Cyclic behavior of soil supporting suction caisson foundation

Cyclique comportement de sol soutenir les caissons d'aspiration fondation

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ABSTRACT: The use of offshore wind power has been rapidly increased over the last decade as an environment-friendly source of energy, and suction caissons are considered as alternative foundations to typical monopile foundations. Offshore wind turbine is subjected to large cyclic horizontal load and overturning moment, in this study numerical simulations are conducted to determine the dynamic behavior of seabed soil due to cyclic horizontal wind load. The displacement and rotation of the bucket foundation, and stress behavior of soil inside/outside of a bucket with various embedment ratios were investigated. The results show that bucket displacement and rotation are highly dependent to the embedment ratio. In addition, dynamic behavior of soil inside and outside of the bucket is quite vary and needs to be taken into account for the design of offshore wind turbines.

RÉSUMÉ : En tant que source d'énergie respectueuse de l'environnement, le nombre d'éoliennes offshores utilisées a très vite augmenté durant la dernière décennie, et les caissons d'aspiration sont considérés comme une solution de fondation alternative aux bases monopiles typiques. Comme une éolienne est exposée à une très grande charge horizontale cyclique et un fort moment de torsion, des simulations à analyse numérique seront menées dans cette étude afin de déterminer le comportement dynamique des sols du fond marin dû à la charge horizontale cyclique du vent. La déformation et la rotation de ces fondations, ainsi que le comportement sous pression du sol à l'intérieur ou à l'extérieur du monopode avec divers rapports d'enfouissement soumis à des charges cycliques ont été étudiés. De plus, le comportement dynamique du sol à l'intérieur ou à l'extérieur du caisson qui s'avère être assez varié nécessitera d'être pris en compte dans la conception des éoliennes.

KEYWORDS: Offshore wind turbine, suction bucket foundation, cyclic load, silty sand.

1 INTRODUCTION

Recently, with an increase in the demand of energy supply, the utilize of renewable source of energy like offshore wind power has been considerably increased. In the design of offshore wind turbines, due to exposing to the large horizontal cyclic load and overturning moment compared to the relatively low vertical loads, highly attention is needed to be paid for the design of such structures' foundations. Owing to the cost effectiveness and easy installation, suction buckets can be considered as a reliable and promising foundation for offshore wind turbines.

Previous studies have been mainly concentrated on the monotonic response of the bucket foundation (Feld 2001, Houlsby et al. 2005). Few laboratory model tests which is mostly based on the cyclic loading response for the small numbers of cycles were also carried out (Byrne 2000, Villalobos et al. 2006).

Since the dynamic behavior of seabed soil supporting the bucket foundations subjected to the cyclic wind load has not been yet investigated, in this paper the bucket response consist of bucket displacement and rotation, subjected to the long term cyclic load, in addition to the cyclic behavior of soil supporting the bucket are evaluated by using numerical analyses.

2 NUMERICAL MODELING

1.1 *Soil and structural modeling*

In this study, a three-dimensional finite element (FE) model of a suction bucket foundation was used to analyze the cyclic behavior of the bucket and the soil supporting the bucket. The finite element program Plaxis 3D (Brinkgreve 2012) was used in the simulation.

A suction bucket foundation is a hollow steel cylinder with diameter *D*, skirt length *L*, and the skirt thickness of t_s, which is closed on top side with the severely stiffened steel lid. With regard to the symmetry of the geometry of the foundation structure, only one-half of the suction bucket was modeled. Hardening Soil constitutive model was used to simulate the soil properties. The formulation of the Hardening Soil model is indeed based on the hyperbolic relationship between the vertical strain and the deviatoric stress. Two different denisties of the silty sand soil were considered for modeling. To define the soil properties, previous studies already accomplished by (Tae Gyung Ryu 2014), in addition to the given equations in Plaxis 3D program manual (Brinkgreve 2012) were employed (Table 1). To get adequate accuracy of the results and avoid the boundary conditions effect, mesh convergence and model dimensional analysis were carried out. The bucket was modeled using steel plate element with the skirt thickness of *30 mm*, which is the common thickness of the buckets in practice. $E=210\ GPa$, $\upsilon=0.3$ were also used for the steel properties where represent the modulus of elasticity and poisson's ratio respectively. The unit weight of the steel γ, was also set to $77\ kN/m^3$. To consider the rigid behavior of the bucket due to the stiffeners placed on the upper side of the bucket, a very large modulus of elasticity ($E=210\times10^{6}\ GPa$) with bucket lid thickness of *100 mm* were exerted.

