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Influence of scour on the natural frequency of offshore wind turbines with tripod bucket foundation in sand

Seung-Won Oh
Seoul National University, Seoul, South Korea

Kyeong-Sun Kim, Jun-Woo Kim, Sung-Ryul Kim*
Seoul National University, Seoul, South Korea

**sungryul@snu.ac.kr (corresponding author)*

ABSTRACT: The extent to which scour affects the natural frequency of an Offshore Wind Turbine (OWT) is crucial for its long-term safety, as the Soil–Foundation–Structure Interaction (SFSI) can significantly influence its dynamic behaviour. However, obtaining a reliable estimate of the natural frequency hinges on sophisticated foundation modelling that incorporates Soil–Structure Interaction (SSI). In this study, a finite element (FE) model that considered SSI was developed to examine the effect of scour on the natural frequency of 4.2 MW OWT supported by a tripod suction bucket foundation designed in South Korea. First, the FE model was validated by comparing the natural frequency computed using a theoretical equation and the design value determined by another FE model without SSI. Then, the ratio of scour depth to bucket skirt length (S/L) was varied from 0 to 0.5 for different bucket dimensions (L/D = 1, 1.16, 1.5 and 2.0). The tower and tripod were modelled using beam elements and subjected to static loads by the actual design wind and wave conditions, with the nacelle's self-weight applied at the apex. The foundation was constructed using plate elements with discrete springs, whose stiffness was determined based on soil reactions obtained from PLAXIS. The soil was modelled utilizing HS-Small model with parameters representing loose to dense sand. The findings indicated that the natural frequency decreased by 1.3% to 12.0% as S/L increased from 0 to 0.5. The rate of decrease in natural frequency associated with bucket dimensions (L/D) and relative density was comparatively small.

Keywords: offshore wind turbine; tripod bucket foundation; scour; natural frequency; finite element analysis

1 INTRODUCTION

The marine environment poses several difficulties in the operation and maintenance of offshore wind turbines (OWTs). When subjected to continuous wave action, all bottom-founded structures experience a loss of foundation fixity due to scour, regardless of water depth. This phenomenon alters the dynamic characteristics of the OWT, potentially shifting its natural frequency outside the safe zone anticipated at the design stage. The underlying mechanism involves a reduction in foundation stiffness, influenced by both the loss of embedment and the decrease in confining pressure.

Previous studies have shown that natural frequency decreases as scour depth increases. Prendergast et al. (2013) conducted model tests and demonstrated a reduction in the natural frequency of a bridge supported by a pile foundation as scour depths increased. Mayall et al. (2018) and Bhattacharya & Adhikari (2011) carried out numerical studies to examine the effect of scour on monopile-founded OWTs. In line with these findings, Skau et al. (2018) indicated that the decrease in natural frequency caused by scour was due to a reduction in foundation stiffness. Many researchers argued that scour alters the complex soil–foundation–structure interaction (SFSI) through a reduction in foundation stiffness (Suryasentana et al. 2022).

In this study, we developed an FE model that considered SSI by coupling structural and geotechnical finite element programs. The details of the 4.2-MW OWT prototype were provided by the Korea Electric Power Corporation (KEPCO). This prototype was supported by a tripod suction bucket foundation and installed in Gunsan, South Korea in 2020. Further details of the prototype are described by Ryu et al. (2019). Figure 1 illustrates the geometry of the suction bucket foundation with both the original and scoured ground conditions.

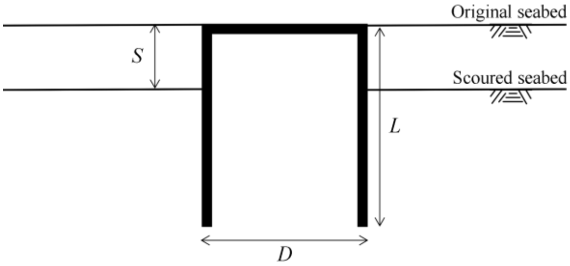

Figure 1. Illustration of the suction bucket foundation geometry under original and scoured seabed conditions

2 NUMERICAL METHOD

The offshore structural program SACS was used to model the tower and the tripod substructure with dimensions equivalent to those of the prototype, while the suction bucket foundation—embedded in loose and dense sand—was modelled in PLAXIS. The soil reactions obtained from PLAXIS were used to calculate the spring stiffness in the SACS model, which then performed dynamic analyses to determine the natural frequency considering SFSI. After verifying the FE model by comparing it with theoretical estimates and the values from the KEPCO design report (KEPRI, 2020), a total of 32 cases were conducted for the parametric study. The scour depth, foundation geometry, and sand density were varied.

