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PERFORMANCE OF HYBRID MONOPILE FOUNDATION FOR OFFSHORE STRUCTURES

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Abstract: In case of offshore structures, a hybrid foundation system is found to be helpful in protecting a structure against strong shaking. These foundations have to distribute the load of the structure over large bearing area so as to bring intensity of loading within the safe bearing capacity of the soil lying underneath to resist moment and horizontal loads due to wind and wave actions. Compared to the traditional monopile foundation, hybrid monopile foundations may be more suitable and stable under severe environmental loads and for particular site conditions. In this paper, the results of analyses of conventional monopile foundation and Hybrid monopile foundation in layered soil are presented and compared. Numerical analyses were carried out using MIDAS GTS NX software with selected parameters of the foundation system and by varying eccentricity of resultant horizontal load. The hybrid monopile foundation, composed of steel wheel at sea bed level, increases the gross bearing area at the top of the monopile and improve the lateral load carrying capacity. As a result, lateral load carrying capacity for Hybrid monopile foundation is more than the conventional monopile foundation.

KEYWORDS: Offshore wind turbine, Hybrid Monopile foundation, Steel Wheel, Ultimate Lateral load capacity, Numerical analysis, MIDAS GTS NX 3D

I. Introduction

The offshore wind energy attracts more industrial interests since the wind condition is stronger and steadier than its onshore counterpart. Moreover, long-distance power transmission can be eliminated if the offshore wind farms are constructed close to large cities along the coasts where the electricity demand is high. With growing size of offshore wind turbines and their deeper water depth, stronger foundations are needed. Thus, the conventional foundations are likely to be insufficient or uneconomical to support the offshore wind turbines. In case of offshore structures, a hybrid foundation system is found to be helpful in protecting a structure against strong shaking. A hybrid foundation system for offshore wind turbines is the combination of shallow and deep foundation and consists of traditional monopile foundation with additional structural elements such as wide shallow bucket, circular footing (wheel) at the mudline, etc.

The hybrid foundation distributes the load of the structure over large bearing area so as to bring intensity of loading within the safe bearing capacity of the soil lying underneath. This system can reduce the installation cost considerably while providing reliable axial, lateral and rocking resistances to meet the requirements of wind turbine foundations. This system can reduce the size of the required monopile from 6 to 4 m, owing to the additional capacity of the precast plate attached to it.

II. Literature Review

The study regarding the behaviour of Hybrid monopile in sandy soil has been carried out analytically and experimentally by various researchers. These works are reviewed and presented briefly as below:

Anastasopoulos, I. *et al.*, (2016)[1] carried out analysis on hybrid monopile foundation for offshore wind turbines, by considering a monopile attached with a lightweight circular footing, using 3D finite element software. The footing was made up of steel wheel having rubble fill compartments, beneficial for buckling prevention and increase in the vertical load capacity. The hybrid foundation showed much stiffer response, than monopile while having 50% reduction in length. Subjected to cyclic loading, the hybrid foundation experienced less intense stiffness degradation and rotation accumulation compared to the reference monopile.

Da Chen *et al.*, (2020)[2] studied the hybrid foundation consisting of a traditional monopile and a wide-shallow bucket. A series of numerical analyses were conducted to investigate its behavior under the static and dynamic loading, considering various loading eccentricities. The moment bearing capacity of the hybrid foundation was found to be larger than monopile. The failure mechanism of both the hybrid foundation and the monopile was excessive rotation. The hybrid foundation was found to be more superior under the combined wave and current loading.

Xuefei Wang *et al.*, (2018)[3] carried out experimental investigation on hybrid monopile foundation, which combined a monopile with a friction wheel. A series of centrifuge tests were performed on foundation models under cyclic loadings in sandy soil and lateral displacements and lateral stiffness were investigated. The hybrid monopile foundation showed better lateral capacity compared to the conventional monopile foundation. The pore water pressure ratios were significantly reduced under and adjacent to the hybrid foundation due to the wheel-induced confining pressure.

