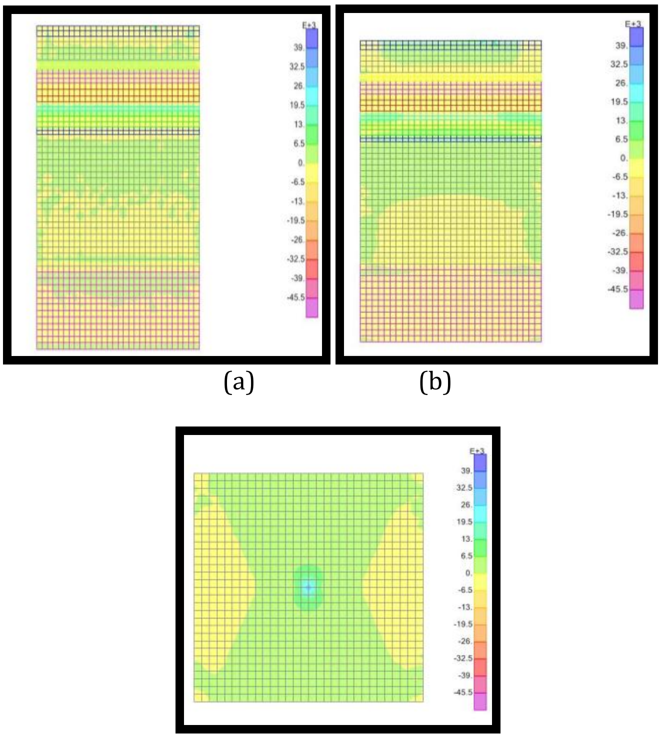
(a) (b) (c)

Fig -4: (a)- Resultant axial force, (b)-shear force, (c)- Bending moment of pile with no earthquake load.



(a) (b) (c)

Fig -5: (a)- stresses in pile XZ , (b)- stresses in pile YZ, (c)- Vertical displacement in pile with no earthquake load

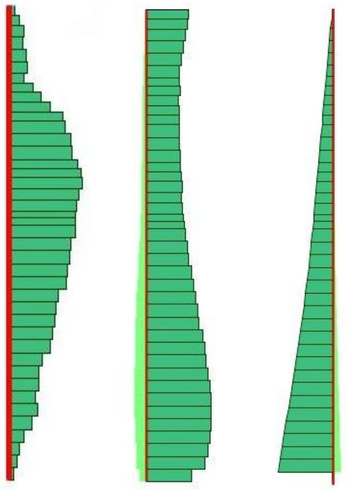


(a) (b)

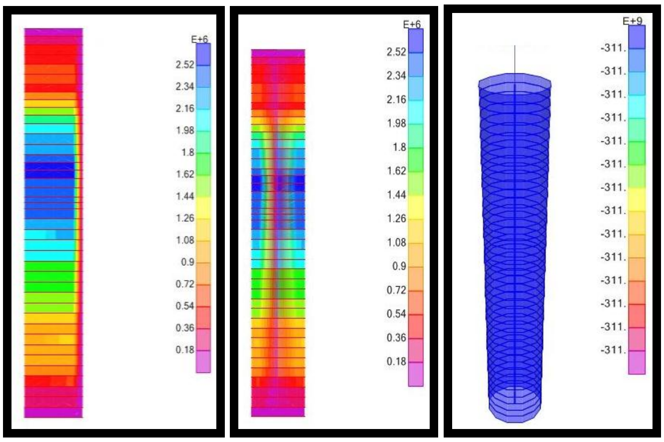
(c)

Fig -6: (a)- stresses in the soil profile in XZ plane , (b)- stresses in the soil profile in YZ plane, (c)- stresses in the soil profile in XY plane with no earthquake load,

The stresses in the soil layers also vary with the layer properties as shown in the figure. For the second case with self-weight and aerodynamic loading and hydrodynamic loading with considering the El Centro record earthquake load data, the maximum resultant axial force 2962730.73 KN at a depth of 13.1 m. The maximum shear force of 12241.5 KN at 30.23m and maximum bending moment of 301056.69 KN-m at depth of 35.07m as shown in the figures.



(a) (b) (c) **Fig -7**: (a)- Resultant axial force, (b)-shear force, (c)- Bending moment of pile with earthquake load.



(a) (b) (c) **Fig -8**: (a) - stresses in pile XZ, (b) - stresses in pile YZ, (c) - Vertical displacement in pile with earthquake load

4. CONCLUSION

The paper presents 3D soil structure interaction models that has created for the behavior of the pile and soil under different loading conditions using numerical analysis carried out in Midas GTS NX software. Pile tends to deflect mainly in the middle length and shows maximum stress at the middle length portion. Different soils show different response to the loading and give the lateral support to the pile. Pile act as the cantilever beam and maximum bending moment accurse at the bottom portion. Since we neglect the effect of scouring, these results are only for the specific conditions taken in this study, actual behavior may differ from the values given in this paper.

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