Visakhapatnam Chapter

Proceedings of Indian Geotechnical Conference 2020
December 17-19, 2020, Andhra University, Visakhapatnam

A Study on the Vertical Pullout Capacity of Suction Caisson Foundation in Sandy and Clayey Soils

Suchit Kumar Patel[1][0000-0003-1579-4352] and Baleshwar Singh[2]

[1] Central University of Jharkhand, Ranchi, Jharkhand, India
[2] Indian Institute of Technology Guwahati, Guwahati, Assam, India
suchit.patel@cuj.ac.in

Abstract. This paper presents the vertical pullout behaviour of suction caisson foundation in clayey and sandy soils by means of finite element analysis using PLAXIS 2D under vertical static loading. The effect of caisson aspect ratio (*L*/*D*) on pullout capacity and caisson displacement was investigated under drained and undrained loading. The caisson aspect ratio has been varied from 0.5 to 3 by fixing caisson diameter and increasing caisson length. The analysis, predicted that undrained pullout gives the higher limit and drained pullout gives the lower limit of vertical pullout. Undrained pullout capacity is found to be nearly a minimum 1.4 times and 5 times that of drained pullout capacity for clay and sand, respectively. The pullout capacity and failure displacement increases continuously with increasing caisson aspect ratio. Pullout capacity of foundation is greater under sandy soil compare to that of clayey soil under undrained conditions, and at all aspect ratios. The caisson deformation up to failure is greater under drained conditions for both clay and sand, and it is found to be higher for clay than sand in both drainage conditions.

Keywords: Suction Caisson, Vertical Pullout, Caisson Aspect Ratio, PLAXIS 2D.

1 Introduction

Suction caisson foundation is an adequate alternative foundation for offshore structures including offshore wind turbine and offshore oil and gas platform. Its simple installation procedures and overall economy makes it a dependable foundation option compared to the conventional pile foundation especially in the higher water depth [1]. Suction caissons are concrete or steel cylindrical structure with larger diameter, open at bottom and closed at the top. Installation of suction caisson initially starts with self-weight penetration where caisson is permitted to enter the sea-bed under own weight. The self-weight penetration is followed by suction assisted penetration up to the required depth in seabed. In suction assisted penetration, suction pressure is generated inside the cylindrical chamber by pumping out the water from within the caisson chamber. This generates a differential pressure across sealed top, causing a downward hydrostatic force, which acts on the caisson top and pushes it to desired depth. The overall installation process takes a relatively short time and is not weather dependent.

Larger diameter of suction caisson makes it to attain significant horizontal holding capacity. Suction caissons have been used for various offshore structures including single buoy moorings [2], tension leg platforms [3], jackets [4], deep water subsea structures [5] and for anchoring some deep water submersible platforms [6].

Under severe environmental conditions, the acting tensile pullout load on suction caisson develops a passive suction pressure in pore water of soil beneath the caisson, providing the resistance against the pullout. Due to prolonged pullout loading, the generated passive suction pressure dissipates and this may lead caisson withdrawal. The pullout capacity of suction caisson foundation has been studied earlier using experimental approach [7-10] and numerical analysis [11-18]. Pullout capacity is noted to be dependent on caisson length, caisson diameter, soil properties (friction angle, cohesion and undrained shear strength) and soil-caisson interfacial interaction.

Suction caisson foundation resists vertical load, lateral load, and moment in offshore condition. The vertical load (weight of superstructure), lateral load (water current and wind force) and associated overturning moment are the crucial factors for the design of the suction caisson foundation. In the current study, the vertical pullout capacity and vertical displacement of suction caisson foundation in sand and clay with varying aspect ratio has been investigated by using PLAXIS 2D [19].

2 Numerical Analysis

2.1 2-D Finite element modeling

The vertical pullout capacity of 2-D suction caisson foundation was simulated using finite element software PLAXIS 2D. An axisymmetric model was used for modelling the foundation. The caisson was assumed as placed in soil domain to carry out vertical pullout analysis. The soil volume and other was modeled using Mohr–Coulomb elasto-plastic soil model having 15-node triangular elements. The caisson wall was modeled with plate element. For the soil domain boundaries, standard fixity boundary conditions were adopted. The displacements were restricted only in the normal directions at the bottom and lateral boundaries. The displacements of the soil domain at the base boundary and lateral boundaries were limited in the normal directions. To simulate the suction caisson response, the diameter of soil domain and soil domain depth was selected as 5*D* and 4*L*, respectively. Caisson wall and soil (clay and sand) properties under drained and undrained cases used are given in Tables 1 and 2, respectively. R_{inter} is kept unity in order to transfer all soil shear stress to caisson wall. The shear strength of clay was assumed to increase linearly with depth as $s_u = 1.5z$.

