Current research activities at KAIST Geo-Centrifuge Center focusing on soil-foundation-structure interaction under seismic loading

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
This paper presents a general overview of the KAIST Geotechnical Centrifuge Testing Center and the current research activities therein focusing on soil-foundation-structure interaction (SFSI) under seismic loading. The KAIST centrifuge facility, developed in 2009, includes a geotechnical centrifuge with a radius of 5 m, an in-flight shaking table, a four-degrees-of-freedom in-flight robot, and general modeling equipment. The facility is providing a good opportunity to perform various research experiments, and research and development will be further activated in this area. Dynamic centrifuge model tests for a single-degree-of-freedom system with a shallow foundation and offshore wind turbine structures with bucket foundation are among the current research activities at the center. The dynamic behavior of the models under both fixed and SFSI conditions is obtained by applying small-amplitude dynamic loading. The model structures are exposed to various seismic loadings to evaluate the seismic behavior of prototype structures. Through the physical modeling of the model structures, the importance of SFSI in performance-based seismic design is derived.

RÉSUMÉ
Cet article présente un aperçu général du KAIST Geotechnical Centrifuge Testing Center et les activités de recherche en cours portant sur l'intéraction sol-structure (SFSI) sous chargement sismique. Les installations du KAIST, qui ont été développées en 2009, incluent une centrifugeuse géotechnique possédant une plate-forme de 5m de rayon, une table vibrante et un robot à 4 degrés de liberté à bord, et divers équipements de modélisation. Les installations offrent de bonnes opportunités afin de réaliser différentes recherches expérimentales pour les ingénieurs en géotechnique en Corée, et permettent une accentuation de la recherche et du développement dans ce domaine. Parmi les activités de recherche en cours, les essais du modèle de centrifugeuse dynamique pour un système à un degré de liberté pour une fondation superficielle et les structures d'éolienne en mer avec une fondation en caisson sont introduits. Le comportement dynamique des modèles, à la fois en condition fixe et SFSI, est obtenu en appliquant un chargement dynamique à faible amplitude. Les structures modèles sont exposées à divers sollicitations sismiques pour évaluer le comportement sismique des prototypes de structures. L'importance de l'interaction sol-structure dans les conceptions de performance est soulignée par la modélisation physique des structures modèles.

1 INTRODUCTION

The KAIST Geotechnical Centrifuge Center was developed in 2009, and it includes a geotechnical centrifuge with a radius of 5 m, an in-flight shaking table with earthquake simulator, a four-degrees-of-freedom in-flight robot, and general modeling equipment. With a state-of-the-art self-balanced electrohydraulic earthquake simulator and the shaking table mounted on the centrifuge, various sinusoidal and real earthquake motions can be generated to the scaled models (Kim et al. 2013a, Kim et al. 2013b).

Among the current research activities at the center, this study focuses on dynamic centrifuge model tests for a single-degree-of-freedom (SDOF) system with a shallow foundation and offshore wind turbine structures with bucket foundation in order to understand the soil-foundation-structure interaction (SFSI) problem. It is well known that SFSI significantly affects the seismic response of a structure. The phenomena of SFSI have become more important in performance-based seismic designs for foundations and superstructures. Even though considerable research has been conducted using a variety of methods motivated by the importance of SFSI in various types of foundations, many difficulties and uncertainties remain before an understanding of these complicated phenomena can be achieved.

The characteristic effects of SFSI on a foundation system are the changes in the dynamic characteristics of equivalent-system properties under flexible-foundation conditions. This means that the maximum seismic response of a SDOF structure model on the foundation can be predicted by an equivalent fixed-base SDOF oscillator with a changed period and damping ratio (Stewart et al. 1999).

In this study, dynamic centrifuge model tests were conducted to investigate the effects of the parameters of a SDOF structure with a shallow foundation and an offshore wind turbine with bucket foundation on the SFSI of the system. Similar to the manner in which a centrifuge can replicate field stress conditions at the model scale by applying centrifugal acceleration to model structures, it can also conduct a reliable SFSI experiment that is easy to repeat, compared with an actual full-scale experiment.

2 CENTRIFUGE FACILITY AND VERIFICATION FOR SOIL-FOUNDATION-STRUCTURE INTERACTION

2.1 KAIST Geotechnical Centrifuge Center

The basic idea of physical modeling using a geotechnical centrifuge is accelerating a reduced-scale model structure to the appropriate high g-level to simulate the prototype-scale stress field in the model structure. If the earthquake simulator and shaking table can be properly mounted on the centrifuge, the centrifuge modeling provides an excellent opportunity to observe SFSI in a scaled model. To make good use of this test method, reasonable scaled-down modeling with proven scaling factors is important. The scaling factors of the variables related to the centrifuge modeling are listed in Table 1 (Schofield, 1980).