2.1 Environmental specifications for the site

The marine conditions of the Southwest Sea, provided by KEPRI (2016), were applied as environmental factors in SACS. The design values for the tide level and wind speed recorded in the Gunsan region were used.

The water depth was 8.2 m at the lowest tidal level. The 10-minute mean wind speed and instantaneous wind speed at a reference height of 97 m were 27.76 m/s and 32.42 m/s, respectively. The wind direction and power density ratio were greatest from the north-northwest, followed by the north. Significant wave height and peak spectral period varied depending on the design wind conditions. The current profile was divided into a subsurface current of 0.959 m/s and a wind-generated near-surface current of 0.215 m/s. Using the aforementioned design values, equivalent static loads were computed and applied at the foundation reference points (Fig. 2).

2.2 Structure & Foundation modelling

The structure was modelled using beam elements in SACS, with dimensions referenced from the design report (KEPRI, 2020). The tower's cross-sectional area was varied along its length to create a tapered shape. In the SACS model, the structure was modeled with the self-weight of the Rotor-Nacelle-Assembly (RNA) applied at tower apex. Table 1 lists the overall dimensions of the 4.2-MW OWT and the parameters used in this study.

The suction bucket foundation was modelled as an array of plate elements. Equivalent conditions were also modelled in PLAXIS with a reference point at the centre of the bucket cap, serving as a link between the SACS and PLAXIS analyses. The suction bucket foundations were examined under rigid settings to guarantee accurate measurement of the foundation stiffness for natural frequency values. Based on the structural analysis results in SACS, load and moment combinations applied along mutually perpendicular directions are applied as boundary conditions at the bucket reference point in the PLAXIS model. The tripod suction bucket foundations were modelled following Kim (2012) and Kim & Oh (2014). For SACS analyses requiring linear springs, such as modal analysis, the three linearized stiffness values are obtained by fitting the stress-displacement relationship of the soil elements in PLAXIS, adjusted by the effective area and the initial slopes of the curve at small displacements near zero.

Table 1. Overall characteristics of the 4.2-MW turbine (KEPRI, 2020)

Component	Property		Value
Wind turbine	RNA weight		300 ton
Tower	Diameter		3.5–4.2 m
	Length		72.7m
	Thickness		17–45 mm
	Young's modulus		210 GPa
Tripod structure	Main	Diameter	4.5 m
		Thickness	45 mm
	Bracing	Diameter	1.6 m
		Thickness	55 mm
	Length		27.7 m
	Young's modulus		210 GPa
Suction bucket	Center-to-center distance		20 m
	Lid thickness		25 mm
	Skirt thickness		20 mm
	Young's modulus		210 GPa
	Bucket diameter		8 m

The effect of scour on the natural frequency was examined by varying the foundation geometry, soil density, and scour depth. Table 2 presents the test cases and conditions used in the parametric study. The chosen range of parameters was based on the definition of shallow foundations in ISO (2016) and DNV (2024), and the values were selected to represent realistic soil in field conditions.

Figure 2 shows the numerical model using PLAXIS and SACS. The analyses were coupled at the reference points (red dots). To achieve optimal mesh quality, a finer mesh size was employed near the bucket foundation, following after Barari et al. (2021). The extent of the finer mesh zone was set to two times the bucket diameter and skirt length from each bucket, ensuring that the critical region around the foundation was represented with sufficiently accurate stress concentrations and displacement gradients. The values of the applied force and the resulting soil reaction were examined to adjust the coarseness factor via trial-and-error. The final mesh

