NGHIÊN CỨU ỨNG XỬ CỦA MÓNG GIẾNG CHÌM CHO CÔNG TRÌNH ĐIỆN GIÓ Ở NGOÀI KHƠI BẰNG PHẦN MỀM TÍNH TOÁN PHẦN TỬ HỮU HẠN

A PRELIMINARY NUMERICAL STUDY ON BEHAVIOR OF SUCTION CAISSON FOUNDATION FOR OFFSHORE WIND TURBINE BASED ON FINITE ELEMENT ANALYSIS PROGRAM

NGUYỄN TẤN HƯNG[1,*], LÊ HUỲNH NHẬT ĐĂNG[1],
ĐỖ HƯNG THỜI[1], DƯƠNG CHUNG NGUYỆN[2]
[1]Trường Đại học KTCN Cần Thơ; [2]Trường Đại học SPKT Vĩnh Long.
Email[*]: nthung@ctuet.edu.vn

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TÓM TẮT

Móng giếng chìm cho công trình điện gió ở ngoài khơi đang được sử dụng rộng rãi và mang lại hiệu quả rõ rệt như giá thành thấp, sức chịu tải lớn, và thi công dễ dàng. Bài báo trình bày một nghiên cứu sơ bộ về mô phỏng ứng xử của móng giếng chìm bằng phương pháp sử dụng phần tử hữu hạn Plaxis 2D. Móng giếng chìm có kích thước khác nhau được khảo sát khi đặt trong nền đất có góc ma sát trong và lực dính khác nhau. Kết quả cho thấy kích thước của móng có ảnh hưởng lớn đến ứng xử của nó. Móng có tỉ số chiều dài trên đường kính lớn cho kết quả sức chịu tải trọng kéo và nén tốt hơn. Khảo sát về ảnh hưởng của tính chất cơ lý của đất đến ứng xử của móng cho thấy chúng có ảnh hưởng không đáng kể. Khi góc ma sát trong của đất tăng, cường độ chịu kéo và nén của móng tăng ít. Lực dính của đất dường như không ảnh hưởng đáng kể đến ứng xử của móng giếng chìm. Cần chú ý rằng, bài báo này trình bày nghiên cứu sơ bộ về ứng xử của móng giếng chìm bằng phương pháp tính toán phần tử hữu hạn. Các thông số về kích thước, tính chất cơ lý đất và lực tác dụng dựa trên nghiên cứu trước đây và ứng xử của móng giếng chìm được đánh giá theo phương thẳng đứng.

Từ khóa: móng giếng chìm; tính toán phần tử hữu hạn; phần mềm Plaxis 2D;

ABSTRACT

Suction caisson foundation for offshore wind turbine is increasingly used and providing remarkable benefits such as low cost, high capacity and simplicity of installation. This paper presented a preliminary numerical study on behavior of suction caisson foundation by using finite element analysis program Plaxis 2D. The suction caisson foundations with different geometries were modelled and analyzed. They were considered in the embedded soil having different properties as friction angle and cohesion. Results showed that geometry of suction caisson foundation affected significantly its behavior. Suction caisson whose larger ratio of skirt length to bucket diameter provided higher tensile and bearing capacity. The numerical results in this study showed that the soil properties did not affect remarkably the behavior of suction caisson. When the soil friction angle increased, the tensile and bearing capacity of suction caisson lightly increased. Nevertheless, the *soil cohesion seemed not to affect the behavior of suction caisson. The suction caisson geometry, soil parameters and load values were assumed based on literature and the behavior of the suction caisson was evaluated only in vertical direction.*

Keywords: *Suction caisson foundation; finite element analysis, Plaxis 2D program.*

1. Introduction

Suction caisson foundation is widely used for the offshore wind turbine applications. It is constructed by a steel cylinder having a large diameter with a top lid and an opened end or a closed end. In the offshore wind turbine applications, the suction caisson is used to support the jacket, in which the wind turbine is installed. Up to now, the use of suction caisson foundations increases dramatically for offshore wind turbine applications because of their affordability, popularity and reusability (Byrne, Houlsby, Martin, & Fish, 2002). In the field, suction caisson foundation is subjected to the vertical, horizontal loads and moment from wind and waves, which are considered as major design considerations (Houlsby, Ibsen, & Byrne, 2005). Generally, the behavior of suction caisson foundation is dependent on its geometry and the property of the embedded soil (Bhattacharya, 2019). The offshore wind turbine with a type of suction caisson foundations is presented in Figure 1 below.

