Investigation on Horizontal Behavior on Piled Gravity Base Foundation for Offshore Wind Turbine using Numerical and Centrifuge Modeling

Enquête sur le comportement horizontal sur la Fondation Empilée Gravity base pour turbine éolienne en mer en utilisant la modélisation numérique et Centrifugeuse

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ABSTRACT: The aim of this study is to investigate the behavior of a piled gravity base foundation for the offshore wind turbine. A centrifuge test and 3D finite element analysis were carried out. From the both results, the horizontal responses of each pile were evaluated and compared. The numerical results were validated against the centrifuge modelling prior to undertaking a detailed parametric study, exploring the relevant range of parameters in terms of loading direction, loading height, and pile length. The maximum bending moment of piles increases as increasing the loading height, but reduces as decreasing the pile length. The effect of loading direction on the pile response was negligible if the applied loads are lower than the yield.

RÉSUMÉ: Le but de cette étude est d'étudier le comportement d'une fondation de base gravitaire empilée pour l'éolienne offshore. Un test centrifuge et une analyse par éléments finis 3D ont été réalisés. A partir des deux résultats, les réponses horizontales de chaque pile ont été évaluées et comparées. Les résultats numériques ont été validés par rapport à la modélisation par centrifugation avant d'entreprendre une étude paramétrique détaillée, en explorant la gamme de paramètres en termes de sens de chargement, de hauteur de charge et de longueur de pieu. Le temps de pliage maximal des pieux augmente à mesure que la longueur du pieu augmente. L'effet du chargement sur la pile n'était pas possible.

KEYWORDS: Piled gravity base foundation, Centrifuge test, Numerical analysis, Maximum bending moment

1 INTRODUCTION

Recently, wind energy has received attentions in the world because of the increasing interests in renewable energy so that offshore wind farms have been actively constructed. The design and construction costs of the foundation generally take up over 30-40% of the total project budget for the offshore wind farm, and the proportion of the total substructure costs for the offshore wind farms increases as the water depth increases (EWEA 2009). Thus, foundations were investigated to reduce the cost of substructure in terms of design optimization of monopile (Achmus et al., 2009; Kim, 2013), and development of alternatives: hybrid monopile (Arshi et al., 2013), monopod bucket and tripod bucket (Byrne and Houslby, 2003).

In this study, the piled gravity base foundation (piled GBF), which is one of the new foundation type for supporting offshore wind turbines, was considered. In Korea west coast area where domestic offshore wind farm development is being promoted, most of the seabed soil is composed of silty sand and clayey soil. With these soil conditions, conventional gravity base foundation is difficult to construct because of insufficient bearing capacity and excessive soil settlement. Therefore, the piled GBF was proposed to achieve additional vertical bearing capacity and reduce the settlement by reinforcing gravity bases with piles (KICT, 2013; Choo et al., 2016).

The piled GBF is composed of a cone base, a mat and five piles. The cone base is a hollow concrete structure with a thickness of 0.5 m, and its inside is back-filled with sand. The mat is a concrete plate with a diameter of 25 m and a thickness of 1 m, and is connected with a steel pipe pile having a diameter of 1.5 m. The piles are located in a cross array with one center pile and four outer piles. The distance between the piles at the center and the outer is 10.79 m.

The piled GBF has not been sufficiently studied yet and no reference construction guidelines. Recently, numerical studies were carried out on the horizontal behavior of the piled GBF (Choo et al., 2016) but the understanding on the foundation is not enough. Thus, this study aims to investigate the behavior of the piled GBF subjected for the offshore wind turbine using a centrifuge model test and numerical analysis. Then a parametric study was carried out varying loading direction, loading height and pile length.

2 CENTRIFUGE AND NUMERICAL MODELLING

2 .1 *Centrifuge test*

The centrifuge test was conducted using a large-scale centrifuge system built on K-water research institute in Korea. The centrifuge equipment is a beam-type with a radius of 8.0 m and an effective radius of 7.5 m and its capacity is 800 G·ton.

2.1.1 *Soil model*

A soil model for the centrifuge test was made of kaolin clay. The kaolin used in this test is a powdered product with a refined plate-like crystal structure. The plasticity index is 24.3% and the clay is classified as CH in Unified Soil Classification.

