JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

PERFORMANCE OF HYBRID CAISSON FOUNDATION FOR OFFSHORE STRUCTURES

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Abstract: In recent times, hybrid caisson foundation is being considered as an alternative supporting base for offshore wind turbines. These foundations have to resist moment and horizontal loads due to wind and wave actions. This paper describes the results obtained by numerical analysis for hybrid caisson foundation combined with additional structural elements in the form of wings. The ultimate lateral load capacities of conventional caisson foundation and hybrid caisson foundation in layered sand bed are determined numerically with MIDAS GTS NX software and compared. Taking caisson cap as a point of reference, the effect of lateral loads, resulting from wind action and water currents acting on the wind turbine and the foundation respectively is simulated by varying the eccentricities of the resultant horizontal load. It is observed that the lateral load capacity increases with foundation size and decreases with increase in eccentricity. Ultimate lateral load capacity of hybrid caisson foundation is higher than that of conventional caisson foundation. Also, as the width of wings, fixed to caisson foundation, increases, lateral load capacity increases. From the present analysis, lateral load- overturning moment interaction diagrams are developed, which may be useful for preliminary design of hybrid caisson foundation with wings.

Index Terms: **Hybrid Caisson Foundations, Numerical analysis, Lateral Load Capacity, MIDAS GTS NX**

I. Introduction

Wind power is one of the emerging renewable sources of energy. The design of the foundation is a crucial part for offshore wind turbine, and the substructure can cost up to 30% of the total project cost. Offshore wind turbines foundations have to withstand significant lateral wind loads, in addition to other environmental loads, arising from waves and current. The most common type of foundations for offshore wind turbines nowadays are monopile, jacket, tripod, gravity-based foundations etc. There is a tendency that offshore wind farms are planned to be built at locations with deeper water depths and greater distances to land to get even better wind resources; thereby more challenging environmental conditions will be confronted. Thus, the conventional foundations are likely to be insufficient or uneconomical to support the offshore wind turbines. The conventional monopile foundation, suction bucket foundations may not be suitable for these new generations of offshore wind projects, and designs of improved substructures are necessary. Based on these requirements, innovative hybrid Caisson foundations are developed. The hybrid Caisson foundation for offshore structures consists of a traditional caisson foundation combined with additional structural elements such as skirts, wings and skirted mat etc.

II. Literature Review

The study regarding the behaviour of hybrid caisson foundation has been carried out analytically and experimentally by various researchers. Some of them are presented here in brief.

Koohyar Faizi *et al.* (2019)[1] carried out a series of numerical simulations predicting the performance of a novel hybrid suction caisson foundation used for offshore wind turbines under overturning moment. A numerical 3D finite-element model with an elasto-plastic soil constitutive model was developed to simulate the soil-caisson interaction and evaluate the additional overturning capacity provided by the wings. They concluded that the overturning capacity increased compared to a simple caisson foundation because of significant contribution of the wings, through changes in the failure mechanism.

Ning Cheng *et al.* (2019)[2] carried out numerical and experimental stimulations predicting the performance of a hybrid foundation that merges a skirted footing with a deeper caisson, with the motivation to mobilize higher bearing capacities and increase the foundation stiffness. They concluded that the central caisson's dimension plays an important role in the combined bearing capacities, as combined bearing capacity was nearly identical once the footing has been pushed to the depth of its skirt, even if the vertical capacity was not fully preloaded.

Da Chen *et al.* (2020)[3] carried out a series of numerical analyses to investigate the behavior of hybrid foundation, consisting of a traditional monopile and a wide–shallow bucket under the static and dynamic loading, considering various loading eccentricities. From the dynamic response of the foundation, they concluded that addition of the bucket to the foundation could restrain the rotation and lateral displacement effectively. The superiority of the hybrid foundation was more obvious under the combined wave and current loading.

Koohyar Faizi *et al.* (2019)[4] carried out series of experiments on small-scale models of the proposed hybrid tripod bucket foundation subjected to overturning moment under 1g conditions in loose sand. They concluded that there was a significant increase in overturning capacity provided by the novel foundation and could significantly lower the costs associated with installation of foundations to support offshore wind turbines.

Britta Bienen *et al.* (2012)[5] investigated in detail the soil failure mechanisms and resulting foundation capacity under undrained VHM loading of a hybrid foundation comprising of a skirted mat combined with an internal caisson compartment. The proposed foundation design was found to provide significantly increased horizontal capacity that is often critical in offshore applications. They proposed expressions that allow slightly conservative prediction of the combined capacity of a hybrid foundation.