Table 1. Scaling factors for centrifuge modeling

Parameters	Centrifuge Scaling Factor
Length	1/N
Velocity	1
Acceleration	N
Strain	1
Stress	1
Time (Dynamic)	1/N

The beam-type centrifuge facility at KAIST (Figure 1) was used to perform all tests reported herein. The facility has a platform radius of 5 m and a maximum capacity of 240 g-tons (Kim et al. 2013a). A self-balanced electrohydraulic earthquake simulator mounted on the centrifuge can generate sinusoidal and real earthquake motions up to 0.5 g in the prototype scale. The allowable frequency range was from 20–300 Hz on the model scale, and the utilization of the self-balanced shaking table was verified (Kim et al. 2013b, Park and Kim. 2013).

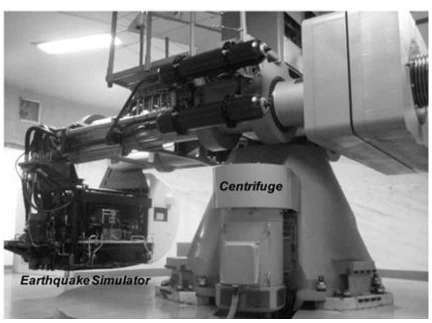

Figure 1. Earthquake Simulator Mounted on the Centrifuge at KAIST

During the dynamic centrifuge test, an equivalent shear beam (ESB) model box was used. The ESB model box can simulate a wall deformation similar to that of soil deposit using the bearing and rubber located between the wall layers (Lee et al. 2012). The dimensions of the ESB payload platform were 670 mm × 670 mm × 650 mm (length, width, and height, respectively).

2.2 Verification of Centrifuge Modeling for Soil-Foundation-Structure Interaction Problem

SFSI is a very complicated problem with several factors that influence seismic behavior. Thus, the reliability of the centrifuge testing system for simulation of SFSI as well as free-field motion should be verified in advance. Lee et al. (2012) performed dynamic centrifuge tests to evaluate the free-field motion and dynamic performance of an ESB model box. They showed that free-field motions measured in the soil model in an ESB box match well with the motions estimated by 1-D response analysis, and the ESB model box can provide a reliable lateral boundary for dynamic site response studies. This was demonstrated through a comparison with the seismic soil behavior inside a rigid-walled model container.

Ha et al. (2014) simulated the Hualien large-scale seismic test (LSST) to assess the effectiveness of centrifuge modeling for studying SFSI. The Hualien LSST program was an international project to observe real SFSI for a 1/4 scale nuclear containment structure, and it began recording earthquake data from 1990 with well-investigated soil information. If centrifuge modeling can properly simulate SFSI during an earthquake—as verified by comparison with real earthquake-induced data such as the data obtained at Hualien—then centrifuge modeling could be a powerful tool for understanding the SFSI mechanism and simulating seismic behavior at a particular site.

To simulate real earthquake phenomena, the soil, structure, and earthquake motion are the most important factors to consider while modeling. Ha et al. (2014) discussed the details for the modeling of soil deposits, the foundation, and the structures in their study.

Figure 2 compares typical acceleration times, histories, and frequency properties measured at the foundation and the free-field surface during Taiwan's Chi-Chi earthquake and those recorded at corresponding locations in the centrifuge test. The amplification characteristics and time histories are well matched at the soil layer and foundation of the structure. This shows the potential of simulating the Hualien LSST using a dynamic centrifuge test and verifying the reliability of the centrifuge test method for SFSI research.

