Centrifuge test and numerical modeling for a suction bucket monopod foundation

Essai en centrifugeuse et la modélisation numérique d'une fondation de type : caisson à succion

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ABSTRACT: A centrifuge load test for a preliminary design of a monopod suction bucket foundation was performed. The target site was the Yellow Sea of Korea and the prototype foundation was a steel monopod caisson with a diameter of 15.5m for a 3MW turbine. The seabed conditions comprised of a dense silty sand above layers of sandy silt were reproduced to a model soil profile using soil samples collected at nearby seashores. Horizontal load and overturning moment were applied and monitored in the test, with vertical load being simulated by self-weight of the bucket model. Series of numerical analysis were performed in order to validate test conditions and compare the effects of soil parameters.

RÉSUMÉ : Un test de chargement en centrifugeuse pour étudier le design préliminaire d'une fondation de type « caisson à succion » a été réalisé. Le site cible était la mer Jaune de Corée et la fondation prototype était un caisson unique en acier caisson de 15.5 m de diamètre pour une éolienne de 3 MW. La stratigraphie du fond marin, sable limoneux dense et limon sableux, a été reproduite pour faire un profil de sol modèle en utilisant des échantillons de sol prélevés sur le rivage à proximité. Un chargement horizontal et un moment de renversement ont été appliqués et contrôlés pendant l'essai, le chargement vertical était simulé en utilisant le poids propre du modèle. La modélisation numérique a été réalisée afin de valider les conditions d'essai et de comparer les effets du choix des paramètres de sol.

KEYWORDS: Suction bucket foundation, Monopod bucket foundation, Offshore wind, Centrifuge Test, Numerical Modeling

MOTS-CLÉS : Caisson à succion, Caisson de fondation, Éolienne Offshore, centrifugeuse, modélisation numérique

1 INTRODUCTION

Suciton bucket (also termed as suction caisson or suction pile) has been considered as a viable alternative to conventional foundations for offshore wind turbines, becuase it has features appropriate for installing large foundations in offshore environment with minimal environmental problems (Byrne and Houlsby 2003, Houlsby et al. 2005, Villalobos 2006, LeBlanc et al. 2009, Hung and Kim 2012, Oh et al. 2012). In Korea, major offshore wind farm projects are planned in the Yellow Sea near the south western coast of Korea. The soil profiles are mainly composed of layers of silty sand and sandy silt.

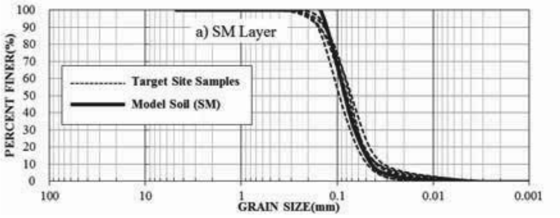
A preliminary design was performed for field testing of suction bucket foundations, and centrifuge load tests were performed to verify and compare alternative designs. In this paper, a centrifuge test for a steel monopod with a diameter of 15.5 m and a length of 10.5 m is described. Expected horizontal load combined with moment load was applied in the test.

Numerical analyses were performed to validate the centrifuge test model conditions such as model weight and soil boundary distance. In addition, the effects of soil parameters such as elastic modulus, internal friction angle, dilation angle, cohesion and wall interface friction angle, on foundation behaviour were evaluated.

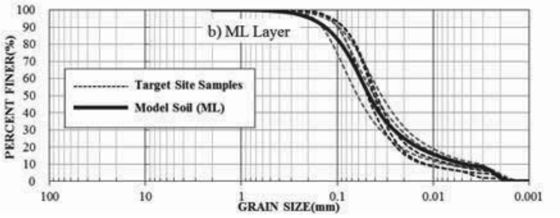
2 CENTRIFUGE MODELING

A centrifuge test was performed with a geotechnical centrifuge at KAIST (Korea Advanced Institute of Science and Technology) in South Korea. It has a maximum capacity of 240 g-ton and 5 m radius (Kim et al. 2012). Detailed description of the centrifuge test for this study can be found in Choo et al. (2012) and Kim et al (2013). The procedures and results are briefly described here.

The soil conditions at the target site were replicated in the model soil container for the centrifuge test. Natural soil samples collected at the Western coastal areas near the target site were used after verifying that the properties of model materials were comparable the soil samples from the target site (Figure 2). The model profile was formed in two layers of dense silty sand and medium dense sandy silt up to the depth of 32 m, which was about two times the diameter of the foundation.