Krzysztof Trojnar *et al.*, (2019)[4] studied the hybrid foundations at three scales viz., small laboratory scale, full-field investigation, and 3D numerical simulation. The hybrid foundation was a combination of a monopile foundation and a footing plate. A horizontal force and the bending moment analysis was carried out in cohesionless soil. Hybrid foundation showed greater lateral stiffness in the ground due to the effectiveness of the vertical shaft, the horizontal plate and soil within a definite range of displacement of up to 40 mm caused by lateral load.

III. Numerical Analyses

Analyses were carried out to evaluate the performance of Conventional monopile foundation and Hybrid monopile foundation embedded in layered soil deposit. Figure 1 shows the schematics of the Hybrid Monopile Foundation for the present study, which consists of a monopile provided with a wheel at sea bed level. Figure 2 and 3 show cross sections of conventional and hybrid monopile foundation considered for analyses, along with notations used.

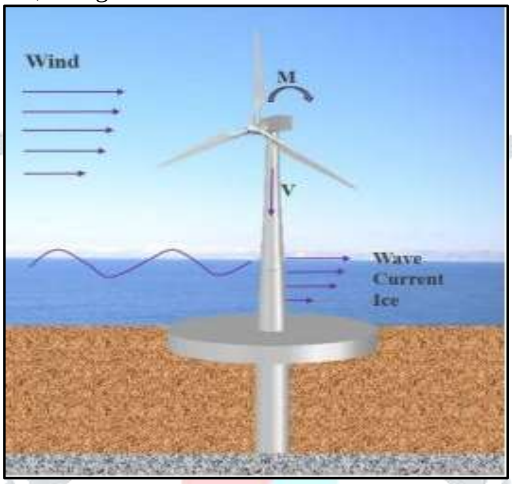

Figure 1: Schematics of Hybrid monopile Foundation adopted for present study

Vertical load equal to the self-weight of structural elements and turbine was applied on the hybrid monopile foundation. Lateral loads were applied at various eccentricities above the sea water level. Overturning moment in the model was assigned by multiplying the horizontal load with the eccentricity height above the sea water level. The analyses were conducted on model conventional and Hybrid monopile foundation and the parameters varied were length of monopile and wheel diameter.

IV. Geometric Details of Hybrid Monopile Foundation

Various geometries were considered in order to perform numerical analyses of Monopile foundations in layered soil deposit. Analyses were carried out for a typical 7.5 MW offshore wind turbine considering the its self-weight to be 4.785 MN. Details of parameters selected for analyses are given in Table 1 and 2. The geometric details of tower, transition piece and wind turbine are given in Table 3, and 4 resp.

Table 1: Details of parametric study for Conventional monopile Foundation

Parameters	Values
Diameter of monopile D_m	4 m
Thickness of monopile T_m	0.2 m
Length of monopile L	15 m, 20 m, 25 m, and 30 m