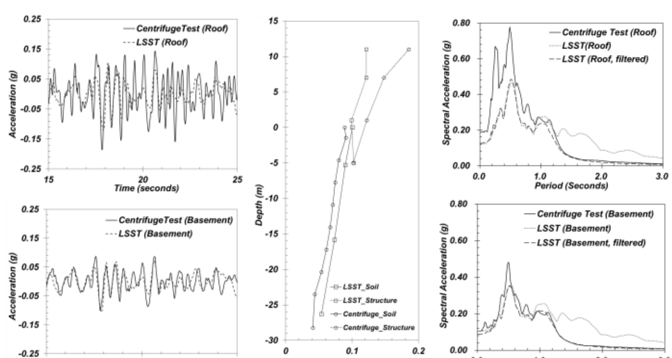

Figure 2. Centrifuge Simulation of Haulien LSST (Ha et al. 2014)

3 SINGLE-DEGREE-OF-FREEDOM SYSTEM WITH SHALLOW FOUNDATION

3.1 Centrifuge Testing Program

The centrifuge test model is composed of a sandy soil layer, a shallow foundation, and the SDOF structure model in the container. The model container used in this study is the equivalent shear beam type to reduce reflection of the waves at the boundary of the container. Dry silica sand was poured into the model container from a sand-raining system at a constant falling height to provide a uniform specimen with a relative density of approximately 80%. Then, the shallow foundation and the superstructure were installed near the surface, and repluviation for embedment was performed. Figure 3 shows a schematic diagram of the centrifuge test model. For observing the dynamic responses of a soil-foundation-structure system, accelerometers, earth pressure transducers, and a linear variable differential transformer (LVDT) were used.

This study focuses on the comparison between a fixed foundation and a flexible foundation. In the current seismic design, a seismic load for the structure is usually determined by a response spectrum, which is determined by free-field surface motion, assuming a fixed-foundation condition; the motion in this case is called fixed-base motion. However, this fixed-base motion would be different from real seismic responses when the SFSI effect is considered. The supporting condition would be changed to the flexible condition owing to SFSI, and the seismic motion for that condition is called flexible-base motion. In this test, spectral accelerations for a fixed foundation were calculated from free-field surface motion; those for a flexible foundation were determined from directly measured data in the centrifuge tests as described at the bottom of Figure 3 (Kim et al. 2015).

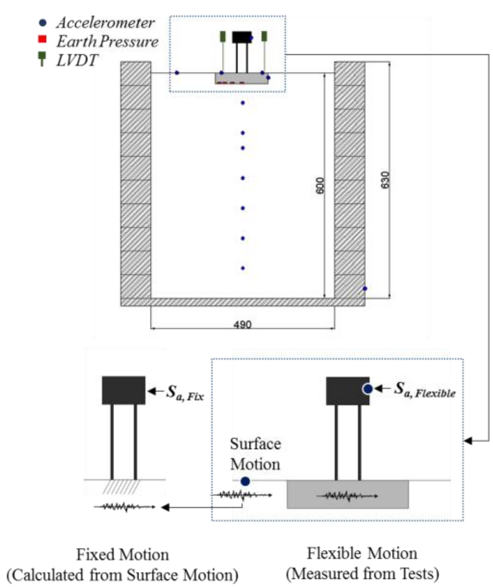

Figure 3. Schematic diagram of centrifuge test and Determination of fixed and flexible base motion

The effect of SFSI on the behavior of the shallow foundation can be changed dramatically by several factors such as subsoil, foundation size and mass, and period of superstructure. Table 2 describes the centrifuge testing program and parameters in the prototype scale. As mentioned in model construction, two soil models with different relative densities were used; foundation size and mass also differed.

Table 2. Testing program and parameters (20g prototype scale)

Soil type	Foundation size	Test name	Natural period of the SDOF structure
Dense silica sand (Relative density 80%)	1.4 m	D-F7-S01	0.09 s
		D-F7-S02	0.26 s
		D-F7-S03	0.45 s
		D-F7-S04	1.00 s
	2.0 m	D-F10-S01	0.09 s
		D-F10-S02	0.26 s
		D-F10-S03	0.45 s
		D-F10-S04	1.00 s
	2.8 m	D-F14-S01	0.09 s
		D-F14-S02	0.26 s
		D-F14-S03	0.45 s
		D-F14-S04	1.00 s

Three sizes of square foundation were used in the experiments. Sides (length and width) of square varied—as 7 cm (F7), 10 cm (F10), and 14 cm (F14)—and depth of foundation was fixed at 3 cm. Two materials (aluminum and steel) were used in the foundation for changing the foundation mass. As the size and mass of the foundation increased and became heavier, respectively, it is possible that the bottom condition of the model structure came close to the fixed condition.

The SDOF structure was composed of two thin steel plates and a lumped mass on the top. By changes to plate length and lumped mass, several structure models were made to represent prototype structures with various natural periods and effective heights.

