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A SIMPLIFIED ASSESSMENT OF THE LOAD BEARING CAPACITY OF SUCTION CAISSON FOR OFFSHORE WIND TURBINES BASED ON FINITE ELEMENT ANALYSIS

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Abstract – *Suction caisson is widely used for offshore wind turbine applications. Its load-bearing capacity depends on the bucket geometry and its embedded soil properties. This paper presents a simplified assessment of the load-bearing capacity of suction caisson based on finite element analysis using the Plaxis 2D program. The load-bearing capacity of the suction caisson is determined based on the resulting load-displacement curve via the tangent intersection method. In addition, this study developed an equivalent equation exploring the relationship between the load-bearing capacity of the suction caisson and the surface foundation. The findings in the study showed that the geometry of the suction has a significant influence on its load-bearing capacity. The suction caissons whose aspect ratios are larger resulted in higher load-bearing capacities. Besides, the equivalent equation in this study could be applied to effectively estimate the load-bearing capacity of suction caisson based on its geometry. The finite element program and the soil ground model analyzed in this study was only an assumption. In the future, experimental studies should investigate the load-bearing capacity of a suction caisson related to its geometry and the embedded soil profile using centrifuge models and large-scale models.*

Keywords: equivalent equation, load-bearing capacity, Plaxis 2D program, suction caisson.

I. INTRODUCTION

As the demand for renewable energy has been greatly increasing in recent years, the number of offshore wind turbines has been continuously growing. The offshore wind turbine uses a type of offshore foundation-suction caisson known as a bucket foundation to support its platform [1]. The implementation of suction caisson illustrates remarkable benefits such as reducing construction costs, having fewer technical requirements, and increasing environmental protection [2].

The suction caisson itself is built from steel and consists of a cylinder with a top lid, a large diameter and an opened-end or a closed-end [3]. The offshore wind turbine with a suction caisson type foundation is presented in Figure 1.

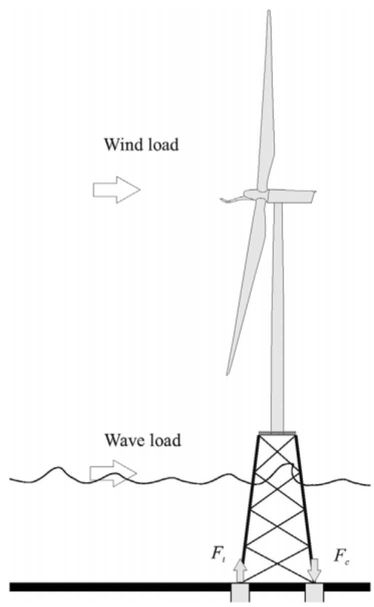

Fig. 1: Offshore wind turbine with suction caisson foundations [4]

The installation of the suction caisson is mainly based on its self-weight structure. After installation, in the field, it is subjected to vertical and horizontal loads from waves and wind [5].

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As a result, the vertical load-bearing capacity of suction caissons is considered one of the main design considerations. The load-bearing capacity of suction caissons is assessed from analytical solutions with some modifications [6, 7]. It can also be determined by the tangent intersection method based on the relationship between the vertical load and the displacement [8, 9]. Figure 2 illustrates the determination of load-bearing capacity using the tangent intersection method.

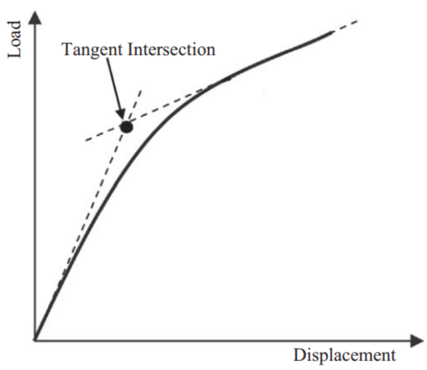

Fig. 2: Determination of load bearing capacity by tangent intersection method [2, 3]

Four general methods have been used to obtain the load-displacement curve for the suction caisson, including the finite element method (FEM), analytical solution, centrifuge model test, and experiment measurement. These methods have a good agreement in developing the load-displacement curve for the suction caisson [2, 6, 9, 10].