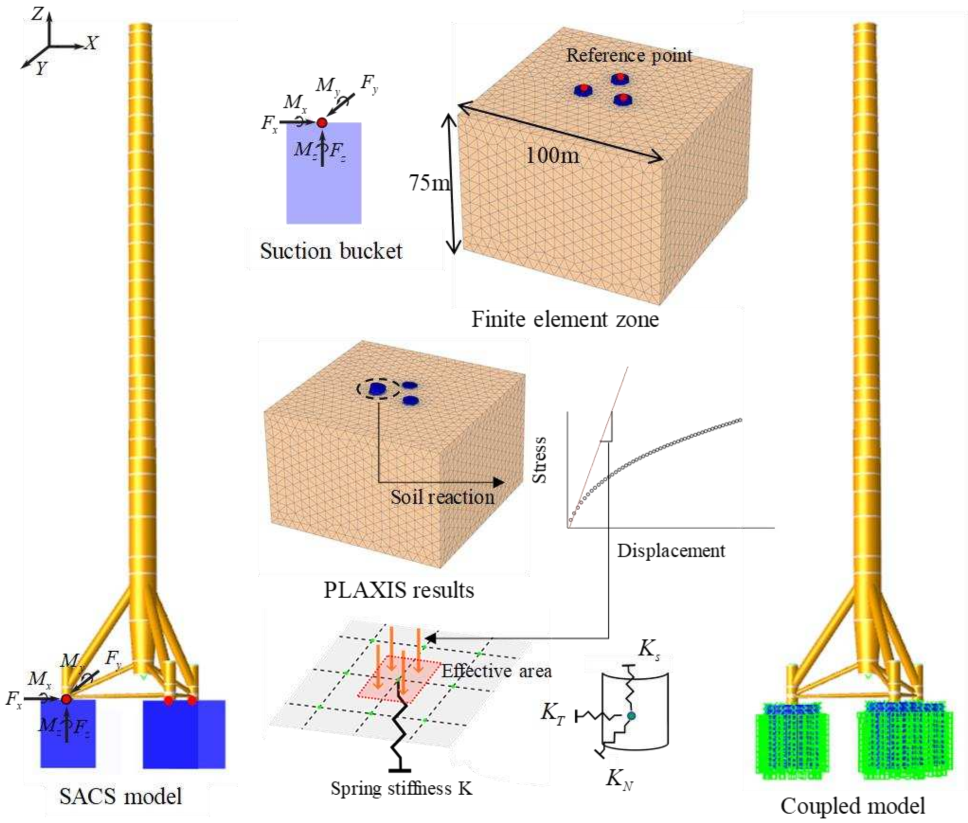

Figure 2. PLAXIS-3D finite element model and SACS model constructed for analysis

parameters were selected based on the sensitivity of the residual error to mesh-size variations.

The soil domain was set to 100 m horizontally and 75 m vertically, following Tran and Kim (2017). In addition, the interface between the soil and foundation was modelled using a strength reduction factor of 0.8, reflecting the reduced shear resistance at the boundary due to potential sliding or detachment. To confirm the adequacy of the model, soil behaviour was assessed by examining both soil strength at the interface and foundation stiffness in the vertical and horizontal directions, ensuring that the interaction between soil and structure was realistically represented.

Table 2. Parametric study plan used in this paper

Variable	Value
S/*L*	0, 0.17, 0.33, 0.50
L/*D*	1.00, 1.16, 1.50, 2.00
Sand Density	Loose, Dense

2.3 Soil modelling

The soil was modelled using the HS-Small (Hardening Soil with Small Strain Stiffness) model in PLAXIS to capture nonlinear stiffness at low strain levels. Since the analysis focuses on the small-strain level, the constitutive model was chosen based on the work of Wood and Belkheir (1994), which supports the assumption that softening does not occur in dense sand within the finite element model. The HS-Small parameter values are summarized in Table 3. The input soil parameters were selected from the Material Manual (Bentley Systems, 2024), representing both loose and dense sand. In this manual, the parameter values were derived from standard drained triaxial tests and cyclic triaxial tests on Hostun Sand, as reported by Desrues et al. (1996) and Biarez & Hicher (1994).

2.4 Scour modelling

In general, there are two types of scour: global and local. In this study, however, only global scour was examined because local scour was considered outside the scope and limited by paper length. Furthermore, Kariyawasam et al. (2020) noted that the difference in natural frequency reduction between global and local scour for shallow foundations embedded in sand was moderately minor, as confirmed by geotechnical centrifuge experiment

Table 3. HS-Small parameters for loose and dense sand

Parameter	Loose sand	Dense sand
Unit weight	17 kN/m³	17.5 kN/m³
E_s	20 MPa	37 MPa
E_{ur}	60 MPa	90 MPa
v_{ur}	0.2	0.2
G_0	70 MPa	112.5 MPa
$\gamma_{0.7}$ (G=0.722G_0)	0.0001	0.0002
K_0	0.44	0.34
m	0.65	0.5
c	0.1 kPa	0.1 kPa
φ	34 °	41 °
ψ	0 °	14 °

The shape and extent of scour were chosen based on relevant publications. Field data recorded at Park Alpha Ventus (Stuyts et al., 2013) provided guidance on the depth of scour, while model tests by Ma et al. (2018) informed that scour occurs throughout the base of the main tower and sorrounding areas of buckets. Detailed modelling of the scour shape and type was deemed beyond the scope of this paper. Herein, only global scour was modelled by varying the scour depth within a realistic range for a tripod bucket foundation embedded in a sandy seabed.

