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Numerical Analysis of Bucket Foundations under Eccentric Lateral Loading in Medium Dense Sand

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Abstract: Wind turbines located near sea shores can be supported by several types of foundation systems amongst which bucket foundation is a sound alternative at shallow water depths. The vertical superstructure load acting on the bucket foundation is usually smaller in comparison to the lateral and moment loads acting on it. Hence, it becomes necessary to investigate the lateral capacity of the foundation under offshore loading conditions due to the forces arising from wind and water currents acting at several heights on the turbine, in order to ensure that the serviceability criteria are satisfied under its intended design period. In this paper, numerical analysis of bucket foundation in medium dense sand is carried out to investigate the response under lateral and moment load acting on it at several eccentricities considering non-linear behaviour of soil. From the results, ultimate and allowable load carrying capacities of the bucket foundation are presented in the form of interaction diagrams.

Keywords: *Wind turbine, Bucket foundation, Lateral capacity, Numerical modelling*

1. Introduction

Wind energy is one of the most promising renewable energy sources which can meet the increasing global requirement of electricity. As wind is generally steadier and stronger in offshore environment than in onshore environment, wind energy farms are moving offshore. These wind turbines under offshore conditions have to resist forces originating from water waves and winds acting at hub heights and at several locations in the stem, which are finally transferred to the supporting foundation system. Several foundation systems are feasible out of which bucket foundation is also gaining popularity.

A bucket foundation is a hollow steel cylinder which is open at the bottom and capped at the top. Generally, a monopod bucket foundation is suitable for water depth up to 40 m. Behaviour of bucket foundation under combined loading has been investigated through laboratory tests, field tests and numerical finite element analyses.

From laboratory experiments, combined response of vertical, horizontal and moment loads were studied in sandy bed considering model bucket foundations taking plasticity behaviour into account and the behaviour of yield surface with the skirt depth of bucket foundations was explored [1]. Design formulations were proposed to evaluate size of monopod and multiple bucket foundations along with their spacing in sandy soil based on the previous laboratory tests [2]. The effects of installation on the vertical and moment capacity of bucket foundation was investigated by conducting laboratory tests on several scaled model bucket foundations, where the buckets were installed by suction and by pushing in saturated sand beds [3].

Large scale model tests on bucket foundations were carried in saturated silts by installing the bucket with suction considering different penetration rates. Lateral loads were applied at several eccentricities above the bucket lid in order to investigate the deformation mechanism and soil structure interaction of bucket [4]. Based on laboratory test results, strain-hardening criterion was developed for bucket foundations subjected to combined loads at different eccentricities and vertical loads, embedded in dense saturated sand with different embedment ratios [5, 6].

Studies on installation of bucket foundation by self-weight and by suction penetration and their behaviour under static and cyclic loading conditions for field and laboratory models founded in sandy and clayey soil were reported [7]. Field investigations were carried to understand the behaviour of bucket foundations in clay. Other field tests were conducted at Bothkennar on buckets for designing monopod and tetrapod foundations in clays. Investigations were carried out considering cyclic horizontal loading and quasi-static loading on monopod bucket foundation. The behaviour of tetrapod foundation was observed by applying vertical load as the self-weight of the superstructure followed by the application of cyclic inclined and pullout loads [8]. Isben at al. [9] discussed about the full-scale field installation of prototype bucket foundation and its performance under static loading and in service performance.

The behaviour of large scale prototype bucket foundation was studied numerically in order to develop insight into the deformation behaviour under offshore loading conditions. The effect of skirt flexibility on load-displacement behaviour of bucket foundation under combined loading was studied numerically using FEA. Based on the numerical study, the dimensionless stiffness of the foundations to the relative stiffness of the skirts were presented in terms of charts [10]. From numerical studies carried on lateral response of large diameter buckets, the ultimate lateral loads at failure and overturning moments were utilized to develop interaction diagrams [11]. The behaviour of bucket foundations in clayey soil were analyzed numerically and based on the numerical behaviour, formulation of horizontal bearing capacity was developed utilizing limit equilibrium method [12]. Drained behaviour of bucket foundation was studied numerically under several eccentric loads by taking non-linearity of sands into account. Based on the response, normalized equations were proposed to determine ultimate lateral capacity and initial stiffness of bucket foundations [13]. The failure condition of several bucket foundations were studied numerically considering several aspect ratios and expressions were developed for ultimate lateral capacity utilizing limit equilibrium method [14].