(a) Silty Sand (SM) Layer



(b) Sandy Silt (ML) Layer

Figure 1. Comparison of grain size distributions between target site samples and model soil

A 1/70 scaled model was used for the test. Horizontal load by a displacement controlled actuator was applied and monitored at the model tower which was located at 33.0 m height from the foundation top in prototype scale. The horizontal displacement of the tower was measured at multiple points so as to calculate the horizontal displacement and rotation of the foundation.

The load – displacement curve of the test are shown in figure 2. The load is presented in moment, which is the horizontal load multiplied by the vertical eccentricity of the load from the foundation top. The displacement is shown in terms of the rotation of the foundation. Gradual decrease in the slope was observed and the method by Villalobos (2006) was used to define the yield load, which was 198 MN-m.

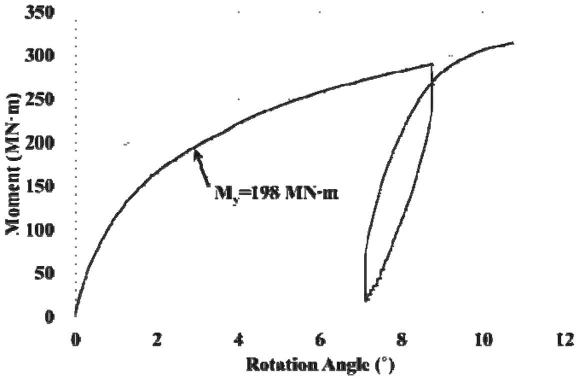


Figure 2. Moment – rotation angle curve of the centrifuge test

The model and nearby soil after the test are shown in Figure 3. Tilting of the foundation by the horizontal and moment load induced several mm of heave in the passive side and 20 to 30 mm of subsidence behind the bucket. Positions of the model before and after the load test are shown in Figure 4.

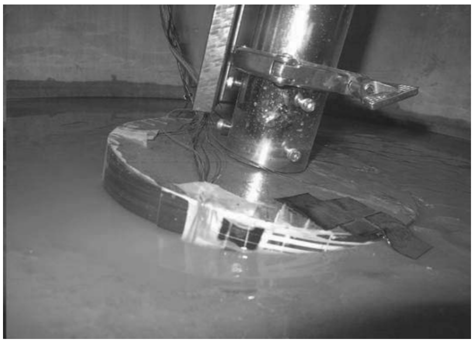


Figure 3. Model and nearby soil after the test

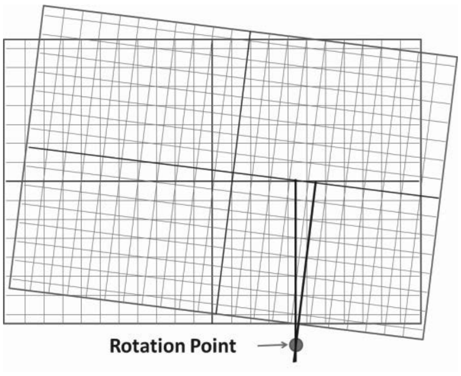


Figure 4. Comparison between positions before and after the test

3 NUMERICAL ANALYSIS

3.1 *Model setup and analysis procedures*

Numerical modeling in this study was performed using FLAC 3D V 5.0 based on the finite-difference method and explicit scheme (Itasca, 2012). The numerical model was modified from a model used in Kim et al. (2013) and detailed descriptions are given for modeling and analysis procedures.

Soil elements were modeled by Mohr-Coulomb failure criterion with linear elasticity up to plastic yield and the bucket body and tower parts were modeled by linear elastic solid elements. In order to represent the load conditions, a solid circular tower was additionally modeled on top of the bucket top lid and horizontal displacement was applied on the top face of the tower. Half section model mesh and boundary conditions were used for the analysis because of the symmetry of the foundations and load conditions. Approximately 4800 elements were used in the model. Actual steel deformation properties were used in the analysis (E = 200 GPa, ν = 0.30). The mesh for the analysis is shown in Figure 5.

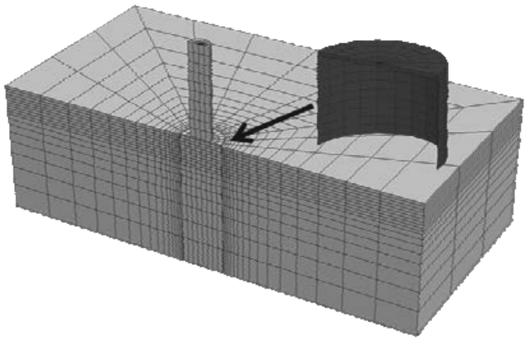


Figure 5. Mesh for numerical model (Bucket body shown in magnified scale)

The base properties for the model are shown in Table 1. The submerged unit weight of the steel used for the bucket body was modified from actual value, because the weight of the centrifuge model bucket was increased by the connection between the bucket body and the vertical rod.