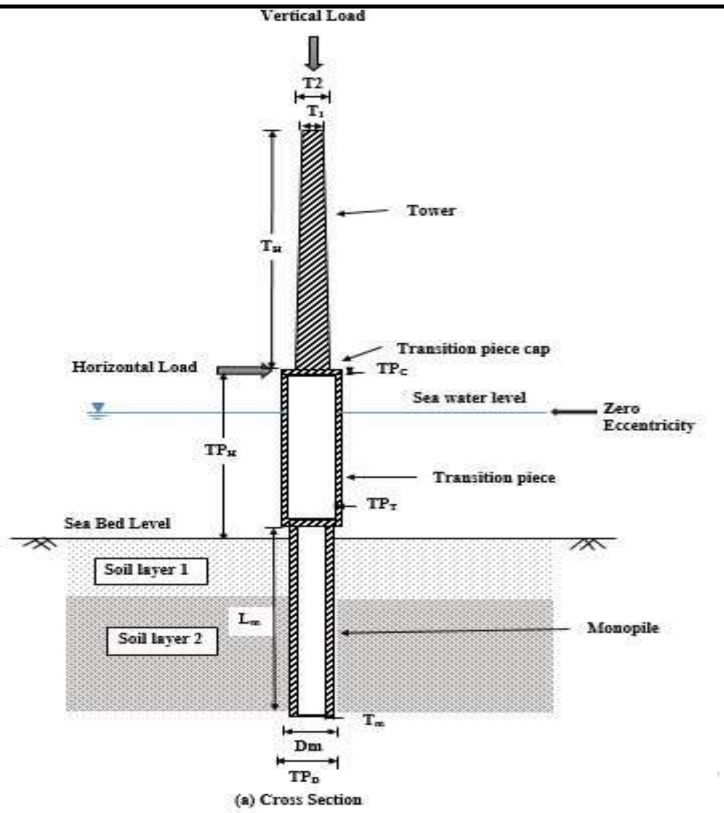

Figure 2: Cross Section of Conventional Monopile Foundation Considered for Analysis

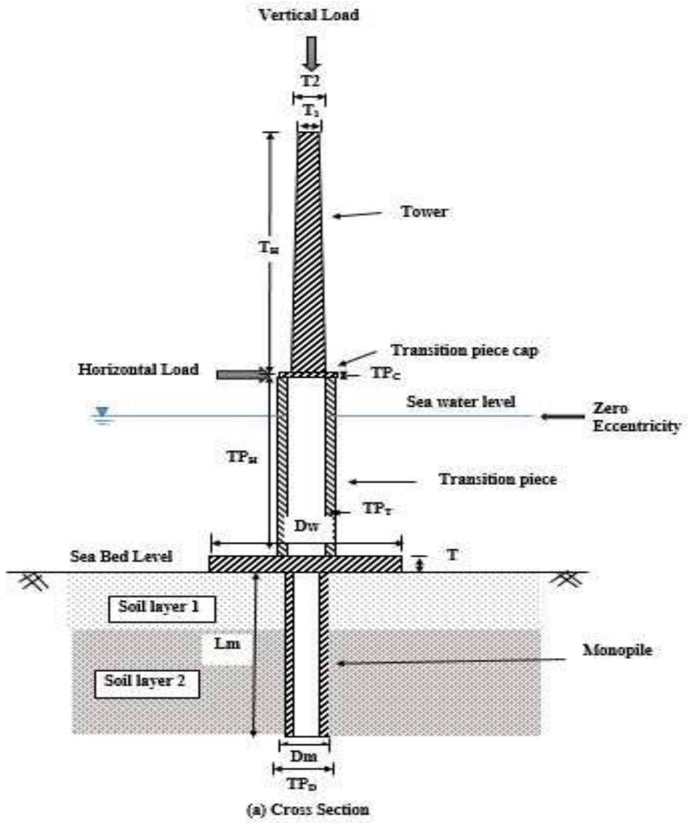

Figure 3: Cross Section of Hybrid Monopile Foundation Considered for Analysis

Table 2: Details of parametric study for Hybrid monopile Foundation

Parameters	Values
Diameter of monopile (D_m)	4 m
Thickness of monopile (T_m)	0.2 m
Thickness of wheel (T_w)	1.5 m
Length of pile (L)	15 m, 20 m, 25 m, and 30 m

Diameter of wheel (D_w)	6 m, 8 m,10 m,12 m, 16 m, 20 m, 24 m

Table 3: Parameters assigned for Tower and Transition piece

Parameters	Values
Height of Tower (T_H)	100 m
Top diameter of Tower (T_1)	1.5 m
Bottom diameter Tower (T_2)	3 m
Height of Transition piece (TP_H)	25 m
Diameter of Transition piece (TP_D)	5 m
Thickness of Transition piece (TP_T)	0.1 m
Thickness of Cap (TP_C)	0.3 m

Table 4: Parameters assigned for wind turbine

Parameter	Values
Wind Turbine	7.5 MW
Vertical loading	4.875 MN
Lateral Loading	0 to 50 MN

The soil bed was considered to be comprised of soft clay and dense sand (Gulf of Khambat, Gujrat). Thicknesses of soil layers are given at Table 5 and their properties are given in Table 6.

