Journal of Structural Engineering and Geotechnics,

8 (1), 11-18, Winter 2018

Evaluation of Influencing Factors on the Pull-out Behavior of Suction Caissons

Adel. Asakereh[*,a], Abdol Hamid Kamali[b]

[a]*Assistant Professor, Civil Department, University of Hormozgan, Bandar Abbas, Iran*

[b]*Graduate Student, Civil Engineering Department, University of Hormozgan, Bandar Abbas, Iran.*

Received 23 March 2017, Accepted 18 August 2017

Abstract

Suction caisson is a type of floor foundation for the offshore structures that is also called suction pile, bucket foundation, suction anchor, or sometimes ridge foundation depending on its application. In two past decades, this type of foundation has been widely used around the world as the fixed offshore foundation, anchor of the floating platforms, as well as the foundation of other marine structures such as the offshore wind turbines. Suction caisson is a metal (or sometimes concrete) hollow cylinder that is open from its bellow while it is top is being closed by flat or dome plates. This type of caisson is called suction caisson mainly because its installation is done by suctioning their water outside after drainage. In this research, numerically study the effective factors on the pullout behavior of the suction caissons. The analyses conducted in two-dimensional form on the drainage condition on clay soil. The results of the analysis show that the strength parameters of the soil are significantly effective on the pullout capacity of the suction caisson.

Keywords: Suction: *Caisson, Pull-Out Capacity, Drain condition, clay, offshore structures*

1. Introduction

Nowadays, the pull-out behavior of the suction caissons is a developing and evolving subject of study. The prediction of the pull-out load capacity of the suction caissons is being done by experimental, analytical and numerical methods. In the past two decades, suction caissons have been applied in the offshore structures. In their application, the estimation of the pullout capacity of these caissons is a very important factor to be considered in a reliable way [1].

The application of the suction for installing offshore structures was first proposed by Goodman, et al. [2]. The anchors that were proposed by Goodman were installed like the current suction caissons, but their vacuum space of the anchors needed continuous suction to work properly.

Goodman had studied the possibility of installing and using vacuum anchors in the hard clay and silt soils through the laboratory experiments. Then Brown and Nacci [3] continued the studies successfully. During 1990s, several researchers investigated the capacity of vacuum anchors in different types of soil [4-5]. In this regard, Brown, et al. [6] studied the efficiency of the suction anchor in the granular soils. Later, they generalized their model to other types of soil. Wang, et al. [4] presented the results of the latter study in the form of some elementary principles to express the performance and designing of suction anchors. Then Wang, et al. [4] conducted a series of research on the pullout capacity of the suction anchors. They used Mohr- Coulomb’s failure theory to provide a general equation for the pullout capacity of the caisson. They introduced suction caisson as the very suitable option for short-time anchoring of the drilling platforms, buoys, and semi-floating platforms. The first experiment on the suction caissons without using active suction after installation was reported by Hogervost[7]. He successfully conducted the installation in sand and

*Corresponding Author Email address: asakereh@hormozgan.ac.ir

then experimented the horizontal loading in sand and hard clay. Then he tested the vertical loading as well.

Dayong et al[8]. conducted a series experimental and finite element analyses on the bearing capacities of modified suction caissons (MSCs) in saturated marine fine sand understate horizontals loading. Results show that the MSC can provide higher horizontal and moment bearing capacity and limit lateral deflection in comparison to a regular suction caisson.

Ukritchon and Keawsawasvong [9] conducted a series Finite element limit analysis with axisymmetric condition is employed to determine plasticity solutions of undrained pullout capacity of cylindrical suction caissons in clay with linear increase of strength with depth and zero strength at the seabed. The proposed equation is used to check the accuracy and validity of the total pullout force and reverse end bearing force by conventional methods. The three-dimensional effect of suction caissons between axisymmetric and plane strain conditions is also deduced to evaluate the validity of conventionally assumed shape factor.

Charlton and Rouainia [10] in their study spatial variability is modelledusing a random field and coupled with finite element analysis to obtain a probabilistic characterization of holding capacity. A study of the autocorrelation distance, a quantity often difficult to obtain accurately in practice, has shown that the vertical autocorrelation distance has a much greater influence on the variability of holding capacity than the horizontal and should be carefully chosen in offshore applications.