In recent years, the number of studies using FEM to investigate the load-bearing capacity of suction caissons has been increasing. In a study conducted in 2020, Fu, Zhang, and Yan [11] observed the load-bearing capacity of a modified suction caisson in clay. The modified suction caisson had a rectangular middle section inserted between two circular halves. The suction caisson was constructed with different loads (vertical, horizontal, and moment) using FEM. The results showed that the modified suction caisson with side-round could provide a larger load-bearing capacity than the conventional suction caissons. Additionally, the study proposed a yield surface, which was determined by the vertical, horizontal, and moment bearing capacity, for estimating the load-bearing capacity of suction caissons. Similarly, Vicent and Kim [2] evaluated the load-bearing capacity of a suction caisson embedded in loose, medium, and dense sands via FEM. The displacement results based on FEM analysis were validated well with ones within the study's experiment. The study applied the tangent intersection method to determine the load-bearing capacity of the suction caisson. It was concluded that the load-bearing capacity of suction caissons embedded in dense sand was the largest among the three sand types. The suction caisson having a larger bucket diameter resulted in higher bearing capacity. Based on the results, the authors proposed an equation to estimate the load-bearing capacity factor Nq of the bucket platform. In another study, Xia et al. [9] also used FEM analysis to investigate the load-bearing capacity of suction caissons in clay under a combination of vertical, horizontal, and moment loads. The study investigated the effect of clay thickness, skirt length, and vertical loading on the failure mechanism of the suction caisson. The results showed that the load-bearing capacity was influenced significantly by the soil domain dimension in the FEM analysis. The combination of vertical, horizontal, and moment loads slightly affected the load-bearing capacity of the suction caisson. Moreover, the study provided an equation to calculate the load-bearing capacity of suction caisson based on the vertical, horizontal, and moment loads domain.

Literature showed that FEM was viable for extracting the relationship between load and displacement of suction caissons. The tangent intersection method was applied to determine the load-bearing capacity of the suction caisson. This study presents an approach to assess the load-bearing capacity of suction caissons via FEM. A suction caisson is modeled by a finite element program, Plaxis 2D 2017. The load-bearing capacity is estimated based on the relationship between the load and displacement. In addition, this study also proposes an equation to determine the load-bearing capacity of the suction caisson.

II. SUCTION CAISSON ANALYSIS MODEL AND MATERIAL PARAMETERS

In this study, the finite element analysis program Plaxis 2D 2017 was used to model the suction caisson with the vertical axis symmetry [12]. The geometry and material parameters of suction caisson were chosen following the literature by Patel and Singh [13].

Table 1: Materials parameters for suction caisson [13]

Material parameters	Value
Diameter, D (m)	20
Skirt length, L (m)	20
Skirt thickness, t (m)	0.03
Axial modulus, EA (kN/m)	6.598×10^{15}
Rigid modulus, EI (kN/m²/m)	5×10^{9}
Unit weight, w (kN/m³)	77
Poisson's ratio	0.25

The suction caisson was assumed to be installed in a cohesive soil with properties adopted from the same literature by Patel and Singh [13]. The soil installed was analyzed using the Mohr-Coulomb model. In the model, the water level was measured from the ground level. Details of the soil parameters are shown in Table 2.

Table 2: Soil parameters in Mohr-Coulomb model [13]

Soil parameters	Value
Modulus, E (kN/m2)	10000
Poisson's ratio, ν	0.25
Cohesion, c (kN/m²)	30
Friction angle, φ (°)	24
Saturated unit weight, γ (kN/m³)	21
Interface between soil and caisson wall, R_{inter}	1
Dilation angle, ψ (°)	0

In the model, the dimension of the soil domain around the suction caisson, with a diameter of 5D and a height of 4L, was chosen based on the recommendation of the previous study [13]. Figure 3 shows the suction caisson model with symmetry along the vertical axis.

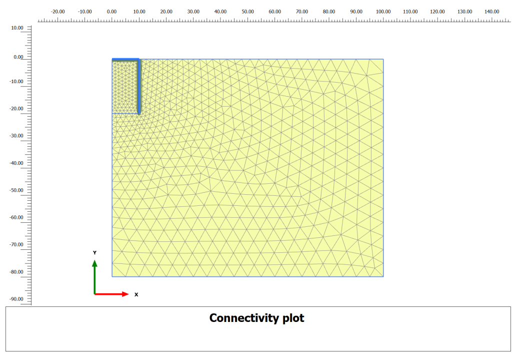

Fig. 3: Suction caisson model [13]

III. RESULTS AND DISCUSSION

A. *Load-bearing capacity of suction caisson*

Suction caissons with different aspect ratios (AP) were analyzed, which was the ratio of skirt length (L) to bucket diameter (D) (L/D). In this study, the load values were applied at the center of the top lid. Based on the results, the relationship between load and displacement was established. Figure 4 shows the load-displacement curve of suction caissons having different AP values.