In this paper, three dimensional finite element analyses was carried out in order to investigate the behaviour of monopod bucket foundation embedded in medium dense sand considering the effect of soil non-linearity into account. The resultant force arising due to wind and water waves on the turbine was simulated by considering eccentric displacement controlled load acting vertically above the lid of the bucket taking the lid as reference. The variation of lateral capacity of the bucket foundation considering several load eccentricities, and the variation of capacity with superstructure loads and sizes of bucket foundations were studied.

2. Numerical Analysis of the Bucket Foundation

The numerical behaviour of bucket foundation was modelled using ABAQUS. Various load combinations were applied in to simulate the offshore loading conditions in order to investigate the influence of lateral load and overturning moment behaviour of bucket foundation under drained conditions in medium dense sand bed.

2.1. Geometric and Loading details of Bucket

The behaviour of bucket foundation in medium dense sand was studied by considering several geometries (D = Diameter and L = Length) and superstructure loads are presented in Table 1.

Table 1: *Geometric and loading details*

Geometric Details	Superstructure load, V (MN)	Load Eccentricity (m)
D = 12 m, L = 12 m	10, 20, 30	0, 2.5, 5, 10, 20, 30, 40,100, Moment
D = 12 m, L = 15 m	10	0, 2.5, 5, 10, 20, 30, 40, 100, Moment
D = 12 m, L = 18 m	10	0, 2.5, 5, 10, 20, 30, 40, 100, Moment

2.2. Non-Linear Behaviour of Soil

The soil bed was considered as medium dense sand and nonlinear behaviour of soil was simulated by considering stress dependent oedometric modulus of elasticity (E_s). The submerged unit weight, internal friction angle and dilation angle of the soil were taken as 9 kN/m^3, 35° and 5° respectively. Mohr-Coulomb elasto-plastic model with non-associative flow rule was considered in order to model non-linear soil behaviour.

$$E_s = \kappa.\sigma_{at}.\left(\frac{\sigma_m}{\sigma_{at}}\right)^{\lambda} \quad (1)$$

where, σ_{at} is atmospheric pressure expressed in the same pressure units as E_s, σ_m is mean principal stress, κ is an empirical parameter which determines the soil stiffness at the reference stress state, and λ represents the exponent that determines stress dependency of soil stiffness.

2.3. Finite Element Model

A bucket foundation installed in medium dense sand was simulated in this study. The disturbance of the soil due to installation of the bucket foundation was not considering in the analysis. Considering the symmetry, only half model of soil and bucket foundation was modelled. The soil domain was established by conducting several trials, such that there were no significant boundary effects on lateral load response of bucket foundation. Boundary conditions were applied by constraining translation in all directions at the base of the model. Along the periphery, horizontal displacements were constrained and at the plane of symmetry, displacement normal to the plane was constrained.

The soil and bucket foundations were discretized using 8 noded brick element with reduced integration. The discretized model of bucket foundation embedded in soil domain is shown in Figure 1. Eccentric loads were applied as displacements at several heights above the bucket lid considering bucket lid as the reference.

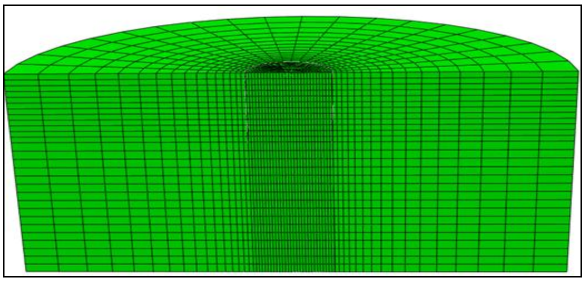

Figure 1 *Discretized model of bucket foundation embedded in medium dense sand (D = 12 m, L = 12 m, V = 10 MN)*

3. Results and Discussion

In general, when a foundation is loaded, failure or ultimate state is assumed to have been reached when there is a continuous increase in settlement or deflection without any further increase of load. In this study, for the monopod bucket foundations, ultimate or failure point was assumed as the lateral deflection at bucket head corresponding to 10% of its diameter, which would be sufficiently large to cause stability problems for the wind turbine.

3.1. Lateral Load Deformation and Moment-Rotation Behaviour of Bucket Foundation

Due to the application of lateral load, significant deformation of the bucket foundation-soil system was observed at failure/ultimate condition. The deformed configuration of bucket foundation embedded in soil domain at failure is shown in Figure 2(a) for a given geometry and superstructure load.