Bagheri et al. [11] presents the results of three-dimensional finite element analyses of the suction bucket foundation used for offshore wind turbines. Numerical analysis modeling results show that the bucket rotation and displacement are highly dependent on the bucket geometry and soil properties in addition to loading conditions.

In this research, study the behavior of suction caissons under the vertical pullout loading with numerical simulation. The numerical model was first calibrated through comparing its results against the laboratory results of previous researchers, and the results were verified against another group of the results of laboratory results. Then the verified model was used to evaluate the effects of some parameters (such as the soil type, angle of internal friction, cohesion, dilation angle, Poisson's ratio of soil, and the apparent ratio of caisson) on the pullout behavior of the suction caissons. Moreover, the effects of nonlinear behaviors in soil, the soil-caisson interaction, drain condition, and the presence of suction was tested. Additionally, presented some simplified relations for expressing the intensity and the scale of the mentioned factors. Finally, these results are compared to some semi-experimental and analytical equations of other researchers to predict the pullout loading capacity of the suction caisson.

2. Pullout bearing of suction caissons

The pullout capacity of the suction caisson under the vertical loading is a very important issue and it is necessary to determine some desirable methods for predicting the amount of such forces in order to conduct the proper designing. In this research, the numerical analysis is performed using finite element method; and based on the obtained results, the effects of different parameters of the soil on the estimation of the tensile loading capacity are presented. Figure 1 shows the failure modes for the suction caissons under the tensile loading [12].

3. Soil parameters and model

In this study, the suction caisson is simulated using PLAXIS2D software as a two-dimensional model with axial symmetry (Figure 2). The surrounding soil was saturated and the Mohr-Coulomb relation was used to determine its behavior. It is supposed that the installation of the caisson has no effect on the change of the primary characteristics of the soil. Of course, this hypothesis has to be tested experimentally. At drained conditions no additional pore water pressure is made. In such a situation, the drainage is possible through the upper cap of the caisson. At drain conditions, the upper cap of the caisson will remain closed during the imposition of the pullout force. In order to calibrate and verify the results of this numerical modeling, relied upon different laboratory results such as Rao, et al. [13], El- Ghrarbawy, and Olson, Is kander, et al. [14-16].

In order to estimate the pullout loading capacity, Rao, et al. [9] conducted some experiments on the suction caissons with different length-diameter (L/D) ratio in soft clay soil. The dimensions of their caisson were as Table 1.

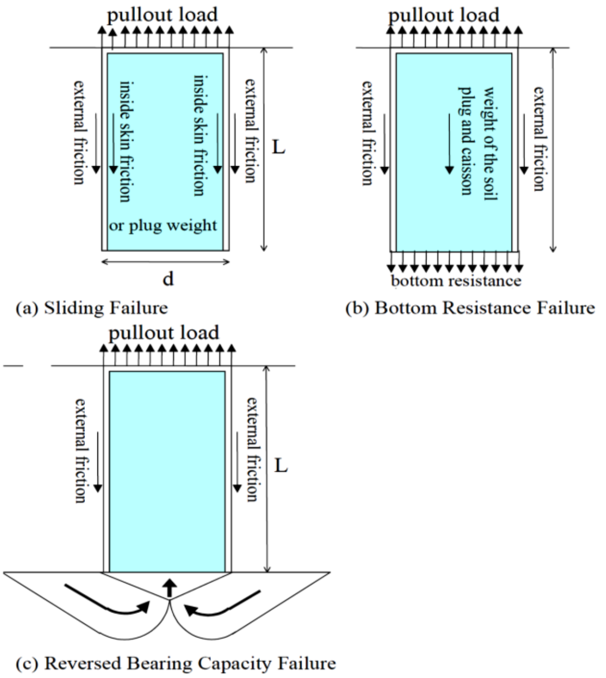

Figure 1. Failure modes for suction anchors under tensile loading [17]

Table1. The dimensions of caisson [13]