The clay was prepared in a cylindrical container with 1.2 m of a diameter and 0.8 m of a height. A kaolin slurry was prepared with a water content of 120% and a height of 700 mm, which was planned to be 437 mm in height of the clay layer after pre-consolidation. the clay slurry was pre-consolidated under 100 kPa by a hydraulic press, finally resulting in a unit weight of 16.5 kN/m^3. A clean sand layer with 50 mm of a thickness is placed on the bottom of the container, for the supporting layer for the pile tips and drainage layer of the clay consolidation.

2.1.2 *Foundation model*

All model structures including the piles are made of aluminum alloy. A scale factor of 68.7 was determined based on possible pile size for manufacturing to scale the flexural rigidity of piles as the main design consideration. The final dimensions of the model are tabulated in Table 1. The outer diameter of the model pile is 21.8 mm, the inner diameter is 20 mm, and the length is 437 mm. The piles and mat are rigidly welded. Strain gages were instrumented at multiple depths and spring lines of the model piles as illustrated in Figure 1.

Table 1. Foundation model specifications and properties

Classification	Prototype	Model
Pile length, L_p	30 m	437 mm
Pile diameter, D_p	1.5 m	21.8 mm
Pile thickness, t_p	0.02 m	0.65 mm
Elasticity of pile, E_p	200 GPa	70 GPa
Flexural rigidity of pile, EI	5246000 t•m^2	0.2286 t•m^2
Mat diameter, D_m	25 m	363.8 mm
Mat thickness, t_m	1 m	14.56 mm

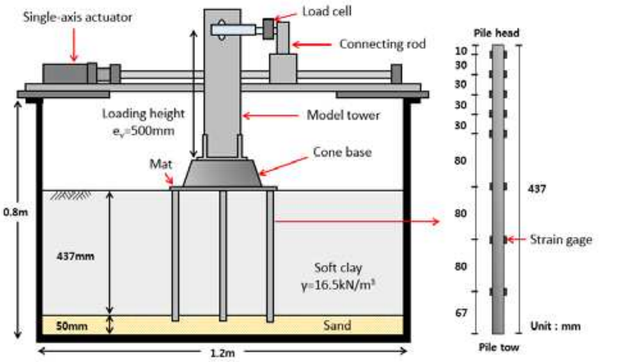


Figure 1. Schematic diagram of centrifuge model test

2.1.3 *Test procedure*

Generally, offshore wind foundations are subjected to horizontal load and significant moment due to wind, current and wave load. In this study, a horizontal load was applied with a loading height of 35m (= 509.5mm in model scale) to simulate combined moment and lateral loads. The load was applied with a single-axis actuator installed on the container. The actuator was connected to the model tower through a connecting rod at the selected loading height and a load cell for measurement of the load.

The centrifuge model pre-consolidated under 100 kPa was accelerated to the target g-level of 68.7 G acceleration for about 3 to 4 hours to induce additional settlement of the clay layer under the centrifugal acceleration field. Then, the foundation model and measurement system were installed at 1g. The foundation model was jacked in with a penetration rate of 0.5 mm/s. Then the centrifuge model was accelerated again upto 68.7g for the main load test. A cone penetration test was carried out and then a horizontal load was applied under a constant displacement rate of 1.1mm/s and the horizontal reaction load was measured by the load cell.

2 .2 *Numerical analysis*

3D finite element analyses (FEA) were also carried out using ABAQUS/Standard (Dassault Systemes, 2014) to investigate the horizontal behavior of the piled GBF. Considering the symmetry condition, a half section of structure and soil were modeled. The diameter and height of the soil domain were 4D_m and 1.67L_p, respectively, ensuring a sufficiently large domain to avoid boundary effect. The mesh for the soil and foundation structure is comprised of 8-noded linear brick elements with reduced integration (termed C3D8R In ABAQUS). The contact surface allows gapping and slippage at the interface between the structure and soil by defining hard contact and frictional behavior.

The foundation structure including the cone base, mat, and piles was simulated with an elastic material, while the clay soil was done with an elasto-plastic Mohr-Coulomb model. The elastic behavior of the clay was defined by a poisson'sratio (ν) of 0.49, young's modulus (E_s) of 200s_u and undrained shear strength (s_u) of 20 kPa which is an average value evaluated from the CPT test. A uniform effective unit weight of 6.5 kN/m^3 was input to the clay layer. The sand layer was set with an effective unit weight of 9.5kN/m^3 and an elastic modulus of 44 MPa. For parametric study, soil layers were changed to a uniform clay layer with 50 m of thickness, simulating friction pile condition. The reference point at which the load was applied was set at the top-center of the cone base in Figure 2.