Once the soil and caisson wall properties were assigned, mesh generation was done. The caisson and soil vicinity was refined by relatively finer mesh. Thereafter, analysis was conducted by applying vertical pullout load at the foundation centerline. Load-displacement curve was plotted to find out the pullout capacity for a particular point where the influence of vertical loading was expected to be the most. The analysis was performed for different caisson aspect ratios (*L/D*), where *L* is the caisson length and *D* is the caisson diameter. *L/D* ratio was varied from 0.5 to 3 (*L/D* = 0.5, 1, 1.5, 2, 2.5 and 3), by fixing the caisson diameter and increasing caisson length for both clayey and sandy soils under drained and undrained conditions.

Table 1. Suction caisson wall material properties [18]

Material properties	Values
Types of material	Elastic
Stiffness (EA)	6.598×10^{15} kN
Flexural rigidity (EI)	5×10^{9} kN/m^2
Unit weight (γ_c)	77 kN/m^3
Poisson's ratio (μ)	0.25
Wall thickness (t)	0.03 m
Caisson diameter (D)	20 m

Table 2. Soil properties

Soil properties	Clay		Sand	
	Drained	Undrained	Drained	Undrained
Unsaturated unit weight (γ_{unsat})	16 kN/m^3	16 kN/m^3	-	-
Saturated unit weight (γ_{sat})	20 kN/m^3	20 kN/m^3	21 kN/m^3	21 kN/m^3
Elastic modulus (E)	10,000 kN/m^2	10,000 kN/m^2	20,000 kN/m^2	20,000 kN/m^2
Poisson's ratio (μ)	0.2	0.49	0.2	0.49
Internal friction angle (ϕ)	22°	22°	36°	36°
Cohesion intercept (c)	40 kPa	40 kPa	0.1 kPa	0.1 kPa
Dilation angle (ψ)	0°	0°	5°	5°
R_{inter}	1	1	1	1

2.2 Model verification

Iskander et al. (2002) experimental results were used to verify the model accuracy by modeling the same foundation dimensions (D = 100 mm, L = 600 mm) and assigning the same caisson material and soil properties. The comparative load-displacement plots for undrained pullout are presented in Fig. 1. A good agreement has been noted between experimental and PLAXIS 2D results and the peak pullout capacity are noted to be comparable. So, it was decided to use this numerical analysis to evaluate the ultimate vertical pullout capacity of suction caissons foundation within permissible limits.

2.3 Failure mode

The pullout capacity of suction caisson foundation depends on the failure mode of foundation. Under varying drainage condition, suction caisson foundation undergoes different failure mechanisms. Under fully drained condition, where the top valve is kept opened, sliding failure mode dominants (Fig. 2a), and the pullout capacity is the sum of the skin friction (both external and internal) and submerged weight of the soil plug. In case of undrained conditions where the top valve is fully closed, reverse bearing capacity failure mode dominant (Fig. 2b) and surrounding soils contributes in pullout resistance. For undrained case, the pullout capacity is the sum of skin friction and the reverse end bearing capacity.

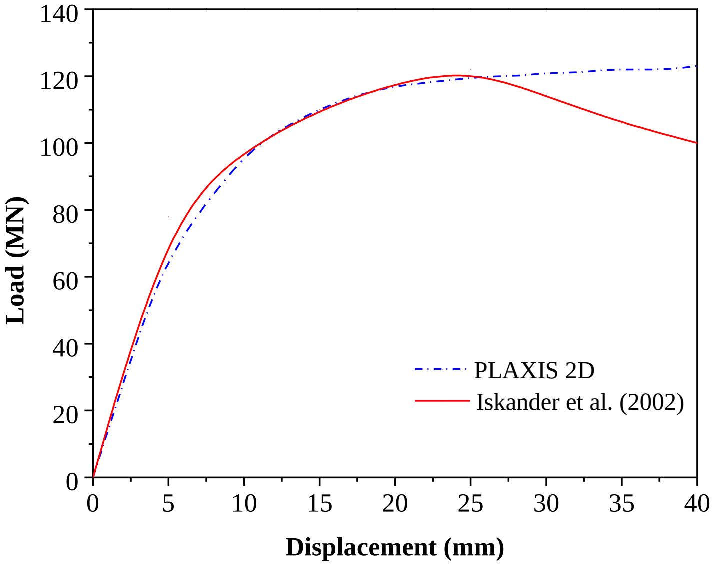

Fig. 1. Comparison of PLAXIS 2D result with Iskander et al. (2002) experimental result