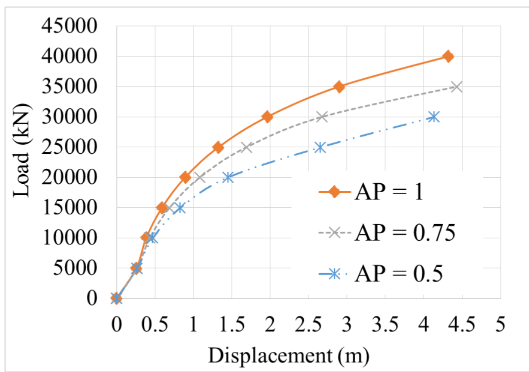

Fig. 4: Load-displacement curve of suction caisson having different geometries

Figure 4 shows that different AP values resulted in different responses to displacement. Under the same vertical load, suction caissons with larger AP produced smaller displacement. Besides, the results found that suction caissons with larger skirt lengths developed lesser displacement. The friction resistance generated by the skirt could be one of the factors attributed to the difference. Due to the larger surface area, suction caissons with higher skirt lengths produced larger friction resistance [14]. The research findings proved that geometry has a remarkable effect on the response of suction caissons. This conclusion is consistent with those in the previous research by Zhai and Li [3].

When applying the load-displacement curve, the tangent intersection method was used to evaluate the load-bearing capacity of the suction caisson. According to some authors [10, 17], the failure state of suction caisson is determined when the displacement is equivalent to 0.2D. Hence, to define the load-bearing capacity of the suction caisson, the displacements with values larger than 0.2D were neglected. The results of the load-bearing capacity of suction caissons with different AP values are illustrated in Table 3.

Table 3: Load bearing capacity of suction caisson.

Aspect ratio (L/D)	Load bearing capacity (kN)
0.5	18000
0.75	20000
1.0	22000

B. Determination of load bearing capacity of suction caisson via surface foundation

This study aims to both explore the relationship between load and displacement and propose an equation for determining the load-bearing capacity of suction caissons as a function of aspect ratio AP and load-bearing capacity of the surface foundation. An equivalent equation that depicts the relationship between the load-bearing capacity of suction caisson and surface foundation was built. Besides, the load-bearing capacity of a surface foundation with a diameter of 20 m was defined. Figure 5 shows the load-displacement curve for the surface foundation extracted from the FEM model.

From the ratio of the load-bearing capacities of both surface foundation and suction caisson, an equivalent equation was determined based on the trend line function in the Excel program. Previous studies have reported their relationship according to the following equations:

Byrne and Houlsby [6]:

$$\frac{F_{caisson}}{F_{sur}} = 1 + 0.89AP \quad (1)$$

Hisham [7]:

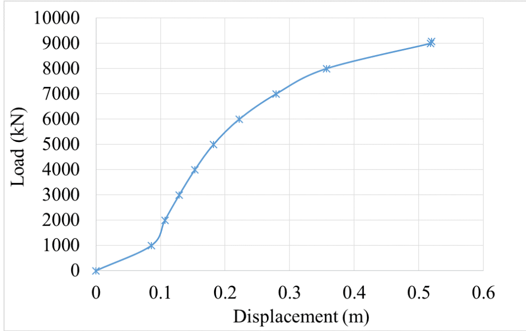

Fig. 5: Load-displacement curve for surface foundation (D = 20 m)

$$\frac{F_{caisson}}{F_{sur}} = 1.8^{AP} \quad (2)$$

Wang et al. [8]:

$$\frac{F_{caisson}}{F_{sur}} = 4.09AP \quad (3)$$

Where Fcaisson and Fsur is the load-bearing capacity of suction caisson and surface foundation, respectively. Based on the results of data points in this study, the equivalent equation was established using the trend line in the Excel program. The relationship is expressed in Eq. (4):

$$\frac{F_{caisson}}{F_{sur}} = 1.14AP + 2 \quad (4)$$

The relationship between the bearing ratio Fcaisson/Fsur and the AP in previous research and this study are displayed in Figure 6.

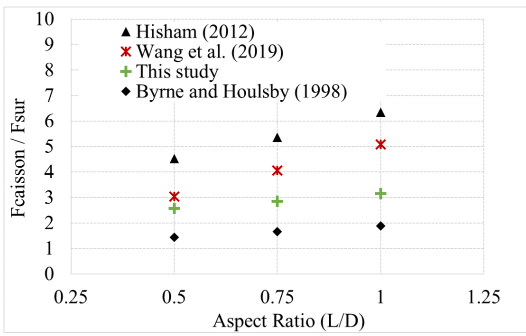

Fig. 6: Relationship between the load bearing capacity ratio and the aspect ratio

The results in Figure 5 show that the data points from this study were bounded by the ones from the two other studies, Byrne and Houlsby

[6] and Wang, Zeng and Li [7]. The results indicate that the data points presented in this study could be reasonably used to determine the load-bearing capacity of the suction caisson. In the future, studies should be conducted about the load-bearing capacity of suction caisson that consider its geometry and the embedded soil properties using centrifuge models and large-scale models.

