Numerical Analysis of Suction Bucket Foundations Used for Offshore Wind Turbines

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Abstract. Offshore wind energy is one of the promising and fast-growing renewable energy sources in the world. Due to cost-effectiveness and easy installation, suction buckets can be considered viable and reliable foundation solution for offshore wind turbines. In this study, three-dimensional finite element analyses were performed to evaluate the load-bearing behavior of the bucket foundations under cyclic and monotonic loading conditions. The effect of various loading conditions and foundation geometries installed in different soil properties were examined. Considering three different embedment ratios of bucket foundation, load-displacement and moment-rotation curves were developed. A parametric analysis of suction caisson reveals that the ultimate capacity and initial stiffness are highly dependent on the bucket geometry, loading conditions and soil properties. The results from cyclic loading conditions show that the accumulated rotation of the bucket foundation with smallest embedment ratio installed in medium dense sand was exceeded the allowable title which results in failure under such loading conditions.

Keywords: Offshore wind turbine · Suction caisson · Cyclic loading
Monotonic loading

1 Introduction

Excessive increase in the demand of energy and wide variety environmental issues associated with burning fossil fuels have forced people across the world to see renewable energy resources such as wind power as future energy supply. Cost-effectiveness, generating more energy, steadier and smoother operation are some advantages offered by the offshore wind turbines compared to the land-based ones. To keep the market of offshore wind turbine competitive with conventional energy supply, the need for cost reduction is essential. The design and installation of foundation of wind turbines play important roles in overall cost of wind energy production. Hence, optimum foundation solution is a big challenge for geotechnical engineers.

Bucket foundation is relatively new foundation concept developed in the last decade for offshore wind turbines. Due to easy and faster installation with significantly

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lower costs compared to the conventional foundations such as gravity bases and mono piles, suction caissons can be alternative foundation solutions.

A suction caisson is a capped top cylindrical steel plate with a severely stiffened steel lid that is moved down into marine sediment and permitted to embed in seafloor layers under its own weight first before being pressed to the full depth with negative pressure created by suction. The installation process can effortlessly reverse for the decommissioning of the foundation.

Although there have been many laboratory-based investigations [1, 2] and few numerical analyses studies [3] regarding suction caissons used for offshore wind turbines, there is still unclear how the foundation behaves under combination of various loading conditions. This study focuses on the behavior of a mono-bucket foundation by means of numerical simulation. Three-dimensional finite element method was conducted to investigate the response of a monopod suction caisson under different loading conditions. The effect of various loading conditions, and foundation geometries installed in two different densities of sandy soil were examined.

2 Numerical Modeling

The finite element program PLAXIS 3D [4] software was used for the simulation modeling. Owing to symmetrical shape of monopod foundation, only half of the entire system was modeled to reduce the computational effort. For modeling simulation, ten-node tetrahedral elements for soil and six-node triangular plate elements for bucket foundation were employed. Interface elements were also used at bucket-soil interfaces. To get an adequate accuracy of the results and avoid the boundary condition effect, mesh convergence and boundary domain analysis were also carried out.

Hardening Soil constitutive model was utilized for simulating of soil behavior in the case of monotonic loading conditions. The soil properties (Table 1) were defined using previous study accomplished by (Ryu [5], Jeon et al. [6]) alongside the given equations in PLAXIS 3D program manual [4].

Table 1. Soil properties.

Soil type	Medium dense sand	Dense sand
Unit weight γ (kN/m^3)	18.5	20
Secant stiffness E_{50}^{ref} (kN/m^2)	74,536	110,110
Tangent stiffness (kN/m^2)	59,629	88,088
Unloading/reloading stiffness E_{ur}^{ref} (kN/m^2)	223,608	330,330
Effective cohesion C' (kN/m^2)	0.1	0.1
Effective angle of friction φ' (°)	35	39
Angle of dilatancy ψ (°)	5	9

Additionally, HS small model was used to simulate soil properties during cyclic loading conditions. Since under cyclic loading conditions, Hardening Soil model generates plastic strains while stress cycles through the hardening contours can only generates elastic strains, HS small model was developed to overcome the mentioned limitation [4]. In current research, similar soil properties with two additional parameters representing the variation of stiffness with strain were used for simulation of soil properties under cyclic loading conditions (Table 2). Although sandy soil behaves as partially undrained during short loading period, drained soil behavior was assumed in the parametric analyses due to lower capacity of foundation under drained condition compared to the undrained condition loading which leads to conservative assumption for the design. Steel plate element was considered for modeling of bucket foundation. To consider the rigid behavior of the caisson due to the stiffeners that usually placed on the bucket lid, a very large modulus of elasticity $\left(E = 210 \times 10^6 \text{ GPa}\right)$ in addition to the bucket lid thickness of 100 mm were implemented.