III. Numerical Analysis

The conventional caisson and hybrid caisson foundation, in the present study, were considered to be provided in the layered soil. Figure 1 shows the schematics of hybrid caisson foundation considered in this study. Figure 2 and 3 show cross section of conventional caisson foundation and hybrid caisson foundation considered for analysis, along with notations used. The soil bed was considered to comprise of top layer of soft soil underlined by dense sand layer. Vertical load equal to the self-weight of structural elements and turbine was applied on the both the foundations. Lateral load was applied at various eccentricity heights (e) above the water level. Overturning moment in the model was assigned by multiplying the horizontal load with the eccentricity. Various widths of wings were considered in order to investigate the influence of lateral load and moment load on the lateral capacities of hybrid caisson foundation.

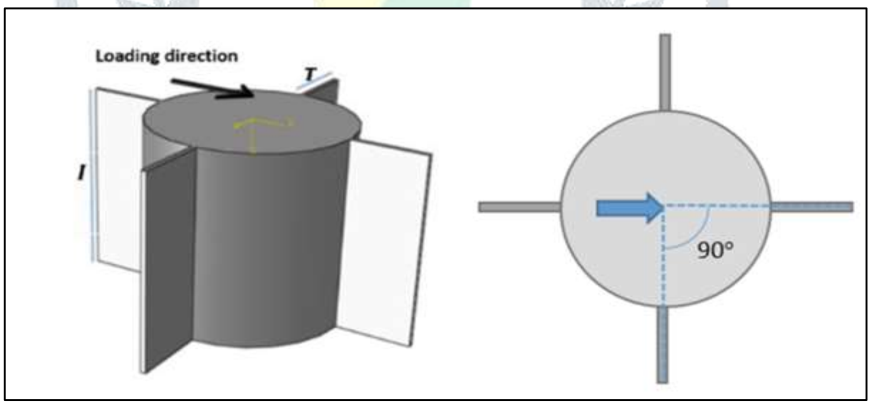

Figure 1: Schematics of Hybrid Winged Caisson Foundation for Offshore Wind Turbine

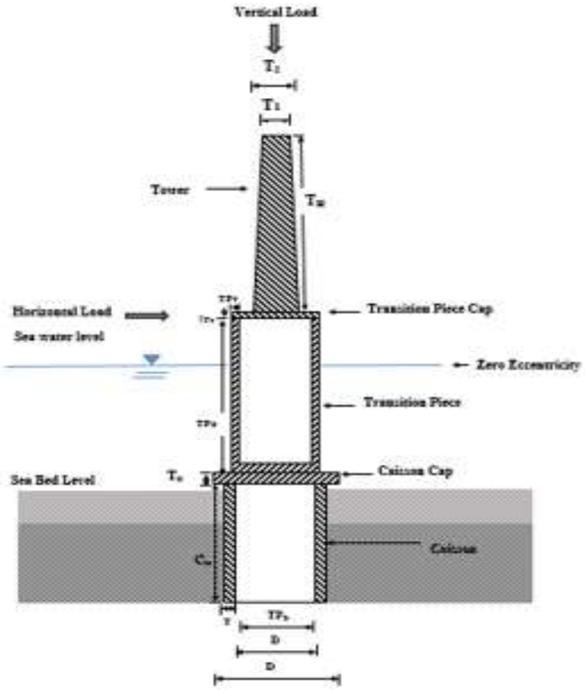

Figure 2: Cross Section of Conventional Caisson Foundation Considered for Analysis