The FEM analyses were conducted in several calculation phases. In initial phase, by applying the gravity load of the only soil elements, geostatic stresses are computed. In this phase, the coefficient of earth pressure at rest, $k_0=1-\sin\varphi'$ was used for the calculation. The installation phase comprising activating the predefined elements applied for the bucket and tower structures were subsequently replaced by steel plate material. In the next calculation phase, a vertical dead load concerning the tower structure and wind energy converter system was applied on the center of bucket lid. The last phase included application of the cyclic horizontal wind load and overturning moment simultaneously.

Table 1. Soil properties.

Soil type	*Medium dense, Silty sand*	*Dense, Silty sand*
Unit weight γ (kN/m^3)	18.5	20
Secant stiffness (kN/m^2)	74,536	110,110
Tangent stiffness (kN/m^2)	59,629	88,088
Unloading/Reloading Stiffness (kN/m^2)	223,608	330,330
Effective cohesion C'(kN/m^2)	0.1	0.1
Effective angle of friction φ (°)	35	39
Angle of dilatancy ψ (°)	5	9
Relative density (%)	60	85

1.2 *Applied loads*

A vertical dead load *V* of *10000 kN* which is typical for a large *5MW* offshore wind turbine was applied on the center of the bucket lid with the diameter *D* of *14 m*. The skirt length *L* of *7, 10.5, 14 m* which represent the embedment ratio *L/D* of *0.5, 0.75, 1* were taken into account for simulation modeling. The horizontal cyclic wind load was applied at the *100 m* eccentricity from the bucket lid. The applied load was obtained using the FAST (Fatigue, Aerodynamics, Structures, and Turbulence) software (Jonkman and Buhl 2005). Figure 1 shows the cyclic horizontal wind load used in this study.

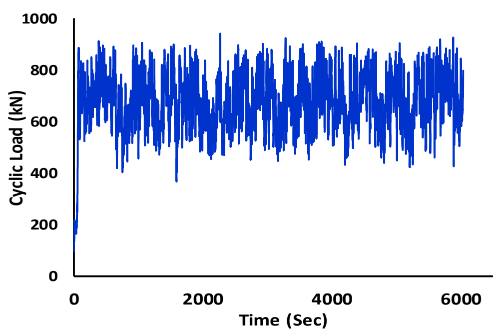

Figure 1. Input horizontal loading.

3 NUMERICAL ANALYSIS RESULTS

3.1 *Bucket rotation and displacement*

To assess the bucket response subjected to the long term cyclic load, two opposite points on the bucket lid for determination of the bucket rotation and one point on the center of bucket lid for bucket displacement were taken into account.

Figure 2,3 depict respectively the horizontal displacement and rotation of the bucket considering various embedment ratios. As to be expected, increasing the bucket skirt length may lead to decrease in both bucket displacement and rotation. In the case of bucket with smallest skirt length (*L=7 m*) and medium dense silty sand soil, around the time of *400 s*, with an increase in the cyclic load, a large bucket displacement and rotation is occured. It means that the bucket with the mentioned dimensions, is not able to withstand the large horizontal cyclic load, and consequently, the soil supporting the structure tends to fail.

