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The Effect of Vertical Load on the Monotonic Behavior of Hybrid Caissons under Combined VHM Loading

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ABSTRACT: In recent years, the development of offshore structures has significantly increased for the exploitation of renewable energy resources and the extraction of underground resources. Hybrid suction caissons comprising skirted or mat foundation with suction caisson has been proposed as an innovative foundation for offshore structures especially offshore wind turbines (OWTs). One of the important factors affecting the performance of these types of caissons is the vertical load imposed on them which can have various effects on their behavior. So far, few studies have been conducted on the effect of vertical load on the behavior of hybrid suction caissons. In this study, a series of geotechnical centrifuge tests at 40g have been carried out to investigate the effect of vertical load on the behavior of hybrid suction caissons subjected to combined VHM monotonic loading. The results reveal that there is a specific limit for the vertical load to the vertical bearing capacity ratio which can enhance the ultimate bearing capacity of caissons under VHM loading.

1 INTRODUCTION

Today, due to global warming and environmental issues, such as the increase in CO_2 emissions from the consumption of fossil fuels, most countries around the world are moving towards using affordable and accessible renewable energy sources, such as wind energy. Wind turbine farms are rapidly being constructed and developed in such a way that it is predicted that, by 2050, approximately 20% of the world's consumed electricity will be generated by wind power. On the one hand, the wind speed is consistently higher in open sea areas compared to the coast; hence, the potential for electricity generation is greater offshore than onshore. On the other hand, the construction of offshore wind turbines will result in higher costs, with a significant portion attributed to the turbine foundation. Therefore, it is necessary to design offshore wind turbine foundations optimally and economically (GWEC,2023).

In general, the offshore wind turbine foundation is subjected to the weight of the turbine and cyclic loads from wind and waves with different point of effect. Figure 1 schematically shows the forces acting on offshore wind turbines.

A suction caisson is essentially like an inverted bucket that, with its weight and by creating suction through holes on its top surface, penetrates the soil and serves the purpose of bearing the load for the wind turbine. In recent years, a combination of skirted foundation with suction caisson, or a combination of mat foundation with a suction caisson, has been used under the name "hybrid suction caisson foundations." Some studies indicate that the use of hybrid suction bucket foundations can significantly increase lateral load-carrying capacity.

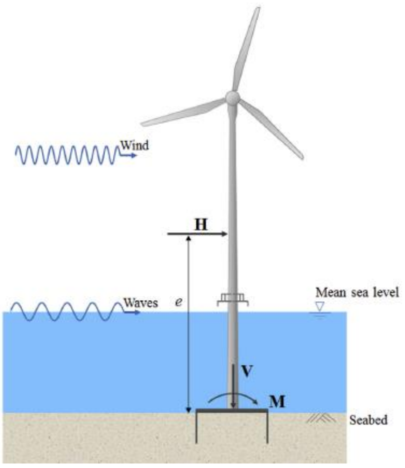

Figure 1. Forces acting on offshore wind turbines (Zhu 2018).

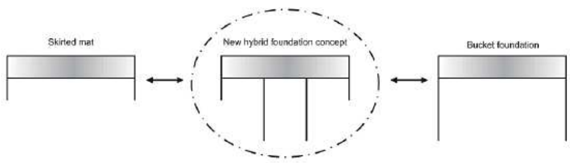

Figure 2. The concept of generation of hybrid suction caisson foundation (Bienen 2012).

The initial idea of using suction bucket foundations as the base for wind turbines was proposed in 1995 (bye,1995), but it was first implemented in Frederikshavn, Denmark, in 2002 (Ibsen,2004). In recent years, extensive research has been conducted on the factors influencing the behavior of suction caissons under monotonic and cyclic loading. In the following section, some of the most important studies related to the subject of this research will be highlighted.

