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BEHAVIOUR OF BUCKET FOUNDATIONS IN SANDY BED SUBJECTED TO ECCENTRIC LATERAL LOADING

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ABSTRACT: Monopod bucket foundations supporting offshore wind turbines have to resist high overturning moment due to water waves and wind currents acting laterally on the structure above the seabed level. Hence, the stability of the bucket foundation system is governed by the lateral load-displacement behaviour. In this study, the drained behaviour of monopod bucket foundation under monotonic eccentric lateral loads has been investigated using finite element analysis. The influence of bucket dimensions and wind turbine self-weight on the lateral load response of the foundation system was also studied. The ultimate lateral load capacity of the bucket foundation has been observed to decrease with the increase of load eccentricity, but it increases marginally with self-weight and noticeably with the foundation size. For a preliminary design of the bucket foundation, the permissible loading state is presented as a lateral load-overturning moment interaction diagram for different geometries.

Keywords: bucket foundation, lateral capacity, offshore wind turbine, eccentricity, sandy site

1 INTRODUCTION

A bucket foundation is a hollow steel or concrete cylinder which is open at the bottom and capped at the top. Generally, a monopod bucket foundation is suitable in water depths near shore up to about 30 m. Under offshore conditions, these monopod bucket foundations have to resist the combined action of vertical and eccentric lateral loads. The overturning moment produced from the eccentric lateral load is a critical aspect in the design of monopod bucket foundation.

Laboratory, field and numerical investigations have been carried out by several researchers in order to assess the behaviour of monopod bucket foundation. The response of bucket foundation under monotonic and cyclic lateral load was investigated by conducting laboratory tests in dry sand bed (Byrne and Houlsby, 1999) and in oil-saturated sand bed (Byrne and Houlsby, 2004). Kelly et al. (2006) **c**arried out laboratory tests on bucket foundations in sand and clayey soils and compared moment capacity and stiffness with results from their own field tests.

Sun et al. (2009) studied the horizontal bearing capacity of bucket foundation embedded in clay numerically based on three-dimensional finite element method and developed a formulation for horizontal bearing capacity using limit equilibrium method. Achmus et al. (2013) investigated the lateral response of bucket foundations numerically using finite element analysis by varying lateral load eccentricities and superstructure loads for several bucket geometries. Ibsen et al. (2015) carried out laboratory tests in order to determine the effect of embedment on strain hardening behaviour of model buckets founded in saturated dense sands under combined loading condition.

In this study, numerical analyses have been carried out on prototype dimensions of monopod bucket foundations embedded in very dense sand bed under combined loading conditions. Based on the numerical analyses, the response of bucket foundation geometries under eccentric lateral loads and superstructure loads are presented herein.

2 NUMERICAL ANALYSIS

The response of bucket foundation under combined loading is simulated numerically using ABAQUS. The bucket foundation and soil domain have been discretized into 480 and 9568 numbers of 8 noded brick elements respectively, as shown in Figure 1. Reduced integration scheme has been utilized.

The non-linear behaviour of soil is simulated using Mohr-Coulomb elastoplastic material model with stress dependent oedometric modulus of elasticity (E_s):

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

where, σ_{at} is atmospheric pressure, and σ_m is mean principal stress. κ and λ are oedemetric stiffness parameters having values of 600 and 0.55. The submerged unit weight, internal friction angle and dilation angle of the soil are taken as 11 kN/m^3, 40° and 10° respectively. The bucket geometries and loading details are presented in Table 1.