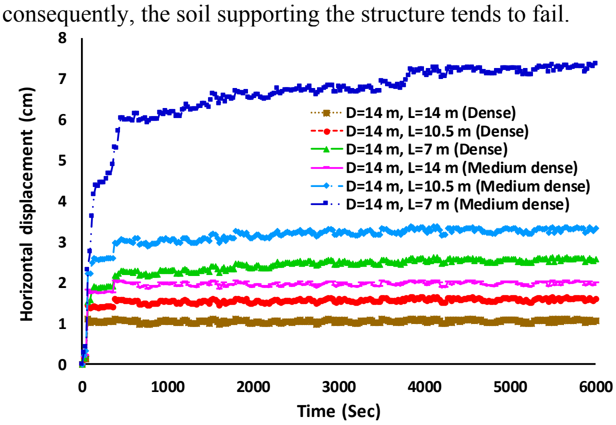

Figure 2. Bucket horizontal displacement for two different soil density considering various embedment ratios.

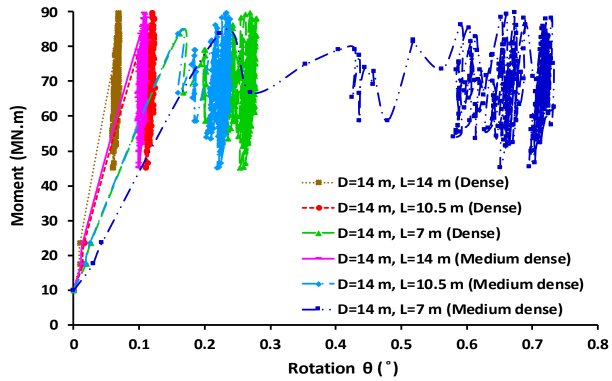

Figure 3. Overturning moment-Rotation curves for two different soil densities considering various embedment ratios.

3.2 *Soil response*

Eight points at the interior and exterior of bucket skirt (left and right side of the bucket) were considered to analyze the horizontal, vertical displacement in addition to stress behavior of the seabed soil during cyclic loading. Figure 4 displays the selected points used in the soil behavior analysis. Note that, bucket with embedment ratio (*L/D=0.75*) for dense silty sand soil was considered to present the soil behavior results.

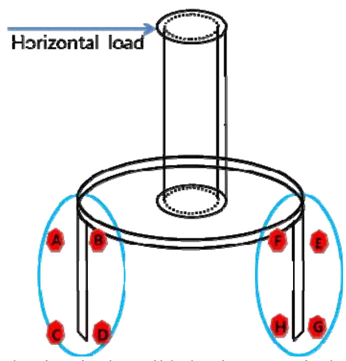

Figure 4. Selected points in the soil behavior numerical analysis.

3.2.1 *Soil horizontal displacement*

Soil horizontal displacements for an exemplary bucket with embedment ratio *L/D* of *0.75* are shown for the mentioned eight points inside/outside of the bucket skirt (Figure 5). Furthermore, Figure 6 represents the maximum soil horizontal displacement corresponding to the various aspect ratios. As to be shown, with an increase in the bucket skirt length, substantial decrease in the horizontal soil displacement are seen. As an example, almost two third reduction in horizontal displacement were observed for the soil near the bucket lid. Additionally, maximum displacement was seen inside of the bucket near the bucket lid.

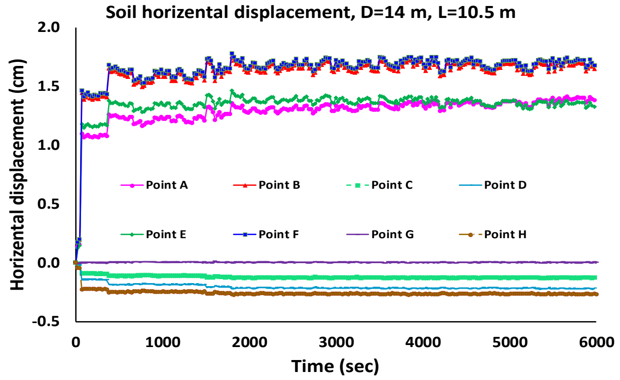

Figure 5. Soil horizontal displacement for dense silty sand with embedment ratio *L/D=0.75*.