IV. CONCLUSION

Suction caisson used for offshore wind turbine applications has a load-bearing capacity that largely depends on its geometry and the embedded soil properties. This paper presented an assessment of the load-bearing capacity of suction caisson using the finite element analysis program Plaxis 2D. Based on the results, the relationship between the load-bearing capacity of the suction caisson and the surface foundation was established and expressed in an equivalent equation. The findings in the study showed that the caisson's geometry contributes mainly to its bearing capacity. It is observed that suction caissons having larger aspect ratios consequently result in a higher load-bearing capacity. Another further finding from this study was the equivalent equation that can be applied to determine the load-bearing capacity of the suction caisson. However, it is noted that the data in this study was analyzed by a finite element program based on an assumbed soil ground model. In the future, laboratory investigations utilizing centrifuge modeling and large-scale models should be conducted to establish a more in-depth analysis of the factors affecting the load-bearing capacity of suction caissons.

REFERENCES

[1] Skau KS, Jostad HP, Eiksund G, Sturm H. Modelling of soil-structure-interaction for flexible caissons for offshore wind turbines. *Ocean Engineering*. 2019;171: 273–285.

[2] Vicent S, Kim SR. Evaluation of horizontal and vertical bearing capacities of offshore bucket work platforms in sand. *Applied Ocean Research*. 2020;101: 102198.

[3] Zhai H, Li D. Experimental Studies on modified suction caissons in fine sand subject to uplift loading. *Transactions of Tianjin University*. 2017;23(6): 562–569.

[4] Nielsen SD. Finite element modeling of the tensile capacity of suction caissons in cohesionless soil. *Applied Ocean Research*. 2019;90: 101866.

[5] Houlsby GT, Ibsen LB, Byrne BW. *Suction caissons for wind turbines*. Frontiers in Offshore Geotechnics: ISFOG, Perth, WA, Australia. 2005; 75–93.

[6] Byrne B, Houlsby G. Foundations for offshore wind turbines. Philosophical Transactions of the Royal Society of London. *Series A: Mathematical, Physical and Engineering Sciences*. 2003;361(1813): 2909–2930.

[7] Wang X, Zeng X, Li J. Vertical performance of suction bucket foundation for offshore wind turbines in sand. *Ocean Engineering*. 2019;180: 40–48.

[8] Le Chi H, Kim SR. Evaluation of vertical and horizontal bearing capacities of bucket foundations in clay. *Ocean engineering*. 2012;52: 75–82.

[9] Xia H, Zhou X, Zhou M, Niu F, Zhang X. Capacity of caissons in stiff-over-soft clay under combined V–HM loadings. *Ocean Engineering*. 2021;229: 109007.

[10] Ahn J, Lee H, Kim YT. Holding capacity of suction caisson anchors embedded in cohesive soils based on finite element analysis. *International Journal for Numerical and Analytical Methods in Geomechanics*. 2014;38(15): 1541–1555.

[11] Fu D, Zhang Y, Yan Y. Bearing capacity of a side-rounded suction caisson foundation under general loading in clay. *Computers and Geotechnics*. 2020;123: 103543.

[12] Brinkgreve R, Swolfs W, Engin E. *PLAXIS 2D 2017*. User manual. 2017.

[13] Patel SK, Singh BA. Parametric study on the vertical pullout capacity of suction caisson foundation in cohesive soil. *Innovative Infrastructure Solutions*. 2019;4(1): 1–11.

[14] Jin SC, Zhang YT, Wu QH. A Study on the failure mechanism of suction caisson under vertical load. *In Applied Mechanics and Materials*. 2013;256: 1985–1989.

[15] Byrne B, Houlsby G. *Drained behaviour of suction caisson foundations on very dense sand*. Offshore Technology Conference. 1999.

[16] Eid HT. Bearing capacity and settlement of skirted shallow foundations on sand. *International Journal of Geomechanics*. 2013; 13(5):645–652.

[17] Andersen KH, Murff JD, Randolph MF. *Deepwater anchor design practice phase II report to API/Deepstar volume II-suction caisson anchors*. Offshore Technology Research Center. 2003.