Long-term cyclic behavior of soils supporting offshore wind turbine foundation

Jin Man Kimⁱ⁾, Su Won Sonⁱⁱ⁾, Pouyan Bagheriⁱⁱⁱ⁾, Tae Gyung Ryuⁱⁱⁱ⁾ and George Sorianoⁱⁱⁱ⁾

i) Professor, Civil and Environmental Engineering, Pusan National University, Busan, Korea.

ii) Ph.D. Student, Civil and Environmental Engineering, Pusan National University, Busan, Korea.

iii) Graduate Student, Civil and Environmental Engineering, Pusan National University, Busan, Korea.

ABSTRACT

Offshore wind farms are being built in pursuit of sustainable and environment-friendly energy. In order to construct these offshore wind farms with a reliable degree of safety, the seabed foundation of these turbines should be able to withstand the forces applied to it. Hence, it is necessary to investigate the dynamic behavior of the seabed under cyclic conditions due to long-term wave, wind, and tidal loading. In this paper, the long-term cyclic behavior of soils supporting wind turbine foundations is presented. Numerical analysis is conducted in order to simulate the behavior of sand at the center of the foundations, in addition to laboratory dynamic testing. The results show that long-term behaviors of marine soil could be very different from short-term behaviors, and should be considered in the dynamic design of offshore wind turbines.

Keywords: long-term, cyclic behavior, offshore wind turbine, foundation, dynamic design, numerical analysis.

1 INTRODUCTION

In the design of offshore wind turbines, it is necessary to investigate the dynamic behavior of the seabed under cyclic conditions due to long-term wave, wind and tidal loading. In past research, soil behavior was analyzed according to cyclic loading resulting from laboratory testing (Andersen, 2009; Safdar et. al. 2014). Hung and Kim (2014) suggested the bearing capacity formula for the static condition of bucket foundations on clay to be used in numerical analysis. In this paper, the long-term cyclic behavior of soils supporting offshore wind turbine bucket foundations is evaluated using numerical analyses. Soil parameters are determined by the results of laboratory dynamic testing, while input loading motion is applied using the result values of multidisciplinary load analysis program. The numerical analyses are performed according to various conditions, evaluated the long-term cyclic behavior of soil.

2 NUMERICAL MODELING

2.1 Soil and structure modeling

In order to analyze the behavior of bucket foundation soil, soil and structure are modeled by using a 3-dimensional finite element program. In the model the bucket foundation has a diameter of 10 m with bucket depth of 5 m, and a plate thickness of 0.025 m. The tower diameter is 2 m with plate thickness of 0.05 m. In order to consider the difference between material

properties of bucket foundation and soil, an interface between the soil and the bucket foundation surface is used. The HS-small constitutive model was used in this numerical model. The small strain coefficients were determined using a G/G_{max} curve previously obtained from dynamic tests. In modeling the bucket structure, the steel material was modeled using a linear-elastic model. Figure 1 shows the geometric configuration of the model.

Fig. 1. 3-D numerical modeling.

2.2 Applied loading

The input values for the vertical, horizontal, and moment loads are obtained from multidisciplinary load analyses. A vertical dead load of 10 MN is applied at the surface of the superstructure. Horizontal loading is applied using the results of the FAST multidisciplinary load analyses. The value corresponds to the member

load of the structure at the seabed level, and is obtained by taking consideration of wind loading, RNA (Rotor-Nacelle-Assembly), and controller movements. The analyses use the NREL 5 MW turbine published data. The cyclic horizontal load is acting at 20 m above the bucket foundation so as to act as a moment loading of 10,000 kN·m to 18,000 kN·m (Fig 2). Figure 3 is a time history of input horizontal loading.

Fig. 2. Loading point.

Fig. 3. Input horizontal Loading.

3 NUMERICAL ANALYSIS RESULTS

The analyses compute the displacement and stress on the inner and outer soils of the bucket foundation. Measurement points are located in the vertical interval of 2.5 m at the soil of the bucket foundation center and 0.3 m away from the side of the bucket foundation.

3.1 Horizontal behavior

Figure 4 presents horizontal displacements versus time. On the graph, (+) displacement is a right direction movement, (-) displacement is left direction movement. The largest displacement at the ground surface occurs at the left side of the bucket foundation. But below the surface, the right side of the bucket foundation shows larger displacement than the left side. The results show that the behavior of inside soil of the bucket foundation is significantly different from that of outside.

