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EFFECT OF ELASTIC MODULUS OF SANDS ON THE *P-Y* RELATIONSHIP OF OFFSHORE WIND TURBINE MONOPILE

Kicheol Lee[1], Byung Soo Kim[2] and Dongwook Kim[1,*]

[1]Department of Civil and Environmental Engineering
[2]Department of Industrial and Management Engineering
Incheon National University
119 Academy-ro, Yeonsu-gu, Incheon 22012, Korea
wlq4619@gmail.com; bskim@inu.ac.kr; *Corresponding author: dwkim@inu.ac.kr

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Abstract. *Monopile is widely used as an efficient foundation of offshore wind turbines. Due to the offshore environmental conditions of current, tide, and wind, a wind turbine structure and its foundation are exposed to significant lateral loads and moments; therefore, an accurate assessment of monopile lateral behavior is important for optimal wind turbine foundation design. Lateral behavior of monopile is typically estimated using the p-y method. The inputs of the current p-y methods do not directly include the elastic modulus of the ground. Therefore, numerical studies were conducted to quantitatively analyze the effect of the soil elastic modulus on the p-y relationship.*
Keywords: Monopile, Shear strength, Soil stiffness, Lateral behavior, Numerical analysis, *p-y* relationship

1. **Introduction.** Power generation from wind turbines is considered as one of the most promising, sustainable, and efficient energy developments. In the EU countries, wind energy has contributed the second largest power generation for the past 10 years, resulting about 30% of capacity growth [1]. Current wind turbines are preferred to be used at offshore rather than at inland (or onshore), because of the better wind quality at offshore and free from noise and vibration issues in inland. In addition, the sizes of the wind turbines are increasing for more efficient energy generation. Accordingly, the vertical and lateral capacities of the supporting foundations should also increase significantly to be able to withstand the much larger loads and moments. To increase the foundation capacity, the embedded length or diameter of monopile should be increased. Achmus et al. [2] numerically studied on the behavior of a large diameter (5 m) monopile installed on offshore under static and cyclic loading conditions.

Unlikely to the conventional pile foundations exposed to dominant axial loads, behavior of wind turbine foundations is more governed by the lateral displacement due to significant lateral loads and moments exerted by wind, current, and tide [3]. Generally, the laterally loaded piles are designed based on the *p-y* relationship, which is proposed by many researchers and institutions. One of the representative institutions is the American Petroleum Institute [4]. The *p-y* method specifies the relationship between the soil reaction (p) and the lateral pile displacement (y). The different *p-y* methods were proposed for different soil types and rocks. In this study, the *p-y* method for a large diameter monopile in sands is derived based on the numerical analysis results.

The *p-y* methods for the laterally loaded piles in sands have been studied by many researchers. Mezazigh and Levacher [5] studied the ground inclination effect on the *p-y* curve of laterally loaded piles in sands. Choo and Kim [6] stated that the initial stiffness from the *p-y* relationship in sands is strongly influenced by the presence of an adjacent

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stiff rock layer. In addition, various other studies [2,7-10] have been carried out, but these studies focus on the applicability of the existing p-y methods or the development of the experimental p-y relationships.

In general, the elastic modulus of the ground is analyzed by triaxial compression test, and it is estimated to be N value through SPT in actual field. When the depth of frictional soil increases, the confining pressure also increases. Then, the stiffness of the frictional soil layer becomes high; therefore, the pile lateral resistance against the lateral load will be also significant. Although the effect of the sand relative density on the p-y relationship has been experimentally studied based on the centrifuge test results [11], there is limited research on the effect of sand stiffness on the p-y relationship. Therefore, in this study, the effect of sand stiffness (elastic modulus) on the p-y curve is analyzed through a numerical analysis. To increase reliability of numerical analysis results, the centrifuge test results of a large diameter (6.1 m-diameter) monopile from the previous study [6] was compared with the numerically analyses results. By changing the parameters of the numerical model, the best fitted parameter values were determined to match the lateral behavior (the load-deflection curves) from the numerical analysis and the centrifuge experiment. For the matched results between the numerical analysis and the centrifuge experiment, the p-y relationship was derived.