Table 2. HS small parameters

Soil type	Medium dense sand	Dense sand
Reference shear modulus G_0^{ref} (kN/m^2)	93,168	137,735
Threshold shear strain $\gamma_{0.7}$ (−)	0.016017	0.010835

2.1 Cyclic Loading

Numerical modeling was carried out on a suction bucket foundation installed in sandy soil with two different densities. A vertical dead load of 10000 kN was applied at the center of bucket lid. Typical 5 MW wind turbine from the National Renewable Energy Laboratory (NREL) was considered for the simulation of cyclic wind load. Horizontal cyclic wind load was also applied at the 100 m away from the bucket lid. To obtain the applied cyclic load, simulation for the mentioned wind turbine was conducted using the FAST software program. Long term wind speed and load obtained from FAST are presented in Fig. 1. In accordance with the FAST recommendation, the first 60 s of the initial loading shows the transient response from the wind turbine start-up and does not represent the steady state of the wind loading, hence, the initial 60 s of the loading was excluded in the analyses. In addition, according to (IEC [7]), the 10-min wind speed is used for wind turbine design loads, therefore, simulation time in the parametric analysis was considered as 660 s.

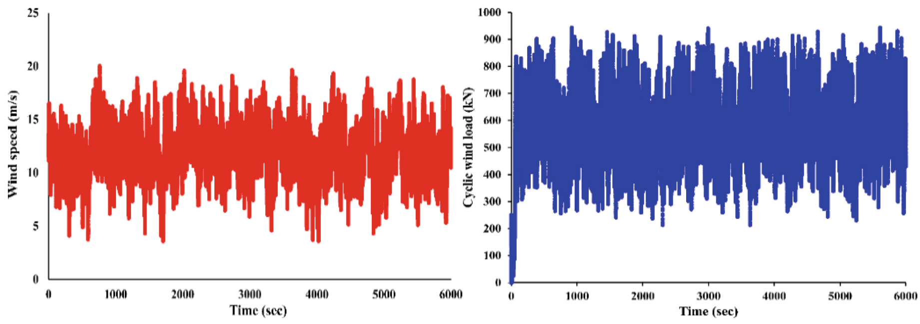

Fig. 1. Time history simulation of typical 5 MW wind turbine; cyclic wind speed (left) and cyclic wind load (right).

3 Parametric Study

Buckets with various diameter and skirt length were considered to define the bucket displacement and rotation subjected to the cyclic load. The horizontal displacement and rotation of the bucket with embedment ratio of 0.75 obtained from numerical analyses are given in Figs. 2 and 3.

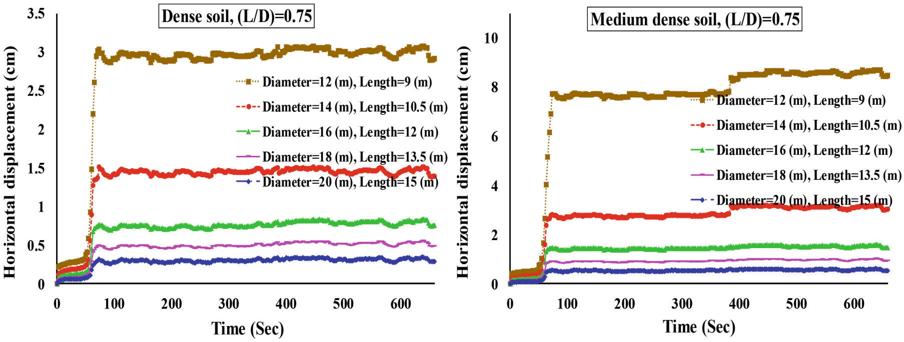

Fig. 2. Horizontal displacement curves for dense sand (left), and medium dense sand (right).

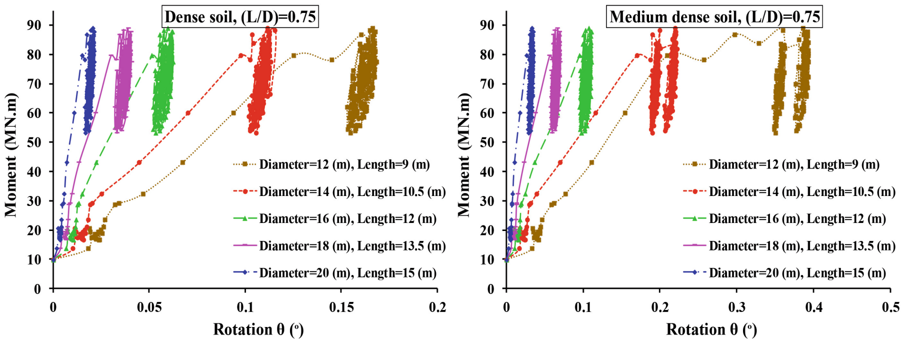

Fig. 3. Moment-rotation curves for dense sand (left), and medium dense sand (right).