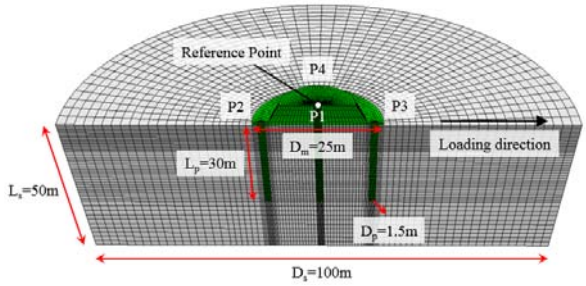


Figure 2. Mesh of numerical analysis model

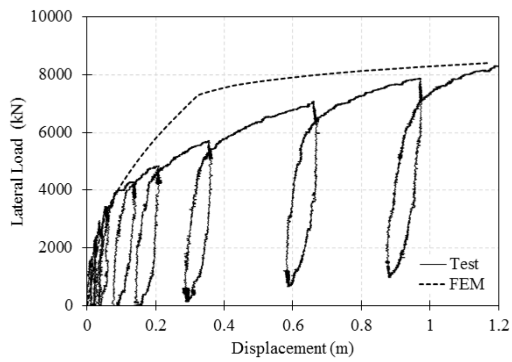


Figure 3. Comparison of load-displacement curves at the reference point from centrifuge model test and numerical analysis

2 .3 *Validation against centrifuge test data*

The resulting load-displacement curves of the centrifuge model test and numerical analysis are plotted in Figure 3. Both load and displacement of the centrifuge and numerical results were selected at the same reference point. Overall, good agreement can be seen not only in terms of the initial slope (65600 kN/m) but also the ultimate resistance (H = 8000kN)

Figure 4 shows the bending moment profiles at the applied horizontal load of 1560 kN and 3440 kN, respectively. The piles were numbered as indicated in Figure 3. Note, the bending moment of the leading pile (P3) could not be measured in the test because of gage failure. For the center pile (P1), the numerical simulations predicted well in terms of the positive maximum bending moment, although the appearing depths are slightly deeper (4.8 times) than the centrifuge tests. Due to this different appearing depth in numerical simulation, the negative maximum bending moment at the pile head indicates considerably high. The numerical results for the tail pile (P2) and side pile (P4) show a reasonable agreement with the test data. These validation analyses have confirmed the capability of the FEA in assessing the horizontal behavior of piles in GBF.

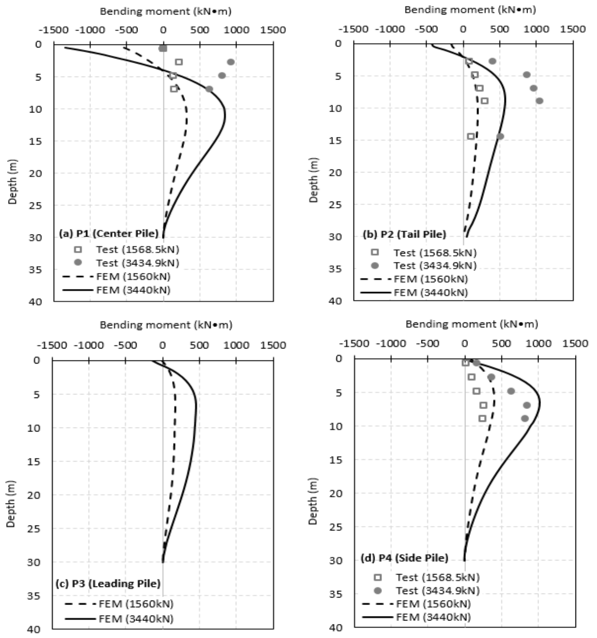


Figure 4. Comparison of bending moment profiles from centrifuge model test and numerical analysis

