Reliability analysis of suction bucket foundation for offshore wind turbine in silty sand

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ABSTRACT

In this study, the reliability analysis was carried out for suction bucket foundation considering the uncertainties in soil and structural parameters. In reliability analysis, the vertical and lateral resistances are defined as base limit states. The case studies were carried out using the preliminarily designed foundations at western-south part of sea of Korea. From reliability analyses, vertical resistance for free-slip condition has overall lower reliability index, and submerged unit weight and internal friction angle of seabed soil are governing factors in vertical and lateral resistance in this case.

Keywords: reliability analysis; suction bucket foundation; offshore wind turbines

1 INTRODUCTION

Unlike Inland wind turbines, offshore wind turbines (OWT) are installed in the open sea using fixed type foundations in shallow and intermediate deep sea regions, and relatively floating foundations executed in very deep, more than 50m, sea regions, so OWT design and construction process are very complicated and the cost for support structural parts including the substructure and foundation and installation accounts for about 30 to 40% of the total cost. Various types of supporting structures have been proposed and applied for securing the structural safety and serviceability with cost reduction of offshore wind turbines, and related research and development are being actively carried out in the world. IEC 61400-3 (2009), DNV-OS-J101 (2013), and ISO 19902 (1998), which are the most widely accepted design specifications in the design of offshore wind turbines, are based on the limit state design (LSD). The LSD method is highly sophisticated design technique that enables optimal design which shows the safety measure using a probability index that the structure is experienced a structural failure by the reliability theory. In South Korea, the allowable stress design (ASD) is still applied for general coastal structures such as breakwaters, piers, and so on, and it is necessary to develop the appropriate advanced LSD specifications and in order to actively cope with international design concept.

In this study, the reliability analysis was carried out for suction bucket foundation considering the uncertainties in soil and structural parameters. In reliability analysis, the vertical and lateral resistances are defined as base limit states. The case studies were carried out using the preliminarily designed foundations at western-south part of sea of Korea.

2 SUCTION BUCKET FOUNDATION

The suction bucket was developed from the suction caisson foundation already used in the offshore technology (Ibsen et al., 2004). Its behavior can be considered as a combination of gravity base and pile foundation systems. Usually the initial penetration of the suction bucket into the seabed takes place under the bucket self-weight. Then suction is subsequently applied in order to push the bucket to the desired depth.

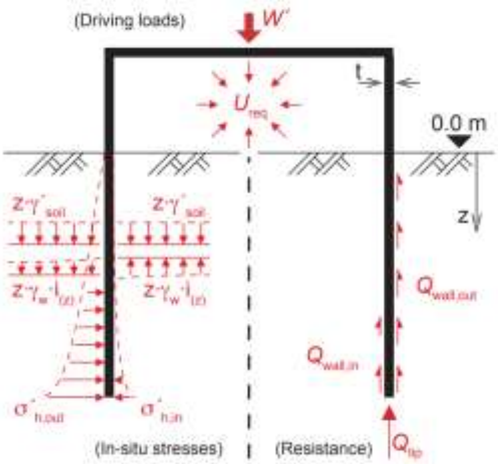


Fig. 1. Forces and stresses acting on bucket during suction installation in a permeable soil (after Sturm et al., 2015)

The bucket is pushed into the seabed under the pressure differential generated on the lid which efficiently increases the downward force on the foundation. In sandy soils, seepage induced by suction plays an important role in the installation process by reducing the soil resistance. In homogenous sand, the downward water flow causes an increase in the soil effective stress outside the bucket, whereas the effective stress in the soil trapped inside the bucket decreases due to upward flow.

The advantages of suction bucket foundation include the accommodation of a variety of soil conditions, accurate positioning, and the ease of installation and retrieval for reutilization compare to deep foundation. Suction bucket also expects to reduce the foundation cost and to enhance environmental friendliness.

It has been known that suction bucket foundation has considerable capacity under short-term loading condition, while the resistance to long-term loading may be low. The dynamic load is transmitted to the soils by platform and causes the degradation of soil layer's strength and modulus. As a result, the bearing capacity of bucket foundation may decrease (Ding et al., 2003).

The installation is considered by many as one of the most challenging aspects of suction bucket foundation application. Most calculation methods of penetration resistance are still applicable for idealized conditions, i.e. uniform and homogeneous soil conditions or perfectly horizontal layering. There are a number of situations which are not covered (Sterm et al., 2017). Therefore, it needs to clarify the suction bucket foundation behavior under various soil conditions.