To observe the effects of the input motion, various earthquake motions as recorded for earthquakes in Northridge, Hachinohe and Ofunato, were utilized for the centrifuge tests. By maintaining the waveform of the earthquake but changing the peak acceleration, staged earthquake loadings from 0.03 g to 0.30 g were applied. The effects of soil nonlinearity on SFSI were observed by changing the earthquake intensities in stage tests.

3.2 Centrifuge Test Result: Rocking Behavior

The relative acceleration ($\ddot{u}_{rel}$) of the structure can be calculated from the difference between the structure and foundation motions. Relative acceleration indicates the earthquake response of the structure model affected by soil-structure interaction. The structural response induced by foundation rocking ($\ddot{u}_{rocking}$) was also determined from the rotation angle of the foundation and the effective structural height. Figure 4 shows the time histories of relative acceleration and rocking acceleration for the structural response. The relative acceleration and the ratio $\ddot{u}_{rocking}/\ddot{u}_{rel}$ are decreased by the foundation size increment.

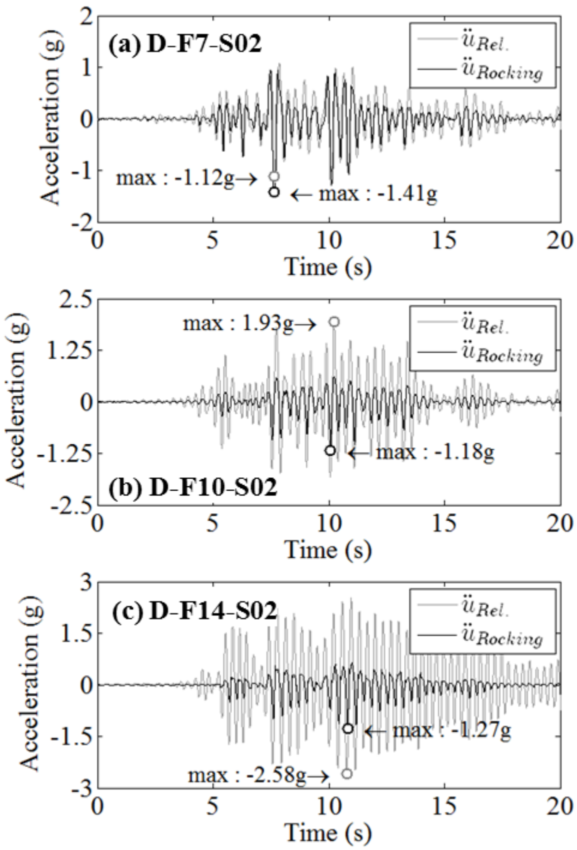

Figure 4. Time history comparison between relative and rocking accelerations for the structural response. (Northridge EQ., 0.30g cases)

The net lateral displacement of the roof—subtracting the effects of horizontal and rotational foundation motions—was compared with the fixed-base motion calculated from the free-field ground accelerations.

On the other hand, different phenomena occurred for the strong-intensity input loading. The structural motion for the fixed foundation was increased, and there is less difference while varying the foundation size. However, the flexible motion in the case of D-F7-S02 is significantly smaller than the fixed motion, although similar motions between flexible and fixed cases are obtained on D-F14-S02. Those results could be related to the substantial amplitude of the rocking motion depicted in Figure 4.

The maximum seismic responses of flexible motion are compared with those of fixed motion. As shown in Figure 5, in most cases, the flexible-base motion was similar to fixed-base motion, which is close to the one-to-one line in small-earthquake intensity. It can be explained that structural response is changed slightly due to soil-foundation-structure interaction such as period lengthening and damping increase. When the level of the input accelerations increased, flexible-base accelerations converged to their limits, and thus, they were significantly less than those of the fixed-base-structure responses. This acceleration limitation is related to the moment capacity of the soil-foundation system. Kim et al. (2014) derived Equation [1] to calculate maximum value, and the estimated maximum accelerations agree with the flexible-base accelerations of the structures evaluated from the measured data. SFSI effects—including rocking behavior—can reduce the seismic demand of the SDOF structure on the shallow foundation.

$$S_a \leq S_{a,max} = \frac{m_t}{m_s} \cdot \frac{L}{h} \cdot \left(1 - \frac{q}{q_c}\right) \cdot g \qquad [1]$$

Where, S_a = spectral acceleration, m_t and m_s = mass of total systems and structure, L and h = foundation length and height of structure, q/q_c = ratio of bearing pressure to ultimate bearing capacity and g = gravitational acceleration.