D (mm)	t (mm)	L/D
75	3	1, 1.5, 2

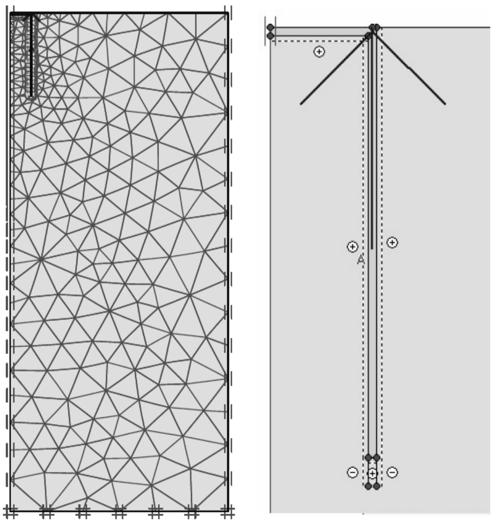

Figure 2. Finite element model and mesh generated

El- Ghrarbawy et al [14]. studied the pullout behavior of the caisson in the depth of 2000-3000 meters from the water level in both drained and un-drained modes in kaolinite type of the clay soil, as Table 2.

Table 2. The dimensions of caisson [14]

D (mm)	t (mm)	L/D
100	3.125	4, 6

Iskander, et al [15]. studied the changes of the pore water pressure in the sandy soil during the penetration of the caisson and its extraction as Table 3.

Table 3. The dimensions of caisson [15]

D (mm)	t (mm)	L/D
110	5	1.7

Their input soil was clay with 0.0001 N/mm^2 cohesion and 27.8° friction angle considered as a drain. The length of the suction caisson is equal to 600 mm, its diameter is 100 mm and its thickness is equal to 3 mm as Table 4.

Table 4. The dimensions of caisson in this study

D (mm)	t (mm)	L/D
100	3	6

The dimensions of the simulated caisson in this research are similar to the laboratory model of El- Gharbawy for the clay soil. The total height of the model is considered as 3.6 m and the width of the model is 0.5 mm. In the resulted diagram of the load-displacement, the load value is calculated per kN/rad obtained by multiplying the load in 1000*2π to obtain the load value per N. Figure 3 shows the result.

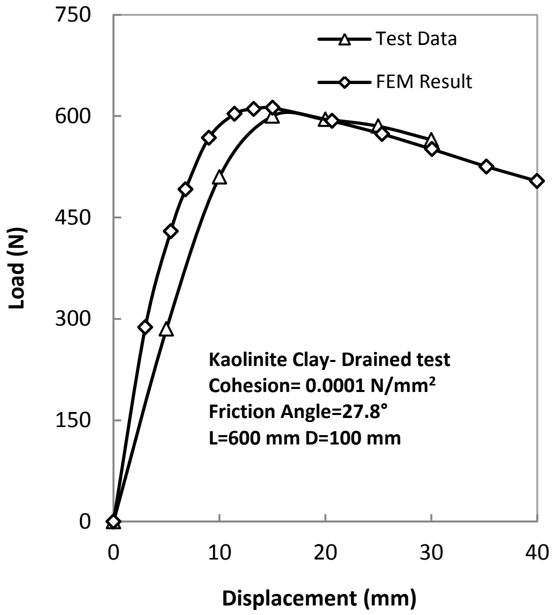

Figure 3. Comparison between the experimental [1] and FEM method

As shown in Figure 3, there is a good accordance between the experimental results and the numerical model. Considering the verification of the numerical model, now come to study the effects of the strength parameters of the soil on the pullout capacity of the suction caissons.

4. Parametric study

To conduct the parametric study of the model changed the values of the parameters of the soil to study its effect on the load-displacement diagram. In order to do the parametric study changed 4 parameters of the soil, including the cohesion (C), friction angle (Φ), Yang modulus (E), and the weight of the soil unit (γ) as Table 5.

Table 5. change the values of the parameters of the soil for this study

parameters	values
C (kPa)	20, 10, 5, 1, 0.1
Φ (degree)	40, 35, 30, 27.8, 25
E (kPa)	15, 13, 11, 9, 7
γ (kN/m3)	21, 19, 17, 15, 13.5

The cohesion of the soil (C) is the first parameter studied its effect on the load-displacement diagram. The load-displacement diagrams that were obtained for different Cs are drawn on a diagram to show the effect of C on the load-displacement diagram. Figure 4 shows the curves of the displacement of suction caisson with the changes of the cohesion of soil.

As shown in Figure 4, the increase of the C will lead to an increase of the load value for any specific displacement. All diagrams have a peak point. The maximal point is approximately 14 mm and then the pullout bearing began to decrease.