3 RESULTS

3.1 Validation

Verification of the formulated model was conducted by comparing its results with the theoretical equation proposed by Jalbi (2020) and with the natural frequency predicted by another FE study using BLADED on the same model provided by KEPRI (2020). A fixed-base condition was used for this verification. The theoretical estimation of the first natural frequency was based on converting multiple foundations into an equivalent Euler–Bernoulli beam with a mass at the top. The natural frequency f considering SSI can be estimated by (Jalbi, 2020):

$$f \cong \frac{1}{2\pi}\sqrt{\frac{3.04EI}{L_T^3(M_1+0.227M_2)}} \quad (1)$$

where L_T is the length of the tower, M_1, the mass of RNA is 300 tons, M_2, the total mass of the tower is 670 tons, and EI is the flexural rigidity.

Table 4 summarizes the natural frequency results from these methods. A moderate difference, corresponding to a 2% error in the first-mode natural frequency, was observed. Since this error was below 5%, it was considered that the model's predictive performance was adequately validated.

Table 4. Validation of natural frequencies by comparison

	FE (This study)	**Theory (Jalbi, 2020)**	**FE (KEPRI, 2020)**
Natural frequency	0.245 Hz	0.240 Hz	0.244 Hz
Design range	0.234 Hz ~ 0.273 Hz		

3.2 Natural frequency

The sensitivity of natural frequency to scour was investigated using the flexibility parameter (β). The flexibility parameter was defined as the ratio of the natural frequency of a flexible-base system to that of a fixed-base system (Futai et al., 2018):

$$\beta = \frac{f_{SSI}}{f_{fix}} \quad (2)$$

where f_{fix} is the fixed-base system natural frequency and f_{SSI} is the natural frequency considering SSI.

Figure 3 shows the flexibility parameter plotted against normalized scour depth *(S/L)*. The foundation geometry (*L*/*D*) and soil density (loose and dense) were also varied. In the figure, the dotted lines represent results for foundations embedded in loose sand, whereas the solid lines represent those in dense sand. The red line indicates the design limit (1P), as specified by the turbine manufacturer (KEPRI, 2020).

As shown in Figure 3, the flexibility parameter decreased as normalized scour depth increased for all cases. Moreover, as skirt length decreased, the flexibility parameter also decreased under both non-scoured and scoured conditions, indicating that greater embedment depth provides better fixity through increased soil confinement. The decreasing trend of the flexibility parameter was more pronounced for loose sand than for dense sand, which is logical because loose sand has a lower shear modulus than dense sand.

For the bucket foundation with *L*/*D* = 1 in dense sand, the first-mode natural frequency decreased by 6.2% as the scour depth increased from 0 to 4 m. In contrast, for the foundation with *L*/*D* = 2, the decrease was only 1.3%, even with the scour depth increasing from 0 to 8 m. These results indicate that *L*/*D* has important implications for the reduction rate of the first-mode natural frequency in OWTs supported by a tripod suction bucket foundation.