In the enlarged view of deformed configuration of the bucket foundation as it approached failure, as shown in Figure 2(b), separation between bucket lid and soil plug was observed. The separation was accompanied by formation of heave which can be seen in the right top corner of the soil plug, as compared to the left corner of the plug where a minor depression was observed. Further, the bucket lid at the left side moved downward while the lid at the right side moved upward, and the adjacent seabed surface in the passive zone at the right side was slightly upheaved while in the active zone at the left side, the ground surface has subsided.

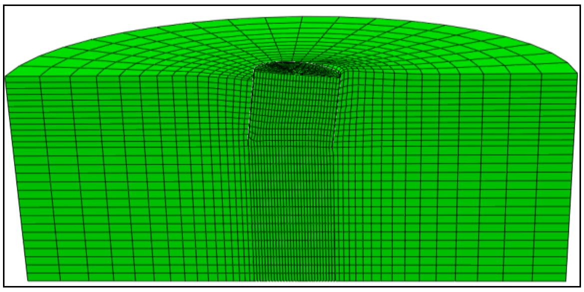

Figure 2(a). *Deformed configuration of bucket foundation at failure (D = 12 m, L = 12 m, V = 10 MN)*

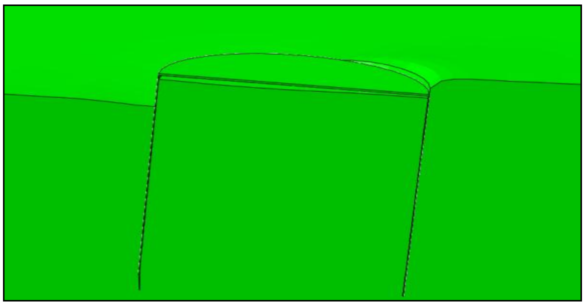

Figure 2(b). *Enlarged view of deformed configuration of bucket foundation at failure (D = 12 m, L = 12 m, V = 10 MN)*

From the results obtained from simulation of lateral load at several eccentricities for the same geometry and superstructure load, lateral load-deformation and overturning moment-rotation plots are presented in Figures 3 and 4. In Figure 3, the lateral load carrying capacity of the bucket foundation is observed to decrease with the increase of eccentric load. From Figure 4, the moment capacity is observed to increases with the increase of eccentric load.

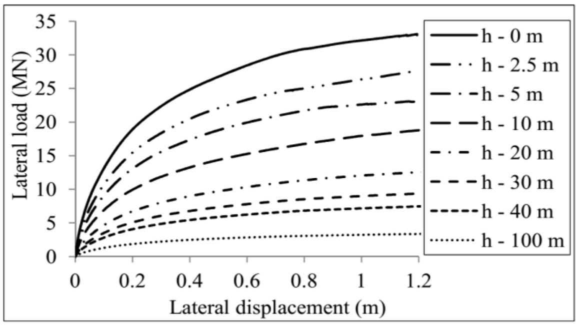

Figure 3 *Lateral load-displacement plot for bucket foundation in medium dense sand (D = 12 m, L = 12 m, V = 10 MN)*

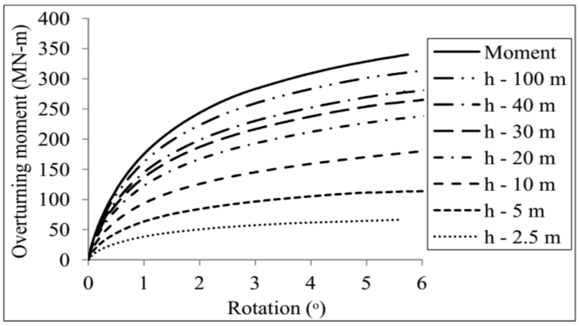

Figure 4 *Overturning moment-rotation plot for bucket foundation in medium dense sand (D = 12 m, L = 12 m, V = 10 MN)*

3.2. Lateral Stress and Depth of Point of Rotation for Bucket Foundation

In order to study the lateral stress along the bucket length at failure for the same geometry and superstructure load, the length was categorized into four surfaces namely left exterior (LE), left interior (LI), right exterior (RE) and right interior (RI) as shown in Figure 5.