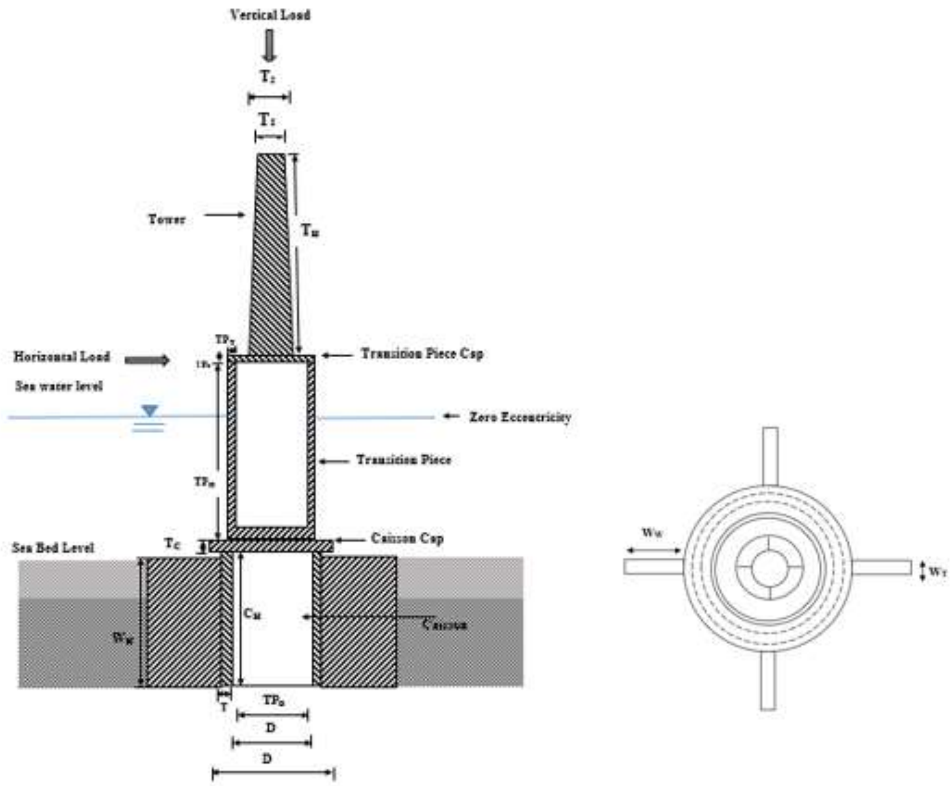

Figure 3: Cross Section and Plan of Hybrid Caisson Foundation Considered for Analysis

IV. GEOMETRIC DETAILS OF FOUNDATION

Several geometries were considered in order to perform numerical analysis of conventional caisson and hybrid caisson foundation in layered soil. In the analysis, the both foundations were assumed to be already installed. Analyses were carried out for a typical 7.5 MW offshore wind turbine considering the self-weight load of wind turbine to be 4.785 MN. Details of parametric study of conventional caisson are given at Table 1, and those for Hybrid Caisson Foundation are given at Table 2. Details Parameters assigned for tower and transition piece are given at Table 3. Parameters assigned for wind turbine and soil bed are given in Table 4 and Table 5 resp.

Table 1: Details of parametric study of Conventional Caisson Foundation

Sr. no	Parameter	Values	
1	Constant Parameters	Thickness of caisson (T) Height of caisson (C_H) Thickness of caisson Cap (T_c) Caisson cap diameter D_C	= 0.3 m = 15 m = 0.5 m = D + 0.4 m
2	Variable Parameters	Caisson diameter (D)	= 6 m, 8 m, 10 m

Table 2: Details of parametric study of Hybrid Caisson Foundation

Sr. no	Parameter	Values	
1	Constant Parameters	Thickness of caisson (T) Height of caisson (C_H) Caisson diameter (D) Thickness of caisson Cap (T_c) Caisson cap diameter D_C Thickness of wings (W_T) Height of wings (W_H)	= 0.3 m = 15 m = 6 m, 8 m, 10 m = 0.5 m = D + 0.4 m = 0.3 m = 15 m
2	Variable Parameters	Width of wings (W_W)	= 0.2D, 0.3D, 0.4D, 0.5D, 0.75D, D
3	Number of wings	4	
4	Position of Wings	90° From Each Other	

Table 3: Parameters assigned for Tower and Transition Piece

Sr. no	Parameter	Values	
1	Tower Dimensions	Tower height (T_H) Tower top diameter (T_1) Tower bottom diameter (T_2)	= 100 m = 1.5 m = 3 m
2	Transition Piece Dimensions	Transition piece diameter (TP_D) Transition piece thickness (TP_T) Transition piece cap thickness (TP_C) Transition piece height (TP_H)	= 5 m = 0.1 m = 0.3 m = 20 m
6	Type of soil and thickness of soil layer from sea bed level	Layer 1 (Soft Clay) = 7.5 m Layer 2 (Dense Sand) = 50 m	
7	Depth of water above sea bed level	16 m	

Table 4: Parameters assigned for Wind Turbine

Sr. no	Parameter	Values
1	Capacity of Wind Turbine	7.5 MW
2	Horizontal loading	0 – 50 MN
3	Vertical loading	4.875 MN

Table 5: Parameters assigned for Soil Bed

Sr. no	Parameter	Values
1	Type of soil and thickness of soil layer from sea bed level	Layer 1 (Soft Clay) = 7.5 m Layer 2 (Dense Sand) = 50 m
2	Depth of water above sea bed level	16 m

The soil bed was considered to comprise of soft soil and dense sand. Properties of sand layers considered were as shown in Table 6.