2. **Centrifuge Model Test.** In geotechnical engineering, centrifuge model test is one of the effective methods to maintain and control the stress level of actual soils and structures using a reduced model [12]. The centrifuge model tests have been implemented to explain diverse geotechnical issues such as slope failure, earth pressure variation on the retaining wall, and soil-structure interactions [13]. The principle of the centrifuge model test is to rotate the reduced model structure at high speed and to give significant acceleration. And then, the self-weight of the model structure can be adjusted to produce the same stress levels as those of the actual structure.

Brief introduction of the centrifuge test results is as follows. In centrifuge model test, a monopile (diameter D of 6.096 m and pile length L of 48 m) with an actual sand ground (depth of 37 m, diameter of 54 m, and embedded depth of 31 m) was simulated. The centrifugal acceleration of the test was set at 60 g. Figure 1 shows the configuration of the reduced model. The homogeneous sand layers with relative density of 85% were constructed using an air pluviation method. When the soil composition and pile installation were completed, water was added very slowly to simulate the undersea condition and ground is formed to saturated sand.

Since the wind turbine monopile is subjected to large bending moment and lateral load due to various combinations of loads such as wind and wave, the position of the lateral load is determined to be 33 m from the seabed considering the stability. The level of the load of the level of 33 m above the seabed represents the location of the wind load in the actual large diameter monopile. The sands used in the experiment were classified as standard sand based on the criterion of International Organization of Standardization (ISO [15]). The monopile was made of stainless steel. The coefficient of friction between the pile and the sand was determined to be 0.57 considering the relative roughness of soil-structure interface.

Figure 2(a) shows the bending moment distribution along the depth. Bending moment at a certain depth is obtained from the measurement of paired strain gauges attached to the same depth on pile shaft. From the bending moment profile in Figure 2(a), the maximum bending moment was found at approximately 8 m from surface of ground (or seabed). Figure 2(b) compares the experimental p-y curve and the theoretical API curve. The experimental p-y curve exhibits much softer behavior with much lower ultimate resistance.

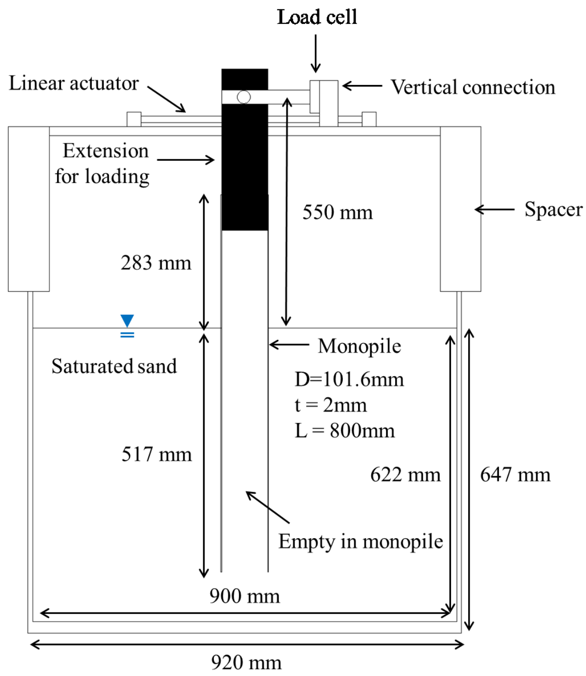
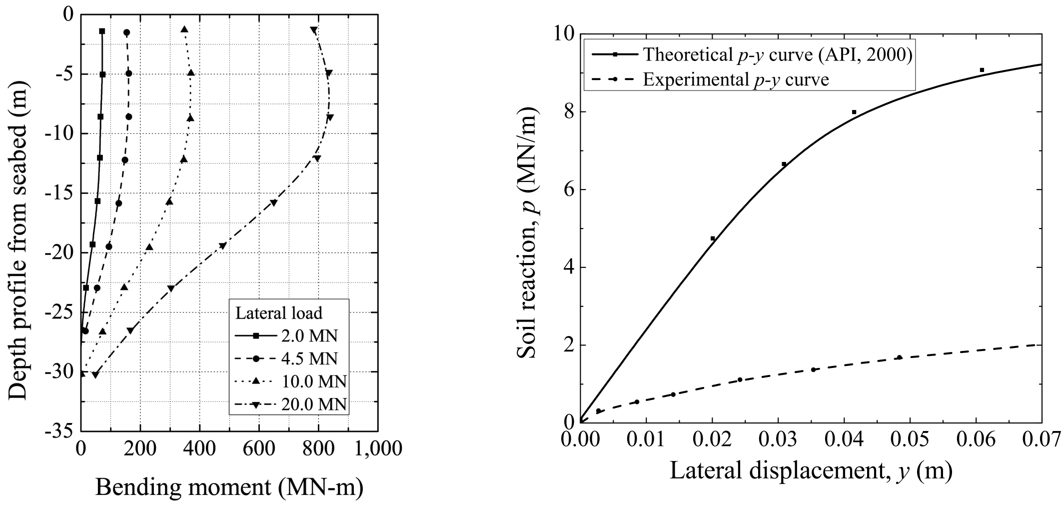