Soil density and bucket geometry have significant effects on the caisson response. Concerning bucket displacement, the largest displacement is occurred for the bucket with smallest dimensions. The displacement of the buckets installed in medium dense soil are almost twice of their counterparts installed in dense soil. Although in dense soil, buckets behave steadily responses under cyclic loading, in medium dense soil, incrementally increasing in horizontal displacement are seen in the bucket with the smallest dimensions. Such behavior is clear after the time corresponding to 400 s. Similar trend may also be found in moment-rotation curves.

4 Monotonic Loading

Similar caisson dimensions and soil properties used in cyclic loading analyses were also employed in the monotonic loading analyses. To obtain horizontal load and overturning moment capacity of each bucket model, the horizontal load and bending moment applied at the 100 m away from the bucket lid were gradually increased and then bucket displacement and rotation were plotted. The horizontal load-displacement and moment-rotation curves obtained from numerical analyses are shown in Figs. 4 and 5.

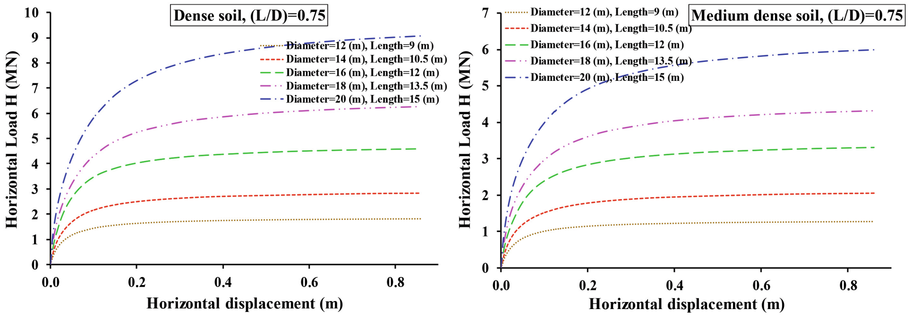

Fig. 4. Horizontal displacement curves for dense sand (left), and medium dense sand (right), monotonic response.

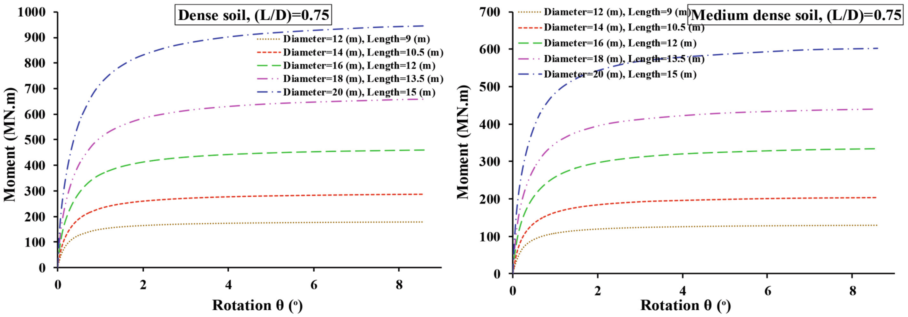

Fig. 5. Moment-rotation curves for dense sand (left), and medium dense sand (right), monotonic response.

Initial stiffness is one of the important factors in the behavior assessment bucket foundations. The initial stiffness for buckets installed in different geometries are shown in Fig. 6. The results show that initial stiffness decreases with increasing the height of applied load. Moreover, soil relative density has considerable effect on the initial stiffness; increasing the relative density results in decreasing the initial stiffness.

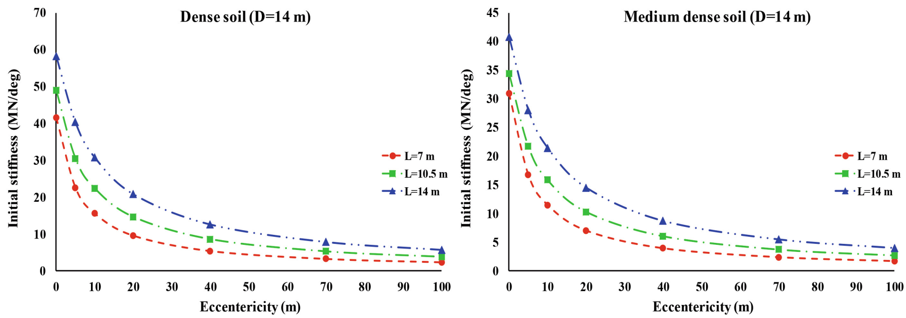

Fig. 6. Effect of height of applied load, bucket geometry and soil density on the initial stiffness.

5 Conclusion

To evaluate the behavior of bucket foundation used for offshore wind turbines under cyclic and monotonic loading conditions, three-dimensional analyses were conducted. Based on the obtained results, the following conclusions can be drawn.

The results show that bucket rotation and displacement due to cyclic loading are highly affected by the bucket geometry and soil densities. Similar behavior can also be seen under monotonic loading condition. Additionally, in all three embedment ratios, the largest displacement is occurred for the bucket with smallest dimensions. Initial stiffness decreases with increasing the height of applied load. Moreover, soil relative density has considerable effect on the initial stiffness; increasing the relative density results in decreasing the initial stiffness.

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