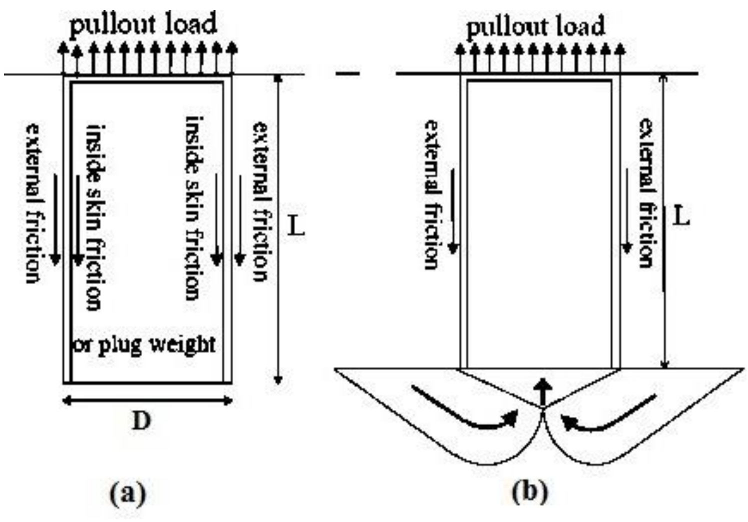

Fig. 2. Failure mode of suction caisson foundation: (a) drained; (b) undrained condition

3 Results and Discussion

3.1 Effect of soil type

The effect of soil type on pullout behaviour under undrained condition of suction caisson foundation (*L* = 10 m, *D* = 20 m, *L*/*D* = 0.5) are shown in Fig. 3. The pullout capacity is noted to be greater for sandy soil at all vertical displacement. The pullout capacity at failure point is noted as 23 MN and 57 MN for clay and sand, respectively. For undrained condition the pullout capacity is due to the wall friction and reverse bearing capacity. In case of sandy soil the frictional resistance between caisson wall and soil particles are much greater than that of clayey soil, and also the reverse bearing capacity will be greater for sand as it has higher friction angle and unit weight values. Therefore, the overall pullout capacity in sandy soil is much greater than the clayey soil. It has also been noted that the failure of foundation takes place at higher vertical displacement in case of clayey soil.

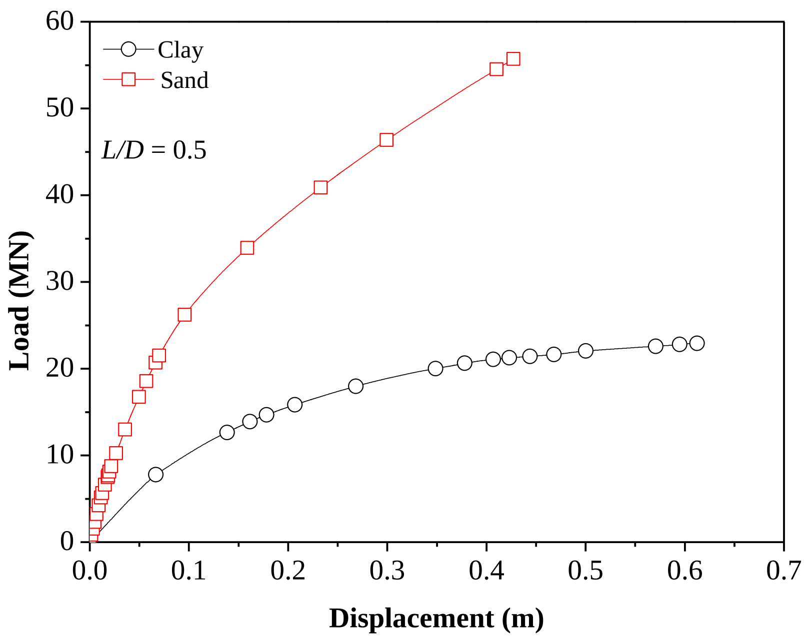

Fig. 3. Effect of soil type on pullout behaviour under undrained condition (*L*/*D* = 0.5)

3.2 Effect of drainage condition

The effect of drainage condition on the vertical pullout response is shown in Fig. 4a and Fig. 4b for clay and sand, respectively for caisson aspect ratio (*L*/*D*) value of 1 (*D* = 20 m and *L* = 20 m). The undrained response is found to be greater than that of drained response for both clay and sand. In case of clayey soil, the undrained pullout capacity (Pu_{UD}) is minimum 1.4 times greater than drained pullout capacity (Pu_D). However, in case of sandy soil, the undrained pullout capacity is at least five time that of drained pullout capacity (Table 3).