Figure 1. Schematic diagram of model chamber used in the centrifuge test (modified after [6])



(a) (b)

Figure 2. Results of literature [6]: (a) bending moment with depth from seabed and (b) p-y curves (modified after [6])

The typical lateral soil resistance-deflection (p-y) relationship in sands for a certain depth is non-linear. The most popularly used p-y relationship is developed by API [4] and its equation at a specific depth z can be represented as:

$$p = Ap_u \tanh\left[\frac{kzy}{Ap_u}\right] \tag{1}$$

where A is the factor to account for cyclic or static loading condition, p_u is the ultimate bearing capacity at depth z, k is the initial modulus of subgrade reaction, and y is the lateral deflection.

The p-y relationship can be experimentally developed from lateral pile load test. For the development of the p-y relationship, the following procedure is required: 1) calculation of bending moment profiles from the measurements of the paired strains at different depths along the pile for each loading step; 2) obtainment of soil reaction p profiles by second derivative of bending moment profiles for each loading step; 3) derivation of lateral pile displacement y profiles by double integration of bending moment profiles for each loading step; and 4) integration of p-y relationship to produce p-y curves. For accurate assessment of the p-y relationship, detailed numerical techniques are needed [14].

3. **Numerical Analysis.** Numerical analyzes were conducted to simulate the previously conducted centrifuge test results [6]. Numerical analysis was performed according to the dimensions (scale of proto type) of Figure 3. Material properties used in the numerical analysis are the same as those (Table 1) used in the centrifuge tests. The implemented constitutive models of sands and monopile are the Drucker-Prager model and the elastic model (SIMULIA [16]), respectively. Mohr-Coulomb model produced non-convergence issue for the model, as indicated by the literature (SIMULIA [16]) emphasizing the non-convergence of the Mohr-Coulomb model interpretation for cohesion of the soil less than 15 kPa. In order to match the lateral behavior between the results from the centrifuge tests and the numerical analysis, the elastic modulus, Poisson's ratio, and friction angle were adjusted. The program used for the numerical analysis is ABAQUS/CAE (SIMULIA [16]).

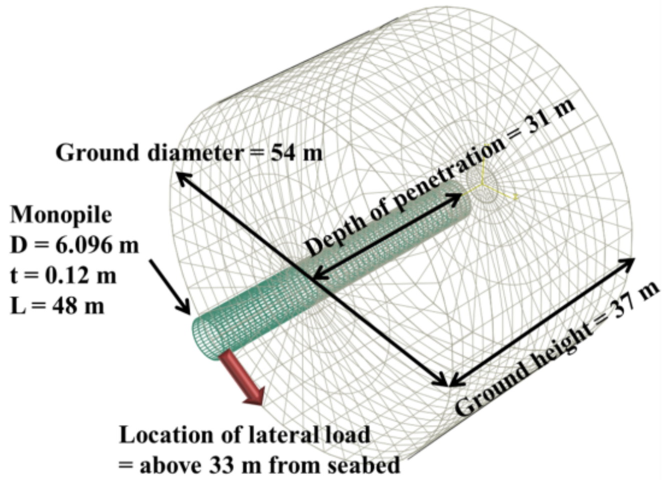


FIGURE 3. Modeling of monopile and soil layer in proto type scale

The boundary conditions of the model are set as follows: 1) the sand layer is fixed so that there is no bottom and side motion; 2) the bottom of the sand layer is fixed in terms of z-axis, and 3) the sides of the sand layer is fixed in terms of both x-axis and y-axis.