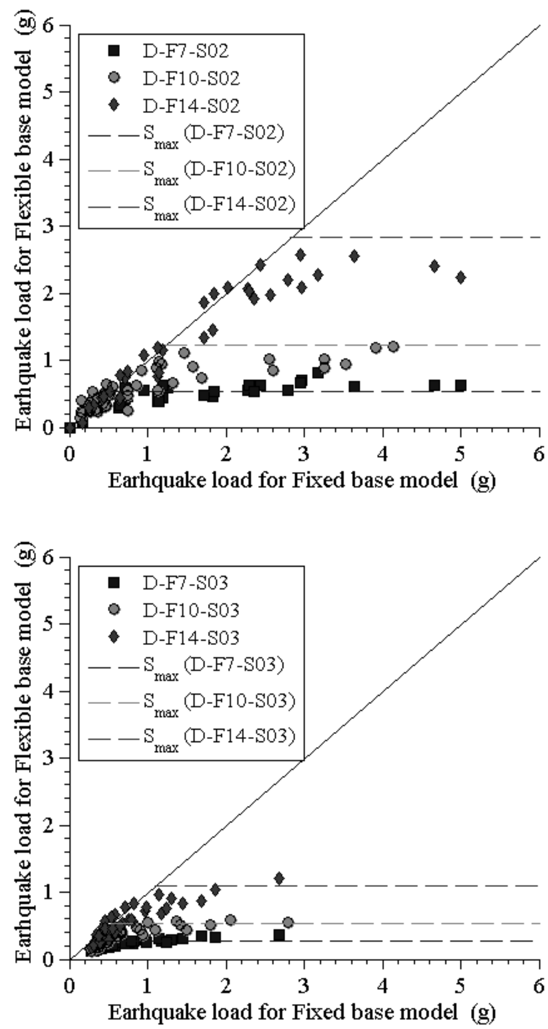

Figure 5. Time history comparison between relative and rocking accelerations for the structural response. (Northridge EQ., 0.30g cases)

3.3 Centrifuge Test Result: Period Lengthening for the Equivalent Period of SDOF Structures

In most current practices, seismic load on structure is determined by the response spectrum obtained from free-field motion, assuming a fixed-boundary condition. At that time, structures' characteristics—such as natural period and damping ratio—become important factors to consider in seismic design. However, they are influenced by SFSI effects in the flexible-foundation condition, and therefore, the equivalent natural periods of the superstructure would lengthen. Veletsos and Meek (1974) proposed the relationship between the period lengthening and foundation spring stiffness as Equation [2].

$$\tilde{T} = T_n \cdot \sqrt{1 + \frac{k_s}{K_x} + \frac{k_s h^2}{K_\theta}} \qquad [2]$$

Where $\tilde{T}$, T_n = flexible and fixed period of structure, k_s=stiffness of SDOF structure and K_x, K_θ = translational and rotation stiffness of foundation

Stewart et al. (1999) observed changing dynamic properties in field-recorded data. Motivated by those properties, the researchers calculated the equivalent natural frequencies from measured acceleration as tabulated in Table 3. In the present study, the lengthened periods of the structures on the shallow foundation were estimated by Fourier transform for measured accelerations at the tops of structures. It was seen that the natural frequency of the structure decreased (period lengthens) with decreasing foundation size and mass.

Table 3. Natural period lengthening as the foundation size

	Natural period of the SDOF structure			
Foundation	S01	S02	S03	S04
Fixed	0.09	0.26	0.45	1.00
D-F7	0.13	0.39	0.59	1.00
D-F10	0.11	0.34	0.58	1.00
D-F14	0.09	0.32	0.55	1.00

4 OFFSHORE WIND TURBINE STRUCTURES WITH BUCKET FOUNDATION

4.1 Centrifuge Testing Program

As various types of offshore wind foundations with limited bearing capacity compared with onshore wind foundation get planned for installation, foundation type and surrounding soil conditions have to be considered in the design. However, currently used numerical simulations focus on structural aspects of towers, considering fixed-base condition as a simplification of nonlinear SFSI in the dynamic loading condition, which is the challenging part.

An experimental approach is needed to supplement and calibrate numerical analysis results in well-described SFSI conditions. However, there has been only little research, including the cases of Liingaard (2006) and Bhattacharya et al. (2011). Liingaard used a full-scale wind turbine; however, this method takes too long and is too expensive for performing one single experiment. A 1/100-model experiment performed by Bhattacharya et al. (2011) was not capable of reproducing field stress conditions, which are important in observing SFSI. To supplement the stated limitations of that previous research, using a centrifuge could be an alternative method. Because a centrifuge can replicate field stress conditions in model scale by applying centrifugal acceleration to a model structure, it can be part of the conduct of a reliable SFSI experiment and is easy to repeat compared with an actual full-scale experiment.