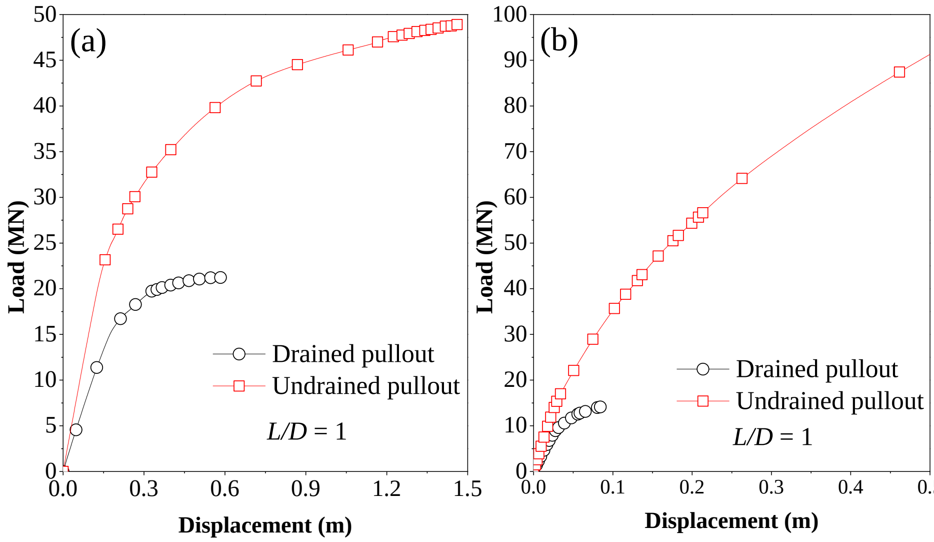

Fig. 4. Effect of drainage condition on pullout response: (a) clay; (b) sand

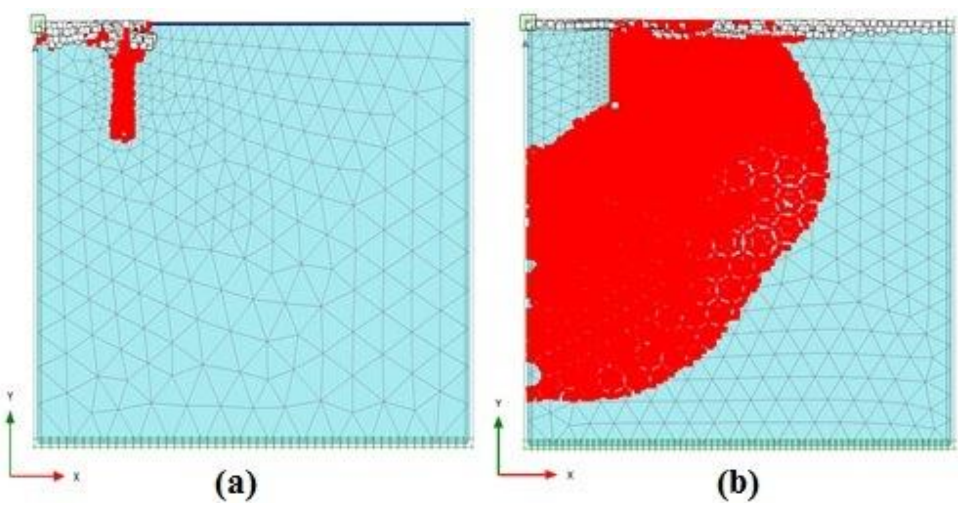

Fig. 5. Generated plastic point at failure in sand: (a) drained; (b) undrained case

The variation in pullout behaviour under drained and undrained condition is due to the different failure mode of foundation (Fig. 2). In case of drained condition, the caisson pullout rate is very slow which allow the inflow of pore water inside the caission soil, restricts the generation of any suction inside the caisson. This causes the sliding failure of foundation and having lower pullout capacity as it involve only wall friction resistance against pullout. In case of fully undrained condition, the caisson is pulled out at relatively fast rate allowing the passive suction in the soil at the caisson bottom. Due to this generated suction the surrounding soil takes part in the total stress resisting the suction pullout, and the failure occurs by reverse bearing capacity mode. Thus resistance under undrained pullout is the summation of external wall friction resistance, soil plug weight and reverse bearing capacity failure, rusting in higher pullout capacity compare to drained condition.