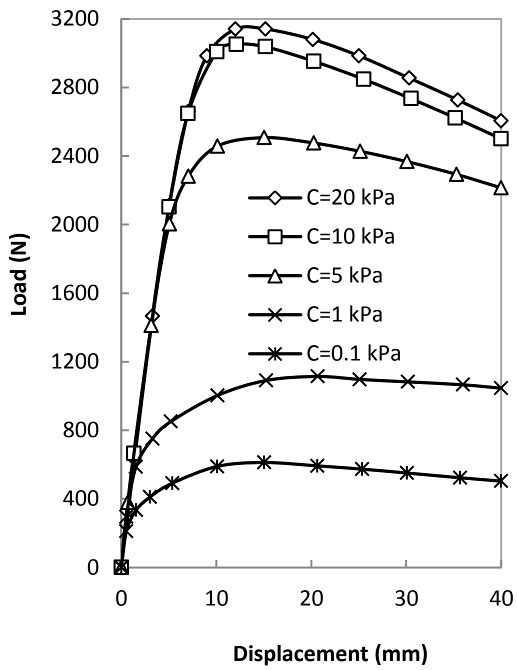

Figure 4. Soil cohesion effects on numerical pullout of suction caissons

In diagrams of Figure 4, the pullout capacity was increased by the increase of the cohesion and then, the increase of the cohesion has had no effect on the increase of the pullout capacity of the suction caisson. Figure 5 shows the changes of cohesion against the tensile capacity of the suction caisson as well.

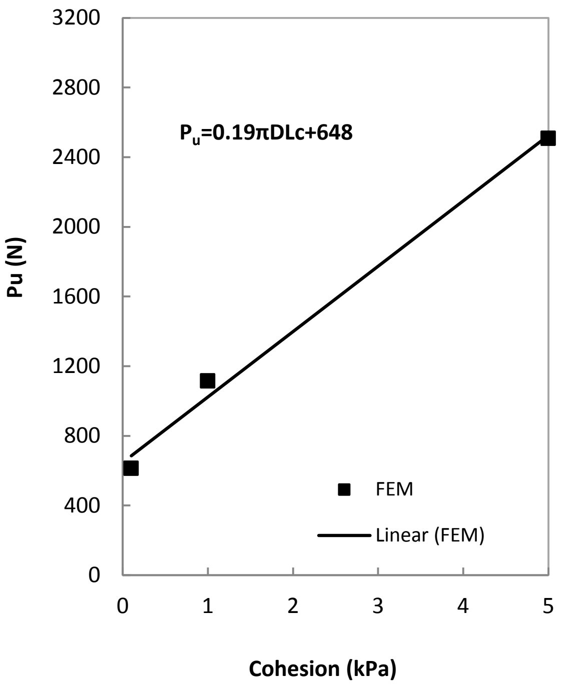

Figure 5. Soil cohesion effects on pull-out capacity of suction caissons

As Figure 5 shows, the changes of the tensile capacity of the caisson against the cohesion is linear due to the direct relation between the un-drained sheer strength of the soil with the its tensile capacity.

Figure 6 shows the load-displacement diagrams of the suction caissons against the changes of the internal friction angles of the soil.

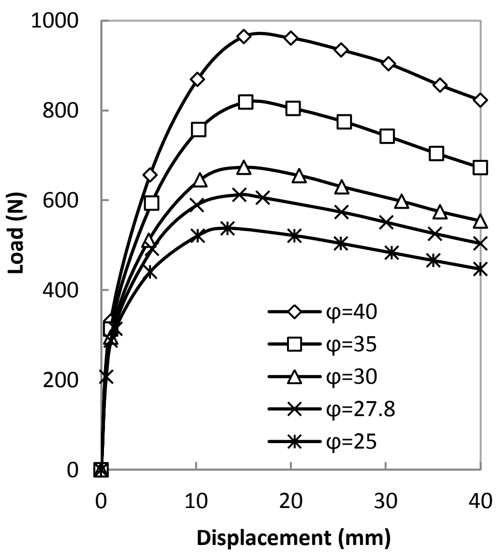

Figure 6. Soil friction angle on numerical pullout of suction caissons

Like Figure 4, in the Figure 6 a peak point of approximately 14 mm is observed in the load-displacement diagram, after which the pullout capacity of the suction caissons is decreased. In the Figure 6, observed that the increase of the friction angle leads to the increase of the pullout capacity.

