

# Analysis of Foundation System for Offshore Wind Mill Structure

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**ABSTRACT:** In recent times, bucket foundations are being considered as an alternative supporting base for offshore wind turbines located at shallow water depths. These foundations have to resist moment and horizontal loads due to wind and wave actions. In this paper, the ultimate lateral load capacity of bucket foundation on layered sand bed is investigated numerically with finite element method. The long term 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 point of application of the resultant horizontal load at several eccentricities taking the bucket foundation lid as a point of reference. It is observed that the lateral load capacity increases with foundation size and for a given foundation geometry, lateral load capacity decreases as the point of application of load is increased. From the present analysis, lateral load- overturning moment interaction diagram are developed for bucket foundation which are useful preliminary design of bucket foundation.

**KEYWORDS:** Wind turbine, Bucket foundation, Ultimate lateral load capacity, Lateral load - overturning moment interaction diagram

## I. INTRODUCTION

Due to huge potential for meeting the increasing demand for clean and renewable energy, wind farms are moving offshore. In order to support these wind turbines, several foundation types are available. These foundations have to undergo huge lateral forces due to wind current and water and water waves apart from the vertical loads due to self weight of superstructure. Developments are taking place on the use of bucket foundations as a sound alternative for supporting wind turbines in shallow water depths. A bucket foundation is a hollow steel cylinder which is open at the bottom and capped at the top. For installation, it can be made to penetrate the seabed under its own weight and then pushed to the required depth using differential pressure applied by pumping water out of the closed top. Also lateral load – overturning moment interaction curve diagram were developed. A typical bucket foundation is as shown in Figure 1. In this study, numerical analysis was carried out using finite element software MIDAS GTS 3D to determine the ultimate lateral load capacity of bucket foundations embedded in layered sand seabed. The effects of bucket diameter and variable loose sand layer thickness on lateral load capacity were studied.

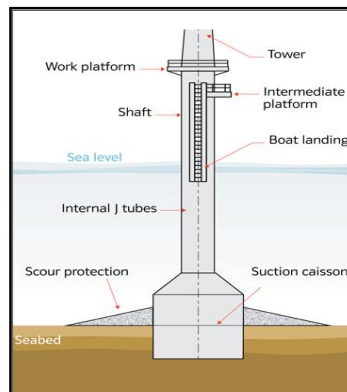


Figure 1: A Typical Bucket Foundation

## II. RELATED WORK

Yuan-Zhan Wang and Xiao Zhong<sup>1</sup> (2008) studied stability analysis for bucket foundation breakwater with finite element method. A 3D elastic-plastic finite element model was established for the stability analysis of the bucket foundation breakwater and three criterions examining the stability of the bucket foundation breakwater, which were the load-bearing capacity criterion, the load-displacement criterion, and the allowable displacement criterion, were proposed.

Khalid<sup>2</sup> *et al.* (2008) had studied the behaviour and the bearing capacity of large bucket foundations for offshore wind energy converters under horizontal and moment loading using numerical modelling. The load-deformation curves and interaction diagrams were presented for buckets with different geometries embedded in medium dense sand. They concluded that the load-moment interaction curves for the ultimate state as well as for specific deformation states could be described by nearly parallel straight lines.

Wenbai Liu<sup>3</sup> *et al.* (2011) carried out the numerical simulation of pile-bucket under mono-load of up-pulling force and horizontal force was compared and analysed, then the bearing capacity of pile-bucket foundation under up-pulling and horizontal force was simulated by ABAQUS software. They concluded that the limit horizontal displacement of pile-bucket foundation increases with the increase of up-pulling load providing a limit horizontal load. The greater horizontal load is applied, the more obvious is the effect of up-pulling load increase on horizontal displacement.

Wenbai Liu<sup>4</sup> *et al.* (2012) analysed the displacement field and stress field of the surrounding soil of the pile-bucket foundation under the multi-cycle horizontal loading using ABAQUS software. They concluded that when the load level is small, the displacement changed little with the load increased.

Wu Ke<sup>5</sup> *et al.* studied the effective stress method for the vertical load and bearing capacity characteristics of bucket foundation based on ABQUS finite element program. One simulation model is established to consider the coupled effect between foundation stress fields with pore water pressure. They concluded that the change in pore water pressure distribution affects overall stability of bucket foundation under vertical load in the foundation.