Byrne et al. (2003) conducted a study on different aspect ratios (L/D), and they provided relationships and charts for determining the load-bearing capacity of suction caissons against vertical and anchor loads based on the caisson dimensions. Additionally, in another section, they examined the effect of the vertical force on the ultimate lateral load capacity of the suction caisson. Byrne and Houlsby (2004) studied the behavior of suction caissons with laboratory-scale dimensions under simultaneous application of combined VHM loads in sandy soil. During this research, they determined the failure surface of VHM and investigated the effects of loading rate and vertical load on the load-bearing capacity of the caisson foundation. They demonstrated that with an increase in the vertical load, the load-bearing capacity increased, and a smaller caisson diameter was required.

Zhang et al. (2007) evaluated the behavior of caissons under cyclic and monotonic loading using centrifuge experiments for different dimensional ratios (0.8, 1.2, 1.5).

Zhu et al. (2011) conducted a study on the behavior of suction caissons under lateral monotonic loading in saturated silty soil. They utilized physical modeling at large-scale dimensions and provided relationships to determine the ultimate lateral load-bearing capacity of the caisson.

Gaudin et al. (2011) studied the effect of changes in dimensional parameters on the load-bearing capacity of hybrid suction caissons in saturated clay under monotonic VHM loading using centrifuge experiments. By comparing it with a conventional caisson, they demonstrated the potential of this idea to significantly increase the lateral load-bearing capacity of the foundation.

Isben et al. (2013) investigated the behavior of suction caissons in drained sandy soil. During this study, considering different factors such as dimensional ratio and embedment depth, they determined the failure surface of the caisson in three-dimensional VHM space. They also demonstrated that the lateral soil pressure acting on the edges of the caisson has a greater effect on the load-bearing capacity compared to the vertical load. Fogila et al. (2014) conducted studies on the behavior of suction caissons under lateral and cyclic loads in compact and saturated sandy soil and investigated the overall response pattern of the caisson foundation under the mentioned loading conditions.

Li et al. (2014, 2015), using 1g physical modeling, investigated the effect of increasing the diameter and length of the edges of mat foundation in hybrid suction caissons on their lateral load-bearing capacity in saturated sand. Additionally, they determined the rotation center and provided relationships for the failure surfaces of hybrid caissons under combined VHM loading.

Liu et al. (2017) conducted physical modeling in laboratory-scale dimensions with monotonic lateral loads on suction caissons of different dimensional ratios. They demonstrated that rotation is the main mechanism of failure in suction caissons; the rotation center is not fixed, and failure occurs when the caisson rotation reaches three degrees. Cheng et al. (2019) investigated the behavior of suction caissons under the simultaneous application of cyclic wave loads and static wind loads. They provided a relationship to calculate the ultimate moment-bearing capacity.

Cheng et al. (2019) studied the behavior of hybrid caissons with different dimensional ratios under combined VHM loading in unsaturated cohesive soil. During this research, they investigated the effects of vertical load, diameter, and length of caisson edges on the load-bearing capacity under combined VHM loading.

Kim et al. (2020) compared the behavior of conventional caissons with hybrid caissons under monotonic loading. They demonstrated that adding a mat foundation to the caisson (hybrid caisson) increases the load-bearing capacity under combined VHM loading. They also provided relationships to estimate the failure surface of hybrid caissons in compacted sandy soil.

Shakeran and Soroush (2024) by a series of centrifuge tests investigated and compared the behavior of ordinary and hybrid caissons under long-term lateral cyclic loading. The results of their research revealed that the hybrid technique can improve the behavior of foundations in terms of accumulated rotation during the service life of the turbine.

Until now, extensive research has been conducted on suction caissons, but only a limited number of studies have investigated hybrid suction caissons and the factors influencing their behavior under combined VHM loading. One significant factor affecting the behavior of these caissons is the vertical load, which has not been explored so far. Therefore, considering the importance of this parameter in analyzing the behavior of hybrid suction caissons, this study focuses on examining the impact of this parameter.

2 DETAILS OF THE EXPERIMENTS

2.1 Geotechnical centrifuge

Modelling in geotechnical centrifuge apparatus is one of the essential tools in the analysis and examination of applied geotechnical engineering issues. By placing a model in a higher gravitational field than the natural acceleration of the Earth, the stresses resulting from the weight increase to levels comparable to stresses met at full scale, and the model behavior becomes analogous to real behavior. Table 1 shows the characteristics of the geotechnical centrifuge at Tehran University.