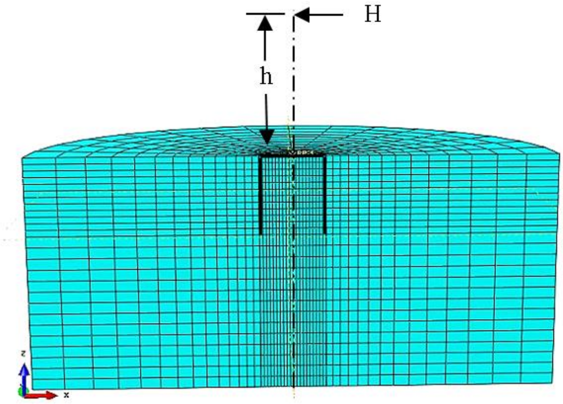

Fig. 1 Discretized bucket foundation soil system

Table 1 Geometric details of bucket foundation considered for the analysis

Geometric details	Superstructure load, V (MN)	Load eccentricity, h (m)
D = 10 m, L = 12 m D = 8 m, L = 12 m D = 6 m, L = 12 m	30, 20, 10	0, 2.5, 5, 10, 20, 30, 40,100, Pure moment

3 RESULTS AND DISCUSSION

3.1 Lateral Capacity of Bucket Foundation

In this study, the ultimate lateral capacity of the bucket foundation at any eccentricity is taken as the lateral load which causes displacement of bucket lid equal to 10% of its diameter. Figures 2(a), 2(b) & 2(c) respectively show typical lateral load-displacement response, lateral load-rotation response and overturning moment-rotation response for a bucket foundation of 10 m diameter, up to ultimate condition corresponding to 1 m displacement.

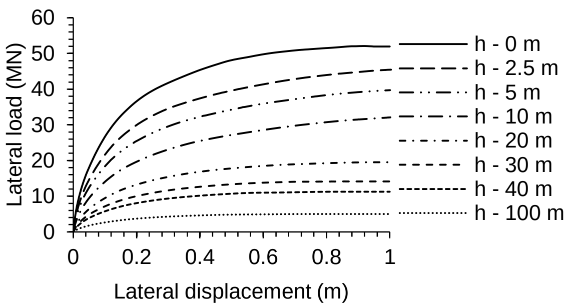

Fig. 2(a) Lateral load-displacement response of bucket foundation (D = 10 m, L = 12 m & V = 30 MN)

From Figure 2(a), at any particular load eccentricity, the displacement of the bucket lid is noted to increase with applied lateral load. The ultimate lateral load capacity of the bucket foundation is observed to decrease from 51.93 MN to 4.97 MN with the increase of load eccentricity from h = 0 m (pure lateral load) to h = 100 m.

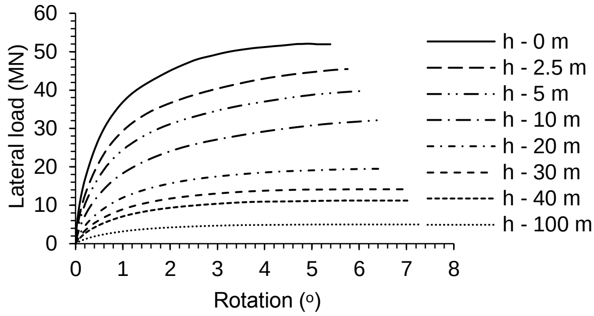

Fig. 2(b) Lateral load-rotation response of bucket foundation (D = 10 m, L = 12 m & V = 30 MN)

From Figure 2(c), it is observed that the maximum rotation of the lid of the bucket foundation at ultimate condition is greater for a higher load eccentricity. The overturning moment causing this maximum rotation increases from 112.5 MNm to 497 MNm when the load eccentricity is increased from h = 2.5 m to h = 100 m. However, this overturning moment is found to be the highest (596.2 MNm) under pure moment load applied at the centre of the bucket lid.

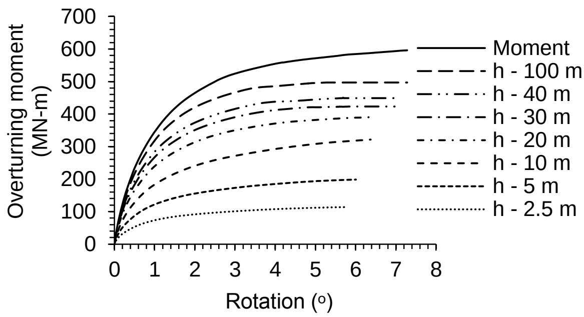

Fig. 2(c) Overturning moment-rotation of bucket foundation (D = 10 m, L = 12 m & V = 30 MN)

3.2 Variation of Ultimate Lateral Capacity

The variation of ultimate lateral load capacity with bucket diameter and superstructure load is shown in Figure 3 for a superstructure load of 30 MN and all load eccentricities. The percentage increase of ultimate lateral capacity ranges between 50-70% when the diameter is increased from 6 to 10 m. The ultimate lateral capacity is found to decrease with superstructure load as presented in Table 2 for load eccentricity of 40 m.