W.U. Ke<sup>6</sup> *et al.* (2013) studied the response of bucket foundation for combined Horizontal (H) and Moment (M) loading using FEM software ABAQUS for 3D finite element analysis. It was found that under horizontal loading or moment loading, the slope of load-displacement relation tended to vanish with increase of displacement and the imposed load sustains in a stable value.

T. K. Deb<sup>7</sup> *et al.* carried out numerical analysis using finite element software ABAQUS to determine the horizontal load capacity of bucket foundations embedded in medium dense sand seabed. The effects of bucket diameter, bucket length and superstructure load on horizontal load capacity were studied. It was concluded that to cause the same horizontal displacement, smaller horizontal load needs to be applied to the bucket foundation with the increase of eccentricity of applied load.

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## III. NUMERICAL ANALYSIS

The bucket foundation was considered to be supported on the layered sand deposit with upper layer of loose sand of varying thicknesses. Vertical load ( $V$ ) equal to the self-weight of structural elements and turbine was applied on the bucket foundation. Lateral load was applied at various eccentricity heights ( $e$ ) above the lid, overturning moment in the model was assigned by multiplying the horizontal load with the eccentricity height above the bucket lid surface. Various thicknesses of upper loose sand layer were considered in order to investigate the influence of lateral load and moment load on the bucket behavior. Figure 2 shows cross section of bucket foundation considered for analysis, along with notations used.

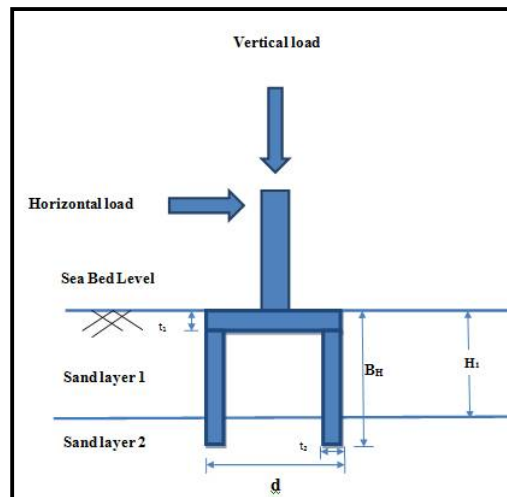


Figure 2: Cross Section of Bucket Foundation Considered For Analysis.

## IV. GEOMETRIC DETAILS OF BUCKET FOUNDATION

Several geometries were considered in order to perform numerical analysis of bucket foundations in layered sand. In the analysis, the bucket foundation is assumed to have been already installed. Analysis was carried out for a typical 5 MW offshore wind turbine considering the self-weight load of wind turbine to be 12 MN. The geometric details and thicknesses of upper loose sand layer are given at Table 1.

Table 1: Details of Layering Thicknesses and Bucket Foundation

Parameter	Values
Dimensions of bucket foundation	Top thickness of bucket $t_1 = 0.8$ m
	Bottom thickness of bucket $t_2 = 0.5$ m
	Bucket diameter $D = 6$ m, 8 m, 10 m
	Height of bucket $B_H = 15$ m
Horizontal loading	0 – 80 MN
Vertical loading	12 MN
Type of soil and thickness of soil layer	Sand 1 (loose sand) ( $H_1$ ) = $B_H/2$ , $(3 B_H)/4$ , $B_H, 1.5 B_H, 2 B_H$
	Sand 2 (dense sand) ( $H_2$ ) = semi-infinity

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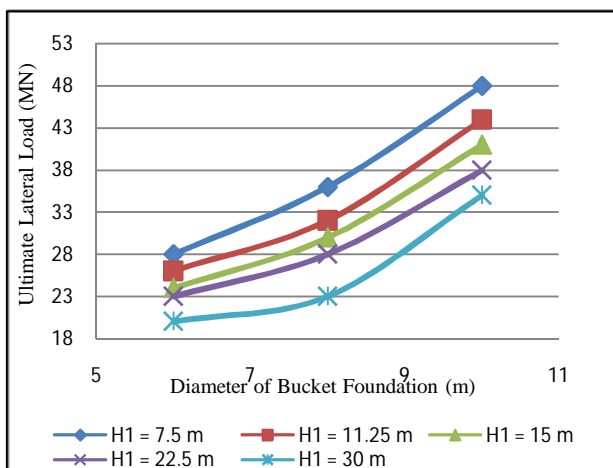
The soil bed was considered to comprise of loose sand and dense sand. Properties of sand layers are as shown in Table 2. Model selected for analysis of bucket foundation was ‘Elastic model’ having Young’s modulus  $2 \times 10^8 \text{ kN/m}^2$ , Density  $78 \text{ kN/m}^3$ , Poisson’s ratio 0.5 and for soil, the model selected for analysis was ‘Drucker – Prager’ model.