Table 1. Base properties for numerical analysis

Items	Parameters		
	Bucket	SM Layer	ML Layer
Submerged unit weight (γ_{sub}, kN/m^3)	75.9	9.50	8.60
Elastic modulus (E, MPa)	200,000	10	10
Poisson ratio (ν)	0.3	0.3	0.3
Internal friction angle (φ)	-	33.7	34.5
Dilation angle (ψ)	-	11.7	0
Cohesion (c, kPa)	-	16.1	5.2
Friction angle between bucket wall and soil (δ,)	-	22.5	-
Coefficient of earth pressure at rest (K_0)	-	0.5	0.5

Bottom face nodes were fixed in vertical displacement, and side face nodes were fixed in horizontal displacement. Coulomb criterion interface elements were applied in contacting faces between the bucket body and soil in order to model sliding and separation behaviour. Shear and normal stiffness values were set to 200 MPa/m which was larger than ten times the elastic modulus of surrounding soil (Itasca, 2005).

The analysis was run in three stages. The first stage simulated the initial K_0 soil condition. The second stage simulated the installation of the bucket in the soil. The third stage was the loading stage where the top of the loading tower was horizontally moved in every step and unbalanced forces were calculated as the resistance of the foundation.

The ramping algorithm was used for the loading velocity control, in which the loading velocity was linearly increased with step to $u_{d,max}$ per step (1□10^{-6} m/step in this study) till prescribed steps were run and kept constant afterwards (Itasca, 2012).

3.2 *Analyses and results*

Cases considered in this study are summarized in Table 2 and a plot of displacement contour for C2 case is shown in Figure 6.

Table 2. Analysis cases

Items	Values
A1. Reference case	Parameters in Table 1
A2. Bucket weight and vertical load	Bucket weight 2220 kN Vertical load 5750 kN
B1. Horizontal boundary distance from model center (5D for reference case)	2D
C1, C2. Elastic modulus of SM layer (E, MPa)	20, 5.0
D1, D2. Internal friction angle (φ)	38.7, 28.7
E1. Dilation angle (ψ)	3.7
F1. Cohesion (c, kPa)	0.1
G1. C2 + F1	

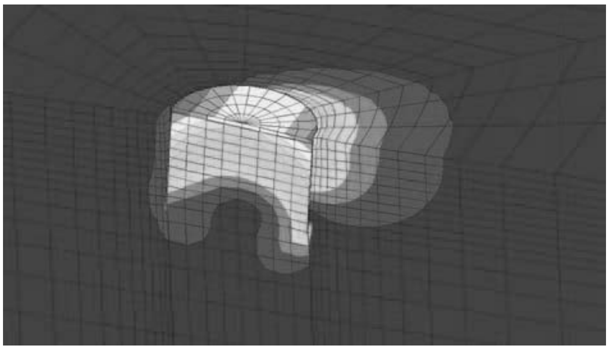


Figure 6. Contour of displacement for case C2

The prototype of the centrifuge test was modeled with larger thickness in the wall and the top plate than the preliminary design due to limitations in fabrication. The vertical rod and the connecting part between the bucket body and the rod were designed to have sufficient stiffness and strength for the centrifuge. These resulted in a heavier prototype and vertical load than the target structure in the preliminary design. Therefore, the effect of heavier structure weight was analyzed in the numerical analysis. The load – displacement curve is shown in Figure 7. Slight decrease in the resistance was observed for the reduced weight and vertical load, after around 0.003 ~ 0.005D.

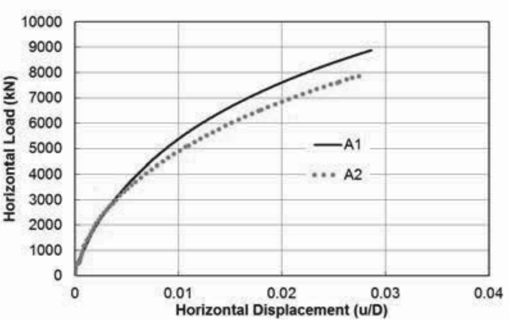


Figure 7. Load – displacement curves for different foundation weight and vertical load

The centrifuge model soil container had a radius of 447.5 mm, which was about two times the diameter of the model foundation. The results between 2D and 5D horizontal boundary distances are compared in Figure 8. The difference was negligible between the horizontal boundary distances considered.