Table 5: Parameter assigned for soil bed

Parameter	Values
Type of soil and thickness of soil layer	Layer 1 (Soft Clay) = 7.5 m
	Layer 2 (Dense Sand) = 42.5 m
Depth of water above sea bed level	16 m

Table 6: Properties assigned to soil layer for analysis (Gulf of Khambat, Gujrat)

Properties	Unit weight	Saturated Unit weight	Young's modulus	Poisson's ratio	Angle of internal friction	cohesion
Symbols	γ	γ_{sat}	E	υ	Ø	c
Unit	kN/m^3	kN/m^3	kPa		degree	kPa
Layer 1	12	16	5,000	0.3	0	5.8
Layer 2	18.28	20.64	29,600	0.3	38.2°	0

Model selected for analysis of Hybrid monopile foundation was 'Elastic model' having Young's modulus 2 x 10^8 kN/m^2, density 78 kN/m^3, and Poisson's ratio 0.5. For soil, the model selected for analysis was 'Drucker – Prager' model.

V. RESULTS AND DISCUSSION

In order to explore the behavior of conventional monopile and hybrid monopile foundation supporting wind turbine, load eccentricity (e) was varied from 10 m up to 70 m above the water level. Figures 4 to 7 show the variation in ultimate lateral load capacity with "Diameter of wheel ratio" (ratio of diameter of wheel to diameter of monopile) for various lengths of hybrid monopile foundation and eccentricities of loads.

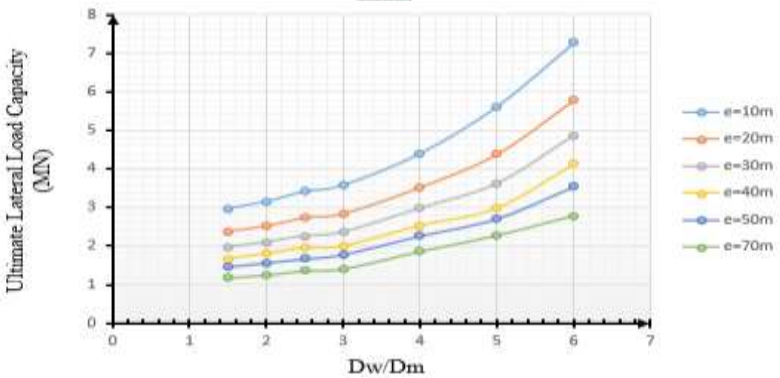

Figure 4: Ultimate lateral load capacity of Hybrid foundation (L =15 m)

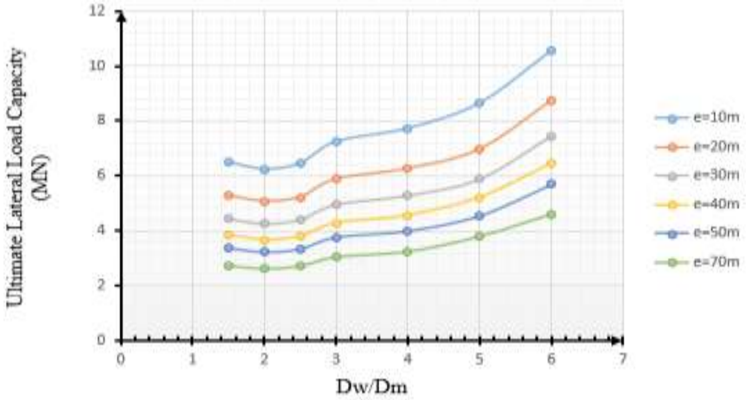

Figure 5: Ultimate lateral load capacity of Hybrid foundation (L =20 m)

