# Numerical modeling of monopod and tripod bucket foundation

Pouyan Bagheri[1], S.W. Son[1], D.H. Lee[1], and J.M. Kim[1]

[1] Department of Civil and Environmental Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan, 46241, Korea.

## ABSTRACT

Monopod bucket foundation is a promising foundation concept which was developed in the last decade to be used as the supporting structures for offshore wind turbines. In this study, a three-dimensional finite element modeling was used to evaluate ultimate horizontal load and moment capacities of monopod and tripod bucket foundations. Various foundation geometries installed in dense sandy soil were considered to obtain load-displacement and moment rotation curves. A comparison between the horizontal load and moment capacities of monopod and tripod bucket foundations was performed. Dimensionless variables for these foundation types were presented. The results show that the loading conditions and foundation geometries affect on the ultimate load and moment capacities.

**Keywords:** Offshore wind turbine; Monopod foundation; Tripod bucket foundation; Monotonic loading; Sandy soil

## 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. Following this trend, the offshore wind energy as a clean and renewable energy is planned to be provided 20% of all electric energy supply in South Korea. The Korea peninsula is surrounded by the sea and this gives it a great advantage to have strong and consistent ocean winds off the coastal areas and transform them into clean and efficient electricity. To keep the market of offshore wind energy competitive with conventional energy supply, the need for cost reduction is essential. The design and installation of foundation of wind turbines play an important role in overall costs of wind energy production. Approximately, 25 to 34% of the total expenditures of wind turbines accounts for the supporting structures. Hence, optimum foundation design 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 lower costs compared to the conventional foundations such as gravity bases and mono piles, suction buckets can be alternative foundation solutions.

A Tripod bucket foundation consists of three single caissons in a triangular shape. Tripod bucket foundation can be used as a promising solution for greater size of offshore wind turbines that are being constructed and used all around the world.

There have been conducted a number of studies for evaluation of monopod and tripod bucket foundations for offshore wind turbines. In order to evaluate the cyclic behavior of bucket foundation in clayey and sandy soil, Houlsby et al. (2005) and Houlsby et al. (2006) carried out field tests. They reported that stiffness, inertia, and damping affect the caisson response. Zhu et al. (2013) conducted small-scale model tests to evaluate settlement and accumulated angular rotation of a suction caisson due to cyclic loading. They discovered that increases of the number of cycles and cyclic amplitude leads to a growth in the accumulated settlement of the bucket.

Bagheri et al. (2017) and Bagheri et al. (2017) evaluated the bearing capacity of a bucket foundation under monotonic loading conditions by using finite element modeling in sand. Bagheri et al. (2017) and Bagheri et al. (2019) studied the behavior of bucket foundations under cyclic loading. Using numerical modeling, Tran et al. (2017) investigated load and moment capacities of tripod bucket foundations.

From those studies, the behavior of suction caissons has been investigated, however, no study has been investigated to evaluate both monopod and tripod bucket foundations under similar loading conditions. Thereby, a three-dimensional finite element analysis was adopted to assess load and moment capacities of monopod and tripod bucket foundations considering different loading conditions and soil properties.

## 2 NUMERICAL MODELING

The finite element program PLAXIS 3D was used to simulate a monopod and tripod bucket foundation used as the supporting structurers of offshore wind turbines. Considering symmetrical nature of the problem, only one-half of the foundation was modeled.

Displacements in all directions of the model boundaries were fixed. The displacement-controlled method was employed to model the horizontal loads.

Hardening soil constitutive model was used to analyze soil behavior. Dense sandy soil was modeled with the soil properties as shown.

Table 1. Soil properties.

| Soil type | Dense sand |
|---|---|
| Unit weight $\gamma$ (kN/m$^3$) | 20 |
| Secant stiffness (kN/m$^2$) | 110,110 |
| Tangent stiffness (kN/m$^2$) | 88,088 |
| Unloading/Reloading stiffness (kN/m$^2$) | 330,330 |
| Effective cohesion $C'$ (kN/m$^2$) | 0.1 |
| Effective angle of friction $\varphi'$ (°) | 39 |
| Angle of dilatancy $\psi$ (°) | 9 |
| Relative density (%) | 85 |

The bucket foundation is modeled as a steel plate element. Table 2 shows the steel plate properties used for the bucket modeling.

