Physical Modelling in Geotechnics

Effect of loading height and end bearing condition on p-y curves of large diameter monopile for offshore wind turbine using centrifuge tests

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ABSTRACT: This study demonstrates the centrifuge model tests of large-diameter monopiles to investigate the effects of the loading height from the ground surface and the end bearing conditions on the p-y curve. The 7-m monopiles are embedded up to 4.67 and 2.67 times the monopile diameter in medium dense sand and in sand overlying stiff rock profile, respectively. In each test, the model monopile is ramped up to 68.83g and subjected to inflight lateral loading at various loading point equivalent to 1 or 5 times its diameter above the ground surface. Based from the experimental results, the derived p-y curves are not influenced by the loading offset above the ground surface. Furthermore, the rock-socketed monopile reveals greater initial stiffness than that in sand embedded monopile.

Keywords: offshore wind turbine, centrifuge modelling, large-diameter monopile, loading height, end bearing condition

1 INTRODUCTION

Nowadays, the development of offshore wind power and technology has increased due to the continuous demand for renewable energy. To satisfy the need for energy production, the size of wind turbine generators and rotor blades is in need of modification accordingly. A larger wind turbine corresponds to increase in foundation size to withstand large axial loads, lateral loads, and bending moments. However, quantifying these monopile loadings on a full-scale laboratory test is practically impossible. Therefore, developing a well-instrumented centrifuge model test is an alternative for investigating effective monopile behavior using the p-y curve.

The p-y curve is an approach for investigating the bearing capacity and frequency analysis through lateral loadings and bending moments. Moreover, the American Petroleum Institute (API) recommends the application of the p-y method for evaluating offshore pile designs (including large-diameter monopiles) embedded in sandy soil deposits. Up-to-date, the API p-y method is based on the "simplified process" proposed by O'Neill and Murchison (1983).

The study of O'Neill and Murchison (1983) utilized 1-m diameter pile, and hence considered as "small-diameter pile" which was initially developed by Reese *et al.* (1974). As such, the API p-y method yields overestimation of the initial stiffness when compared to numerical analysis and centrifuge test results for large-diameter monopiles. This issue was pointed out by some studies who validated the performance of monopoles through centrifuge modelling and numerical anaylses (Dyson and Randolph, 2001; Klinkvort *et al.*, 2010; Hearn and Edgers, 2010; Alderlieste *et al.*, 2011; Miller and Christiansen, 2011; Doherty and Gavin, 2012; Haiderali and Madabhushi, 2013; Choo *et al.*, 2014; 2016; Lee *et al.*, 2019).

In line with this, the present study aims to develop centrifuge model tests of well-instrumented monopiles for (1) two different loading heights on 7m-diameter monopiles, and (2) two different tip bearing conditions and analyze the effects of the tip bearing conditions and different loading height through p-y curves.

2 CENTRIFUGE TEST CONDITION

The centrifuge model tests were peformed at Korea Advanced Institute of Science and Technology (KAIST) The facility includes 5-m radius beam-type centrifuge with capacity of 240 g-tons and maximum acceleration of 130g (Kim et al., 2013). All centrifuge model dimensions and material properties were scaled 1:68.83g (g is the Earth's gravitational acceleration equal to $9.81 m/s^2$) and scaling relationships for centrifuge modelling at enhanced accelerations were reported in Schofield (1980).

In this study, a steel cylindrical container was used to contain the soil specimens. The model container has an inner diameter of 900 mm and a height of 700mm. The model monopiles were fabricated using cylindrical steel pipes, with Young's modulus of 210 Gpa, and the moment inertia was $7.685 m^4$.

Table 1 presents the testing conditions of the experimental study in prototype scale. Two testing parameters are of interest including the comparison of (1) loading height from the ground surface in CASE 1 and CASE 2, and (2) pile tip bearing conditions on the sand

and bedrock in CASE 1 and CASE 3.

Table 1. Testing conditions of prototype scale

CASE		1	2	3
Soil layer		Single sand	Single sand	Sand over rock
Pile	Outer diameter, D (m)	7.0	7.0	7.0
	Thickness, t_p (mm)	58.5	58.5	58.5
	Length, L_p (m)	47.0	62.0	47.0
Sand	Thickness, h_s (m)	32.7	32.7	18.7
	Relative density	55.2	64.8	54.9
Rock	Thickness, h_r	-	-	14.0
Embedded length, d_p (m)		25.7	25.7	25.7
Loading height from the ground surface, l_e (m)		7.0	35.0	7.0

Crushed silica sands were used as soil specimen in this study to minimize scale effects on particle size that could affect the pile's lateral behavior. An automated "sand-pluviator" device was operated to prepare a medium dense sand specimen. During the sand raining, a specific nozzle size opening was set and the falling height between the hopper and surface was kept constant to ensure homogeneity. Table 2 summarizes the geotechnical properties of soil specimen.

After the final layer was achieved, the dry sands were saturated slowly allowing the water to flow in the sand specimen, and hence minimizes entrapment of air voids. All CASEs were kept in drained condition for all static centrifuge model tests.