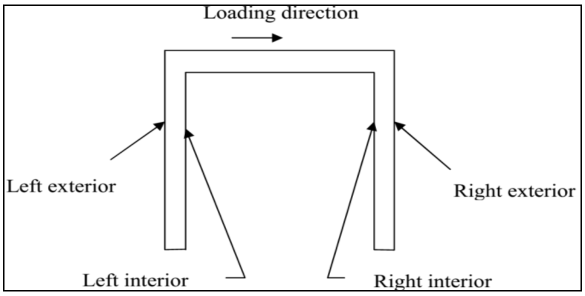

Figure 5 *Schematic diagram representing length in terms of four different location for lateral stress determination*

As shown in Figures 6(b) and 6(c), the lateral stresses along left interior and right exterior surface of bucket length shows parabolic distribution of stresses along the length of caisson up to certain depth along the passive side. These stresses increase up to a certain depth of bucket and gradually decrease at the same load level. Beyond that depth, the stresses are seen to increase along left exterior and right interior surface along the active side or against the direction of loading as shown in Figures 6(a) and 6(d).

The depth of the bucket along which the lateral stress in the passive surface gradually reduces and continues to increase along the active length of bucket, is considered as the point of rotation for the bucket foundation.

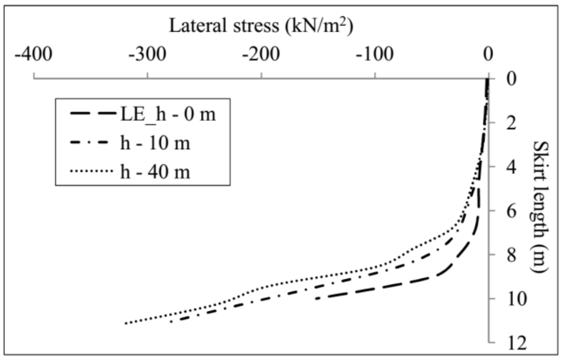

Figure 6(a). *Lateral stress along left exterior surface of bucket (D = 12 m, L = 12 m, V = 10 MN)*

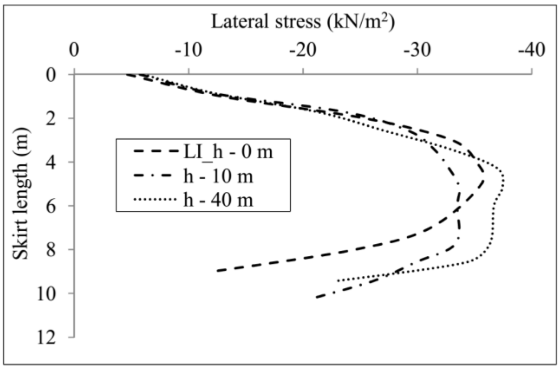

Figure 6(b). *Lateral stress along left interior surface of bucket (D = 12 m, L = 12 m, V = 10 MN)*

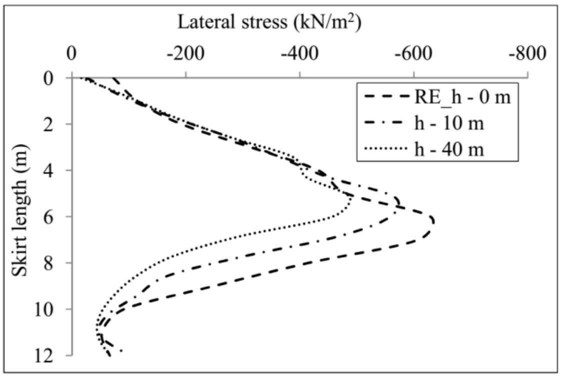

Figure 6(c). *Lateral stress along right exterior surface of bucket (D = 12 m, L = 12 m, V = 10 MN)*

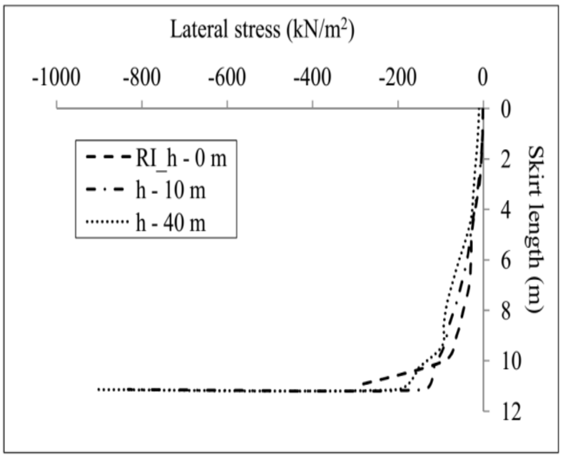

Figure 6(d). *Lateral stress along right interior surface of bucket (D = 12 m, L = 12 m, V = 10 MN)*

For the same geometry and superstructure load, the variations of lateral displacement of the right exterior surface with applied eccentric loads are shown in Figure 7. From the figure, the depth of point of rotation is observed to decrease with the increase of eccentricity.

