Physical Modelling in Geotechnics

Experimental investigation of soil-foundation-structure interaction on seismic behavior of monopile supported structure

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ABSTRACT: Monopiles are widely used as the foundation of offshore wind turbines tower, and the seismic behavior of these systems is complicated due to the soil-foundation-structure interaction. This interaction changes the fundamental system period, and many researchers have studied this phenomenon analytically. However, there are still few cases that quantitatively validated this through experiments. In this study, the seismic behavior of an offshore wind tower system supported on a monopile was evaluated using dynamic centrifuge model tests. The primary test model was composed of dry sandy soil and reduced models of monopile and wind tower structures. The comparative test on a fixed-end tower structure was also conducted to compare seismic behavior by the supporting conditions. The acceleration response of the soil, piles, and tower structures by depth was evaluated, and the soil and the monopile-tower system frequencies were discussed. In addition, the bending moment and deformation shape of monopile during earthquakes were analyzed based on the strain gauge records attached to piles and structures.

Keywords: centrifuge test, monopile foundation, soil-foundation-structure interaction, bending moment, system frequency.

1 INTRODUCTION

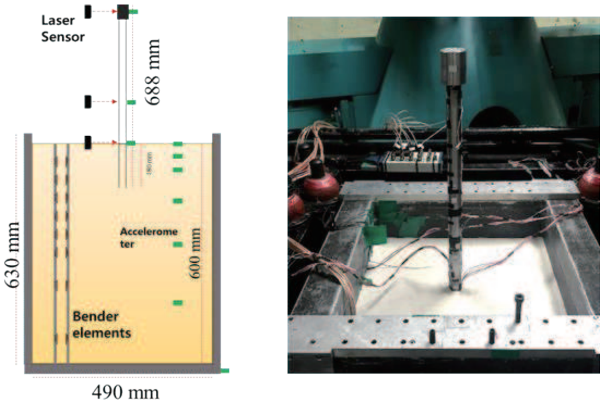
Wind energy is an attractive alternative to fossil fuel energy, along with the social demand for clean and renewable energy. The output of offshore wind turbines is about 1.7 times higher than that of onshore turbines. With these advantages of the offshore wind industry, more offshore wind towers have been constructed even in high seismicity regions. Accordingly, it is necessary to secure the safety of offshore wind towers against earthquakes.

The monopile has a relatively large diameter and short length and is widely adopted as the foundation of most offshore wind towers because of its simplicity and low cost. The natural frequency of the offshore wind tower system varies according to the interaction between the surrounding soil, monopile, and tower. And the seismic safety is also affected by this natural frequency and corresponding responses. Arany et al. (2017) suggested a procedure for designing an offshore wind tower system supported on a monopile, and various numerical studies related to it have been conducted (Zania, 2014; Ko, 2020; Kaynia, 2021). However, experimental studies to elucidate complicated soil-structure interactions are still not enough.

In this study, the seismic behavior of an offshore wind tower system supported on a monopile was evaluated using a dynamic centrifuge model test. We analyzed the acceleration response by height and observed the system's natural frequency change according to the soil-structure interaction. And the bending moment distribution of the pile and tower was scrutinized by the height and time.

2 CENTRIFUGE TEST MODEL

In this study, two sets of centrifuge model tests were conducted depending on the condition of the soil and foundation. The main centrifuge test model for investigating the soil-structure interaction of the offshore wind tower system was composed of sandy soil, monopile, and wind tower structure. The test section view and setup are shown in Figure 1. And the comparative test was carried out with the fixed tower model structure without soil and monopile foundation. These two tests were performed on a 5 m radius beam-type geotechnical centrifuge with an electro-hydraulic shaking table at KAIST, and the target centrifugal acceleration level is 50 g. The model soil layer was built by pouring dry artificial silica sand (D_{50} = 0.22 mm, Cu = 1.96) into a rectangular model box with a target relative density (Dr) of 80%. The shear wave velocity was evaluated using a bender element array installed inside the soil.



(a) Section view (Model Scale) (b) Test Setup

Fig. 1. The section view and setup of the centrifuge test for the flexible wind tower system with the soil and the monopile foundation.