This study aims to develop and verify experimental procedures that observe the natural frequency and seismic behavior of an offshore wind turbine structure considering SFSI and using a geotechnical centrifuge. First, a scale model of the target National Renewable Energy Laboratory (NREL) 5-MW offshore wind turbine and 5-MW-class bucket foundation will be produced by applying two-staged scaling methods, which use a scaled-down 1-g virtual model as the prototype for centrifuge scaling. Second, a centrifugal model of an offshore wind turbine structure and measurement of natural frequency in fixed conditions will be discussed. Third, the natural frequency of the produced model in the SFSI condition will be evaluated and compared with the fixed condition to observe the effect of SFSI on the natural frequency of the offshore wind turbine. Finally, a model structure with a soil-foundation base will be exposed to various seismic loadings to evaluate (1) the seismic behavior of the offshore wind turbine and (2) permanent deformation.

A fixed-base test is conducted to confirm the natural frequency of the wind turbine model in the fixed-based condition and to verify 1-g scaling laws for time and frequency factors. Three models are fixed on the base plate, which is connected on an ESB model box as shown in Figure 6 and then installed on a centrifuge-mounted shaking table (Kim et al. 2013b) for applying dynamic loadings to the model to measure the dynamic response. Accelerometers attached at the tower head and body of each model measure the dynamic behavior of the structure, and accelerometers attached on the ESB box and base plate measure actual input loadings applied to the model (Seong et al. 2015).

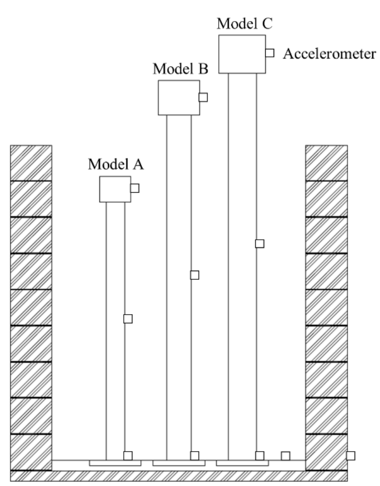

Figure 6. Fixed test schematics

The experiment was conducted at six different g levels ranging from 22 g to 44 g. The natural frequency was evaluated at each g level by (1) applying three different types of low-amplitude dynamic loading using the shaking table and then (2) performing fast Fourier transform (FFT) analysis on the retrieved time-based signal. The result was converted into a 1-g condition by applying the centrifuge scaling law, which is generally verified.

First, dynamic loading of a frequency bandwidth of 20–300 Hz was applied from low frequency to high frequency (forward sweep). Second, the same dynamic loading from high frequency to low frequency was applied to prevent interference of the low-frequency signal in the higher-frequency response. Third, the Hachinohe earthquake signal was applied to evaluate whether the model structure showed the same natural frequency in the real earthquake signal. Because the Hachinohe earthquake signal is a time-based signal and because time is affected by the scaling law, the time signal shape of it was also changed by the scaling factors.

After performing the fixed-base test, the SFSI test was conducted to observe the wind turbine's dynamic behavior in SFSI condition in comparison with the fixed-base condition. This experiment was conducted by using a 1/44 scale model of a 1/4 scale virtual model (model A). The model was connected with a monopod bucket foundation that was scaled in the same ratio as the structure and was then installed in the model sand layer. As the purpose of this experiment is to observe the effect of SFSI compared with a fixed condition, the model soil layer was produced in a very dense condition to provide sufficient bearing capacity for the structure. A 30-cm-thickness silica sand layer with 88% relative density was produced by sand raining methods. While producing a soil layer, five accelerometers are installed in the soil to observe the site response through depth and measurement of peak ground acceleration through the soil layer (Ha et al. 2014). Five sets of Bender Element arrays with 15 cm of distance were installed to measure soil stiffness through depth during the experiment (Kim and Kim, 2010). A detailed schematic for the SFSI test is described in Figure 7.