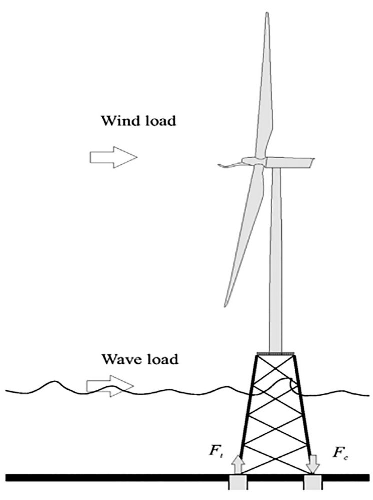


Fig.1. ***Offshore wind turbine with suction caisson foundations, after (Nielsen, 2019)***

Numerous studies have been carried to observe the behavior of suction caisson foundation considering the above design considerations. To archive the objective, the finite element analysis and experimental methods have been utilized. (Sawicki, Wachowski, & Kulczykowski, 2016) performed the finite element analysis for the suction caisson foundation to investigate its tensile capacity. The results of finite element method were compared to those of experimental method with lab-scale model. The results of the study showed that there was a good agreement between the finite element method and the experimental measurement for the tensile capacity. They concluded that the axis symmetric model seemed to be the simplest and the most realistic one for modeling the suction caisson foundation behavior.

Sun et al. (2020) performed the finite element analysis to extract the tensile capacity of offshore bucket foundations in clay in different pullout loading rates (Sun, Qi, Feng, & Liu, 2020). The finite element analysis was utilized using Abaqus program. The bucket foundation was modeled with vertical axis symmetry. Based on the results, they figured the tensile capacity of the bucket foundation and normalized the tensile capacity as a function of the foundation's geometry and the pullout loading rate. The results showed that as the pullout loading rate increased, the tensile capacity of the foundation increased. In addition, the study concluded that the tensile capacity of foundation strongly depended on the bucket's geometry. They developed a useful procedure to determine the tensile capacity of bucket foundation based on the results of finite element method.

Furthermore, the behavior of suction caissons foundation has been also studied based on finite element analysis by (Bagheri, Son, & Kim, 2017) . They performed the three-dimensional finite element analysis via Plaxis 3D for a suction caisson foundation in a dense and medium dense sand. The results of the model were used to compare with those of the field test and they were compared well. Furthermore, the study indicated that most of the applied load transferred to the skirt and the displacement of the suction caisson was primarily dependent on the suction caisson geometry. They proposed a figure for calculating the horizontal capacity and overturning moment capacity for the suction caisson in a sand layer.

Recently, Nielsen (2019) studied on the tensile capacity of suction caissons in sand using finite element analysis. The results showed that the two finite element programs in the study Plaxis 2D and OptumG2 provided different results for soil-structure interface strength. Thus, different results of tensile capacity were revealed. They concluded that the soil-structure interface strength also had a significant impact on the tensile capacity of suction caisson. The study provided to us a preliminary design procedure of suction caisson in sand.

Literatures have shown that the behavior of suction caisson foundation is dependent on its geometry and the embedded soil properties. To investigate the behavior of the suction caisson foundation, experiment and finite element analysis could be used effectively. This present study assessed the behavior of suction caisson in terms of considering its geometry and the embedded soil property via finite element analysis program Plaxis 2D. While the effect of geometry of suction caisson was evaluated through the ratio of skirt length to bucket diameter (*L/D*), the effect of soil properties was evaluated through the friction angle (φ) and cohesion (*c*).

2. Finite element model and Material parameters

Finite element analysis program Plaxis 2D 2017 (Brinkgreve et al., 2017) was used in this study with the axis symmetry model. The geometry of the suction caisson and model size were used following ones presented in the study of (Taebi & Mousavi, 2014). Plate element was used to model the suction caisson and skirt structure. The tensile and compression loads were applied to the lid of the suction caisson. Details of the geometry and materials parameters for suction caisson foundation were displayed in Table 1.