The pullout response variation under drained and undrained case can also be discussed based on the generated plastic point during pullout. The generated plastic points at failure for drained and undrained conditions are shown in Fig. 5a and Fig 5b, respectively. For drained condition, the plastic points only developed around the surficial interface of soil and caisson (Fig. 5a), and only caisson wall moves upward under pullout loading without any soil plug results in lower pullout capacity. For undrained case, the plastic points also spread around the caisson wall and the bottom of foundation in the more extended area at failure (Fig. 5b). Thus the surrounding soil also supports the bearing capacity under undrained case, and the foundation shows higher reverse bearing capacity, resulting higher pullout capacity.

3.3 Effect of aspect ratio

The caisson aspect ratio (L/D) which the ratio of caisson length to the caisson diameter has been varied by keeping diameter constant (D = 20 m) and varying caisson length up to 60 m (L = 10, 20, 30, 40, 50 and 60 m). At the time of analysis the soil parameters were kept constant for both soils as per Table 1.

The effect of caisson aspect ratio on vertical pullout response is shown in Fig. 6a and Fig. 6b for clay and sand, respectively under undrained condition. With increasing L/D ratio, the pullout capacity increases continuously for both soils. The failure displacement of caisson is also found to increase with increasing caisson aspect ratio. As the caisson length increases, the external and internal surface area of caisson, and caisson volume increases continuously. This increases the surficial frictional resistance, soil plug volume in the caisson and the passive suction generation inside the caisson, increases the reverse bearing capacity, causing overall increase in pullout capacity. With clay, the pullout behaviour shows strain softening response at greater displacement, while in sand, the pullout behaviour is noted to be strain hardening for all aspect ratio.

The drained and undrained vertical pullout capacities are summarized in Table 3 for both clay and sand along with the ratio of undrained pullout capacity to drained pullout capacity (Pu_{UD}/Pu_D). Drained pullout capacity is greater for clayey soil than that of sandy soil for all L/D ratios, whereas undrained pullout capacity is higher for sandy soil. It can further be noted that Pu_{UD}/Pu_D ratio decreases with increasing L/D ratio for both soils. This indicates that undrained pullout (fast removal of suction caisson) requires much higher pullout load, whereas drained pullout (slow removal of suction caisson) is much easier as it require lower pullout load.

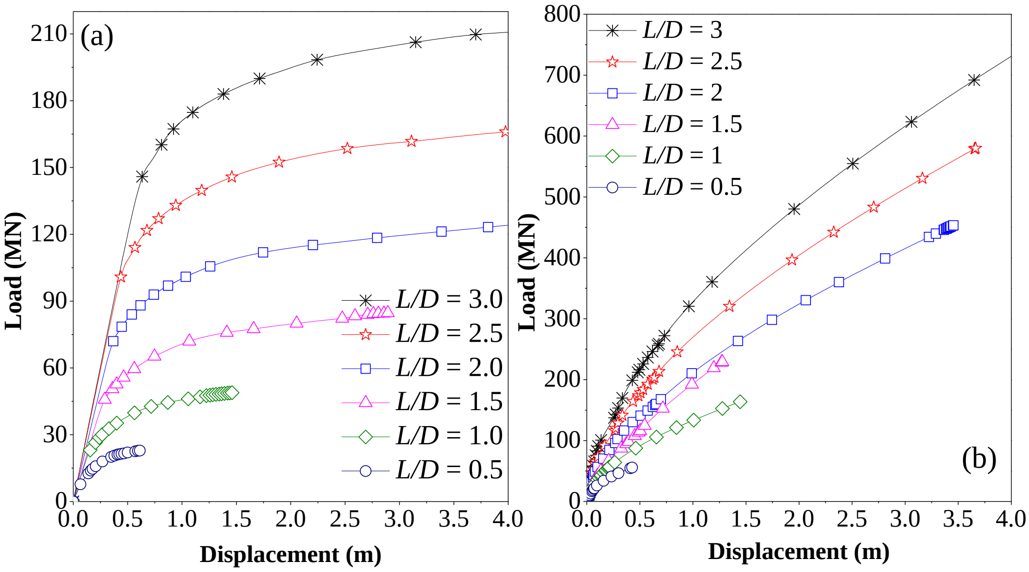

Fig. 6. Effect of caisson aspect ratio on vertical pullout response: (a) clay; (b) sand