The target prototype of the wind tower and monopile was a 1/4-scale virtual model of the National Renewable Energy Laboratory 5-MW wind turbine system. The dimensions of the reduced model are shown in Table 1, and the structural models were manufactured using SM45C. The blades of the offshore wind tower were simplified as the lumped mass at the upper part of the tower, and the mass ratio of the upper concentrated mass and the tower itself is about one-to-one. For monopile, the diameter and thickness are the same as the tower, but the length is less than half the tower. From the criteria based on the flexural stiffness of the monopile (Leblanc, 2010), the monopile behavior was expected as the rigid case which rotates without flexing significantly and develops a 'toe kick' under moment loading.

Table 1. Dimension of target wind tower and monopile system

Part	Prototype (m)	Model (mm)
Pile & Tower diameter (D)	1.5	30
Pile length (L_P)	9	180
Tower length (L_T)	25.4	508
Pile & Tower thickness (t)	1.25	2.5

A total of 22 strain gauges were attached by height to measure the bending moment of the monopile and the upper tower during earthquakes. The permanent deformation of the tower was observed using three laser sensors. Acceleration responses of the soil and offshore wind tower structures were also observed using accelerometers. All results were converted to the prototype scale and reported in this paper.

As input seismic waves, random waveforms containing energy in a wide frequency range, several sine waves of various frequencies, and recorded earthquake motion in Hachinohe (May 16, 1968, ML 7.9 recorded at Tokachi Oki, Japan) were used. The amplitude and frequency of input motions were scaled to meet the capacity of the shaking table. Due to the limit of paper volume, only the test results subject to the Hachinohe earthquake input wave results are presented in the following sections. The time history and response spectrum of the Hachinohe earthquake for the test are described in Figure 2. It was expected to cause the more significant behavior of the offshore wind tower system because of the relatively more prominent long-period components.

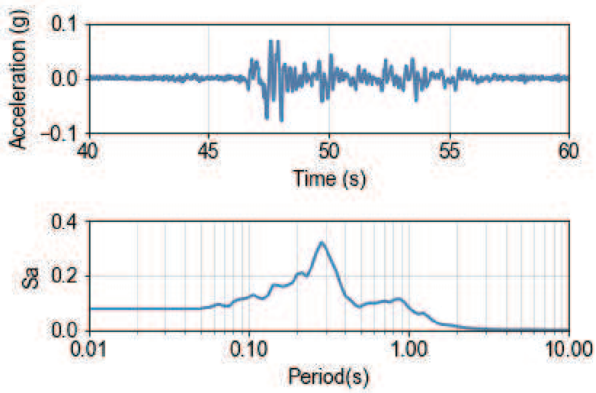


Fig. 2. Input seismic wave of the recorded Hachinohe earthquake

3 CENTRIFUGE TESTS RESULTS

3.1 Acceleration Responses of Soil and Tower

Figure 3 shows the acceleration response spectra for each soil layer depth and the spectrum ratio to the input motion at the base during the Hachinohe earthquake excitation. The acceleration response of the soil was amplified as it got closer from the bottom to the surface, and the most significant amplification occurred around 0.4~0.5 seconds. This frequency is similar to the first mode period of the soil layer derived from the equation defined by the thickness and the shear wave velocity of the soil layer. The soil layer's second and third mode periods are determined around 0.1 seconds, and the second most amplification from the test results was observed. These amplification characteristics mean that the seismic response spectrum at the free-field surface can vary with the soil layer's mode period and the spectrum of the input motion. Therefore, when assessing the seismic response of the wind tower above the soil surface, it is better to use the free-field surface motion rather than the bedrock motion.