3 RELIABILITY ANALYSIS

For reliability assessment of suction bucket foundation, reliability analyses were conducted primarily in idealized conditions, i.e. uniform and homogeneous soil conditions, and no structural imperfections.

3.1 Case considered

This study was carried out on the preliminary design of OWT foundation model at the West South offshore wind farm site in the Yellow Sea of Korea. Details of suction bucket foundation are shown in Fig. 2 and Table 1. Suction bucket has length of 16.5m, bottom diameter 18.0m, wall thickness of 0.5m, cover thickness of 0.9m. Total weight of bucket is 33,150kN. Ground conditions and soil properties are also shown in Table 2, which were obtained through the SPT results at the site.

Table 1. Details of suction bucket foundation model

Items	Values
Substructure height	39.0 m
Bucket length	16.5 m
Bottom diameter (outer)	18.0 m
Wall thickness	0.5 m
Cover thickness	0.9 m
Total weight	33,150 kN

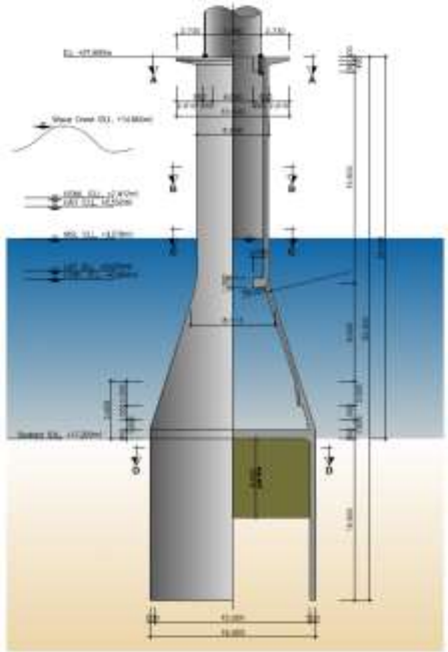


Fig. 2. Dimensions of suction bucket foundation model

Table 2. Ground conditions and soil properties

Items	Values	Items	Values
Water depth	20.5 m	Soil wet unit weight	18.6 kN/m^3
Sea water unit weight	10.1 kN/m^3	Soil dry unit weight	8.5 kN/m^3
Soil type	Silty sand	Cohesion	0
N-values	14~37	Internal friction angle	35~50 °

The combined loads at the tower bottom, i.e., vertical and horizontal loads, are 66,245kN and 16,800kN respectively.

3.2 Reliability analysis methods - AFOSM

In this study, reliability analyses were performed using the Advanced First-Order Second-Moment (AFOSM) approach, in which the information on the distribution of random variable, as well as mean value and standard deviation, can be appropriately used as a kind of the First Order Reliability Method. It is an analytical approximation in which the reliability index (β) is interpreted as the minimum distance from the origin to the limit state surface in standardized normal space and the most probable failure point (design point) is searched using mathematical methods. AFOSM is also called 'Hasofer-Lind method' and details of AFOSM can be found in Ang and Tang (1990).

3.3 Limit states and random variables

Limit states can be considered for the reliability analysis including ultimate limit state (ULS), serviceability limit state (SLS), fatigue limit state (FLS) and accidental limit state (ALS). Among them, this study focuses on the vertical and lateral resistance of bucket foundation related to ULS as follows:

1) Vertical resistance (non-slip condition)

$$G_1 = R - S = Q_1 - V \tag{1}$$

where R is the resistance, S is the loading function, Q_1 is ultimate vertical resistance of non-slip condition and V is vertical load.

$$Q_1 = Q_{skin,out} + Q_{tip,gross} - W_{inside,soil} \quad (2)$$

where $Q_{skin,out}$ is skin friction on the outside of the bucket (kN), $Q_{tip,gross}$ is end resistance of the bucket tip and the plug (kN) and $W_{inside,soil}$ is weight of plug / area of the plug (kN).

$$Q_{skin} = \sum_{i=1}^{N} \int_0^{L_i} \pi D f_s dz = \sum_{i=1}^{N} \int_0^{L_i} \pi D(\sigma' K_0 \tan\delta) dz \quad (3)$$

where D is diameter of the bucket (m), f_s is unit skin friction (kPa), σ' is effective overburden pressure per depth (kPa), K_0 is at rest earth pressure coefficient ($K_0 = 1 - \sin\phi$) and δ is wall friction angle between bucket and soil ($\delta = 2/3\phi$).

$$Q_{tip} = \left(\gamma' L N_q + 0.5\gamma' D N_\gamma\right)\frac{\pi D^2}{4} \quad (4)$$

where γ' is submerged unit weight of soil (kN/m^3), L is length of the bucket (m), D is diameter of the bucket (m), N_q, N_γ is bearing capacity factors and $\pi D^2/4$ is sum of area of the bucket tip and area of the plug (m^2).