Table 2. Foundation material properties.

| Bucket | Skirt | Lid |
|---|---|---|
| Thickness (*mm*) | 30 | 100 |
| Elastic modulus $E$ (*GPa*) | 210 | 210*10$^6$ |
| Poisson's ratio $\upsilon$ | 0.3 | 0.3 |
| unit weight $\gamma$ (*kN/m$^3$*) | 77 | 77 |

Numerical modeling was carried out in several phases. In the initial phase, the at-rest lateral earth pressure coefficient was used for the calculation. In the next phase, by activating the predefined plate material, foundation system was installed. The interface concept was used to consider the soil-structure interaction at the interior and exterior of the bucket skirt and beneath the lid. In the subsequent phase, a vertical load of 10 MN representing the tower structure and wind energy converter system was applied on the reference point. The center of the bucket lid was considered as the reference point for the monopod foundation. Additionally, for tripod bucket foundation, the reference point was assumed to be the intersection point from the top center of each bucket directly beneath the center of tower of wind turbine. The following phase consisted of the application of a horizontal load and overturning moment concurrently with respect to different load eccentricities. The horizontal and moment load was gradually increased to define the ultimate load and overturning moment capacity of the foundation system.
The bucket foundation is modeled as a steel plate element. Table 2 shows the steel plate properties used for the bucket modeling.

## 3 LOAD AND MOMENT CAPACITIES OF MONOPOD AND TRIPOD FOUNDATION

A numerical modeling was performed on a typical model of monopod and tripod bucket foundation installed in dense sand. In this study the foundation diameters of 10 m and embedment ratio, L/D=0.75 were considered to be analyzed. The spacing ratio, S/D=1 was also considered for the tripod bucket foundation as the distance between the center of each bucket to the reference point. Push-over analysis was used to obtain ultimate load and moment capacities for different load eccentricities (h=0 m,5 m,10 m,20 m,40 m,70 m and100 m). The results of horizontal load-displacement and overturning moment-rotation curves for both monopod and tripod bucket foundations are shown in Fig. 1.

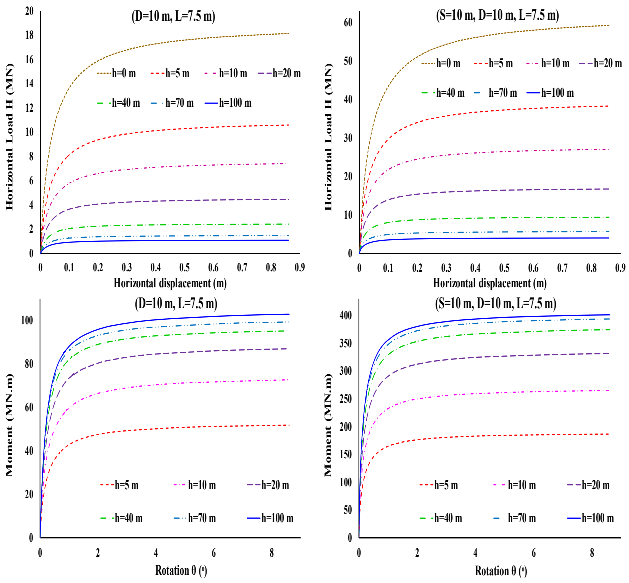


Fig. 1. Load-displacement and Overturning moment-rotation curves for monopod bucket foundation (left); and tripod bucket foundation (right).

As to be expected, the foundation geometry and load eccentricity significantly affect the ultimate horizontal load and moment capacities. As an example, the ultimate horizontal load and moment capacities in tripod foundation are almost 3.8 times higher than the ultimate load and moment capacities of monopod foundation with similar bucket geometries (D=10 m, L=7.5) under load eccentricity of 100 m. The highest ultimate horizontal loading capacity occurred with no load eccentricity h=0 m.