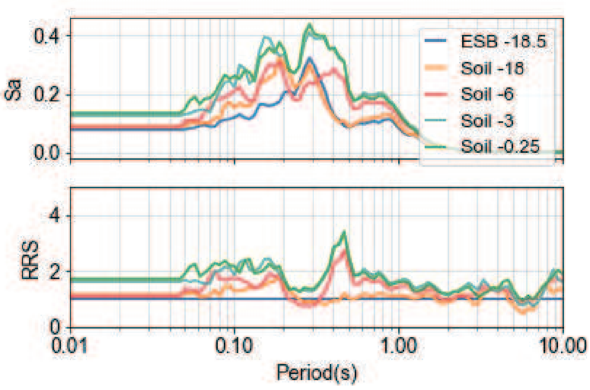


Fig. 3. Response spectra of soil layer by depth

Figures 4 and 5 show the acceleration response spectra by the height of the wind tower structure with and without soil and monopile foundation, respectively. When the tower has the fixed bottom condition with no soil and the monopile, the response at the top of the tower showed the most remarkable amplification around 1.5 seconds. This period is similar to the first mode period obtained from the analytical calculation. Moreover, a following significant amplification appeared in the vicinity of 0.11 seconds, and the amplification of the accelerometer located 5 m above the bottom was the largest. However, since the intensity of the input seismic motion was small in the first mode of the tower, the maximum response of the accelerometer occurred in the second mode period.

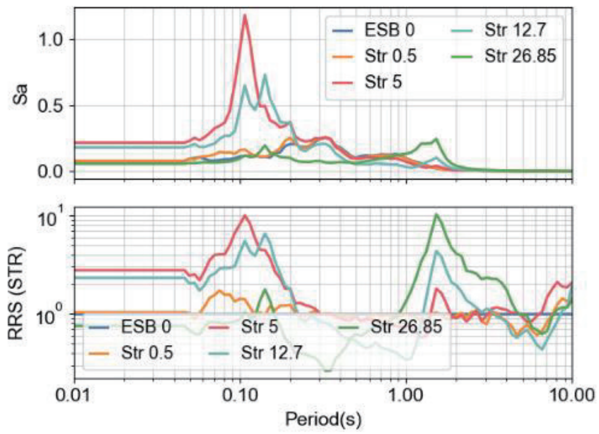


Fig. 4. Response spectra of the wind tower by height with the fixed bottom condition

The soil and monopile foundation make the supporting conditions under the wind tower structure relatively flexible and increase the fundamental period of the system. As shown in the amplification of the accelerometer at the top of the tower in Figure 5, the most significant amplification appears around 1.9 seconds. It indicates that the first mode period was lengthened compared to when the tower is fixed. The second mode period of the flexible tower systems was also about 0.18 seconds, which was increased from 0.11 sec. The method of calculating the lateral and rotational stiffness of the tower lower part according to the monopile foundation and the soil conditions and the corresponding fundamental period of the wind tower system has been suggested by various studies (Arany et al., 2017; Bouzid et al., 2018). The lengthened ratio of the fundamental period for the soil-monopile foundation-structure system based on the calculated stiffnesses using the equations of Gazetas(1984) is about 40%. This value is similar to the average between the lengthened ratio of the first mode (25%) and the second mode (50%) from the test results.

Another peculiarity is that the height showing the largest response and amplification in the second mode period was changed from 5 m in the fixed condition to 12.7 m in the flexible condition. This is considered to be because the mode shape was changed along with the natural period of the system due to the lower ground and monopile foundation.

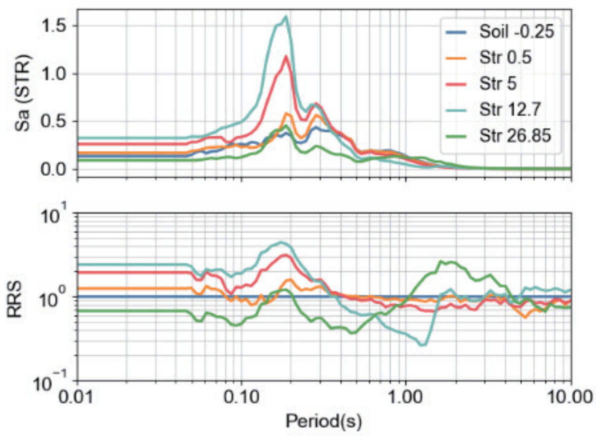
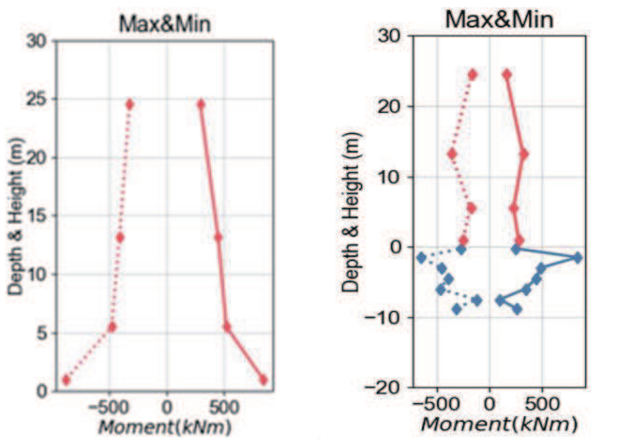