Table 1. Technical specifications of the centrifuge.

Parameter	Value
Width of the swinging basket [m]	0.8
Height of the swinging basket [m]	1
Rotation arm [m]	3
Maximum radial acceleration [g]	130
Maximum model mass [kg]	1500

The relationships and scaling factors can be obtained using dimensional analysis or equations governing the problem. A sample of scaling factors for various parameters is provided in Table 2.

Table 2. The scale factor in the centrifuge modeling.

Parameter	Scale factor (model/prototype)
Length, Displacement [m]	1/N
Mass, Volume	$1/N^3$
Specific Mass	1
Specific Gravity	N
Strain, Stress	1
Force	$1/N^2$
Energy	$1/N^3$

Modelling with a centrifuge involves various errors that should be minimized to the extent possible. Among the most significant sources of error and limitations in centrifuge testing are errors in changing the centrifuge acceleration field due to changing radius, errors arising from 1g Earth acceleration, changes in the direction of the acceleration field, Coriolis acceleration, and the size of the soil particle.

2.2 Soil properties and sample preparation

In this study, firouzkouh sand #161 was utilized to simulate bed conditions. Initially, the soil was placed in the box in 11 layers and compacted to a relative density of 50% with wet tamping method. To saturate the sample, CO_2 gas was first injected into the sample for two hours through the drainage valve located at the bottom of the sand box to remove air bubbles between the sand particles. Then, using deaerated water, the sample was saturated through the same valve. The caissons were installed by jacking method with penetration speed of 0.1mm/s at 1g condition and force variations were monitored.
After complete saturation and the installation of the suction caisson, the model was subjected to lateral monotonic loading under a centrifuge acceleration of 40g. Loading was performed in displacement control with a speed of 0.1 mm/s. The specifications of this soil are shown in Table 3. The method of sample prepration was similar for all tests.

Table 3. Specifications of the soil and sample.

Parameter	Value
Sand [%]	99
F_{200} [%]	1
C_u	1.87
C_c	0.88
G_s	2.65
e_{min}	0.548
e_{max}	0.943
D_{10} [mm]	0.16
D_{30} [mm]	0.21
D_{50} [mm]	0.27
D_{60} [mm]	0.3
e	0.7475
D_r [%]	50
γ_d [kN/m^3]	14.89
γ [kN/m^3]	15.63

2.3 Model design and test configuration

In the process of constructing the samples, a rigid metal box with dimensions of 77 by 59 centimeters and a depth of 50 centimeters was used. The dimensions of the hybrid suction caisson were determined proportionally to the desired scale and used in the physical models. Figure 3 shows the dimensions of the hybrid caisson used in this research. Also, to measure the lateral displacement and rotation of the suction caisson, two LVDT (linear variable displacement transducer) sensors were utilized. Their placement is illustrated in Figure 4.

Considering the length of the box in the direction of load application (70 cm) and the maximum diameter of the caisson (12 cm), the distance between the edges of the caisson and the box's body is more than twice the caisson diameter. Therefore, the effect of boundary conditions on the test results can be neglected (Kim et al.,2020).

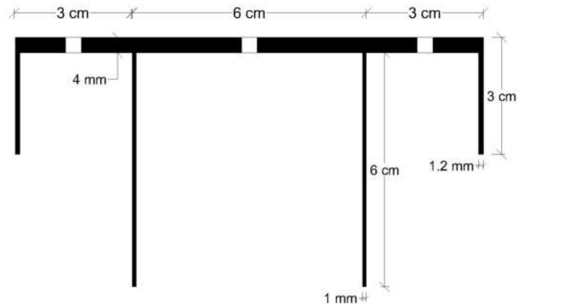

Figure 3. The dimensions of the hybrid caisson.