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
(Units)	kN/m^3	kN/m^3	kPa		degree	kPa
Soft clay	12	16	5000	0.3	0	5.8
Dense sand	18.28	20.64	29600	0.3	38.2°	0

Model selected for analysis of conventional caisson and hybrid caisson foundation was 'Elastic model' having Young's modulus 2×10^8 kN/m^2, Density 78 kN/m^2, Poisson's ratio 0.17 and for soil, the model selected for analysis was 'Drucker – Prager' model.

V. RESULTS AND DISCUSSION

In order to explore the behavior of conventional caisson and hybrid caisson foundation supporting wind turbine, load eccentricity (e) was varied from 10 m up to 70 m above the water level. The effect of diameter on lateral load capacity was studied by varying the diameter and keeping the caisson length as constant. Figures 4 to 6 show the variation of ultimate lateral load capacity with width of wing ratio (W_w/D) for various eccentricities and for different diameters of hybrid caisson foundation.

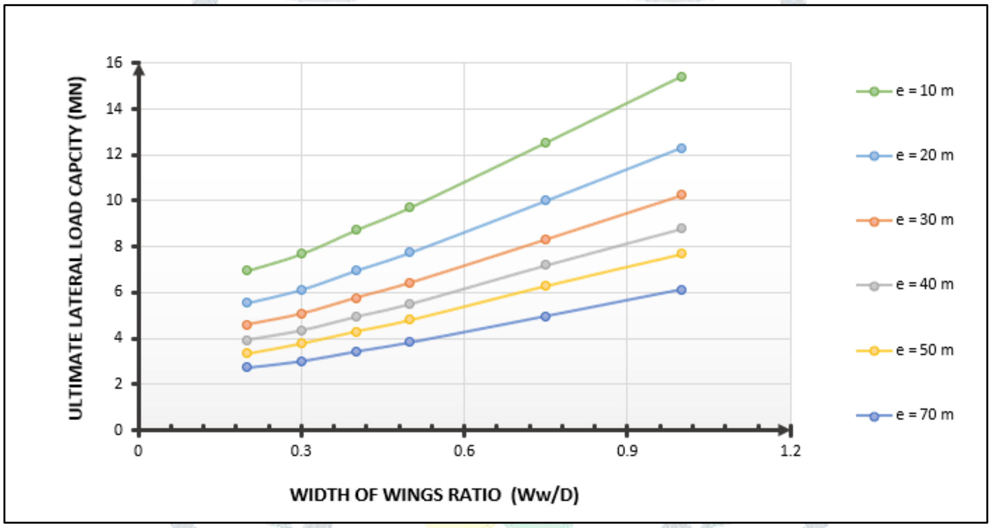

Figure 4: Ultimate Lateral Load Capacity of Hybrid Caisson Foundation (D = 6 m)

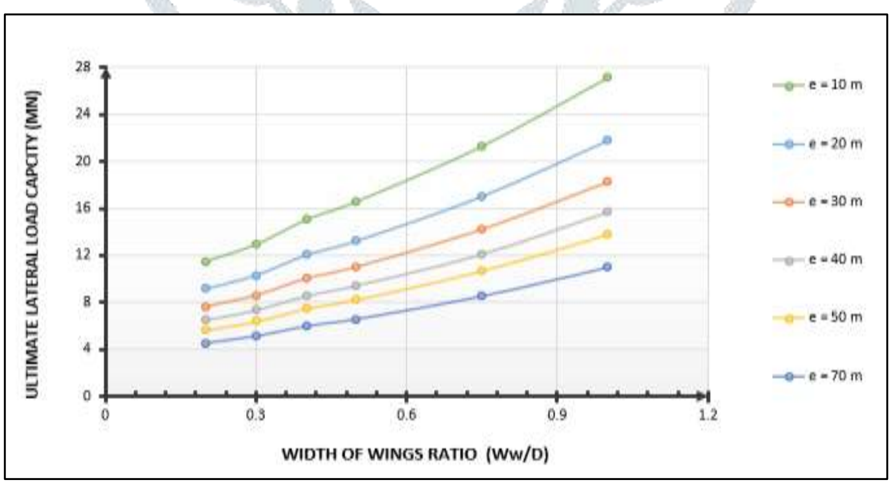

Figure 5: Ultimate Lateral Load Capacity of Hybrid Caisson Foundation (D = 8 m)