Table 2: Properties assigned to soil layer for analysis.

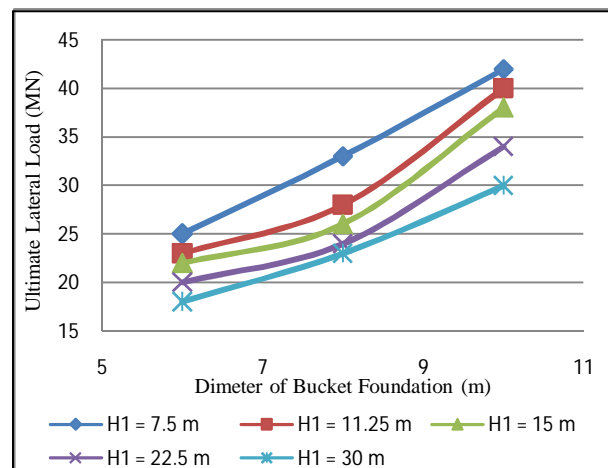
Properties	Unit weight	Young’s modulus	Poisson’s ratio	Angle of internal friction	Cohesion
Symbols	$\gamma$	E	$\nu$	$\phi$	C
Unit	$\text{kN/m}^3$	kPa		degree	kPa
Loose Sand	22	30,000	0.3	33°	0.05
Dense Sand	24	35,000	0.3	35°	0.05

## V. RESULTS AND DISCUSSION

In order to explore the behaviour of bucket foundation supporting wind turbine, load combinations were varied between pure lateral loading (no eccentricity) and up to 100 m above the bucket lid. The effect of bucket diameter on lateral load capacity was studied by varying the diameter and keeping the bucket length as constant. Figures 3 to 5 show the variation of ultimate lateral load capacity with diameter of bucket foundation for various eccentricities under superstructure loads of 12 MN, and various thicknesses of upper layer of sand ( $H_1$ ). The main purpose of plotting ultimate lateral load capacity curves for Bucket foundation is to determine ultimate lateral load for a bucket foundation of particular diameter.

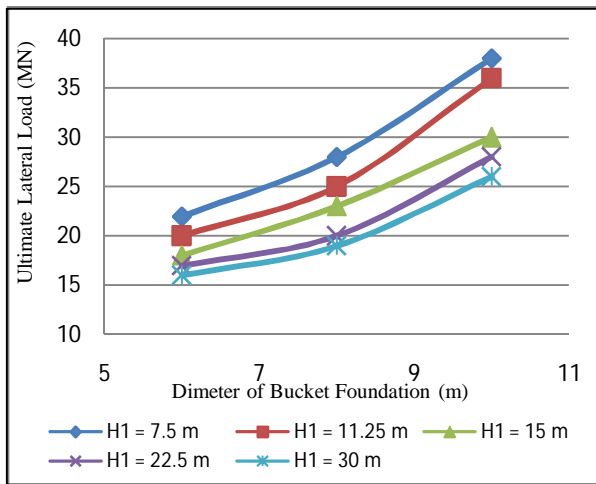


(a) e = 0 meter

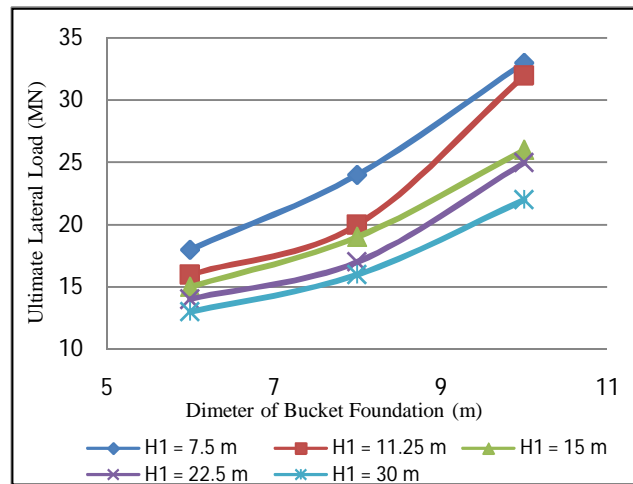


(b) e = 5 meter

Figure 3(a – b): Ultimate Lateral Load Capacity of Bucket foundation in Layered Sand for Different Eccentricities