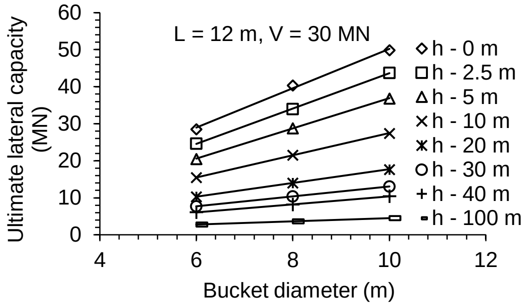

Fig. 3 Ultimate lateral load capacity of bucket foundation

Table 2 Variation of ultimate capacity with superstructure load for h = 40 m

Geometric details	Ultimate lateral capacity (MN)		
	V = 30 MN	20 MN	10 MN
L = 12 m, D = 10 m	11.22	10.80	10.45
L = 12 m, D = 8 m	9.97	9.15	8.20
L = 12 m, D = 6 m	7.14	6.64	6.14

3.3 Variation of Initial Stiffness

Determination of the initial stiffness of the bucket foundation is necessary to compute its rotational stiffness, which should be lesser than the prescribed value provided by the wind turbine designer to avoid resonance. From the lateral load-rotation plot in Figure 2(b) for a particular load eccentricity**,** the initial stiffness can be obtained as the slope of the line drawn from the origin to a rotation of 0.5°. Typical plots of variation of initial stiffness with load eccentricity are shown in Figure 4. The initial stiffness is observed to increase with bucket diameter and superstructure load as presented in Table 3.

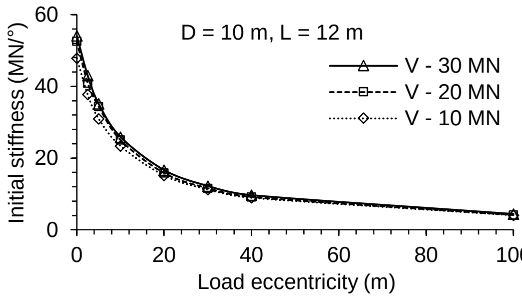

Fig. 4 Initial stiffness of bucket foundation

Table 3 Initial stiffness of bucket foundation for h = 40 m

Geometric details	Initial stiffness (MN/°)		
	V = 30 MN	20 MN	10 MN
L = 12 m, D = 10 m	9.64	9.18	8.94
L = 12 m, D = 8 m	7.66	7.22	6.82
L = 12 m, D = 6 m	5.24	5.02	4.42

3.4 Variation of Depth of Point of Rotation

The left exterior (LE) and right exterior (RE) sides of the bucket foundation are indicated in Figure 5, and typical variation of depth of point of rotation of bucket foundation with load eccentricity is shown in Figure 6. For the superstructure load of 30 MN, with an increase in eccentricity from 0 to 10 m, there is a decrease in the depth of point of rotation from about 10.98 m (0.91L) to 9.41 m (0.78L). The variations of lateral earth pressure at the ultimate condition along the depth for both sides are shown in Figure 7.