2) Vertical resistance (free-slip condition)

$$G_2 = R - S = Q_2 - V \quad (5)$$

where Q_2 is ultimate vertical resistance of free-slip condition.

$$Q_2 = Q_{skin,out} + Q_{skin,in} + Q_{tip,net} \quad (6)$$

where $Q_{skin,out}$ and $Q_{skin,in}$ are skin friction on the outside and inside of the bucket (kN), respectively. $Q_{tip,net}$ is end resistance of the bucket tip (kN).

$$Q_{tip,net} = \left(\gamma' L N_q + 0.5\gamma' t N_\gamma\right)\frac{\pi(D^2 - d^2)}{4} \quad (7)$$

where t is wall thickness of the bucket (m), D is outer diameter of the bucket (m), d is inner diameter of the bucket and $\pi(D^2-d^2)/4$ is sum of area of the bucket tip (m^2).

3) Lateral resistance

$$G_3 = R - S = Q_3 - L \quad (8)$$

where Q_3 is ultimate lateral resistance and L is lateral load.

$$Q_3 = \frac{K_p \times \gamma' \times D \times L^2}{2} \quad (9)$$

where K_p is Rankine passive earth pressure coefficient ($K_p = (1+\sin\phi)/(1-\sin\phi)$).

It is important to quantify the uncertainties of loads and material properties as random variables in reliability analysis, which requires probability distribution function and variability of such parameters. In this study, unit weight of bucket foundation, submerged unit weight of seabed soil (γ_s'), internal friction angle (ϕ), unit weight of bucket foundation (γ_b), vertical load (V) and lateral load (L) are defined as random variables. They are regarded as normally distributed and coefficients of variance (COV) are estimated $COV_{\gamma s'}$ = 0.2 and COV_ϕ = 0.05~0.1, $COV_{\gamma b}$ = 0.1, COV_V = 0.1 and COV_L = 0.1, respectively. Here, COV$_\phi$ are evaluated based on the correlation between SPT blow counts (N-value) and internal friction angle (ϕ) as Table 3.

Table 3. Statistical properties of internal friction angle

N-value	Correlation equation	Internal friction angle	
		mean	COV
14 ~ 37	Wolff (1989)	35.41	0.0939
	Kulhawy & Mayne (1990)	50.23	0.0505
	Hatanaka & Uchida (1996)	43.86	0.1066

3.4 Analysis results

Table 4~6 show reliability indices (β) and probabilities of failure (P_f) computed by the AFOSM method for each failure mode. P_f herein means the probability exceeding vertical and lateral resistance against each loading component. It can be observed that vertical resistance for free-slip condition has overall lower reliability index, so that it is dominant failure mode in this case. The lowest reliability is also obtained when Wolff's equation is applied to obtain the internal friction angle from SPT N-values.

Table 4. Reliability analysis results of vertical resistance failure mode for non-slip condition

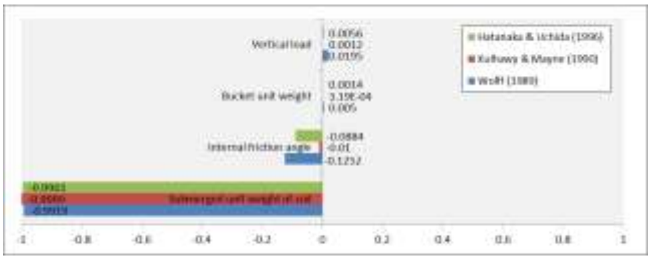
Correlation equation	Reliability analysis results	
	β	P_f
Wolff (1989)	4.811	7.53×10^{-7}
Kulhawy & Mayne (1990)	4.986	3.08×10^{-7}
Hatanaka & Uchida (1996)	4.954	3.63×10^{-7}

Table 5. Reliability analysis results of vertical resistance failure mode for free-slip condition