The implemented contact conditions between the pile and sand layer are 1) normal behavior with "hard" contact and 2) tangential behavior with "penalty" option with friction coefficient. Also, geostatic process was implemented at the initial condition to suppress ground deformation by gravity. Finally, a lateral load was applied to the pile head through displacement control. The lateral behavior of the monopile from the numerical analysis using the best fitted parameters (Table 1) was compared with that from the centrifuge test.

Figure 4 shows the lateral load measured at the top load cell of 33 m above the seabed versus displacement of the pile at 5.5 m above the seabed. In general, it is difficult to measure the displacement of piles in contact with the ground on the ground, which is considered to have been raised to a certain height. The failure of monopile occurs near 1.3 m and lateral load at failure is 30 MN. In the centrifuge test results, the lateral load

Table 1. Modified material properties of sand

Model/Material properties	Model name or values
Model	Drucker-Prager plastic model
Unit weight	13.43 kN/m^3
Elastic modulus	7,000 kPa
Poisson's ratio	0.3
Friction angle	30°

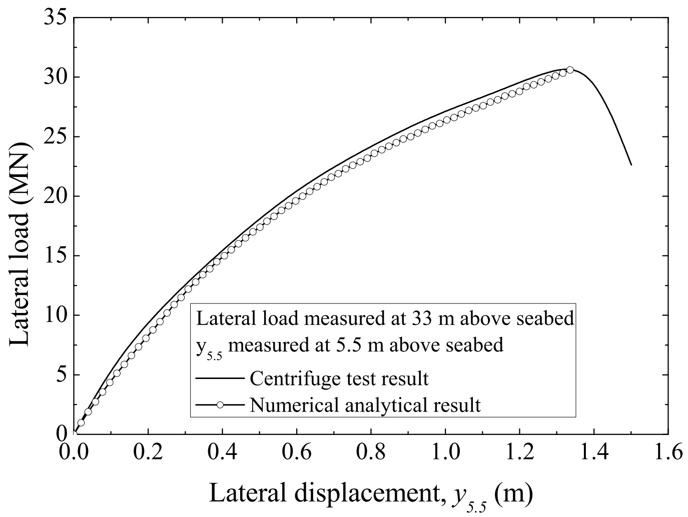


Figure 4. Comparison between analytical results of modified material properties and centrifuge test of literature

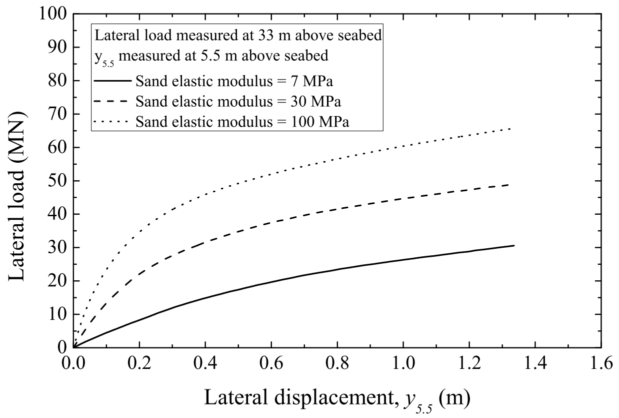
decreased sharply after the failure, but the numerical analysis terminated the analysis after the failure. Also, the centrifuge test performed by Choo and Kim [6] and the numerical analysis results based on this were similar. Therefore, it can be said that the reliability of the analytical model is secured.