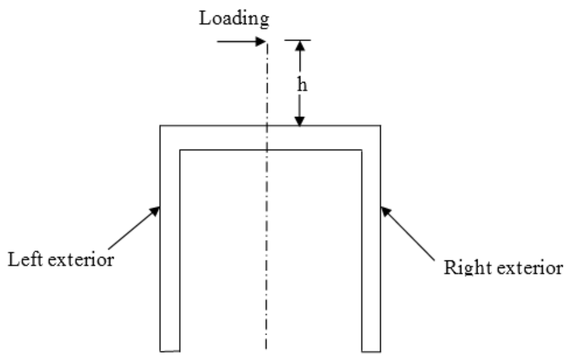

Fig. 5 Schematic diagram indicating bucket sides

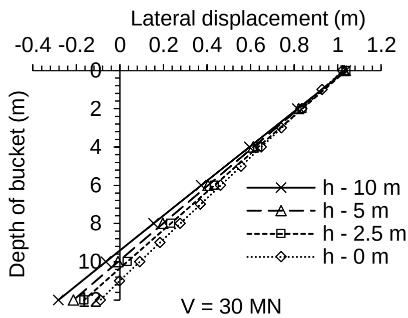

Fig. 6 Depth of point of rotation of bucket foundation (D = 10 m, L = 12 m)

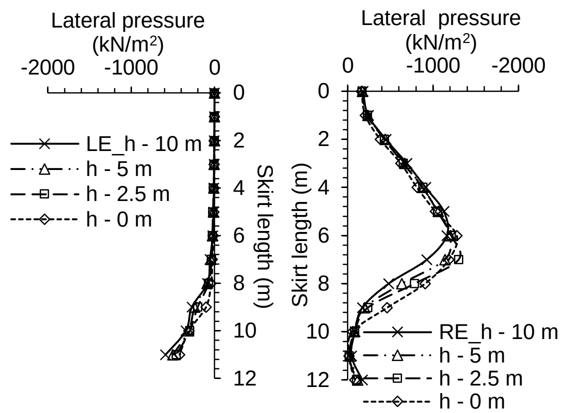

Fig. 7 Lateral pressure along bucket depth

As the point of rotation moves upwards, a greater soil reaction force is exerted below this point on the left exterior face. In contrast, on the right exterior face, the resultant horizontal soil reaction force decreases, which is the reason that the ultimate lateral load capacity reduces with an increase of the eccentricity.

3.5 Lateral Load-Overturning Moment Interaction Diagram

In case of bucket foundations for wind turbines, deflection control at sea bed level is vital from stability point of view. In the present study, an angular rotation of 0.5° has been considered to arrive at the permissible lateral load capacity.

The capacity of the bucket foundation can be described graphically by using lateral load–overturning moment interaction diagram. To plot this diagram, the values of lateral load and overturning moment corresponding to 0.5° rotation of bucket lid are obtained for each load eccentricity of the three geometries used.

These values have been used to obtain an interaction diagram as shown in Figure 8, consisting of three envelopes for the three geometries and superstructure load of 30 MN. Any combination of lateral load and overturning moment, located outside the envelope of respective bucket geometry, will cause instability of the bucket foundation. In that situation, the next larger geometry can be selected in a step-wise manner till the stability requirement is fulfilled.

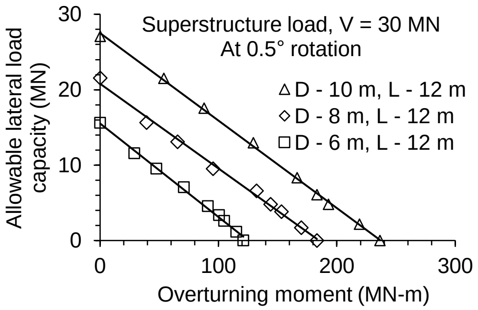

Fig. 8 Interaction diagram at 0.5° rotation

4 CONCLUSIONS

Based on the three-dimensional numerical analysis of bucket foundation embedded in very dense sand subjected to lateral loads, the following conclusions have been made:

- The ultimate lateral load capacity of the bucket foundation decreases with load eccentricity. The increase in the capacity with a larger geometry is noticeable, but the influence of superstructure load is marginal.
- The initial stiffness of the bucket foundation is higher for a lower load eccentricity.
- The depth of point of rotation decreases with an increase of the load eccentricity.
- For a particular load combination of superstructure weight and resultant lateral load from water waves and wind currents, the lateral load-overturning moment interaction diagram enables a selection of the required geometry of the bucket foundation as a preliminary design.

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