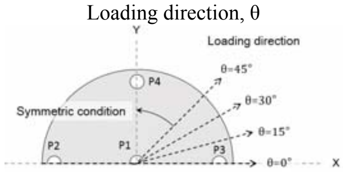
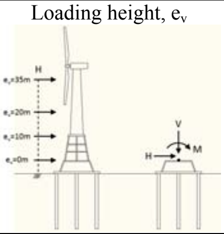
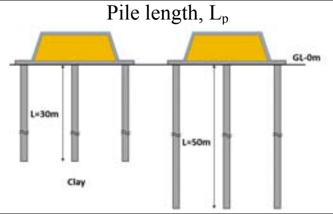
3 PARAMETRIC STUDY

To examine the effect of various factors on the behavior of piled GBF, an extensive parametric study was carrying out varying (a) loading direction θ, (b) loading height e_v, and (c) pile length L_p. As listed in Table 2, the reference case was taken from the centrifuge model and the selected parameters (i.e. loading direction, loading height, and pile length) were changed from the reference case. The loading direction of an external force to the offshore wind structure is not always constant so that various loading directions were considered. The loading angle (θ) is defined as an angle between a line passing P2-P1-P3 and the load direction. Because of the symmetry of the foundation, four different loading directions were simulated from a range of 0° to 45° (see Table 2).

Figure 5 is the load-displacement curves of all the parametric cases. The load direction and pile length do not much affect the horizontal load. But, in the case of e_v = 0 m, the horizontal resistance greatly increases because combined moment reduces the horizontal capacity.

As the parametric cases, the bending moment profiles at H = 4000 kN are shown in Figure 6. Figure 6(a) compares the effect of loading directions (θ = 0° & 45°). For the leading pile (P3), the maximum bending moment (M_{max}) occurs at the pile head, while for the side pile (P2), the depth of M_{max} is around 5~7 m (in the middle of the pile). However, the effect of loading direction is minimal on the shape of bending moment profile. The effect of the loading height (e_v) and pile length (L_p) on the bending moment profile were also investigated in Figure 6(b). The bending moment profile dramatically reduces with decreasing e_v (compare the hollow symbols of e_v = 0 m in Figure 6(b) to the hollow symbols of e_v = 35 m in Figure 6(a)). It can be explained that the overturning of the foundation becomes less. As expected the long pile (L_p = 50 m by solid symbols in Figure 6b) reduces the bending moment profile, but the effect is lower than the ones of e_v.

Table 2. Summary of FE analysis performed

Parametric cases	Reference case	Parametric cases
Loading direction, θ 	0˚	15˚ 30˚ 45˚
Loading height, e_v 	35m	0 m 10m 20m
Pile length, L_p 	30m	40 m 50 m

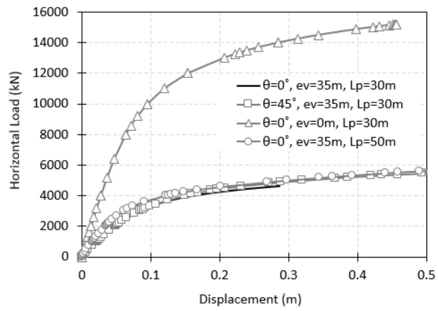


Figure 5. Load-displacement curve on each parametric case

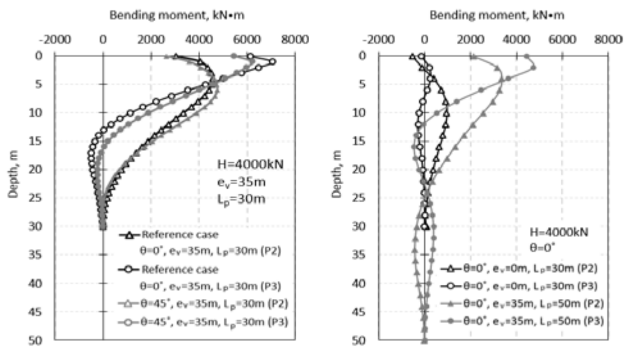


Figure 6. Comparison of bending moments profiles of the cases: (a) the reference case with θ = 0° and the case with θ = 45°; and (b) the case with e_v = 0 m and the case with L_p = 50 m.

Figure 7 summarizes the parametric cases in terms of M_{max}. The maximum is selected among the M_{max}s of the piles from each case and plotted in Figure 7. The corresponding pile numbers are indicated. For most of cases, the maximum of the M_{max}s

among the piles appears at the P3 among the piles but the case with e_v = 0 m results in the maximum of M_{max}s at P2 (see Figure 7(b)).
Overall, M_{max} decreases with increasing the loading direction angle (θ). The highest M_{max} recorded at low θ = 0 to 15˚. With the different loading angle, the moment transmitted to the pile is changed because the change in the loading angle alters the relative location of piles from the center of the mat (i.e. the reference point).