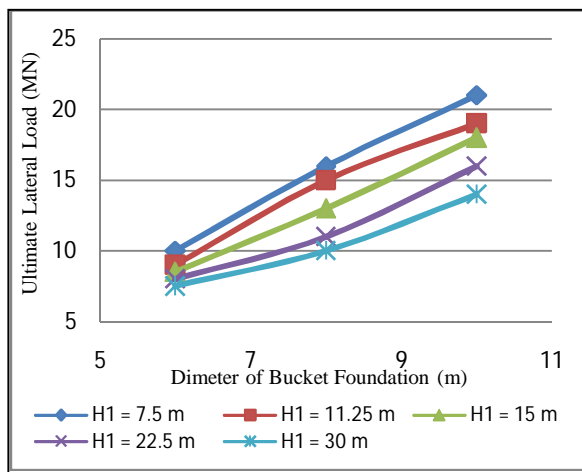


(c) e = 10 meter

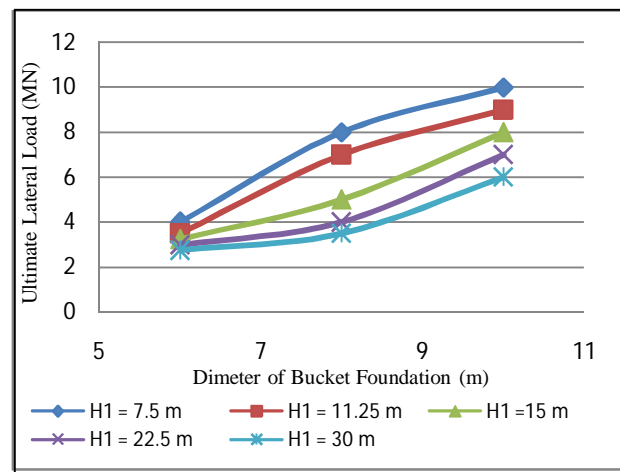


(d) e = 20 meter

Figure 4(c – d): Ultimate Lateral Load Capacity of Bucket foundation in Layered Sand for Different Eccentricities



(e) e = 40 meter



(f) e = 80 meter

Figure 5(e – f): Ultimate Lateral Load Capacity of Bucket foundation in Layered Sand for Different Eccentricities

### Lateral Load- overturning Moment Interaction Diagram of Bucket Foundation

The moment acting on the bucket foundation can be obtained from the Lateral load and the respective eccentricity. For any geometry of bucket foundation and different thickness of upper loose sand layer, a lateral load- overturning moment interaction diagram can be constructed. The interaction diagram consists of several plots between lateral load and moment corresponding to failure condition. Any combination of lateral load and overturning moment, located outside the envelope of respective Bucket geometry, will cause instability of Bucket foundation. In that case, the next larger geometry can be selected in a step wise manner till the stability requirement is fulfilled. Figure 6 to 8 shows the

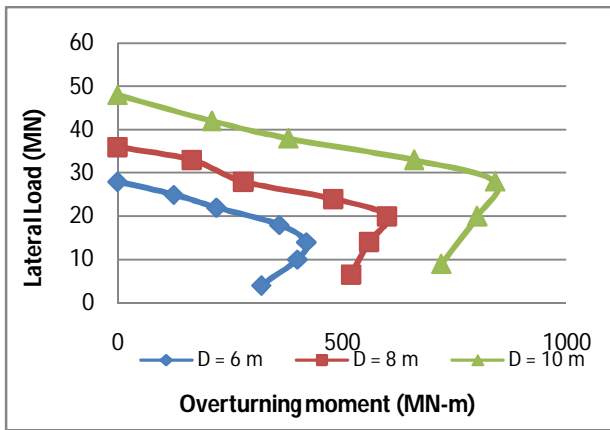
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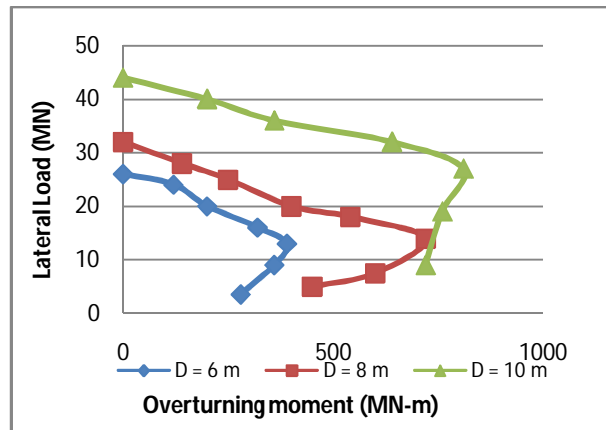
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lateral load- overturning moment interaction diagram with diameter of bucket foundation with respect to varying upper loose sand layer thickness under superstructure loads of 12 MN.