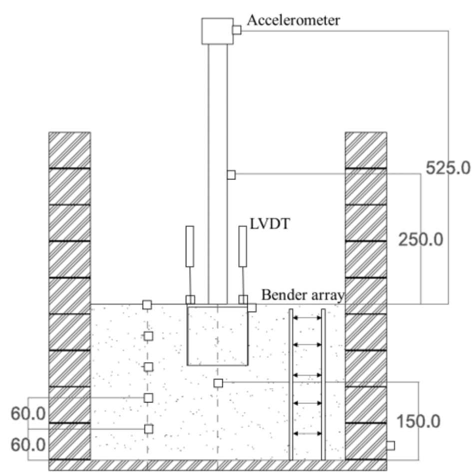

Figure 7. SFSI test schematics

The experiment was conducted at three different g levels from 29 g to 44 g, which is the correct g level to convert model A into 1/6, 1/5, and 1/4 1-g virtual models as described in Table 4. To evaluate natural frequency, low-amplitude dynamic loading as used in the fixed-base test was applied. Then, FFT analysis was conducted on retrieved time-based signals from the accelerometers. From this experiment, change in natural frequency compared with fixed condition can be observed.

Table 4. G levels and converted model size of SFSI test

G-level (g)	Model A	Model B	Model C
29	1/6	2/9	1/4
33	1/5	1/4	2/7
44	1/4	1/3	3/8

4.2 Test Results: Fixed-Base Test

Before the centrifuge experiment, a 1-g test is conducted to measure the model's natural frequency. FFT results showed 44.8 Hz for model A, 31.5 Hz for model B, and 26.8 Hz for model C. Model A's FFT result showed small resonance at 30-Hz frequency off from large peak point at 44.8 Hz. This was due to the resonance of model B, which—positioned right next to model A—propagated through the base plate. After the 1-g experiment, a centrifuge experiment for measuring natural frequency at six different g levels was conducted. The FFT result of the centrifuge test also shows clear peak resonance. The natural frequency of each model in the fixed condition is given in Table 5.

Table 5. Model's natural frequency in 6 different g levels.

Testing	Natural frequency (Hz)		
G-level (g)	Model A	Model B	Model C
21.8	2.10	1.40	1.23
24.4	1.87	1.25	1.10
29.2	1.57	1.00	0.85
32.7	1.40	0.94	0.76
36.6	1.25	0.84	0.66
43.8	1.05	0.70	0.57

There are two main points to measure in this test. The first point is to obtain the natural frequency of various 1-g virtual models by converting the natural-frequency results of three models at 6-g levels; to plot the obtained results in terms of 1-g scale to expect the natural frequency of the model in prototype size, and to compare it with the simulation results of a target NREL 5-MW wind turbine model to verify whether the model clearly represents the target structure. The second point is to observe the dynamic behavior of the target model (model A) at a target g level of 44 g to measure the natural frequency and damping ratio in a fixed-base-model experiment.

By this centrifuge test, natural frequency and damping ratio in fixed condition can be clearly obtained by process FFT analysis on an accelerometer signal from the head of the model structure. In addition, by plotting the 1-g virtual model's natural frequencies obtained from combining g levels and model scales, a 1-g scaling law for the frequency factor can be retrieved, which makes it possible to convert model-scale experiment results into prototype scale and compare them with an NREL 5-MW target structure.

4.3 Test Results: SFSI Test

It is important to evaluate a structure's natural frequency under SFSI conditions in comparison with a fixed condition. However, the monopod structure did not have established numerical methods for evaluating nonlinear SFSI in dynamic loading conditions. Therefore, the purpose of this experiment was to measure experimental data about natural frequency and damping ratio of the structure and compare it with fixed experimental results, which can be compared with numerical methods.