## 4 DIMENSIONLESS ANALYSIS

### 4.1 Dimensionless quantities for monopod bucket foundation

By implementing the power law and using the Buckingham's Theorem, the following dimensionless quantities for the horizontal load-displacement (Eq. (1)) and overturning moment-moment (Eq. (2)) relations can be obtained.

$$\frac{u}{L} = \left(\frac{H}{\gamma' L^3}\right) \quad (1)$$

Where u is the foundation displacement, H horizontal load, L the bucket skirt length, and $\gamma'$ is the effective unit weight of soil and $\vartheta$ and E are a constant exponent and coefficient, respectively.

$$\theta = \left(\frac{M}{\gamma' L^4}\right) \tag{2}$$

Where M is the overturning moment and θ is the bucket rotation.

Dimensionless curves for the given bucket geometry are shown in Fig. 2.

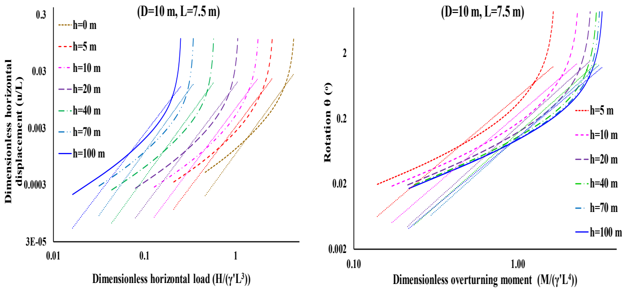


Fig. 2. Results for monopod foundation in double logarithmic scale; (a) Dimensionless load-displacement curves (left); (b) Dimensionless overturning moment-rotation curves (right).

The curves are plotted on a double logarithmic scale. Straight lines specified with certain positive slope can approximate the first part of each curve. The lines may be fitted to the FEM analyses data within $0.7H_u$, where $H_u$ is the ultimate horizontal load. After reaching these points, the lines tend to bend until failure occurs. Similar match trends can also be seen for the moment-rotation curves within $0.75M_u$. To clarify the mentioned statements the curves in arithmetic scale are also presented in Fig. 3.

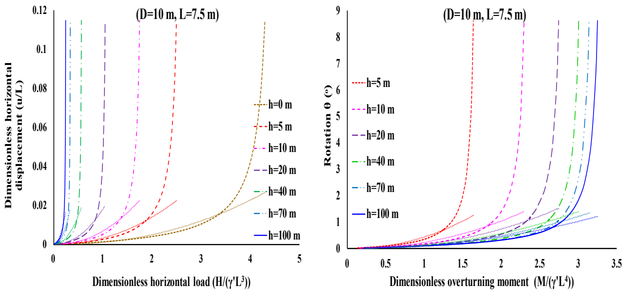


Fig. 3. Results for monopod foundation in arithmetic scale; (a) Dimensionless load-displacement curves (left); (b) Dimensionless overturning moment-rotation curves (right).

### 4.2 Dimensionless quantities for tripod bucket foundation

Similar to the monopod foundation, by implementing the power law and using the Buckingham's Theorem, dimensionless variables for the horizontal load-displacement (Eq. (3)) and overturning moment-moment (Eq. (4)) relations were obtained.

$$\bar{H}_T = \left(\frac{H_u}{3\gamma' L^3}\right) \tag{3}$$

Where $\bar{H}_T$ is non-dimensional ultimate horizontal load for tripod bucket foundation and $H_u$ is an ultimate horizontal load.

$$\bar{M}_T = \left(\frac{M_u}{3\gamma' L^4}\right) \tag{4}$$

Where $\bar{M}_T$ is non-dimensional ultimate overturning moment for tripod bucket foundation and $M_u$ is an ultimate overturning moment capacity.

Fig. 4 shows the dimensionless load-displacement and moment-rotation curves for the given tripod bucket foundations.