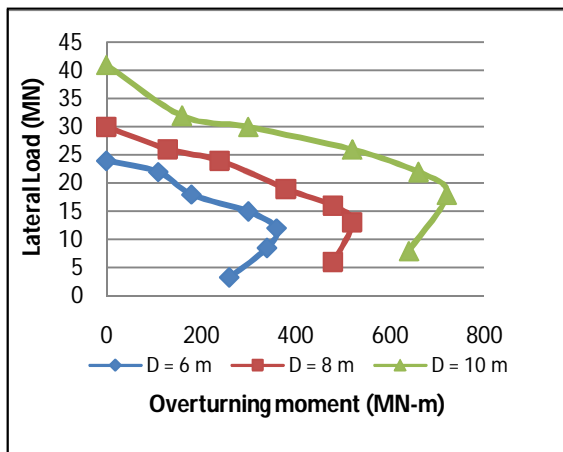


(a)  $H_1 = 7.5$  m

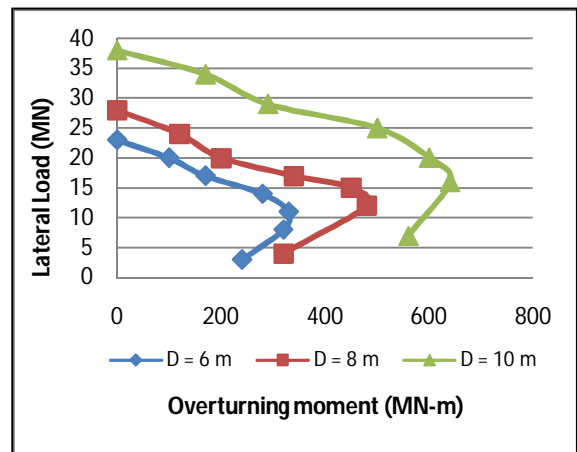


(b)  $H_1 = 11.25$  m

Figure 6 (a - b): Lateral Load - Overturning Moment Interaction Curve for Bucket Foundation for Various Depth of Loose Sand Layer



(c)  $H_1 = 15$  m



(d)  $H_1 = 22.5$  m

Figure 7 (c - d): Lateral Load - Overturning Moment Interaction Curve for Bucket Foundation for Various Depth of Loose Sand Layer

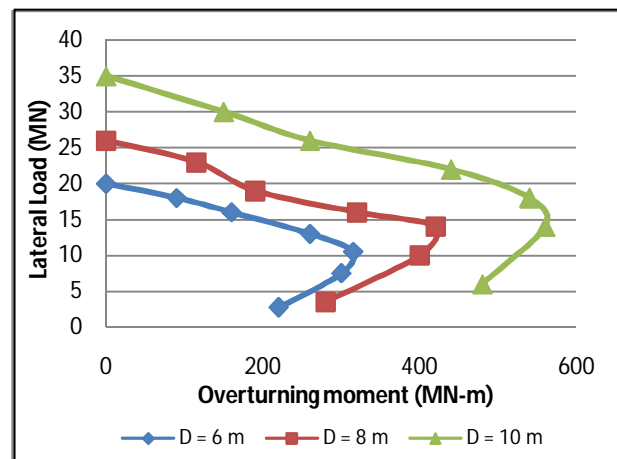


Figure 8: Lateral Load - Overturning Moment Interaction Curve for Bucket Foundation ( $H_1 = 30$  m)

## VI. CONCLUSIONS

Bucket Foundation for offshore windmill structures have been analysed using MIDAS GTS 3D. Behaviour of Bucket foundation has been studied in layered sand bed considering different parameters. From the present study, following conclusions are drawn.

1. Lateral load capacity of Bucket foundation in case of layered sand bed decreases with increase in depth of upper loose sand layer
2. In case of multilayer sand bed, the effect of lower dense sand layer diminishes when the depth of upper loose sand layer becomes greater than 10 – 15 m below the bottom of Bucket foundation.
3. The lateral load overturning moment interaction diagram developed for Bucket foundation enables a selection of the required geometry of Bucket foundation for preliminary design.
4. From the ultimate lateral load capacity layered sand bed, ultimate lateral load capacity can be evaluated for preliminary design of Bucket foundation.

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