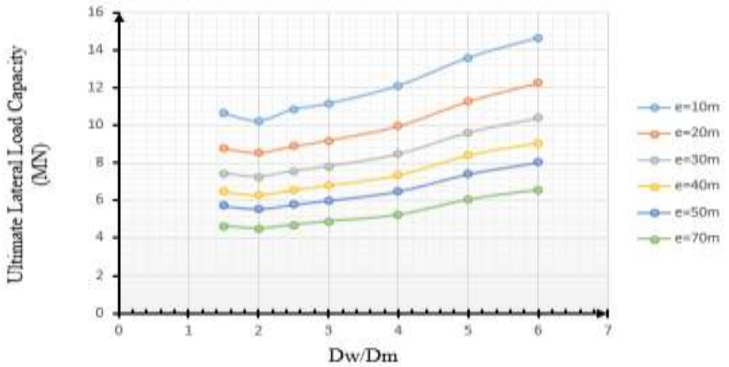

Figure 6: Ultimate lateral load capacity of Hybrid monopile foundation (L = 25 m)

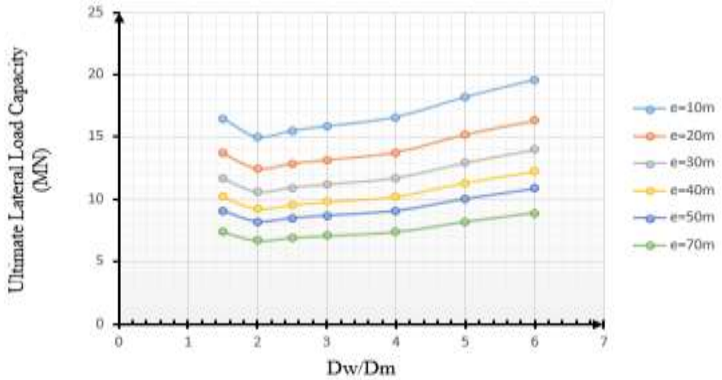

Figure 7: Ultimate lateral load capacity of Hybrid monopile foundation (L =30 m)

Fig 8 to Fig 11 shows the percentage increase in ultimate lateral capacities of hybrid monopile foundation with respect to eccentricity ratio for various diameter ratios of wheel.

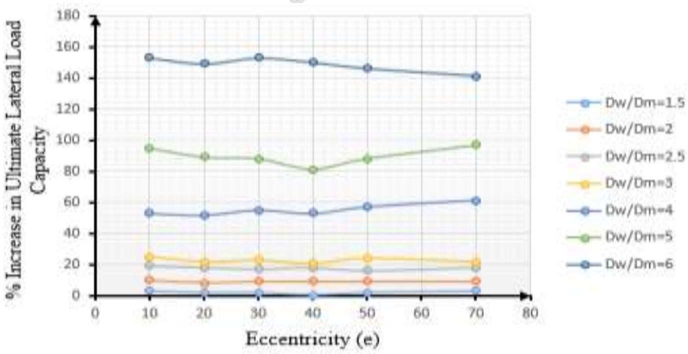

Figure 8: % Increase in ultimate lateral load capacity of Hybrid monopile foundation (L=15 m)

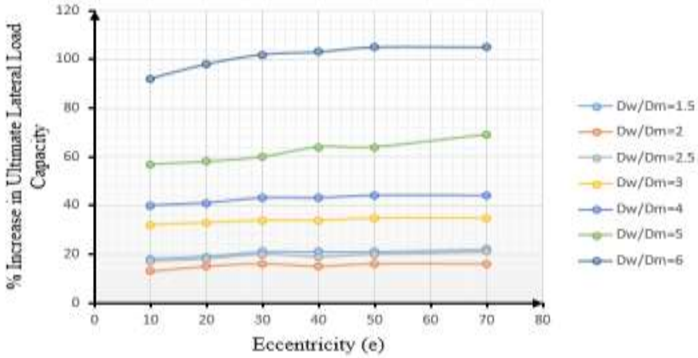

Figure 9: % Increase in ultimate lateral load capacity of Hybrid monopile foundation (L= 20 m)