Table 3. Ultimate pullout capacity of suction caisson foundation

L/*D*	Clay			Sand		
	P_{uD} (MN)	P_{uUD} (MN)	P_{uUD}/P_{uD}	P_{uD} (MN)	P_{uUD} (MN)	P_{uUD}/P_{uD}
0.5	6.0	23.0	3.8	4.2	55.7	13.3
1.0	21.2	49.0	2.3	14.1	149.0	10.6
1.5	44.6	84.7	1.9	32.3	229.3	7.1
2.0	72.0	128.1	1.8	52.6	416.4	7.9
2.5	108.2	183.0	1.7	75.4	537.0	7.1
3.0	146.7	212.0	1.4	128.0	647.6	5.1

3.4 Pullout capacity equation

From the pullout capacity values of Table 3, an attempt has been made to predict the pullout capacity of suction caisson foundation under drained and undrained conditions for clayey and sandy soil in term of power equation as presented in Fig. 7 in terms of caisson aspect ratio only for the soil and caisson properties used in this study. As the fitting lines R^2 values is close to 0.99 for all conditions, the equation seems to be reliable for the limited data points of this present study. The pullout capacity equations are as:

For clayey soil

$$Pu_D = 21.69(\frac{L}{D})^{1.743}, R^2 = 0.99 \quad (1)$$

$$Pu_{UD} = 51.949(\frac{L}{D})^{1.307}, R^2 = 0.99 \quad (2)$$

For sandy soil

$$Pu_D = 11.842(\frac{L}{D})^{2.135}, R^2 = 0.987 \quad (3)$$

$$Pu_{UD} = 145.473(\frac{L}{D})^{1.392}, R^2 = 0.987 \quad (4)$$

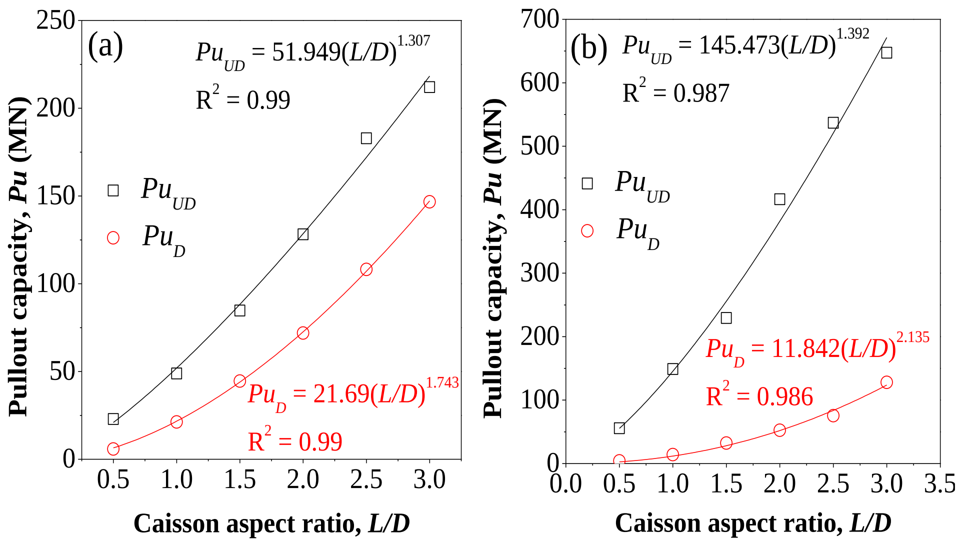

Fig. 7. Ultimate pullout capacity regression equations: (a) clay; (b) sand

4 Conclusions

Following conclusions have been made from the present study

1. Undrained pullout capacity is always larger irrespective of soil types, and undrained pullout capacity with sandy soil is much greater than that with clayey soil.