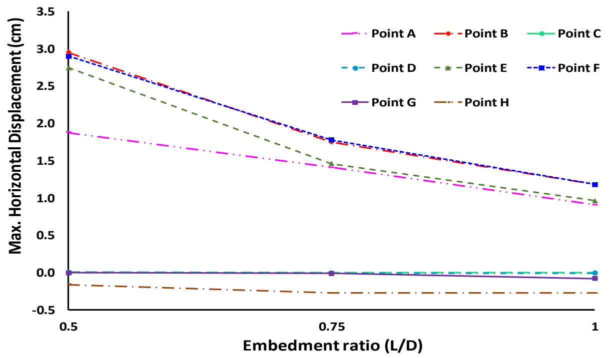

Figure 6. Maximum soil horizontal displacement corresponding to various embedment ratios.

3.2.2 *Soil vertical displacement*

Vertical displacement of soil for the considered points in the bucket with embedment ratio *L/D* of *0.75* are illustrated in Figure 7. Similar trend of soil horizontal displacement can also be seen in the given figure. Likewise, maximum vertical displacement is observed at the interior of the bucket near the lid.

Figure 8 shows the maximum soil vertical displacement corresponding to the various aspect ratios. Increasing bucket skirt length results in decrease in soil vertical displacement. For instance, around 70% reduction in the soil vertical displacement near the lid can be seen by increasing the bucket skirt length twice.

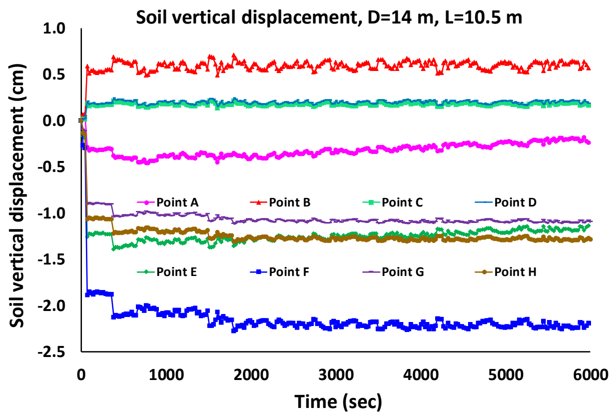

Figure 7. Soil vertical displacement for dense silty sand with embedment ratio *L/D=0.75*.

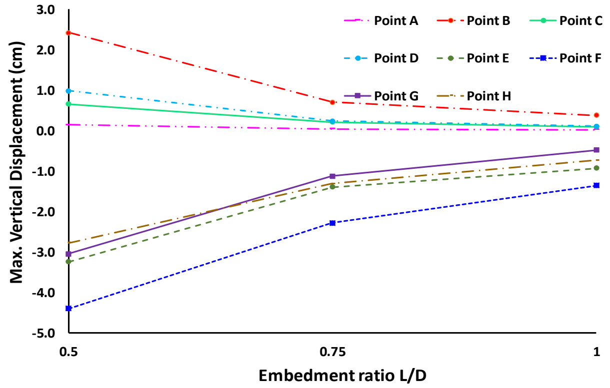

Figure 8. Maximum soil vertical displacement corresponding to various embedment ratios.

3.2.2 *Soil stress distribution*

In figures 9, 10 soil shear and normal stress distribution in the plane of symmetry for both interior and exterior of the bucket subjected to the cyclic load are presented. It can be induced that the concentration of the stresses is located at right inside of the bucket near the tip. The reason might be once the bucket is exposed to the applied load, the soil inside of the bucket tends to densify due to bucket movement, hence, maximum stresses are seen in this area.