Table 1. Suction caisson geometry and material parameters, after (Taebi & Mousavi, 2014)

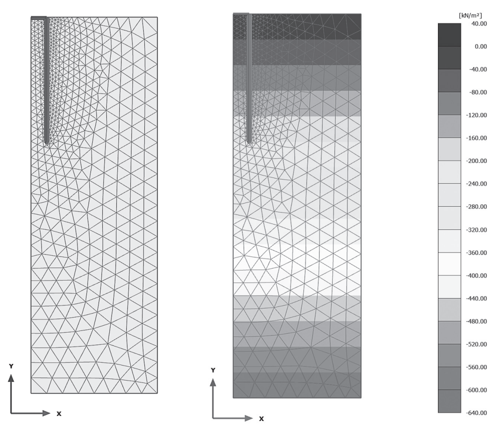
Geometry and Material parameters	Value
Diameter, *D* (m)	5
Skirt length, *L* (m)	20
Skirt thickness, *t* (m)	0.03
Axial modulus, *EA* (kN/m)	3.19e12
Rigid modulus, *EI* (kPa/m)	2.58e8
Distributed weight plate element, *w* (kN/m/m)	0

In this study, it was assumed that the suction caisson was installed in the sand. The soil was analyzed with the Mohr-Coulomb model. The sea level is higher than the ground level. Thus, the soil is considered as totally saturated. The soil parameters were used following that in the study of (Nielsen, 2019). In this study, the limit analysis included the associated flow was utilized and the interface strength between the soil and the structure was equal to that between the adjacent soil. Thus, the dilation angle (ψ) was set to equal to the friction angle (φ) and the interface parameter R_{inter} value was set to 1. The other parameters were original used from the Plaxis 2D program. Details of the soil parameters are shown in Table 2 below.

Table 2. Soil parameters in Mohr-Coulomb model, after (Nielsen, 2019)

Parameter	Value
Modulus, *E* (MPa)	30
Poisson's ratio, ν	0.25
Cohesion, *c* (kPa)	0
Friction angle, φ (^{o})	30
Saturated unit weight, γ (kN/m^3)	15
Interface between soil and caisson wall, R_{inter}	1

The model of suction caisson with axis symetry in the finite element program Plaxis 2D is presented in Figure 2.



(a) Conectivity plot (b) Water pressure

Fig. 2. *Suction caisson model in the Plaxis 2D program in this study*

3. Results and Discussions

3.1 Effect of suction caisson geometry

The effect of geometry on suction caisson behavior was evaluated by analyzing for suction caisson with different ratios of skirt length to bucket diameter (*L/D*) as 2, 4 and 6. This ratio was changed following to the studies of (Taebi & Mousavi, 2014) and (Ahn, Lee, & Kim, 2014). The results of displacement in the tensile and compressive analysis can be found in Figure 3 and 4.

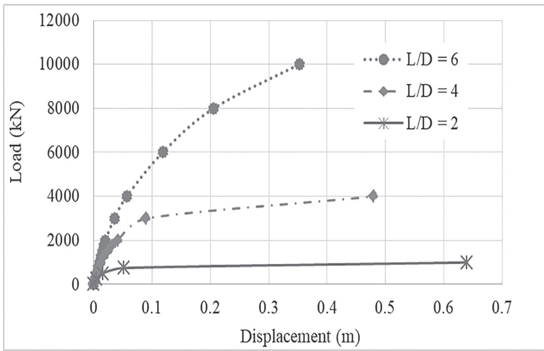


Fig.3. *Displacement of different suction caisson geometries in tensile analysis (c=0, φ =30°)*

Based on the results, it can be seen that different suction caisson geometries resulted different displacements. Generally, suction caisson whose smaller ratio of *L/D* provided smaller tensile capacity than one whose larger ratio of *L/D* did. It could be attributed to the frictional resistance of the skirt of suction caisson. Suction caisson that has larger ratio of *L/D* resulted in higher frictional resistance. Thus, it had higher tensile capacity. The reason could be found in previous study of (Zhai & Li, 2017). In Fig. 3, it is clearly seen that for the suction caisson with the lowest ratio of *L/D* = 2, the maximum tensile capacity peaked about 1500 kN. Whereas the two other ones with higher ratio of *L/D* = 4 and 6, their maximum tensile capacity seems to be larger. The conclusion was made that geometry of suction caisson affects significant the behavior of suction caisson in tensile analysis.