4. **Effect of Elastic Modulus on Bending Moment Profile and *p*-*y* Relationship.** In order to determine the horizontal behavior of the monopile reflecting the elastic modulus of the sand, the lateral load, bending moment diagram and *p*-*y* curve were analyzed. The elastic moduli used in the numerical analyses were 7 MPa, 30 MPa and 100 MPa. The lateral load-displacement curves for different sand elastic moduli are shown in Figure 5(a). For larger elastic modulus of soil, stiffer lateral behavior was observed. The sand elastic modulus significantly influenced the lateral behavior of the large diameter monopile. From Figure 6, the elastic lateral behavior (linear increase of lateral load with increasing lateral displacement) of monopile was observed for its lateral displacement less than approximately 0.2 m.

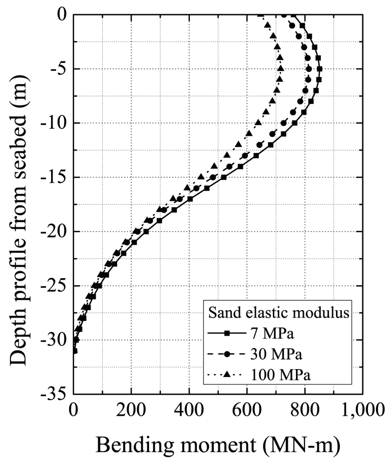
In order to examine the effect of sand elastic modulus on the *p*-*y* relationship of the monopile, the bending moment depth profiles should be obtained for different sand elastic moduli. Figure 5(b) indicates the bending moment depth profile for the lateral load of 20 MN. Since the bending moment is difficult to obtain from the analysis directly, the strain distribution of the pile wall is used to calculate bending moment M using the following equation:

$$M = 2\varepsilon_m E_p I_p / d \tag{2}$$

where ε_m is the relation between maximum strain, E_p is the Young's modulus of pile, I_p is the moment of inertia of pile cross section, and d is the diameter of pile cross section.



(a)



(b)

FIGURE 5. Results of numerical analysis: (a) lateral load-displacement curves and (b) bending moment when lateral load is 20 MN according to elastic modulus

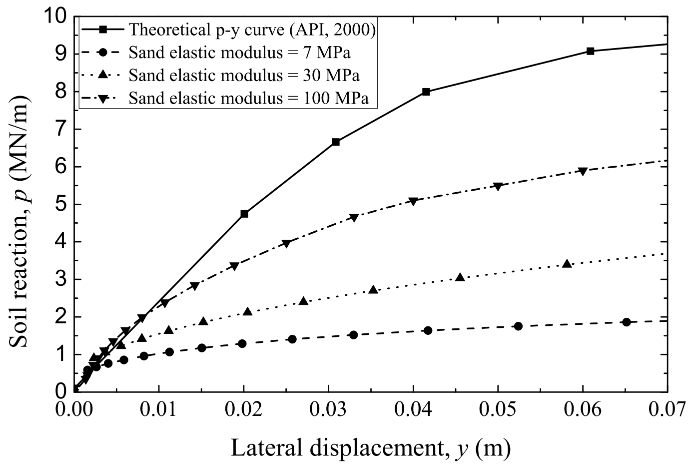


FIGURE 6. The p-y curves according to elastic modulus

For a given depth, the magnitude of moment decreased with increasing sand elastic modulus. In other words, the monopile shows a more flexible behavior for smaller sand elastic modulus.

From the bending moment depth profiles in Figure 5(b), the p-y relationships were derived as shown in Figure 6. In this case, p and y are extracted at depth of 5 m from the seabed where the bending moment is maximum. When the bending moment with depth is plotted, it is used to calculate the p-y curve. The soil reaction (p) and lateral displacement (y) were calculated using the following equations:

$$y = \int \left(\int \phi dz \right) dz = \int \left(\int \frac{M}{EI} dz \right) dz \tag{3}$$

$$p = -\frac{d^2 M}{dz^2} \tag{4}$$

where ϕ is the curvature of the monopile (the ratio of the difference between the compression and tension strains measured at a given depth to the distance between the two corresponding strain gauges) and EI is the flexural modulus of the pile.

For higher sand elastic modulus, stiffer *p-y* relationship was observed. Although not identified in Figure 6, the ultimate soil reaction is expected to increase with increasing soil elastic modulus. At a small lateral displacement, the gradient of *p-y* relationship was almost independent of sand elastic modulus; however, for increasing lateral displacement, soil reaction was highly dependent on sand elastic modulus. Also, the *p-y* relationship proposed by the API [4] is much stiffer than the *p-y* relationships developed in this study varying sand elastic modulus from 7 MPa to 100 MPa. Consequently, it is confirmed that the effects of the sand elastic modulus on the *p-y* curve and lateral load-displacement relationship are significant.