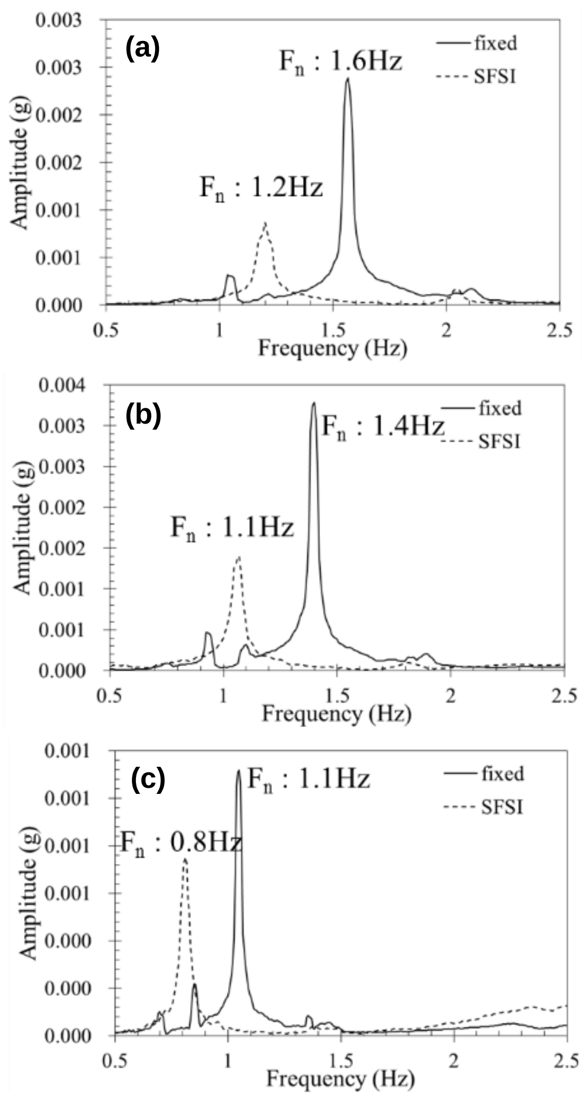

Figure 8. Dynamic responses in the frequency domain for fixed-based and SFSI condition in (a) 29g, (b) 33g, (c) 44g

The change of natural frequency in SFSI compared with the fixed condition can be evaluated using a 1/44 scale model of a 1/4 virtual model of the target structure (model A) connected on a bucket foundation, with the same scale installed on a model soil layer. The test was conducted at three different g levels of 29 g, 33 g, and 44 g, with which models can be converted to 1/6, 1/5, and 1/4 scaled 1-g virtual models by the centrifuge scaling factors. Natural frequency is obtained by conducting FFT analysis using head accelerometer data. Results described in Figure 8 show clear peak resonance at each g level. Natural frequency of structure is measured as 1.2 Hz at 29 g, 1.1 Hz at 33 g, and 0.8 Hz at 44 g as shown in Figure 8.

To compare SFSI and fixed results more precisely, FFT results of fixed and SFSI condition test were normalized using the FFT analysis result of foundation (base plate for fixed condition) as the base motion. Results at target g level of 44 g show reduction of natural frequency in SFSI to 0.82 Hz, which is 23% reduced compared with 1.05 Hz of fixed condition. Further, from the shape of the graph, the amplification of the tower head compared with the base motion did not show significant changes in both cases; however, the damping ratio increased in the SFSI test as distribution of amplitude around peak point widened. The half-power bandwidth method showed that the damping ratio of SFSI condition increased to 1.5% compared with 1.3% of fixed test—approximately 15%. Results in other g levels show a constant reduction of natural frequency—approximately 23%.

The results showed the clear effect of SFSI on the dynamic behavior of an offshore wind turbine model from observation of decreased natural frequency and increased damping ratio. Test results were consistent in three different g-level tests under the same SFSI conditions, which demonstrates the possibility of determining the actual natural frequency and damping ratio value of an offshore wind turbine by way of a centrifuge experiment.

5 CONCLUSION

A series of dynamic centrifuge tests were performed with the parameters affecting SFSI of the shallow foundation and offshore wind turbine structures with bucket foundation. The seismic responses of structures and foundations were generally evaluated by comparison between fixed-foundation motion and flexible-foundation motion.

In the dynamic centrifuge tests for shallow foundations, the structural behavior of the shallow foundation was similar to that of the fixed-foundation model—as expected from the free-field surface motion as foundation size increases and foundation mass becomes heavy. The foundation rocking motion greatly affected the soil-foundation-structure system during a strong-input earthquake.

In dynamic centrifuge tests for offshore wind turbine structures with bucket foundation, a fixed-base test evaluated the natural frequency of a produced wind turbine model and verified the 1-g scaling law. The natural frequency of a model structure in prototype scale was estimated. The SFSI test showed a clear effect of SFSI on the dynamic behavior of a wind turbine structure as natural frequency and damping ratio showed certain differences between fixed and SFSI tests. The results suggested the need for parametric study on the effects of SFSI by foundation types and soil conditions on natural frequency and damping ratio. This study showed that consideration of SFSI in foundation design is a complicated phenomenon but has the potential to reduce seismic demand.

ACKNOWLEDGEMENTS

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (grant number 2014R1A6A3A04056405). The authors acknowledge the KREONET service provided by Korea Institute of Science and Technology Information.

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