2. Undrained pullout capacity under clayey soil is minimum 1.4 times of drained pullout, and in sandy soil undrained pullout capacity is at least five times of drained pullout.
3. Under drained condition the foundation fails with relatively small vertical displacement than that of undrained condition, and the foundation displacement is higher for clay than sand irrespective of drainage condition.
4. Increasing caisson aspect ratio causes continuous increase in pullout capacity and foundation failure displacement under both clayey and sandy soils.

References

1. Colliat, J.-L., Dendani, H.: Girassol: Geotechnical Design Analyses and Installation of the Suction Anchors. Proceedings of SUT International Conference on Offshore Site Investigation and Geotechnics, London, November 26-28, (2002).
2. Senpere, D., Auvergne, G.A.: Suction Anchor Piles – A Proven Alternative to Driving or Drilling. Proceedings of Offshore Technology Conference, Houston, USA, OTC 4206, pp. 483-489 (1982).
3. Andersen, K.H., Dyvik, R., Schroder, K., Hansteen, O.E., Bysveen, S.: Field Tests of Anchors in Clay. II: Predictions and Interpretation. Journal of Geotechnical Engineering 119(GT10), 1532-1549 (1993).
4. Baerheim, M., Hoberg, L., Tjelta, T.I.: (Development and Structural Design of the Bucket Foundations for the Europipe Jacket. Proceedings of Offshore Technology Conference, Houston, USA, OTC 7792, (1995).
5. Hefer, P.: Oil and gas floating facility to be anchored in 390m deep imor sea. Civil Engineers Australia, (1998).
6. Dendani, H., Colliat, J-L.: Girassol: Design Analysis and Installation of the Suction Anchors. Proceedings of Offshore Technology Conference, Houston, USA, OTC 14209 (2002).
7. Clukey, E.C., Morrison, M.J., Gariner, J., Corte, J.F.: The response of suction caissons in normally consolidated clays to cyclic TLP loading conditions. Proceedings of Offshore Technology Conference, Houston, Texas, 909-918 (1995).
8. Iskander, M., EI-Gharbawy, S., Olson, R.: Performance of suction caissons in sand and clay. Canadian Geotechnical Journal 39, 576–584 (2002).
9. Sawicki, A., Wachowski, L., Kulczykowski, M.: The pull-out capacity of suction caissons in model investigations. Archives of Hydro-Engineering and Environmental Mechanics 63(2-3), 157-171 (2016).
10. Dai, G., Zhu, W., Zhai, Q., Gong, W., Zhao, X.: Characteristic test study on bearing capacity of suction caisson foundation under vertical load. China Ocean Engineering 34(2), 267-278 (2020).
11. EI-Gharbawy, S.L., Olson, R.E.: Modelling of suction caisson foundations. Proceedings of the 10th International Offshore and Polar Engineering Conference, Seattle, USA, 2, 670-677 (2000).
12. Rahman, M.S., Wang, J., Deng, W., Carter, J.P.: A neural network model for the uplift capacity of suction caissons. Computers and Geotechnics 28, 269-287 (2001).
13. Deng, W., Carter, J.P.: A theoretical study of vertical uplift capacity of suction caissons. International Journal of Offshore and Polar engineering 12(2), 89-97 (2002).

14. Gonzalo Vásquez, L.F., Dilip R. Maniar, D.R., John L. Tassoulas, J.L.: Installation and axial pullout of suction caissons: numerical modeling. Journal of Geotechnical and Geoenvironmental Engineering 136(8), 1137-1147 (2010).
15. Gandomi, A.H., Alavi, A.H., Yun, G.J.: Formulation of uplift capacity of suction caissons using multi expression programming. KSCE Journal of Civil Engineering 15(2), 363-373 (2011).
16. Ahmed, S.S., Hawlader, B.C.: Numerical analysis of inclined uplift capacity of suction caisson in sand. International Journal of Offshore and Polar Engineering 25 (2), 145-155 (2015).
17. Deb, T., Singh B.: Response and capacity of monopod caisson foundation under eccentric lateral loads. Marine Georesources and Geotechnology (2017). DOI: 10.1080/1064119X.2017.1330374
18. Patel, S.K., Singh, B.: A parametric study on the vertical pullout capacity of suction caisson foundation in cohesive soil. Innovative Infrastructure Solutions 4(1), 1-11 (2019). doi: 10.1007/s41062-018-0188-6
19. Brinkgreve, R.B.J., Engin, E., Swolfs, W.M.: Plaxis 2D 2012 reference manual. Delf University of Technology and Plaxis bv, the Netherlands (2012).