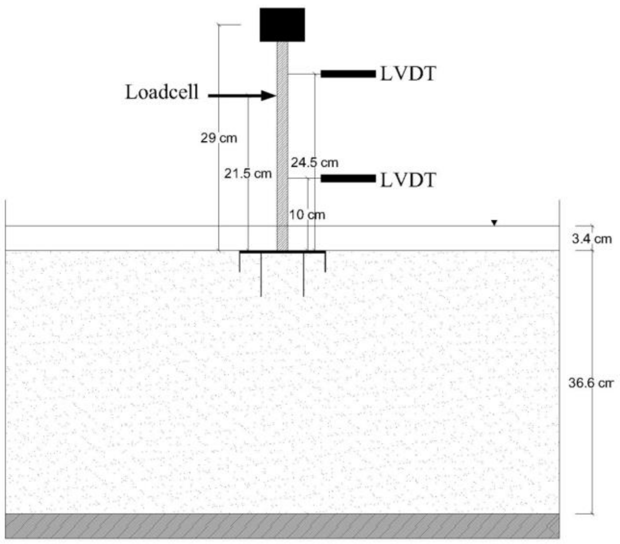

Figure 4. Model configuration.

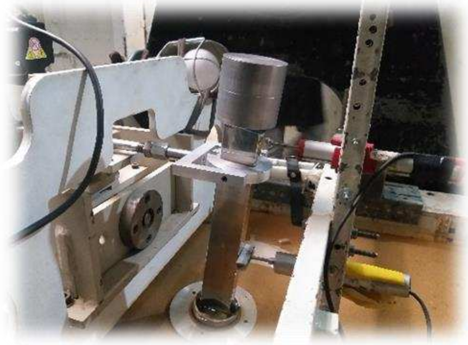

Figure 5. Centrifuge Model.

In this study, to determine the effect of vertical load and achieve the desired goal, three models with the V/V_0 ratios of 0.04, 0.07, and 0.1 were constructed and subjected to experimentation. The parameter "V" represents the vertical force acting on the suction caisson, including the weight of the caisson and the weight of the turbine on it and "V_0" is the vertical ultimate bearing capacity. Additionally, for the sake of reproducibility in sampling, one of the models was reconstructed and evaluated to ensure similar results were obtained compared to the other model.

3 RESULTS AND DISCUSSION

In this part, the results of laboratory tests conducted are presented in figures 6-7. In these diagrams, the horizontal load applied to the caisson can be attributed to the combined effect of wind and wave loads with eccentricity, entering the caisson. In the calculations performed on the data obtained from the experiments, the results related to displacements recorded by the LVDTs have been utilized. Additionally, the central point on the caisson has been considered as the center of rotation.

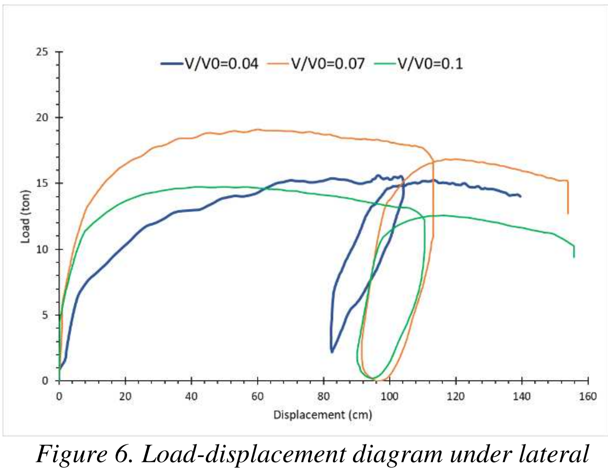

Figure 6. Load-displacement diagram under lateral monotonic load.

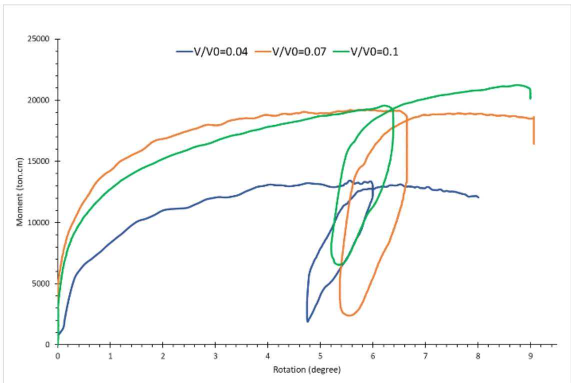

Figure 7. Moment-rotation diagram under lateral monotonic load.