5. **Conclusions.** The effect of layer stiffness on lateral monopile behavior based on numerical analysis was quantified. From the numerical analyses results, the elastic modulus of the soil significantly influences the *p-y* curves. The elastic modulus of soil layer effect is more pronounced with larger lateral displacement of monopile. However, the current practices in lateral pile designs do not use the elastic modulus of sand as a direct input in calculating the *p-y* curve. Therefore, a new *p-y* method emphasizing the effect of the elastic modulus of the ground is required. Also, in general, the ground is not homogeneous and shows various layered structures, so further research is required. Therefore, in future studies, the ground will be constructed nonhomogeneous and the ground behavior should be analyzed.

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REFERENCES

[1] P. Maunu, *Design of Wind Turbine Foundation Slabs*, Master Thesis, Dept. Civil. Eng., Luleå University of Technology, Luleå, Sweden, 2008.
[2] M. Achmus, Y. S. Kuo and K. Abdel-Rahman, Behavior of monopile foundations under cyclic lateral load, *Computers and Geotechnics*, vol.36, no.5, pp.725-735, 2009.
[3] S. Shrestha and N. Ravichandran, Design and analysis of foundations for onshore tall wind turbines, *Proc. of Geo-Chicago 2016*, Chicago, pp.217-226, 2015.
[4] American Petroleum Institute (API), *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design*, 2000.
[5] S. Mezazigh and D. Levacher, Laterally loaded piles in sand: Slope effect on p-y reaction curves, *Canadian Geotechnical Journal*, vol.35, no.3, pp.433-441, 1998.
[6] Y. W. Choo and D. Kim, Experimental development of the p-y relationship for large-diameter offshore monopiles in sands: Centrifuge tests, *Journal of Geotechnical and Geoenvironmental Engineering*, vol.142, no.1, 2015.
[7] G. J. Dyson and M. F. Randolph, Monotonic lateral loading of piles in calcareous sand, *Journal of Geotechnical and Geoenvironmental Engineering*, vol.127, no.4, pp.346-352, 2001.
[8] R. T. Klinkvort, C. T. Leth and O. Hededal, Centrifuge modeling of a laterally cyclic loaded pile, *Proc. of International Conference on Physical Modelling in Geotechnics*, London, pp.959-964, 2010.
[9] E. N. Hearn and L. Edgers, Finite element analysis of an offshore wind turbine monopile, *Proc. of GeoFlorida 2010*, Florida, pp.1857-1865, 2010.
[10] E. A. Alderlieste, J. Dijikstra and A. F. van Tol, Experimental investigation into pile diameter effects of laterally loaded mono-piles, *Proc. of ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering*, New York, pp.985-990, 2011.
[11] D. Kim, Y. W. Choo and K. Kwak, Comparison of lateral behavior of rock-socketed large-diameter offshore monopiles in sands with different relative densities, *International Journal of Offshore and Polar Engineering*, vol.25, no.2, pp.156-160, 2015.
[12] G. Zhang, Y. Hu and J. M. Zhang, New image analysis-based displacement-measurement system for geotechnical centrifuge modeling tests, *Measurement*, vol.42, no.1, pp.87-96, 2009.
[13] A. N. Schofield, Cambridge geotechnical centrifuge operations, *Geotechnique*, vol.30, no.3, pp.227-268, 1980.
[14] A. E. Haiderali and G. Madabhushi, Evaluation of curve fitting techniques in deriving p-y curves for laterally loaded piles, *Geotechnical and Geological Engineering*, vol.34, no.5, pp.1453-1473, 2016.

[15] ISO (International Organization for Standardization), *Cement – Test Methods – Determination of Strength*, ISO 679, PA, 2009.
[16] SIMULIA, *ABAQUS/CAE User's Manual*, Dassault Systemes Simulia Corp., Providence, RI, USA, 2014.