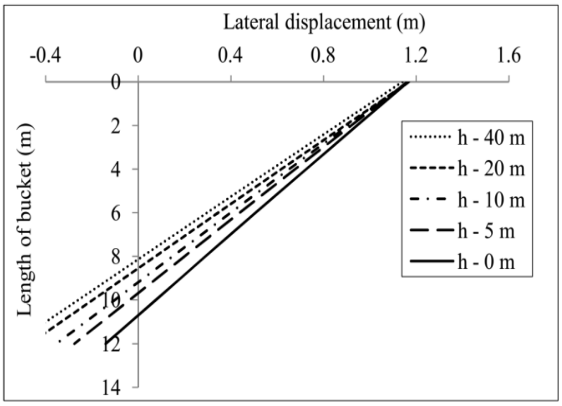

Figure 7 *Variation of lateral displacement at right exterior surface of bucket foundation with eccentric loading (D = 12 m, L = 12 m, V = 10 MN)*

3.3. Effect of Superstructure Load

The effect of superstructure load on lateral capacity and initial stiffness of bucket foundation was determined for the same geometry.

3.3.1. Lateral capacity at failure

The variation of ultimate lateral load capacity with superstructure load at several eccentric loading conditions is shown in Figure 8. The ultimate capacity has been observed to increase with superstructure load and there is a near linear relationship between superstructure load and lateral load at failure, for all the eccentric loads. The percentage increase of ultimate lateral capacity lied in the range between 8-15% when the superstructure load was increased from 10 MN to 20 MN. When the superstructure load was increased from 10 MN to 30 MN, the percentage increase lied in the range between 15-18%.

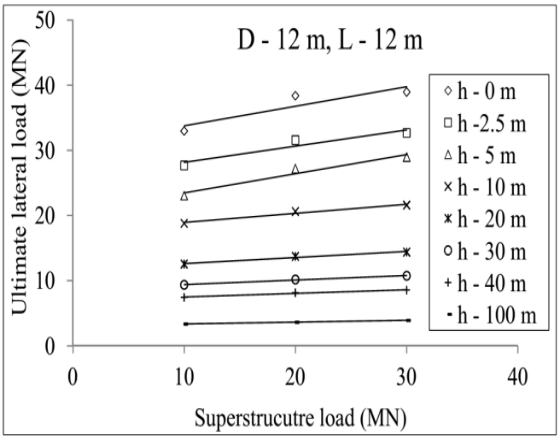

Figure 8 *Variation of ultimate lateral capacity with superstructure load*

3.3.2. Initial stiffness of the foundation

The initial stiffness is one of the main concerns for the design of bucket foundation. In this study, initial stiffness is obtained from the lateral load-rotation plot as the slope of the line drawn from origin to rotation of 0.5° [15]. The effect of superstructure load on initial stiffness is minimal and the initial stiffness is observed to decrease with the increase of eccentricity as shown in Figure 9. The effect of superstructure load on initial stiffness becomes insignificant from an eccentricity beyond 40 m.

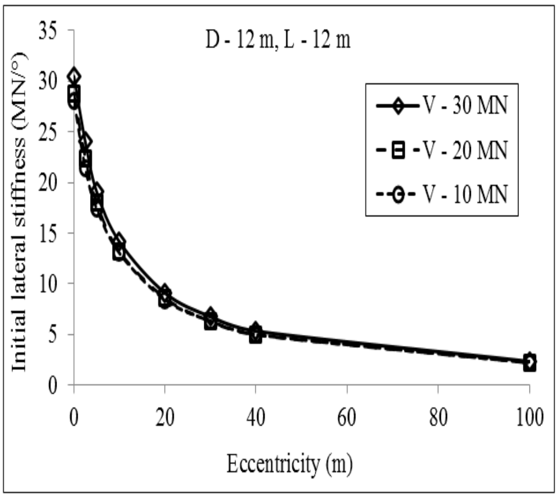

Figure 9 *Effect of superstructure load on initial stiffness*

3.4. Effect of Bucket Length on Lateral Capacity

The behaviour of lateral load capacity of bucket foundation was studied by varying the bucket length for a superstructure load of 10 MN under several eccentric loads as shown in Figure 10. The percentage increase of ultimate lateral capacity ranges between 40-60% when the length of the bucket was increased from 12 m to 15 m. For the same superstructure load, when the bucket length was increased from 12 m to 18 m, the percentage increase of capacity ranges between 65-120%.