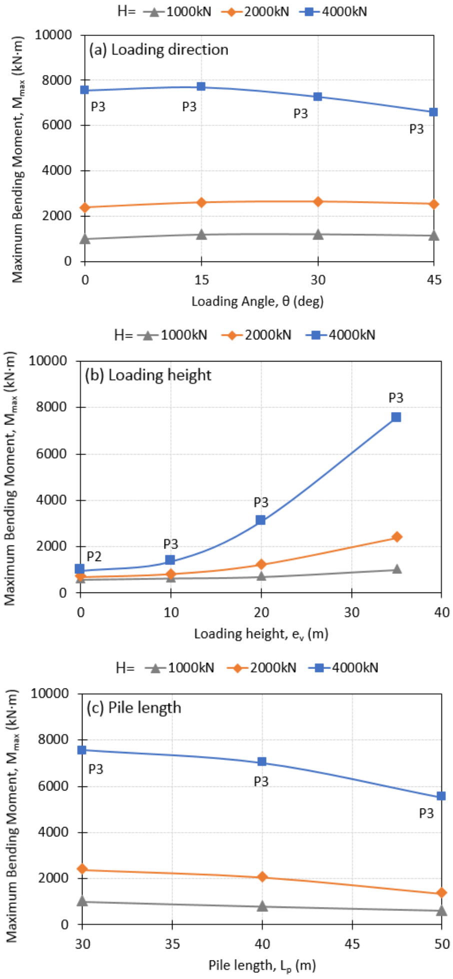


Figure 7. Comparison of maximum bending moments with: (a) loading direction; (b) loading height; and (c) pile length

The effect of loading height (e_v = M/H) was investigated, increasing the loading height to e_v = 20 m. At a horizontal load of 1000kN, the M_{max} slightly increases with the increase in the loading height e_v but significantly does at the loads higher than 2000 kN because of the significant increment of overturning moment. Especially, at 4000kN of horizontal load, the M_{max} at e_v = 35 m is considerably large, which is about 7.8 times higher than that at e_v = 0 m. At e_v = 0 m, the maximum of M_{max} appears at P2 but the maximum does at P3 with the increase in e_v.
The effect of the pile length was considered with the pile lengths (L_p) of 30 m, 40 m, and 50 m. As the pile length increases, the M_{max} tends to decrease. The increment of the M_{max}s for the pile length of L_p = 50 m becomes relatively small as the horizontal load increases. At a horizontal load of 4000 kN, the difference between M_{max}s for L_p = 30 m and 50 m is 2,054 kN·m. The bending moment decreases as pile length becomes longer because the rotation of the mat is limited due to the increase in the pull-out resistance of the tail pile and compressive resistance at the front part of the foundation supported by the leading pile.

4 CONCLUSIONS

In this study, a centrifuge model test and numerical analysis were carried out to study the horizontal behavior of piled gravity bases foundation for offshore wind turbine. The load-displacement curves and bending moments were compared. In addition, the effects of loading direction, loading height and pile length on the M_{max}s of the pile were analyzed using the numerical analysis. The findings in this study are as follows.

(1) The numerical model was verified with the centrifuge model tests. As a result, the load-displacement curves and bending moment profiles obtained from the centrifuge model test and numerical analysis are comparable.
(2) From the parametric study, it was found that the load direction and pile length has minimal effect on the load-displacement curve but the horizontal load greatly decreases with the increase in the loading height. But, the bending moment profiles of piles are significantly affected by the parameters.
(3) The maximum bending moment from the piles appears at θ = 0° to 15° and decreases with the increase in the loading direction. This result is caused by the change of the relative pile location from the load and the corresponding reduction in the moment at the pile head. The maximum bending moments is slightly affected by the loading height at a horizontal load of 1000kN. But at the horizontal loads higher than 2000kN, the maximum bending moment significantly increases with increasing the loading height because of the significant overturning of the structure. For the pile length, the maximum bending moment decreases as the pile length increases because the rotation of the mat decreases due to the increase in pull-out resistance of the tail pile and compressive resistance at the front part supported by the leading pile.

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