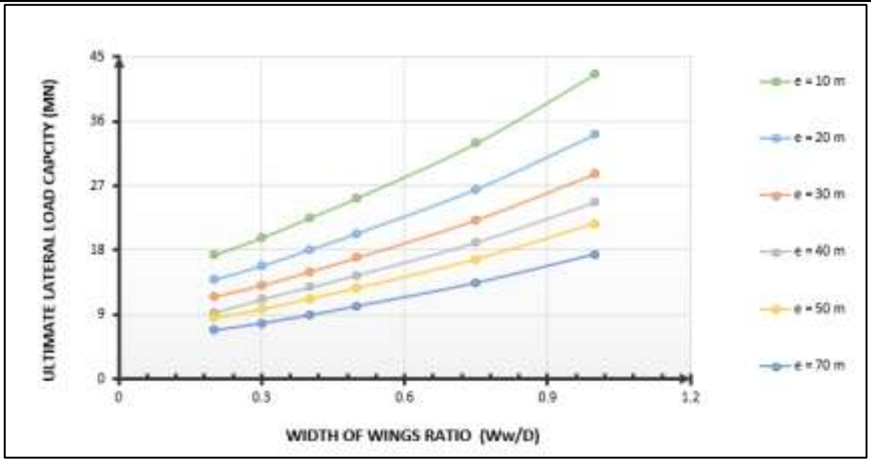

Figure 6: Ultimate Lateral Load Capacity of Hybrid Caisson Foundation (D = 10 m)

Percentage Increase in the Ultimate Lateral Load Capacity of Hybrid Caisson Foundation

It was observed that the ultimate lateral load capacity of hybrid caisson foundation is increased up to 35% to 236% as compared to conventional caisson foundation, as the width of wings is increased from 0.2D to D. Fig 7 to Fig 9 shows the percentage increase in ultimate bearing capacities for various diameters of caisson and width ratio of wings.

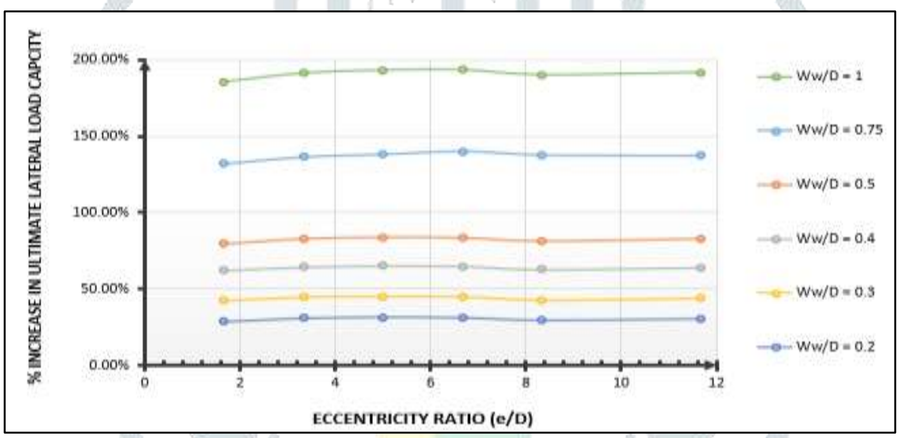

Figure 7: Percentage Increase in the Ultimate Lateral Load Capacity of Hybrid Caisson Foundation (D = 6 m)

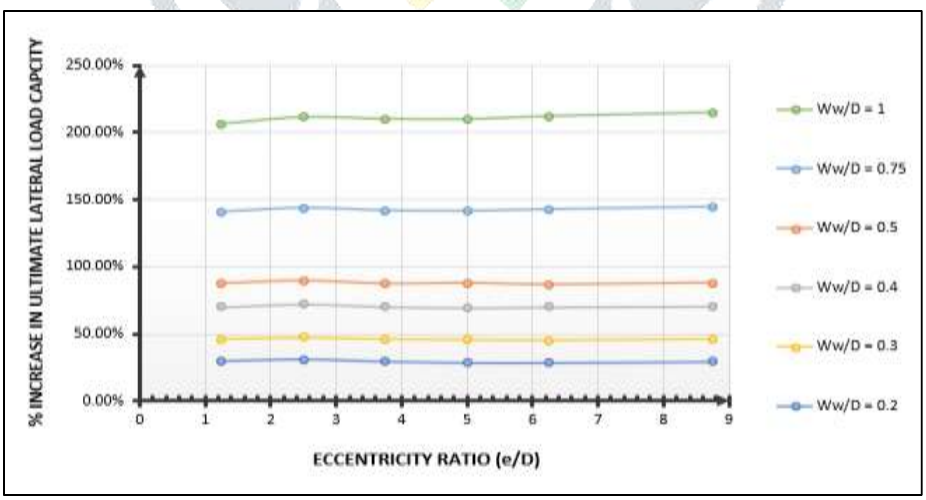

Figure 8: Percentage Increase in the Ultimate Lateral Load Capacity of Hybrid Caisson Foundation (D = 8 m)