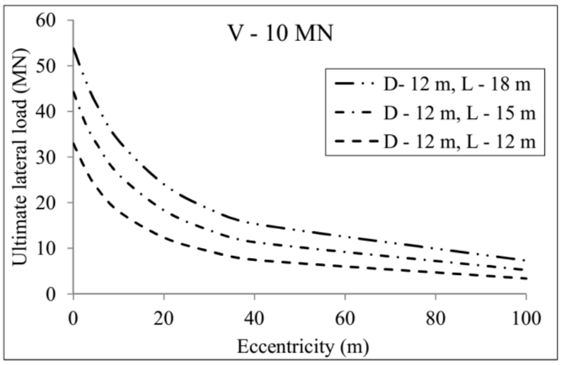

Figure 10 *Effect of bucket length on lateral capacity of bucket foundation*

3.5. Lateral Load-Overturning Moment Interaction Diagram

The capacity of bucket foundation can be better described by plotting lateral load-overturning moment interaction diagrams as shown in Figures 11(a) and 11(b)**.** From the interaction diagrams, lateral capacity of bucket is observed to increase with the increase of length of bucket. The shape of the interaction curves are seen to remain almost linear for all the three lengths.

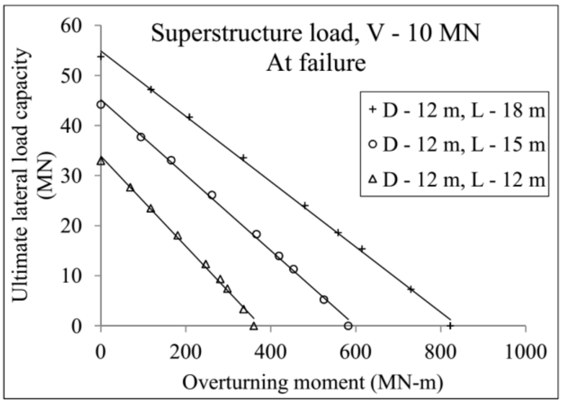

Figure 11(a). *Lateral load-overturning moment interaction diagram at failure*

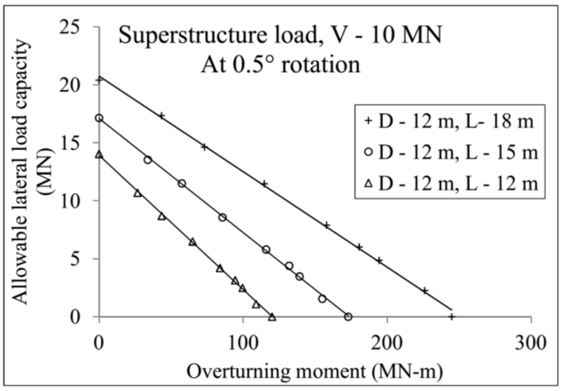

Figure 11(b). *Lateral load-overturning moment interaction diagram at 0.5° rotation*

From stability point of view, deflection control of foundation is vitally important in order to ensure the normal functioning of the offshore wind turbine under its design period. The deflection corresponding to the maximum angular rotation of the wind tower may be limited by serviceability constraint of the wind tower [16]. The German standard uses 0.5° as limiting value of angular rotation of offshore wind turbines [17]. In this paper, deflection at bucket head less than or equal to a rotation value of 0.5° was considered as permissible. The interaction diagrams of lateral load capacity at 0.5° rotation and corresponding moment are shown in Figure 11(b), and any combination of lateral load and moment within the respective interaction diagram would be considered as safe for the bucket foundation system.

4. Conclusions

Three-dimensional numerical analysis was carried out using finite element method to determine the lateral load capacity of bucket foundation in medium dense sand, subjected to several eccentric loadings. The following conclusions can be drawn from the study:

1) The load capacity of bucket foundation increases with the increase of vertical load and bucket length for a given eccentricity. The lateral load capacity decreases with load eccentricity.
2) The point along the bucket length, where the lateral stress gradually decreases from passive to active side is considered as the point of rotation of bucket. The depth of point of bucket foundation at failure is seen to decrease with the eccentric loading.
3) A comparison of initial stiffness of bucket under several superstructure loads indicates that the effect on the change of initial stiffness with vertical load becomes insignificant as the load eccentricity is increased.
4) The ultimate lateral capacity is found to follow near linear variation with superstructure load for all eccentricities.

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