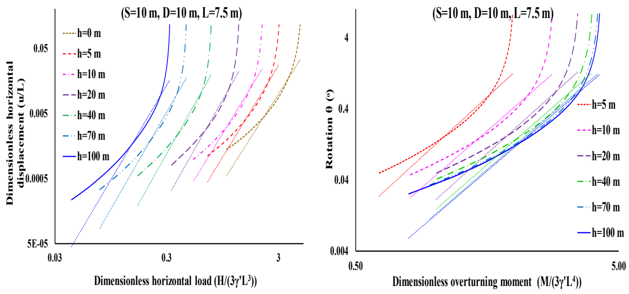


Fig. 4. Results for monopod foundation in double logarithmic scale; (a) Dimensionless load-displacement curves (left); (b) Dimensionless overturning moment-rotation curves (right).

The straight lines obtained from power law can be fitted to the FEM analyses data within $0.8H_u$, which indicates further stability of tripod foundation comparted to the monopod foundation. Concerning moment-rotation curves, the straight lines agreed well with the obtained results from FEM analyses data within $0.8M_u$.

## 5 CONCLUSION

Three-dimensional analyses were conducted to evaluate the behavior of monopod and tripod bucket foundations used for offshore wind turbines. The analyses lead to the following conclusions:

The foundation geometry and load eccentricity significantly affect the ultimate horizontal load and moment capacities.

By implementing the power law and using the Buckingham's Theorem, dimensionless variables for the horizontal load-displacement and overturning moment-moment relations for both monopod and tripod foundation were presented.

Straight lines obtained from plotted dimensionless curves with positive slopes can approximate the first part of each curve for both monopod and tripod foundation. After reaching certain points, the lines tend to bend until failure occurs.

These values in tripod bucket foundation is higher than monopod bucket foundation indicating its capability against higher loads and moments

The effect of the installation procedure and long-term cyclic loading were eliminated in the current study. Therefore, in future studies, it is recommended to consider these factors. The FEM results may need to be examined with experimental laboratory and large-scale model tests.

## ACKNOWLEDGMENTS

This research was supported by the Basic Science Research Program funded by the National Research Foundation of Korea. We thank them for their support (NRF-2017R1A2B4010201).

## REFERENCES

Houlsby G.T., Ibsen L.B. and Byrne WB., (2005). Suction caissons for wind turbines. Frontiers on Offshore Geotechnics (ISFOG 2005)-Gourvenec & Cassidy (eds). Taylor & Francis group, London, ISBN 041539063X, 75-93.

Houlsby, G.T., Kelly, R.B., Huxtable, J., and Byrne, B.W. (2006). Field trials of suction caissons in sand for offshore wind turbine foundations, Geotechnique 56 (1), 3–10.

Zhu, B., Byrne B.W., and Houlsby, G.T. (2013). Long-term lateral cyclic response of suction caisson foundations in sand, J. Geotech. Geoenviron. Eng. 139 (1), 73–83.

Bagheri P., Son S.W., Kim J.M. (2017). Investigation of the load-bearing capacity of suction caissons used for offshore wind turbines. Applied Ocean Research. (67):148–161.

Bagheri P., Son S.W., Kim J.M. (2017). Evaluation of the bearing capacity of suction bucket foundations used for offshore wind turbine by using finite element modeling. ATC7 Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul. 17–20.

Bagheri P., Son S.W., Kim J.M. (2017). Cyclic behavior of soil supporting suction caisson foundation. Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul. 2141–2144.

Bagheri P., Yoon J.C., Park D., Kim J.M. (2019). Numerical Analysis of Suction Bucket Foundations Used for Offshore Wind Turbines. In: Randolph M., Doan D., Tang A., Bui M., Dinh V. (eds) Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering. VSOE 2018. Lecture Notes in Civil Engineering, vol 18. Springer, Singapore.

Tran, N.X., Hung, L.C., Kim, S.R., (2017). Evaluation of horizontal and moment bearing capacities of tripod bucket foundations in sand. Ocean Eng. 140, 209–22.

Brinkgreve, R.B.J., Engin E., and Swolfs, W.M. (2012). Manual for PLAXIS 3D, 2012.