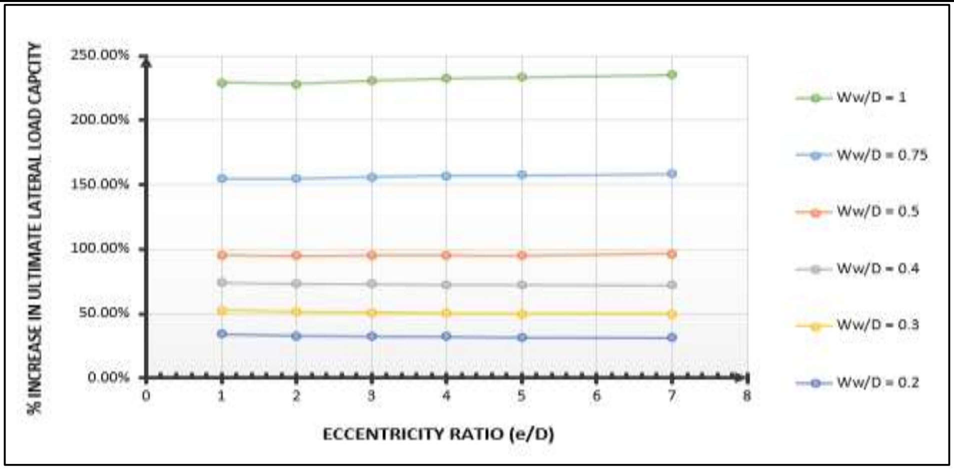

Figure 9: Percentage Increase in the Ultimate Lateral Load Capacity of Hybrid Caisson Foundation (D = 10)

Lateral Load- Overturning Moment Interaction Diagram of Conventional Caisson Foundation and Hybrid Caisson Foundations

In case of Caisson 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 caisson 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 geometry of the hybrid caisson foundation. The selected geometry of the foundation may then be analyzed in detail to confirm its stability. Figures 10 to 15 show the lateral load-overturning moment interaction diagrams for hybrid caisson foundation with wings for various wing-width ratios.

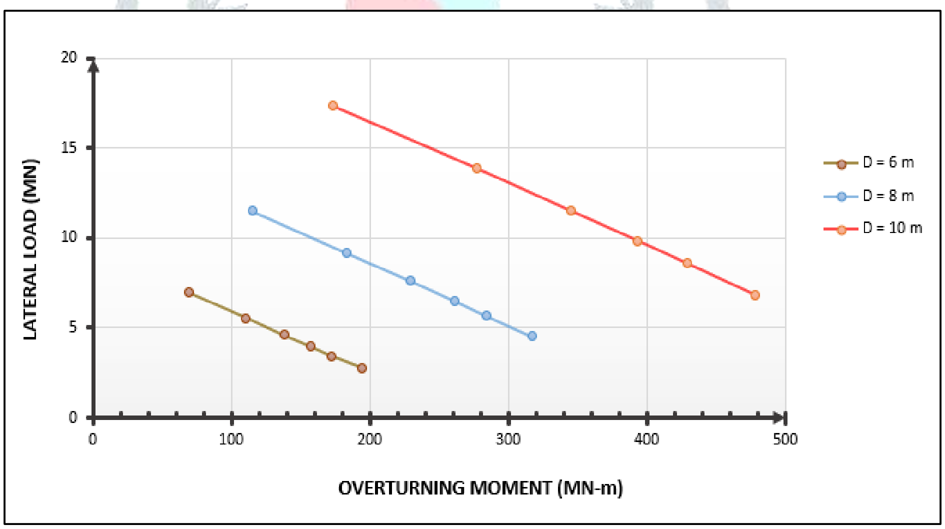

Figure 10: Lateral Load - Overturning Moment Interaction Curve for Hybrid Caisson Foundation ($W_W = 0.2D$)