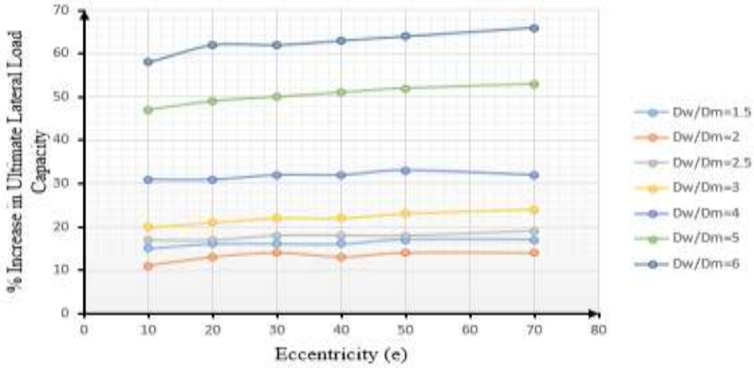

Figure 10: % Increase in ultimate lateral load capacity of Hybrid monopile foundation (L=25 m)

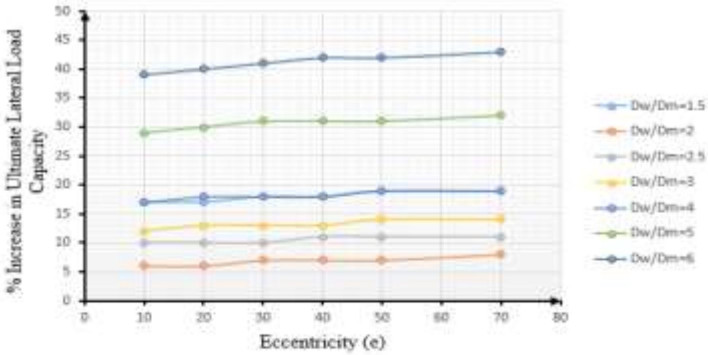

Figure 11: % Increase in ultimate lateral load capacity of Hybrid monopile foundation (L=30 m)

It is observed that the ultimate lateral load capacity of hybrid monopile foundation is increased up to 153% as compared to conventional monopile foundation, due to provision of wheel with diameter greater than trice the diameter of monopile. The percentage increase in lateral capacity is, however, not influenced by eccentricity ratio of lateral load. Also, provision of wheel to monopile foundation is found to be more effective in case of monoplies of shorter lengths.

Lateral Load- Overturning Moment Interaction Diagrams

In case of Monopile foundations for offshore wind turbines, the capacity may be described graphically by using lateral load overturning moment interaction diagram. The interaction diagram consists of several plots between lateral load and corresponding moment to failure condition. Any combination of lateral load and overturning moment, located outside the envelope, will cause instability of monopile foundation. In such a situation, the next larger geometry may be selected in a step wise manner till the stability requirement is fulfilled. These curves may be used to determine for the preliminary design of the hybrid monopile foundation. The selected design of the foundation may then be analyzed in detail to confirm its stability. Figures 12 to 19 show the lateral load- overturning moment interaction diagram with length of foundations.