Fig. 4. Horizontal displacement along the depth from the surface

Figure 5 shows vertical displacements versus time. On the graph, (+) displacement is a right direction movement, (-) displacement is a left direction movement. The result shows settlement at the left side and center of the bucket foundation. Meanwhile, the right side exhibited an upward tilt of around 15 cm. The results suggest that the size of the bucket foundation needs to be increased to avoid excessive tilting.

Fig. 5. Vertical displacement along the depth from the surface (Left side of the bucket foundation).

3.2 Stress behavior

Figure 6 shows larger shear and vertical normal stresses inside of the bucket foundation compared to the outside. The difference in stress is caused by the impedance of the transmission of stress by the bucket foundation. More study is needed to determine the effect of different load values and bucket sizes on the propagation of stress. The maximum values for shear and normal stresses are found below the center of the bucket foundation with corresponding values of 110 kPa and 300 kPa.

(a) Shear stress distribution.

(b) Normal stress distribution.

Fig. 6. Stress distribution for cyclic horizontal loading.

Figure 7 shows the relationship between vertical effective and shear stress for different depths. The concentration shown in the graphs indicates that the vertical and shear stresses caused by the cyclic loading belong to the specific stress range. Figure 8 shows the development of shear strain versus time. The converged values at different depths indicate that shear strains on the left side of the foundation is higher than the shear strains on the right side. The surface of the foundation at the left side exhibits rapid increase in strain after 3000 seconds due to the development of large cyclic loads within that region. Therefore, it is recommended that dynamic laboratory tests be conducted for the highest stress and strain range obtained in this numerical study in order to validate the results.

(a) Left side of bucket foundation.

(b) Right side of bucket foundation.

Fig. 7. Normal stress – shear stress curve for cyclic horizontal loading.

(a) Left side of bucket foundation.

(b) Right side of bucket foundation.

Fig. 8. Shear strain time histories.

4 SUMMARY AND CONCLUSIONS

Three-dimensional numerical analyses are performed to analyze the behavior of the bucket foundation and the foundation soil due to cyclic loading. The summary and conclusions are as follows.

1. The largest horizontal displacement at the ground surface occurs at the left side of the bucket foundation. But below the surface, the right side of the bucket foundation shows larger displacement than the left side. The results show that the behavior of inside soil of the bucket foundation is significantly different from that of outside.

2. The result shows settlement at the left side and center of the bucket foundation. Meanwhile, the right side exhibited an upward tilt of around 15cm. The results suggest in this particular case that the size of the bucket foundation needs to be increased to avoid excessive tilting.

3. Stress and strain characteristics of the bucket foundation due to cyclic horizontal loads analysis results show larger shear and vertical normal stresses inside of the bucket foundation compared to the outside. The difference in stress is caused by the impedance of the transmission of stress by the bucket foundation. More study is needed to determine the effect of different load values and bucket sizes on the propagation of stress.

4. The vertical and shear stresses caused by the cyclic loading belong to the specific stress range. Therefore, it is recommended that dynamic laboratory tests be

conducted for the highest stress and strain range obtained in this numerical study in order to validate the results.

5. It is necessary to perform further analyses for a variety of load conditions and foundation shapes in future research.

ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program funded by the National Research Foundation of Korea. We thank their support. (NRF-2014R1A1A2058110).

REFERENCES

- 1) Andersen, K.H. (2009). "Bearing capacity under cyclic loading - offshore along the coast, and on land. The 21st Bjerrum Lecture presented in Oslo, 23 November 2007" . *Canadian Geotechnical Journal*, Vol.45, No.2, pp.513~535.
- 2) Hung, L. C. and Kim, S. R. (2014), "Evaluation of Undrained Bearing Capacities of Bucket Foundations Under Combined Loads" , *Marine Georesource and Geotechnology*, Vol.32, pp.76~92
- 3) Safdar, M., Son, S.W., Kim, J.M. (2014), "Effect of Average and Cyclic Shear Stress on Undrained Cyclic Behavior of Marine Silty Sand" , *Korea Geotechnical Society*, Vol.30, No.1, pp.17~25. (reference with DOI is also recommended)