In CASE 3, the Hwang-deung granite hard rock is positioned at the bottom of the model container to prepare a "sand-over-rock" layer as shown in Fig. 1(c).

Table 2. Geotechnical properties of sand and rock specimens

Soil	Item	Parameter
Sand	Type	Silica sand
	Specific gravity, G_s	2.65
	Grain size, D_{50}	0.22mm
	Curvature coefficient, C_c	1.11
	Uniformity coefficient, C_u	1.96
	Soil classification	SP
Rock	Type	Hwang-deung granite rock (hard rock)
	Uniaxial compressive strength	150,145.17kN/m^2
	Specific gravity, G_s	2.63

The lateral actuator was used to simulate lateral loadings, which act as the external forces experienced by wind turbines located on offshore sites. The loading simulation system comprises a lateral actuator, a rod of loading, loadcell, hinge connections, and an aluminum collar with Teflon. The lateral actuator has a maximum load capacity of 9.8kN on the model scale (corresponding to 46.43MN in the prototype scale), and a maximum speed of 8.3mm/s, which can be controlled through a "remote control system".

Four contactless laser sensors were installed above the ground surface wherein the target point is directed at the exposed monopile's surface to measure the monopile's displacement. Fig. 1 depicts the testing system for CASEs 1 to 3.

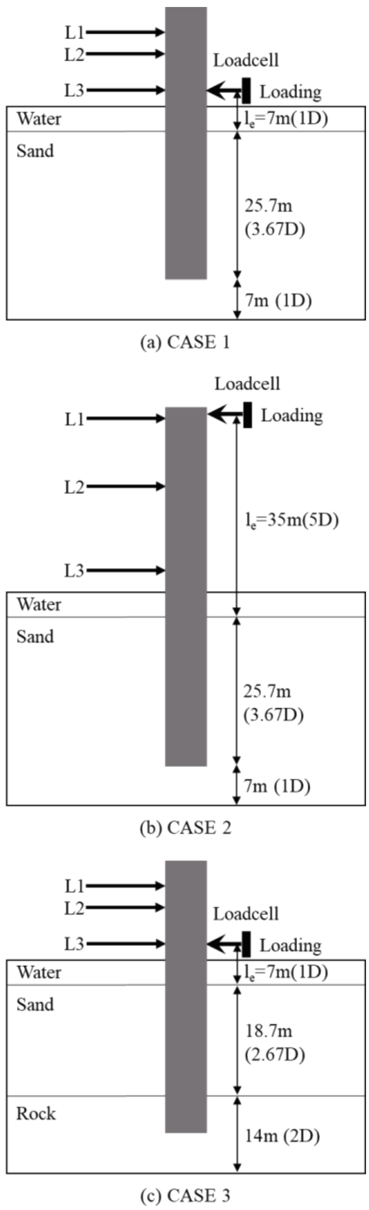


Fig. 1. Schematic diagram of centrifuge models

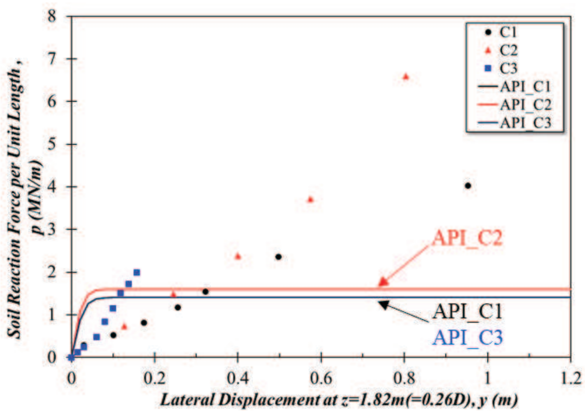
3 TEST RESULTS AND DISCUSSION

The bending moment formula, M_{Test} presented in Eq. (1), is used to derive the bending moment distributions acquired from the strain gauge couple instrumented along the pile shaft. Subsequently, the resulting bending moment distributions were curve fitted mathematically, $M_{Fitting}$, using Eq. (2). The fitting method shows a good relationship between bending moment diagrams at each load step.

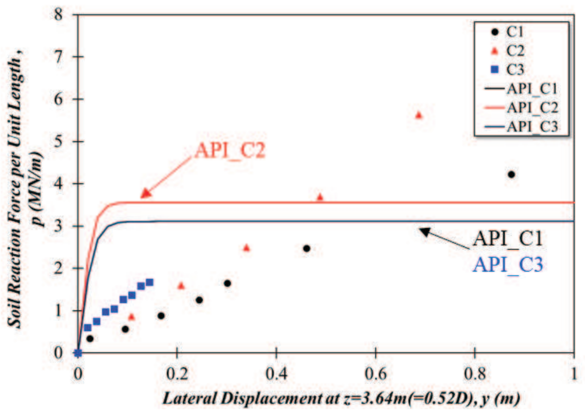
$$M_{Test} = \frac{0.5(\varepsilon_c - \varepsilon_t)\cdot E \cdot I}{0.5D} \quad (1)$$

$$M_{Fitting} = a_0 + a_1 z + a_2 z^{2.5} + a_3 z^3 + a_4 z^4 + a_5 z^5 \quad (2)$$

where, ε_c = strain of compression; ε_t = strain of tension; E = elastic modulus of monopile; I = geometrical moment of inertia; D = pile outer diameter; $a_0 \sim a_5$ = coefficients of fitting method formula; and z = depth from the ground surface.