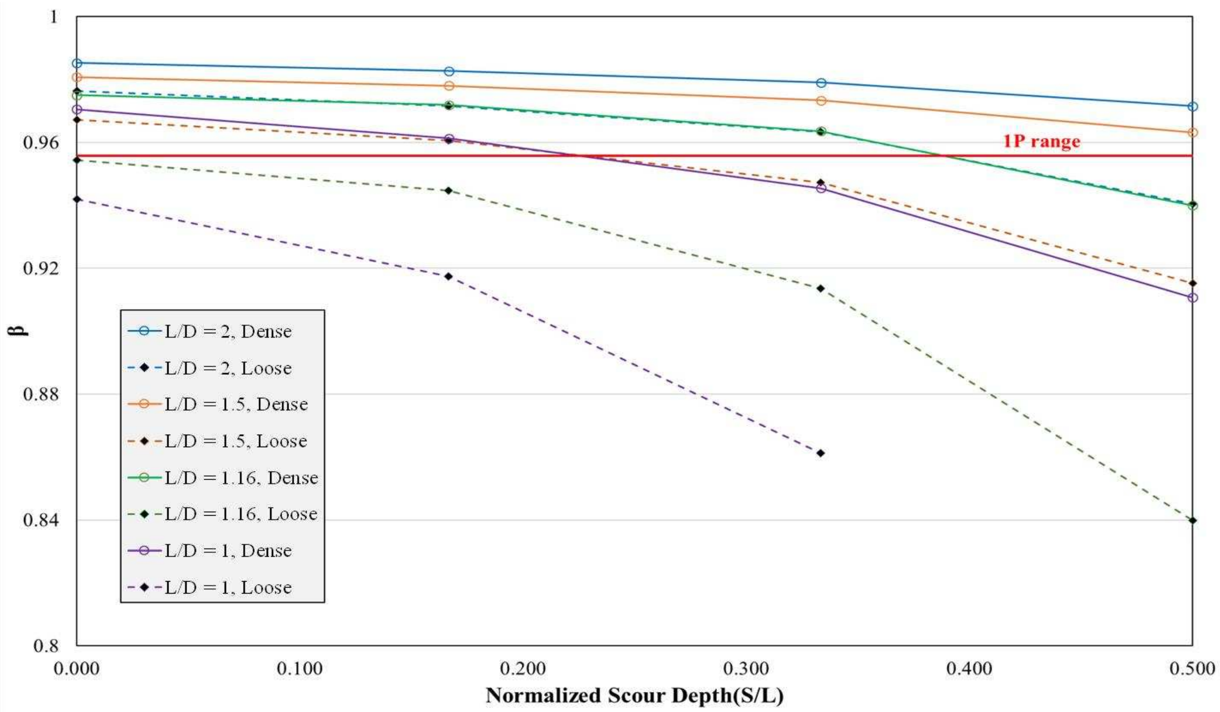

Figure 3. The plot of the first mode natural frequency flexibility parameter versus normalized scour depth for various foundation geometries and soil densities

Under loose sand conditions, the natural frequency reduction was 3.7% and 12.0% as *S*/*L* increased from 0 to 0.5 for skirt lengths of 16 m and 9.3 m, respectively. Furthermore, the natural frequency decreased by 1.5% to 10.6% as the *L*/*D* ratio decreased from 2.0 to 1.0, and it fell by 0.9% to 10.7% as the relative density decreased. Out of the 32 cases examined, 13 showed that the first-mode natural frequency values fell below the design limit (1P), indicating that the possibility of resonance should not be overlooked as scour depth increases.

4 CONCLUSIONS

In summary, this paper described a coupled FE model developed to examine variations in natural frequency with changing scour depth. The parametric study was conducted by varying the scour depth, suction bucket skirt length, and soil density. The tower and tripod bucket foundation were modelled using the design specifications of a 4.2-MW OWT installed in Gunsan, South Korea. To appropriately account for SSI effects, the soil reactions computed from PLAXIS were used to generate spring stiffness values for the structural beam elements.

Dynamic analyses of the model were performed to estimate the first-mode natural frequency. Validation of the model, achieved by comparing its predictions with theoretical values and another FE model (without SSI), showed a residual error of approximately 2%. In all cases, the natural frequency decreased as scour depth increased. The bucket foundation with shorter skirts embedded in loose sand exhibited higher sensitivity of the natural frequency to scour. Comparing conditions without scour to those with a scour depth of 0.5*L* revealed natural frequency reduction ranging from 1.3% to 12%. Scour-induced potential risks for resonance were noted in 13 cases. This study successfully developed a coupled FE model to estimate the OWT natural frequency under varying scour conditions. Further research is expected to empirically predict the natural frequency as a function of suction bucket geometry and soil density under various scour conditions.

AUTHOR CONTRIBUTION STATEMENT

Seung-Won Oh: Data Curation, Formal Analysis, Writing- Original Draft, **Kyeong-Sun Kim**: Conceptualization, Methodology, Writing- Reviewing and Editing, **Jun-Woo Kim**: Data Curation, Visualization, **Sung-Ryul Kim**: Supervision, Funding Acquisition, Writing- Reviewing and Editing

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