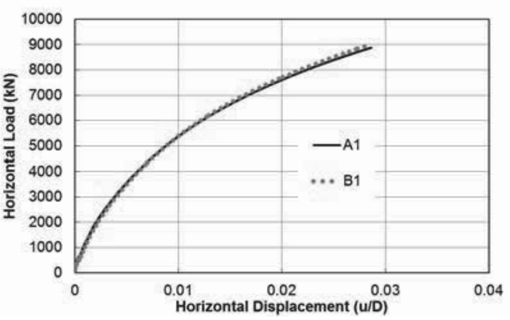


Figure 8. Load – displacement curves for different horizontal boundary distances

Different elastic moduli resulted in a noticeable variation in the slopes of the curves (Figure 9). Therefore, proper estimation of the elastic modulus and application in the numerical model are thought be important for the load – displacement behaviour in the conditions of this study.

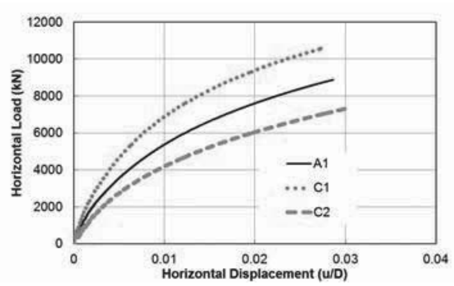


Figure 9. Load – displacement curves for different elastic moduli of the silty sand layer

The effect of variations in the internal friction angle and dilation angle of the silty sand layer was considered (Figure 10). Slight changes in slopes were observed after around 0.005 ~ 0.01D, but they were found to be relatively small in the displacement range considered in this study.

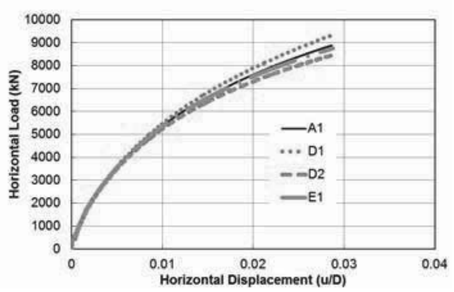


Figure 10. Load – displacement curves for different internal friction angles and dilation angles of the silty sand layer

The resistance was affected by the cohesion of the surrounding soil (Figure 11).

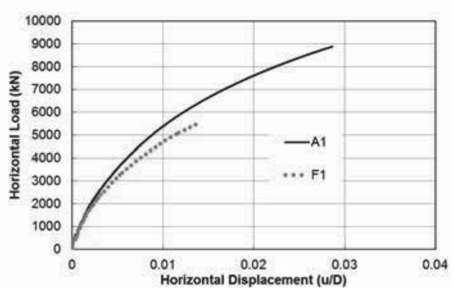


Figure 11. Load – displacement curves for different cohesions of the silty sand layer

Figure 12 shows the result when the elastic modulus and cohesion were decreased from the reference values. The curve is closer to the centrifuge test result than others. However, this does not mean that this set of parameters are the actual properties, but provides a guide on which parameters are more influential than others and how the numerical model can be improved. Further researches are needed to model the nonlinearity and the dependency on confining stress of elasticity of the silty sand layer.

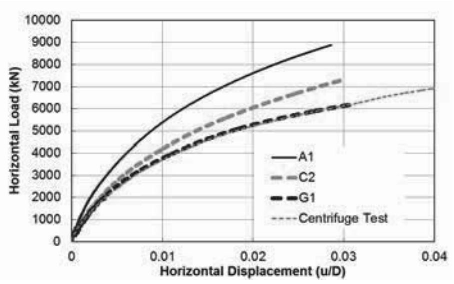


Figure 12. Comparison of load – displacement curves for the centrifuge test result and numerical model

4 CONCLUSIONS

The load – displacement behaviour of a monopod suction bucket foundation was studied by a centrifuge test and numerical modeling. The centrifuge model test was performed with a model soil which represented key soil characteristics of the target site. Horizontal load combined with overturning moment was applied according to the preliminary design of an offshore wind tower. In the centrifuge test, the foundation and soil behaviour was observed for a wide load range from the initial to the post-yield load, so that the foundation design be verified and improved based on the test result. A series of numerical modeling were performed to validate the centrifuge test condition and study the effects of soil parameters on the load-displacement curves. It was found that the increased weight and vertical load provided slight increase in the resistance. The effect of the limited horizontal boundary distance in the tested centrifuge model was analysed to be minimal. Soil parameters such as elastic modulus and cohesion were found to have significant impacts than other factors in this study on the load – displacement behaviour of the monopod foundation in the silty sand layer. Refinement of the numerical model related to these parameters and elaborate estimation of them are important for realistic modeling of the foundation behaviour.

5 ACKNOWLEDGEMENTS

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