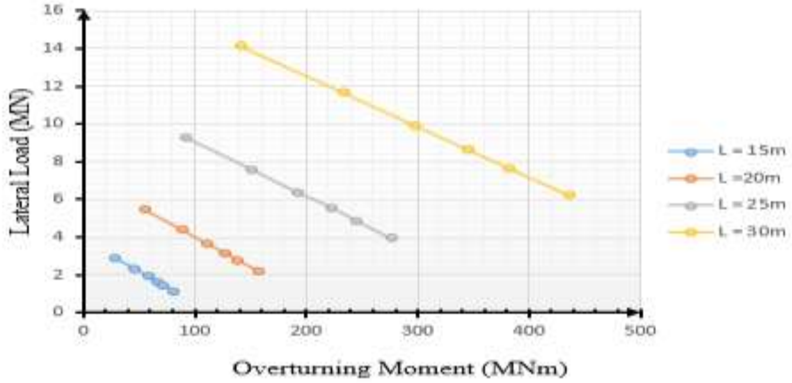

Figure 12: Overturning moment of Conventional monopile foundation

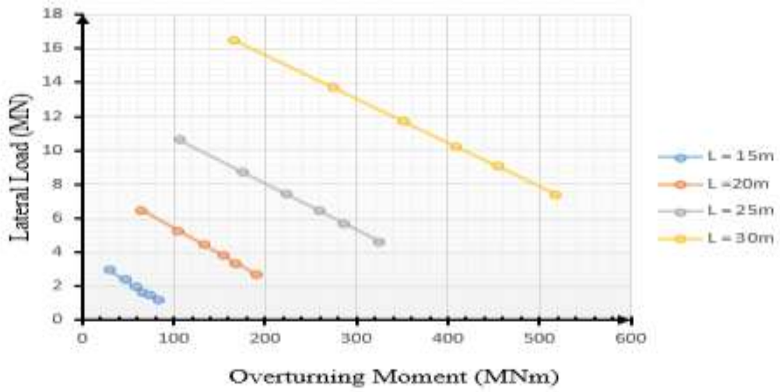

Figure 13: Overturning moment of Hybrid monopile foundation (D_w/D_m= 1.5)

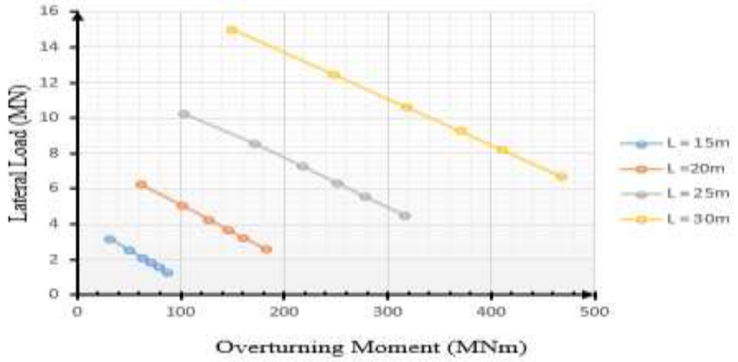

Figure 14: Overturning moment of Hybrid monopile foundation (D_w/D_m= 2)

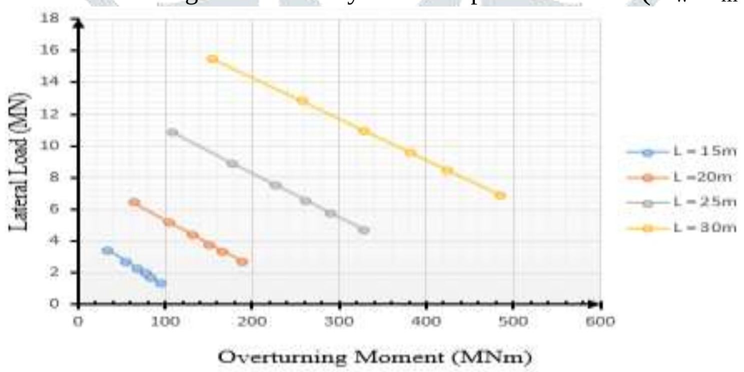

Figure 15: Overturning moment of Hybrid monopile foundation (D_w/D_m= 2.5)

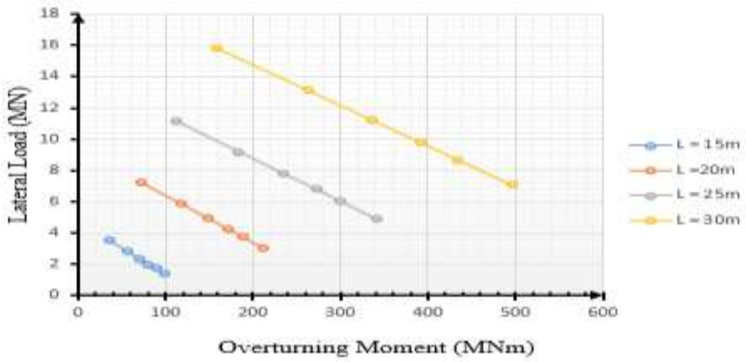

Figure 16: Overturning moment of Hybrid monopile foundation (D_w/D_m= 3)