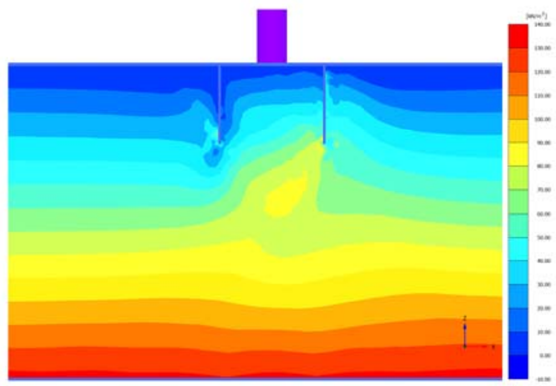

Figure 9. Soil shear stress distribution for the bucket with embedment ratio *L/D=0.75*.

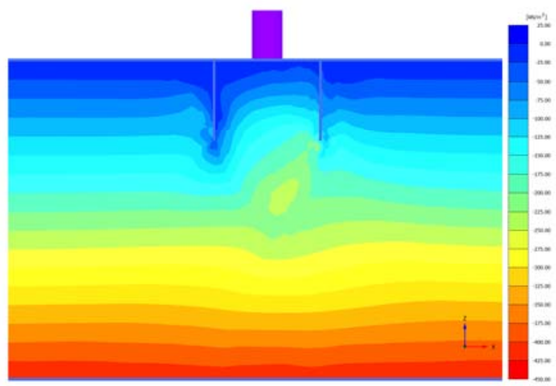

Figure 10. Soil normal stress distribution for the bucket with embedment ratio *L/D=0.75*.

The difference in stress values is caused by the impedance of the transmission of stress by the construction of the bucket foundation.

3.2.3 *Shear stress-normal stress curves*

Soil shear stress versus normal stress curves for the considered points with regard to embedment ratio *L/D*, *0.75* are shown in

figure 11. Two clear trends may be perceived from the given figure; 1. The normal and shear stresses caused by the cyclic loading belong to the certain stress ranges. 2. Due to increase in the soil density, the largest values of stresses are seen near the bucket tip at the interior right side of the bucket skirt.
Figure 12 demonstrates combination of the aforementioned certain stress ranges for three different bucket skirt lengths. Obviously, increasing the bucket skirt results in decreasing the mentioned stress ranges. Additionally, all three stress bandwidths show almost similar slope, and increasing the bucket skirt length may lead to shifting the stress ranges to the right.

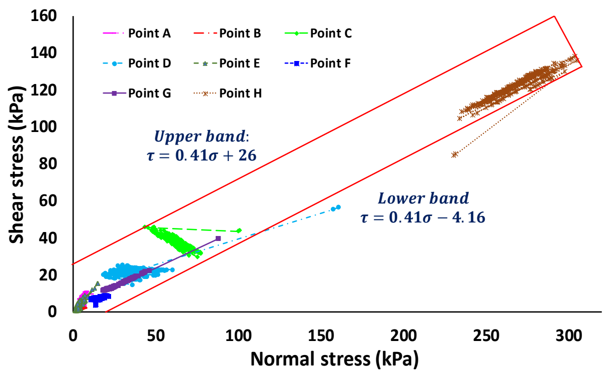

Figure 11. Soil shear stress-normal stress curves for the bucket with embedment ratio *L/D=0.75*.

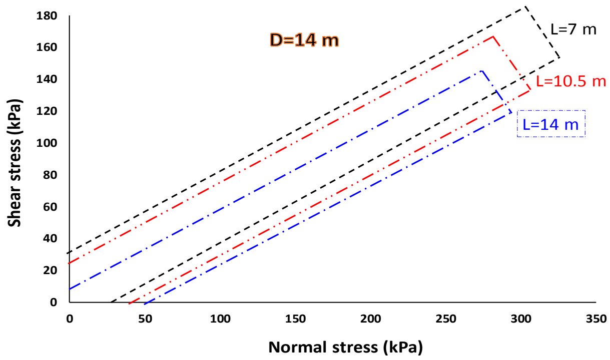

Figure 12. Soil shear stress-normal stress bandwidths, Comparison between different embedment ratios.