Considering figure 6, with an increase in the V/V_0 ratio from 0.04 to 0.07, the maximum horizontal load capacity (peak point on the chart) has increased from around 15 tons to about 19 tons. Therefore, it can be said that the increase in vertical load had a positive effect. However, with an increase in the V/V_0 ratio from 0.07 to 0.1, the maximum horizontal load capacity decreased from 19 tons to approximately 14.9 tons, indicating a negative effect. Moreover, as the vertical load increases, the hybrid caisson reaches its maximum horizontal load capacity with less displacement and rotation, exhibiting a stiffened behavior.

Figures 6 also illustrate changes in initial stiffness and unloading-reloading stiffness. With an increase in the V/V_0 ratio from 0.04 to 0.07, the initial stiffness has increased, but with a further increase in this ratio from 0.07 to 0.1, the initial stiffness remains constant and does not change. The graphs corresponding to V/V_0 ratios of 0.04, 0.07, and 0.1 show that the trend of changes in unloading-reloading stiffness due to an increase in the V/V_0 ratio is similar to the changes in initial stiffness. Additionally, the residual displacement and rotation values are almost the same for both ratios of 0.07 and 0.1 but are slightly lower for 0.04.

Referring to figure 7, with an increase in the V/V_0 ratio from 0.04 to 0.07, the maximum moment capacity (peak point on the chart) has increased from approximately 13000 ton-centimeters to about 19000 ton-centimeters, indicating a positive effect of the increased vertical load. However, with a further increase in the V/V_0 ratio from 0.07 to 0.1, the maximum moment capacity has remained almost constant, showing little change. Additionally, with an increase in the vertical load, initially the hybrid caisson reaches its maximum moment capacity in a greater rotation, but beyond a certain point, the moment capacity becomes almost constant, and further increase in the vertical load have little effect on this matter. Furthermore, in the ratios of 0.04 and 0.07, the trend after the peak point is almost horizontal, while in the ratio of 0.1, there is an ascending trend, indicating a stiffening behavior.

Figure 7 represents changes in initial stiffness and unloading-reloading stiffness. With an increase in the vertical load ratio from 0.04 to 0.07, both initial stiffness and unloading-reloading stiffness have increased. However, with a further increase in this ratio from 0.07 to 0.1, the initial stiffness and unloading-reloading stiffness remain almost the same, with a slight decrease in residual rotation. Additionally, during the reloading of the caisson with a vertical load ratio of 0.04 and 0.07, it almost reaches the same moment capacity as before unloading and follows a horizontal trend, but in the case of a ratio of 0.1, it shows an ascending trend during reloading.

It should be noted that the above results are based on a limited number of experiments, and further tests are required in this field to make definitive conclusions.

4 CONCLUSIONS

Considering the importance of the optimal and economical design of offshore wind turbine foundation structures, it is necessary to investigate the effects of various factors, such as the vertical load, on the horizontal load bearing capacity and moment capacity. Therefore, in this study, the effect of the vertical load on the hybrid suction caisson under monotonic loading has been examined, and the following results have been obtained:

- Increasing the vertical load ratio up to a certain extent leads to an increase in the maximum horizontal load and moment capacity, as well as the initial stiffness and unloading-reloading stiffness. However, with further increases in the vertical load ratio, the horizontal load capacity decreases, while the moment capacity and the mentioned stiffness values remain constant;
- As the vertical load increases, the caisson reaches its maximum horizontal load capacity with less displacement and rotation;
- Increasing the vertical load has not much effect on the rotation equivalent to the ULS (Ultimate Limit State) surface;
- With an increase in the vertical load, the caisson exhibits stiffening behavior.

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