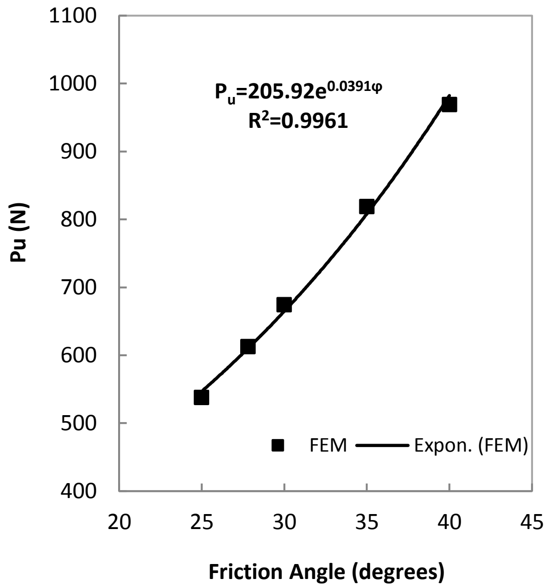

Figure 7. Soil friction angleon pull-out capacity of suction caissons

Figure 7 shows the changes of the pullout capacity against the changes of internal friction angle of the soil. Considering the above figure, the changes of the pullout capacity with the internal friction angle of the soil is exponential. Based on the mentioned figure, these changes are formulated by the relation 1 as follow:

$$p_u = 205.92e^{0.0391\varphi} \qquad (1)$$

Wherep_u is the pullout capacity of the suction caisson per N, and φ is the internal friction angle of the soil per degree.

Figure 8 shows the load-displacement diagrams of the suction caissons against the changes of the soil density.

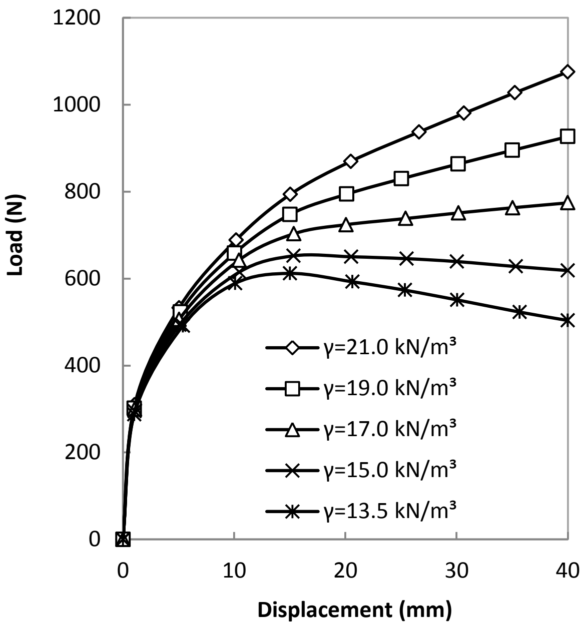

Figure 8. Soil density on pull-out capacity of suction caissons

As the Figure 8 shows, the increase of the soil density leads to the removal of the peak point in the load-displacement. Figure 9 shows the diagram of the pullout capacity after the increase of the increasing procedure of the displacement.

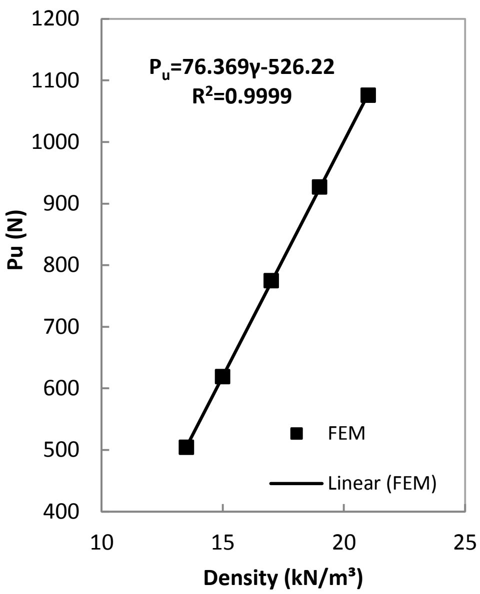

Figure 9. Pullout capacity of the suction caissons against the changes of the soil density

Considering the Figure 9, the changes of the pullout capacity of the suction caissons with the soil density is linear. Based on the above diagram, these changes are formulated by the relation 2 as follow:

$$p_u = 76.369\gamma - 526.22 \qquad (2)$$

Wherep_u is the pullout capacity of the suction caissons per N, and γ is the soil density per kN/m³.