Fig. 5. Response spectra of the wind tower by height with the soil layer and the monopile foundation

3.2 Bending Moments of Monopile and Tower

Figure 6 shows the maximum and minimum bending moment of the wind tower system by height. In the case of a fixed tower without soil and monopile, the most prominent bending moment was observed at the bottom of the tower because the first mode shape is a bent shape that is curved around the floor. On the other hand, from the centrifuge test result with soil and monopile, the largest moment appeared at the central location, not at the bottom of the tower. The most significant moment occurred about 1-2 m below the ground surface in the monopile foundation.

The distribution of bending moment of monopile foundation and upper wind tower structure is closely related to the deformation shape of the system during the earthquake. Therefore, the variation of bending moment according to the time and the height is described in three-dimensional graphs in Figures 7 and 8. Although there was some change with time, the distribution shape of the bending moment indicated a similar tendency to the result shown in Figure 6. In the case of the fixed wind tower, most of the moments acted about 5 m below the lower part. And in the case of the flexible wind tower, it was found that the moment acts evenly based on the center of the tower. For the wind tower system with the soil and the foundation, the maximum bending moment appeared at the upper part of the monopile. It is considered a phenomenon that seems because the mode shape of the system is changed, as discussed in the acceleration response of the second mode periods.



(a) w/o soil and monopile (b) w/ soil and monopile

Fig. 6. Maximum and minimum bending moment of the wind tower system by the height

4 CONCLUSIONS

Two sets of centrifuge model tests were performed on a wind tower structure with a bottom-fixed condition and a wind tower structure installed on the ground and monopile. For the tower system with monopile foundation, Due to the soil-monopile-tower structure interaction, the first and second modes of the wind tower system lengthened. The position of the maximum acceleration response of the wind tower structure was also changed to the half-height of the wind tower. In addition, we also observed that the location of the maximum bending moment also changed from the base to the center part of the tower structure. It is judged that this phenomenon results from the change of the mode shape as well as the frequency characteristics of the system.

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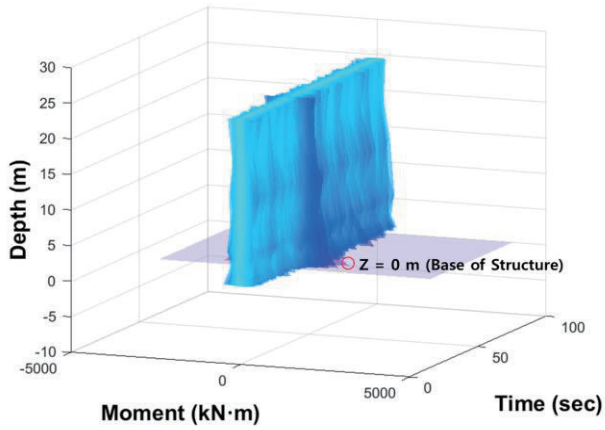

Fig. 7. Bending moment distribution of wind tower system by the height and the time for the fixed tower model

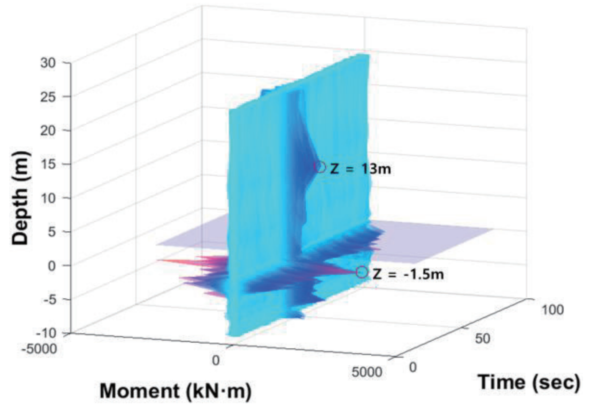

Fig. 8. Bending moment distribution of wind tower system by the height and the time for the flexible tower model with the soil and the monopile foundation

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