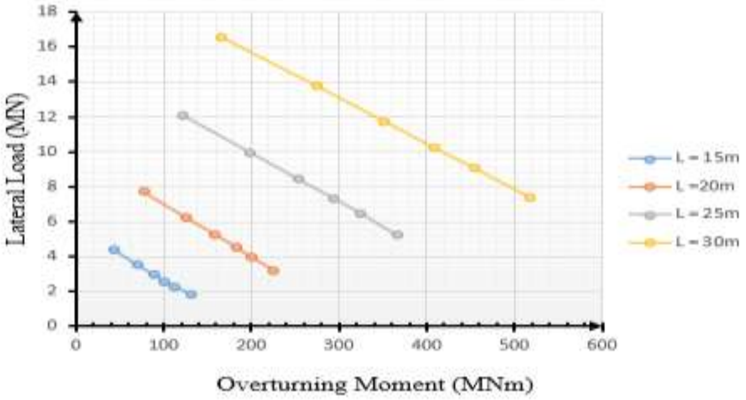

Figure 17: Overturning moment of Hybrid monopile foundation (D_w/D_m= 4)

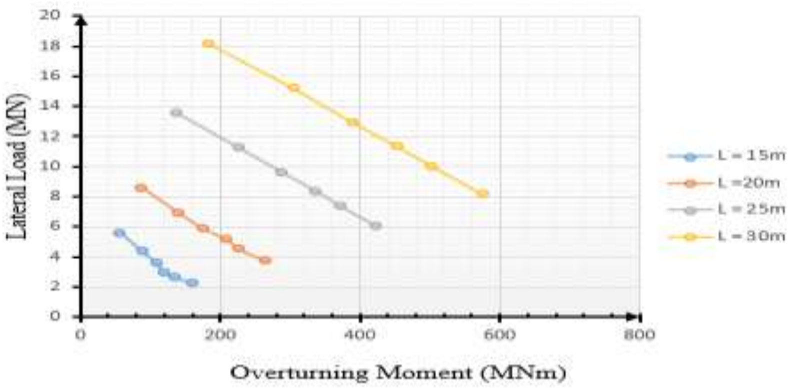

Figure 18: Overturning moment of Hybrid monopile foundation (D_w/D_m= 5)

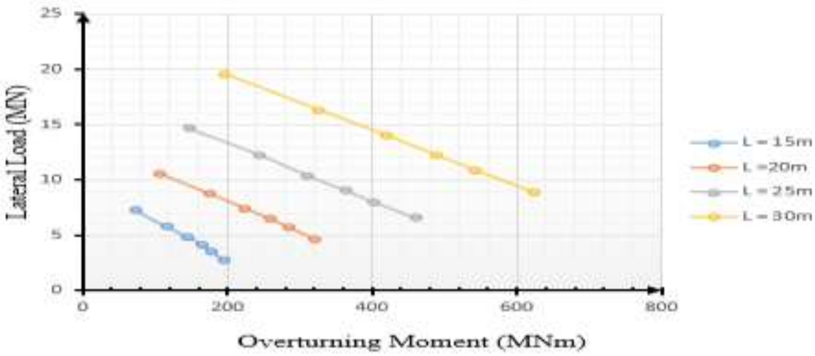

Figure 19: Overturning moment of Hybrid monopile foundation (D_w/D_m= 6)

VI. Conclusions

Conventional monopile foundation and hybrid monopile foundation for offshore wind turbine structures have been analysed using MIDAS GTS NX software, considering different parameters. From the present study, following conclusions are drawn.

1. Lateral load capacity of Conventional monopile foundation and Hybrid monopile foundation increases with increase in length of monopile and decreases with increasing load eccentricity.
2. Ultimate lateral load capacity of hybrid monopile foundation is higher than conventional monopile foundation, up to 153%. Thus, Steel wheel provided to the monopile enhances the stability of monopile foundation of offshore wind turbines.
3. The ultimate lateral load capacity of hybrid monopile foundation increases with its increase in Wheel diameter, in excess of trice the diameter of monopile.
4. The lateral load- Overturning Moment Interaction Curves for Hybrid monopile foundation, developed in the present study, may be used for preliminary design of the hybrid monopile foundation. The selected design may then be analyzed in detail to confirm the stability of foundation.

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