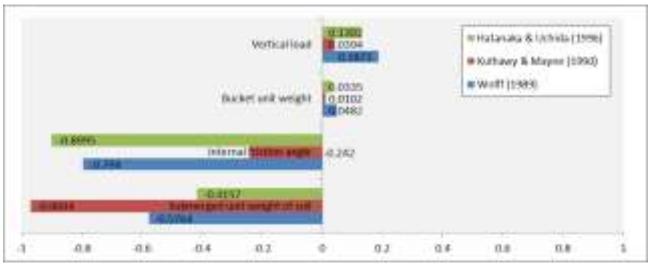
Correlation equation	Reliability analysis results	
	β	P_f
Wolff (1989)	1.956	2.52×10^{-2}
Kulhawy & Mayne (1990)	4.665	1.54×10^{-6}
Hatanaka & Uchida (1996)	3.022	1.30×10^{-3}

Table 6. Reliability analysis results of lateral resistance failure mode

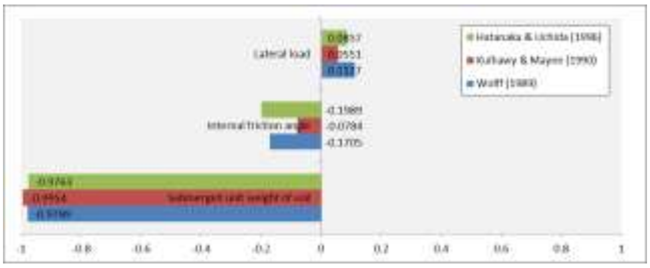
Correlation equation	Reliability analysis results	
	β	P_f
Wolff (1989)	3.880	5.22×10^{-5}
Kulhawy & Mayne (1990)	4.453	4.23×10^{-6}
Hatanaka & Uchida (1996)	4.190	1.40×10^{-5}



(a) vertical resistance failure mode for non-slip condition



(b) vertical resistance failure mode for free-slip condition



(c) lateral resistance failure mode

Fig. 3. Sensitivity of random variables on reliability analysis

Sensitivity indices of random variables were derived by AFOSM as shown Fig. 3. Although there are some differences depending on the application of the correlation equations, submerged unit weight and internal friction angle of seabed soil are governing factors in vertical and lateral resistance in this case. This means uncertainty of soil is greater, probability of failure or exceeding the ultimate resistance increase.

4 SUMMARY & CONCLUSION

Reliability analyses of suction bucket foundation for the preliminary design of OWT foundation model at the West South offshore wind farm site in the Yellow Sea of Korea. Advanced First-Order Second-Moment (AFOSM) were used to the reliability analyses focused on the vertical and lateral resistance of bucket foundation related to ultimate limit state.

From reliability analyses, vertical resistance for free-slip condition has overall lower reliability index, and submerged unit weight and internal friction angle of seabed soil are governing factors in vertical and lateral resistance in this case.

This results are based on the soil properties and statistical properties estimated by SPT results, and the reliability difference is relatively large according to the each N-ϕ correlation equation. Therefore, further analysis is required by evaluating the soil properties and statistical properties of design parameters through sufficient soil investigation.

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REFERENCES

Ang, A.H.-S. and Tang, W.H. (1990). Probability concepts in engineering planning and design, Volume II: Decision, Risk, and Reliability, John Wiley & Sons, Inc., New York.

Ding, H.Y., Qi, L., and Du, X.Z. (2003). Estimating soil liquefaction in ice-induced vibration of bucket foundation. Journal of Cold Regions Engineering, 17(2), 60-67.

DNV (2013). Design of offshore wind turbine structures, Offshore Standard DNV-OS-J101, Det Norske Veritas, Høvik

Hatanka, M. and Uchida, A. (1996). Empirical correlation between penetration resistance and internal friction angle of sandy soils. Soils and Foundations, 36(4), 1-9.

Ibsen, L.B., Schakenda, B., Nielsen, S.A. (2004). Development of the bucket foundation for offshore wind turbines, a novel principle. 3. Gigawind-Symposium "Offshore-Windenergie, Bau- und umwelttechnische Aspekte, Hannover.

IEC (2009). 61400-3 Design requirements for offshore wind turbines.

ISO (1998). ISO 2394: General principles for reliability based design

Kulhawy, F.H. and Mayne, P.W. (1990). Manual on estimating soil properties for foundation design, Electric Power Research Institute, Palo Alto, CA

Sturm, H., Nadim, F., and Page, A. (2015), A safety concept for penetration analyses of suction caissons in sand, in V. Meyer, ed., 'Frontiers in Offshore Geotechnics III, Oslo, Norway', 1393–1398.

Wolff, T.F. (1989). Pile capacity prediction using parameter functions. ASCE Geotechnical Special Publication, No. 23, 96-107.