The final parameter in our study is the parameter of Yanl modulus of the soil (E) whose effect on the load-displacement diagram is focused (Fig. 10). The values of E is equal to 7, 9, 11, 13 and 15 MPa, respectively; and the load-displacement diagram is obtained for each value of E. As the Figure 10 shows, the changes of E have had no significant effect on the load-displacement diagram.

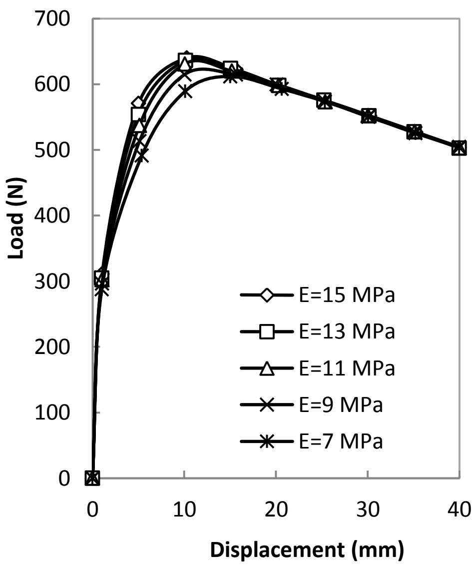

Figure 10. Yong modulus of soil on numerical pullout of suction caissons

As Figure 10 shows, the changes of E have a small effect on the load-displacement diagram, and just could observe a little difference at the peak point of the diagrams.

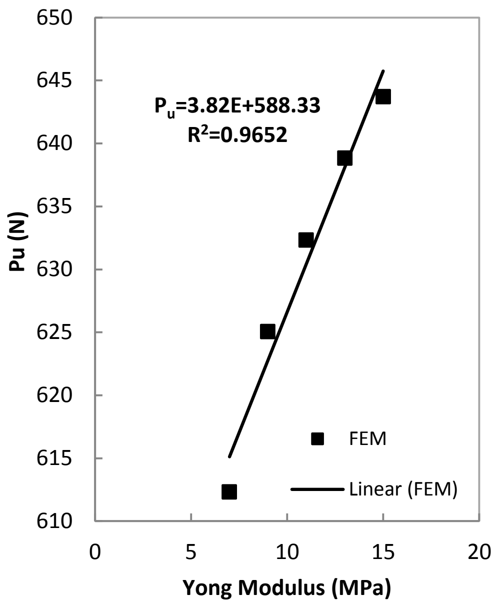

Figure 11. Yong modulus of soil on pull-out capacity of suction caissons

Figure 11 shows the changes of the pullout capacity of the suction caissons against the changes of the elasticity modulus of the soil. Considering the above figure, the changes of the pullout capacity with the elasticity modulus of the soil is linear. Based on the above diagram, these changes are formulated by the relation 3 as follow:

$$\mathrm{p_u} = 3.82\mathrm{E} + 588.33 \qquad (3)$$

Where$\mathrm{p_u}$ is the pullout capacity of the suction caissons per N, and E is the elasticity modulus of the soil per MPa.

5. Conclusions

In the past two decades, the suction caissons have been used under different environmental conditions in the offshore structures. Currently, the application of the suction caissons in the offshore structures and in the costal structures such as the wind turbines has been increasingly developed. In this research, the behavior of the suction caissons was studied subjected to the vertical pullout load using the numerical simulation. In this regard, the following points have to be mentioned:

In the load-displacement diagrams, the peak point was observed as approximately equal to 14 mm after which the pullout force of the suction caisson begins to decrease.

The results of the analyses showed that the increase of the cohesion, the pullout capacity of the suction caissons increases from the linear degree, so that the increase of the cohesion from 0.1 kPa to 5 kPa leads to the increase of the mentioned capacity up to three times.

The conducted analyses showed that the changes of the pullout capacity of the suction caissons against the internal friction of the soil are exponential, therefore, that every 15° changes of the friction angle led to the double increase of the pullout capacity.