3.2.4 *Effective stress path curves*

In the case of stress path, same trend from soil shear stress-normal stress curves are witnessed. Figure 13 shows soil effective stress path curves for the taken points with regard to embedment ratio *L/D, 0.75*. It is found that maximum stress values are seen at right inside of the bucket near the tip which can be interpreted by soil densification in this area after subjecting the bucket to the cyclic load.

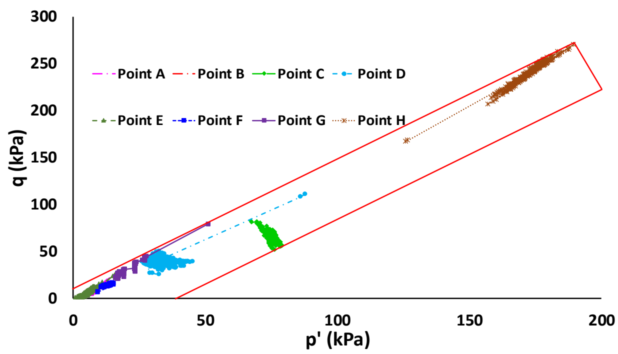

Figure 13. Soil effective stress path curves for the bucket with embedment ratio *L/D=0.75*.

2 CONCLUSION

Three-dimensional numerical analyses were conducted for a suction bucket foundation with different embedment ratios used for offshore wind turbines to evaluate the bucket response and soil supporting the bucket subjected to the long term cyclic horizontal wind load. The following conclusions may be drawn using the obtained results:
The numerical analysis results show that bucket rotation and horizontal displacement are strongly dependent on the geometry and soil relative density. As an example, doubling the bucket skirt length may decrease almost 58% of horizontal displacement and 75% of the rotation of the suction caisson subjected to the cyclic load in dense silty sand.
The results reveal that bucket with the smallest embedment ratio (*L=7m*) in medium dense silty sand soil is not suitable dimension for the design due to large rotation and displacement after exposing to the cyclic load.
Obtained results show that the major part of the load bears by the bucket skirt while bucket lid withstands only small part of the applied load. Thereby the largest soil horizontal and vertical displacement are seen near the bucket lid at both left/right interior of the bucket foundation.
The normal and shear stresses caused by long term cyclic loading, fall within certain ranges, hence, it is recommended to carry out experimental laboratory test considering those ranges.
According to the numerical analysis results, all three stress bandwidths with almost same slope meanwhile increasing the bucket skirt length may lead to shifting the stress ranges to the right.
Owing to the bucket movement and soil densification, maximum stresses are seen near the bucket tip at the right inside of the bucket skirt.
Finally, study research is currently being conducted to determine the effect of different load values and bucket sizes on the propagation of stresses.

3 ACKNOWLEDGEMENTS

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4 REFERENCES

Feld, T. (2001). Suction Buckets, a New Innovative Foundation Concept, applied to Offshore Wind Turbines. PhD Thesis, Aalborg University, Denmark.
Houlsby, G.T., Ibsen L.B. & Byrne B.W. (2005). Suction caissons for wind turbines. In Gourvenec & Cassidy (eds.), Frontiers in Offshore Geotechnics: ISFOG, Perth, Australia, 19-21 September 2005. London: Taylor & Francis.
Byrne, B.W. (2000). Investigations of suction caissons in dense sand. DPhil Thesis, The University of Oxford.
Villalobos, F.A. (2006). Model Testing of Foundations for Offshore Wind Turbines. DPhil Thesis, University of Oxford, UK.
Brinkgreve, Engin, and Swolfs, 2012. R.B.J. Brinkgreve, E. Engin, and W.M. Swolfs. Manual for PLAXIS 3D 2012, 2012.
Tae Gyung Ryu, 2015. Long-term Dynamic Behavior Study of Marine Silty Sand for Offshore Structure Foundation Design. Master thesis.
Jonkman, J., Buhl, M.L., 2005. FAST User's Guide. National Renewable Energy Laboratory. Technical Report No. NREL/EL-500-38230.