The results of displacement of suction caisson with different geometries in the compressive analysis is introduced in Figure 4 below. They were almost linear according to compressive load values. The response of suction caisson in the compressive analysis is similar to that in the tensile analysis. Different ratio of *L/D* provided highly different in load capacity. The suction caisson with higher ratio of *L/D* resulted higher bearing capacity. Similarly, Jin and Wu (2013) and, Wang and Li (2019) reported this result in their studies (Jin, Zhang, & Wu, 2013; X. Wang, Zeng, & Li, 2019).

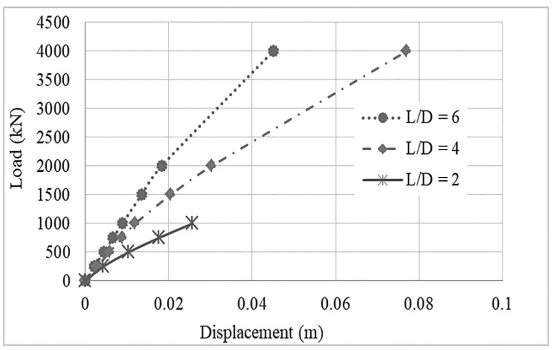


Fig.4. Displacement of different suction caisson geometries in compressive analysis (c=0, φ =30o)

3.2 Effect of soil friction angle

In this study, to observe the effect of soil friction angle on the behavior of suction caisson, three different soil friction angle values were evaluated. They were 10, 20 and 30^{o}. The results of displacement according to the soil friction angle are shown in Figure 5.

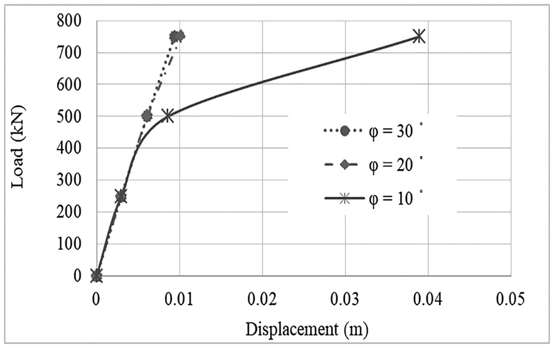


Fig.5. Displacement of suction caisson in different soil friction angles in tensile analysis, (L/D=4, c=0)

The results in Figure 5 show that as the friction angle increased, the tensile capacity of suction caisson increased. Similar performance could be found in the study of (Y. Wang, Faran, & Zhang, 2020). The soil with friction angle φ = 10^{o} gave the lowest tensile capacity. A possible explanation is that the soil whose lower friction angle gave the weaker interlock strength between the particles. Hence, it resulted a lower tensile capacity than the soil whose higher friction angle. It is noticed that the results for friction angle φ = 20^{o} and 30^{o} did not vary much. It can be inferred that the tensile behavior of suction caisson is relatively similar at the high friction angles.

The displacements of suction caisson in compressive analysis are shown in Figure 6. In the compressive analysis, the behavior of suction caisson is similar with that in the tensile analysis. It was found that the friction angle increased made an increase in the bearing capacity of suction caisson. It was reported that the bearing capacity of the suction caisson is formed by the soil plug inside the bucket and the skirt (Zhang, Guo, Liu, & Ding, 2016). Therefore, as the soil friction angle increased, the load bearing capacity of suction caisson increased. In addition, the results also presented that at high friction angles as 20 and 30°, the behavior of suction caisson under compression load was similar. The conclusion was made that the compressive behavior of suction caisson does not vary much at the high friction angle.