The analyses showed a tangible change in the pullout capacity of the suction caissons against the density of the soil.

The changes of the elasticity modulus of the soil showed no significant effect on the pullout capacity of the suction caissons.

See also, observed that the strength parameters of the soil have more effect on the pullout capacity than the elasticity modulus; so that any small change of each of these strength parameters leads to the increase of this capacity up to three times.

Finally, in order to increase the pullout capacity of the suction caissons, suggested using some methods whose effects are mainly on the soil density and cohesion parameters because even small changes in these two parameters can lead to more increase in the pullout capacity of the suction caissons.

6. References

[1] Zeinoddini, M. & Nabipour, M. A Parametric Study on the Pullout response of Suction Caissons. Journal of Marine Engineering, Vol. 0, No. 5, pp. 1/E-16/E, 2009.

[2] Goodman, L. J.; Lee, C. N. & Walker, F. J. The Feasibility of Vacuum Anchorage in Soil. Geotechnique, 1, pp. 356- 359, 1961.

[3] Brown, G. A.; Nacci, V. A. and Demars, K. R. Performance of hydrostatic anchors in granular soils. Offshore Technology Conference, Huston, Texas, OTC 1472, 1971.

[4] Wang, M. C.; Nacci, V. A. and Demars, K. R. Behavior of underwater suction anchor in soil. Ocean Engineering. Vol. 3, No. 1. pp. 47-62. Pergamon Press Ltd., London, 1975.

[5] Helfrich, S.C., Brazill, R.L., and Richards, A.F. Pullout characteristics of a suction anchor in sand. Proceedings of the 8th annual Offshore Technology Conference, Houston, Texas, OTC 2469, May 3-6, pp. 501-506, 1976.

[6] Brown, G. A.; Nacci, V. A. and Demars, K. R. Performance of hydrostatic anchors in granular soils. Offshore Technology Conference, Huston, Texas, OTC 1472, 1971.

[7] Hogervorst, J.R. Field trials with large diameter suction piles. Proceedings of the 12th annual Offshore Technology Conference, Houston, Texas, OTC 3817, May 5-8, pp. 217-224, 1980.

[8] Dayong, L., Yukun, Z., Lingyun, F. and Yufeng, G. Capacity of modified suction caissons in marine sand under static horizontal loading. Ocean Engineering, 102, pp. 1-16, 2015.

[9] Ukritchon, B. and Keawsawasvong, S. Undrained pullout capacity of cylindrical suction caissons by finiteelement limit analysis. Computers and Geotechnics, 80, pp. 301-311, 2016.

[10] Charlton, T.S. and Rouainia, M. Probabilistic capacity analysis of suction caissons in spatially variable clay. Computers and Geotechnics, 80, pp. 226-236, 2016.

[11] Bagheri, P., Son, S.W. and Kim, J.M. Investigation of the load-bearing capacity of suction caissons used for offshore wind turbines. Applied Ocean Research, 67, pp. 148-161, 2017.

[12] Deng, W., Carter, J. P. and Taiebat, H. Prediction of the Lateral Capacity of Suction Caissons. Proceedings, 10th International Conference of the International Association for Computer Methods and Advances in Geomechanics; Rotterdam: Balkema. 1, pp. 33-38, 2001.

[13] Rao, S. N.; Ravi, R.; Prasad, B. S.Pullout behavior of suction anchors in soft marine clays. Marine Georesources and Geotechnology, Vol. 15, pp. 95-114, 1997.

[14] El-Gharbawy, S.L., and Olson, R.E.Modeling of suction caisson foundations. Proceedings of the International Offshore and Polar Engineering Conference, Vol. 2, pp. 670- 677, 2000.

[15] Iskander, M. El-Gharbawy, S. and Olson, R. Performance of suction caissons in sand and clay. Canadian Geotechnical Journal, 39, pp. 576-584, 2002.

[16] El-Gharbawy, S. and Olson, R.The pullout capacity of suction caissons for tension leg platforms. Proceedings of 8th International Offshore and Polar Engineering Conference, Montrea., 1998.

[17] Jun Huang, A., Jianchun Cao and Jean M. E. Audibert, M. Geotechnical Design Of Suction Caisson In Clay. Proceedings of The Thirteenth International Offshore and Polar Engineering Conference Honolulu, Hawaii, USA, May 25–30, 2003.