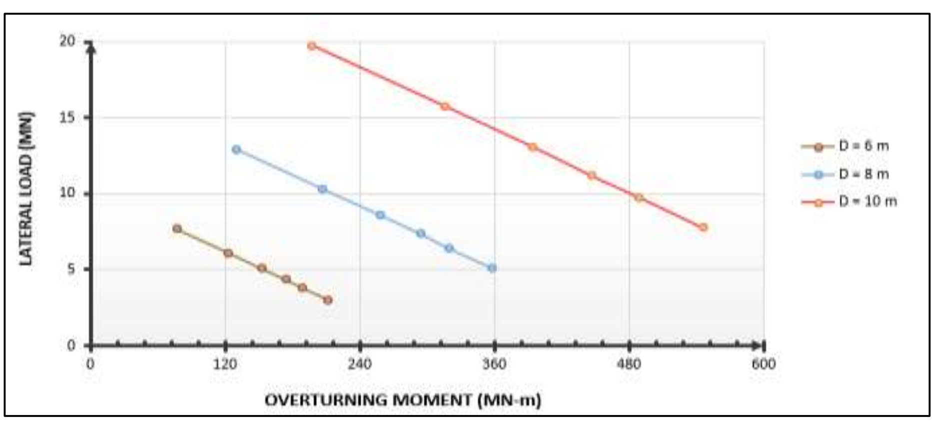

Figure 11: Lateral Load - Overturning Moment Interaction Curve for Hybrid Caisson Foundation ($W_W/D = 0.3$)

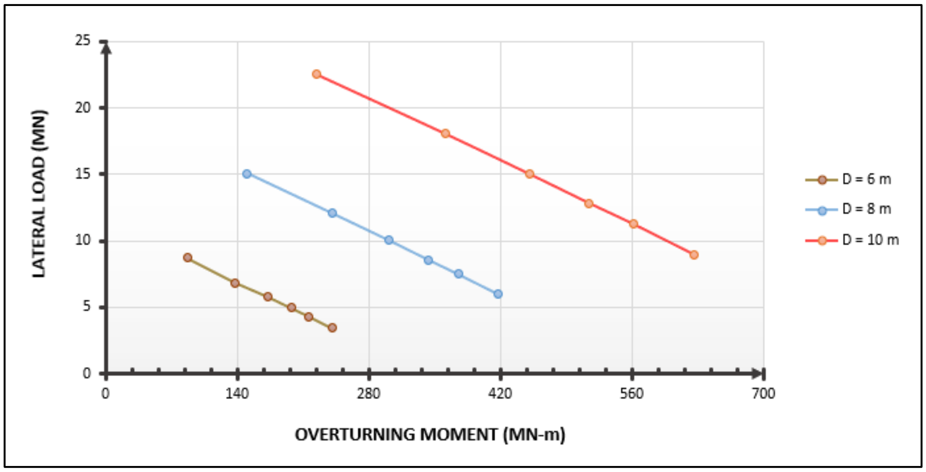

Figure 12: Lateral Load - Overturning Moment Interaction Curve for Hybrid Caisson Foundation ($W_W/D = 0.4$)

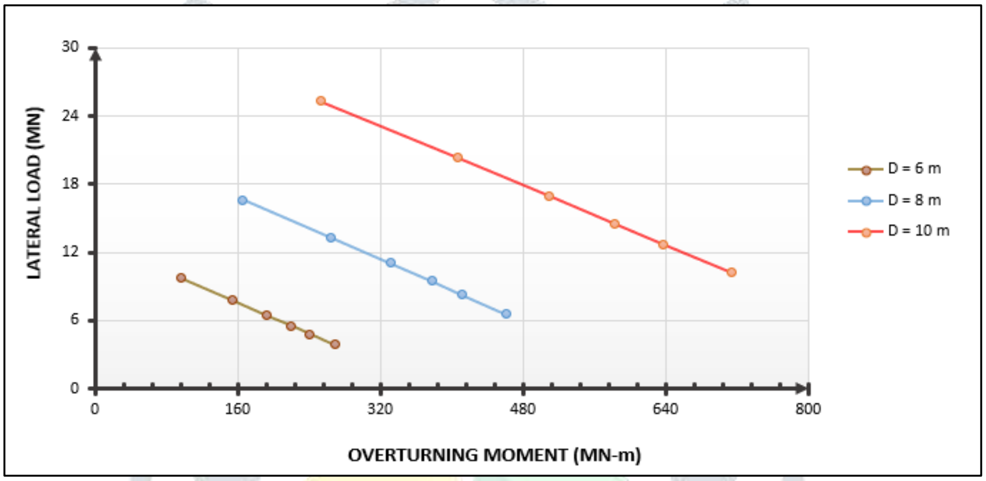

Figure 13: Lateral Load - Overturning Moment Interaction Curve for Hybrid Caisson Foundation ($W_W/D = 0.5$)