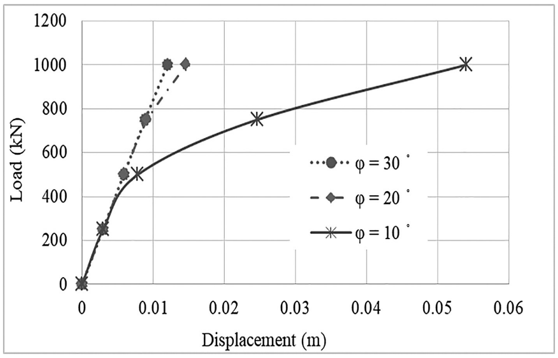


Fig.6. Displacement of suction caisson in different soil friction angles in compressive analysis, (L/D=4, c=0)

3.3 Effect of soil cohesion

Another soil property evaluated in this study was the soil cohesion. This study analyzed the suction caisson with soil cohesion as 0, 10 and 30 kPa. The relationship between the soil cohesion and the displacement for suction caisson in tensile and compressive analysis can be referred in Figure 7 and 8.

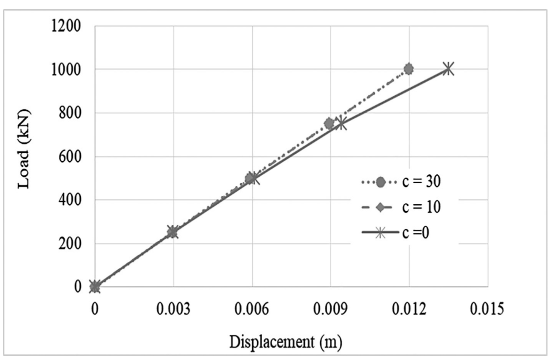


Fig.7. Displacement of suction caisson in different soil cohesions in tensile analysis, (L/D=4, φ=30°)

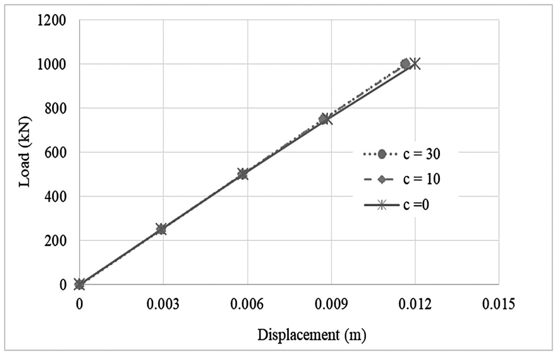


Fig. 8. Displacement of suction caisson in different soil cohesions in compressive analysis, (L/D=4, φ=30°)

Based on the results in Figure 7 and 8, it can be seen that the behavior of tensile and bearing capacity of suction caisson is similar. They reacted a similar trend when the soil cohesion variable changed. It indicates that the soil cohesion had a low impact on the behavior of the suction caisson, both in tensile and compression analysis. The performance of suction caisson under tensile analysis in the embedded soil having different cohesion is consistent with that in the study of (Patel & Singh, 2019).

4. Conclusions

Suction caisson foundation for offshore wind turbine is increasingly used and providing remarkable benefits such as low cost, high capacity and simplicity of installation. The use of suction caisson foundations in the field depends on many factors such as the axial load, horizontal load, geometry of suction caisson and the soil property. This paper presented a preliminary study on the behavior of suction caisson by using finite element analysis program Plaxis 2D. The analysis was carried out in the tensile and compression modes for the suction caisson with considering its geometry and the embedded soil property. Based on the results, the following conclusions were derived. The geometry of suction caisson affected significant the behavior of suction caisson. Suction caisson with different geometries performed very different behaviors. Generally, suction caisson whose larger ratio of L/D provided higher tensile and bearing capacity. The observation of effect of soil property on the suction caisson behavior in this study showed that the soil property did not affect remarkably the behavior of suction caisson. When the soil friction angle increased, the tensile and bearing capacity of suction caisson lightly increased. At the high soil friction angle, the behavior of suction caisson was similar. The soil cohesion seemed not to affect the behavior of suction caisson. It is noted that this paper is a preliminary study of suction caisson foundation behavior via finite element analysis. In the study, the soil parameters and load values were assumed based on literature and behavior of the suction caisson was evaluated in vertical direction. Further studies of the suction caisson behavior with considering the other components as horizontal displacement, overturning, and soil plug consolidation will be carried out.

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