(a) p-y curve at z=1.82m(=0.26D)



(b) p-y curve at z=3.64m(=0.52D)

Fig. 2. The p-y curves of CASE 1, CASE 2, and CASE 3

Soil reaction (p) and lateral deflection (y) were derived using Eqs. (3) and (4) based from the beam theory to establish the p-y curve relationships.

$$p = -\frac{d^2M}{dz^2} \quad (3)$$

$$y = \int(\int \emptyset\, dz)dz = \int(\int \frac{M}{EI} dz)\, dz \quad (4)$$

where, p = soil reaction per unit length for the monopile; M = bending moment at depth, z; y = lateral deflection along with the depth of the monopile; $\emptyset$ = curvature of the monopile; and EI = flexural modulus of the monopile.

The resulting p-y curves for all CASEs are depicted in Fig 2. It is noteworthy that the results of CASE 1 will be the reference of comparison since it is the simplified layer condition (short pile embedded in a sandy soil layer). The experimental findings show that the effects of the loading height on the initial stiffness of the p-y curves are deemed insignificant. Although the loading height increased CASE 2 from the ground surface as compared to CASE 1, there was only minimal difference in the p-y curves at all depths in Figs 2(a) and 2(b).

When the monopile tip was socketed in the rock (CASE 3), the initial stiffness of their p-y curves is higher than that of the single sand layer (CASE 1) as shown in Fig. 2(c). It is noteworthy that experimental research on the p-y curve for large diameter monopiles is still lacking, and there is no experimental data on large diameter monopiles over 7m.

In the API curves, a difference is observed between CASE 1 and CASE 2 but it would be caused by slightly different relative densities of CASEs 1 and 2 although both fall in the range of "medium dense sand". A large difference in the measured initial stiffness shown in the API curves when compared with the experimental p-y curves. The API p-y curves at z = 3.64 m for the CASEs 1 and 3 are comparable in Fig. 2(b) despite the different soil layers of CASE 1 and CASE 3. It can be deduced that the API p-y method does not perform well in multi-layered soil profiles.

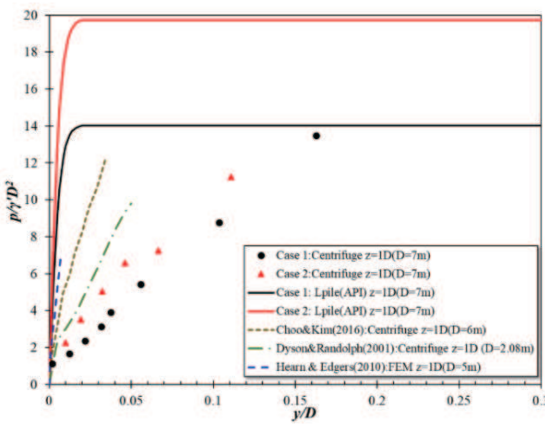


Fig. 3. Normalized p-y curves of in this study and literature studies

The experimental results of this study were normalized with pile diameter and effective unit weight to compare with other experimental evidences (Doherty and Randolph, 2001; Hearn and Edgersm, 2010; Choo and Kim, 2016). Fig 3 shows that all initial stiffness from the literature (as denoted by the dotted plots) are smaller than the normalized p-y curve of API and larger than the experimental results of this study. The reason of these results is that the pile embedded depth in this study is shallower than the previous studies.

4 CONCLUSIONS

This study performed a series of centrifuge model tests for large-diameter monopile foundation (7m diameter) at 68.83 g-level. The instrumented model monopiles embedded in single medium dense sand and sand-over-rock profiles. The effects of loading heights, and the tip bearing conditions were investigated through p-y curve relationships and were compared with the API method.

The experimental findings show that the effect of loading height on the p-y curves is insignificant for the range of one to five times the monopole diameters in the "medium dense" sand layers and shallow embedded depths showing similarities to the "rigid pile" behavior. On the other hand, the initial stiffness of the p-y curve was significantly affected by the "rock socketed" condition compared to the "sand" condition. This could be attributed to the constraints provided by the rock to the monopole tip. Consequently, the measured deflection of the sand-over-rock case was very small.

Both the experimental and API p-y curves present a minimal effect on the loading height. However, the present study confirmed that the initial stiffness using API p-y curves was over-estimated in single sand layer, yet those of the API p-y curves were comparable despite of different soil profiles. This might be an indication of the API p-y curves limitation for a multi-layered soil configurations.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government and Ministry of Science and ICT (MSIT) (No. 2021R1A2C2009985 and 2021R1A4A1031509).

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