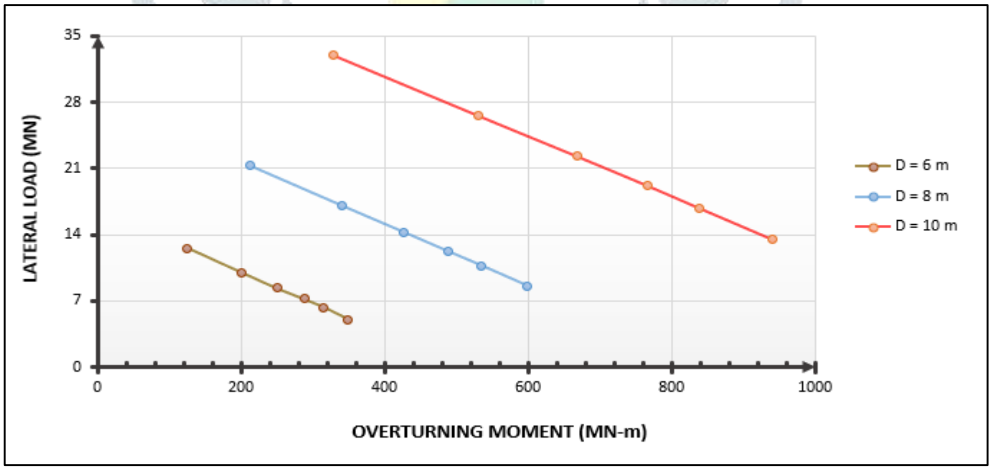

Figure 14: Lateral Load - Overturning Moment Interaction Curve for Hybrid Caisson Foundation ($W_W/D = 0.75$)

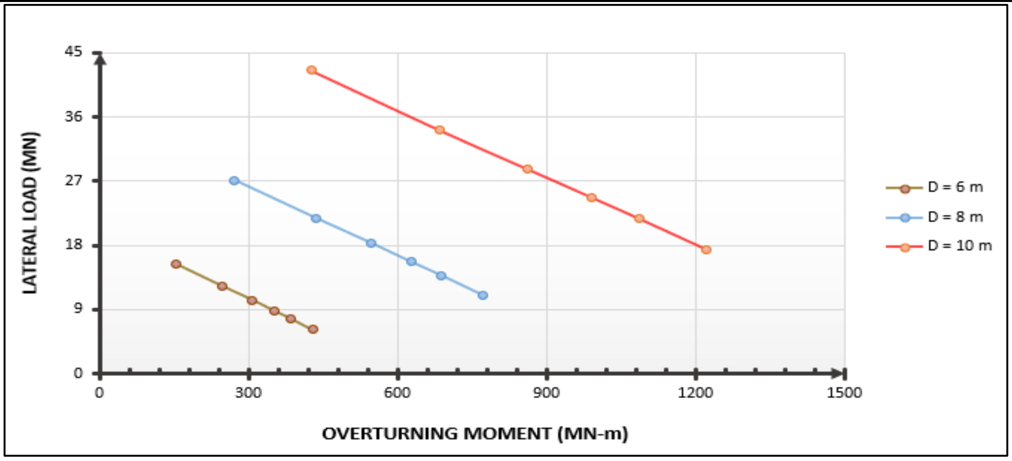

Figure 15: Lateral Load - Overturning Moment Interaction Curve for Hybrid Caisson Foundation ($W_W/D = 1$)

VI. Conclusions

Numerical analysis of conventional caisson foundation and hybrid caisson foundation with wings for offshore wind turbine structures have been carried out using MIDAS GTS 3D. Their performance in layered soil has been studied, considering different parameters. From the present study, following conclusions are drawn.

1. Lateral load capacity of conventional caisson foundation as well as of hybrid caisson foundation increases with increases in their diameter.
2. Lateral load capacity of conventional caisson foundation and of hybrid caisson foundation decreases with increase in the eccentricity of lateral load.
3. Ultimate lateral load capacity of hybrid caisson foundation is higher than conventional caisson foundation (35% to 236%).
4. In case of hybrid caisson foundation, as the wing-width ratio increases, the lateral load capacity also increases.
5. The lateral load overturning moment interaction diagram developed for hybrid foundation enables a selection of the required geometry of conventional caisson foundation and hybrid foundation for preliminary design.

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