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TECHNICAL NOTE

A parametric study on the vertical pullout capacity of suction caisson foundation in cohesive soil

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Abstract

The pullout capacity of suction caisson foundation plays a vital role in its field performance. This study presents numerical investigation on the vertical pullout capacity of suction caisson foundation in cohesive soil under both drained and undrained conditions. The influence of soil cohesion, internal friction angle and caisson aspect ratio on the ultimate vertical pullout capacity of suction caisson foundation has been investigated. It is noted that the upper limit of pullout capacity is governed by undrained condition and the lower limit by drained condition. The pullout capacity increases with increasing soil cohesion, friction angle and caisson aspect ratio when caisson diameter is kept constant, whereas it decreases with increasing caisson aspect ratio when caisson length is kept constant. Mathematical models have been developed for both drained and undrained pullout capacity. The pullout capacity values have been compared with those of available analytical and simplified relationships, and it has been found that the developed models can accurately predict the vertical pullout capacity of suction caisson foundation.

Keywords Suction caisson foundation · Vertical pullout capacity · Cohesion · Friction angle · Caisson aspect ratio

List of symbols

A	Area of caisson base
D	Caisson diameter
E	Young's modulus of elasticity
f	Bearing capacity correction coefficient
K	Earth pressure coefficient
L	Caisson length
L/D	Caisson aspect ratio
N_c	Bearing capacity factor
OCR	Over-consolidation ratio
Pu	Ultimate pullout capacity
Pu_d	Ultimate pullout capacity under drained condition
Pu_{ud}	Ultimate pullout capacity under undrained condition
t	Caisson wall thickness
R_{inter}	Interface between soil and caisson wall
W_c	Caisson weight
s_u	Undrained shear strength
$s_{u,avg}$	Average undrained shear strength
$s_{u,tip}$	Undrained shear strength at caisson tip
c	Soil cohesion
γ_{sat}	Saturated soil unit weight
γ_{unsat}	Unsaturated soil unit weight
γ_c	Caisson unit weight
γ'	Submersed unit weight of soil
$\sigma'_{v,bottom}$	Vertical effective stress
ϕ	Soil friction angle
ψ	Dilation angle
ν	Poisson's ratio
δ	Caisson displacement
α	Skin friction factor
ξ_s	Shape factor
ξ_d	Depth factor
ξ_e	Embedment factor

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Introduction

Suction caisson has been considered as a promising alternative foundation for offshore structures under variable offshore environment. Suction caisson is a hollow cylindrical structure open at the bottom and closed by a lid at the top. This is also known as bucket foundation, suction pile, suction can, suction anchor and skirted foundation [1]. Geometrically, suction caissons are larger in diameter and shorter in length than monopile foundations. During installation, initially, the foundation is allowed to penetrate into soil under its self-weight. Thereafter, further penetration is carried out by generating suction pressure inside the hollow chamber of caisson by pumping out water from within them. Installation method of suction caisson is much quicker and simpler than that of other foundations. Suction caisson is still viewed as a relatively new concept, although its first use as anchorage and foundation system dates back to the late 1950s [2]. It is relatively economical solution in offshore environment due to its lower cost which includes geotechnical investigation cost, steel and fabrication cost and installation cost. Suction caisson can serve as the most economical and attractive solution in place of traditional piled or gravity foundation for offshore wind turbines [3].

The behaviour of suction caisson foundation for offshore environment has been studied through several laboratory tests, field model tests, analytical and numerical methods. Clukey et al. [4] established a combination of cyclic load ratio (cyclic load divided by static uplift resistance) and number of applied cycles that cause failure of the foundation by conducting centrifuge study on suction caissons in normally consolidated clays, under typical Gulf of Mexico (GOM) cyclic loading conditions for Tension Leg Platform (TLP). Under combined loading, the variation of angle of inclination during the cyclic loading caused a reduction in the number of cycles required to cause failure for a given cyclic load level.

The ultimate vertical pullout capacity of suction caisson has been investigated by several researchers [1, 5–13]. It has been noted that the ultimate capacity is influenced by the weight of suction caisson and foundation templates, caisson aspect ratio, point of application and angle of inclination of the loading, ballast loads, submerged weight of the soil plug, undrained shear strength of soil, soil permeability, ambient pore pressure, loading rate, shearing resistance between the surrounding soil and caisson wall, reverse bearing capacity mechanism developed due to suction and load path. Larsen et al. [10] found that the combined capacity of bucket foundation is a function of the tensile capacity and the inclination factor which depend on the embedment ratio and impact height. Soil pressure and friction on the outer skirt of caisson at the passive zone contribute most to the moment capacity of the caisson, with the aspect ratio and the horizontal subgrade reaction constant [14].

Test results of laboratory study on model caissons in sand and clay indicated that the use of suction pressure for installation of caissons could be a viable alternative to conventional methods [1]. Penetration resistance of suction caisson increases linearly with depth during both self-weight and suction penetration in normally consolidated and slightly over-consolidated clays [15]. House and Randolph [16] found that the surrounding soil undergoes re-consolidation during the pullout of stiffened caisson in cohesive sediments. The neural network method could be a reliable and simple predictive tool for the uplift capacity of suction caisson [11].

By conducting cyclic loading test on model caisson in test beds made of two different gradings of dense sand, Kelly et al. [17] suggested that the windward footing should be designed for tensile loading not greater than the drained friction on the skirt. The displacements required to mobilize the loads were large compared to the diameter of the foundation. Taiebat and Carter [18] developed a unique failure envelope of suction caisson, in a non-dimensional form, which can be presented regardless of the location of the padeye. The resistance of the foundation against any combination of axial, lateral and torsional loading can be obtained using the failure envelope. Due to the reduction in shaft friction and end-bearing resistance under cyclic loading, less resistance against uplift of caisson is obtained compared to that developed under short-term monotonic undrained loading [19].

Under monotonic compression and tension tests on suction caisson foundation in clay, tensile loading response is noted to be softened substantially when the caisson is loaded into compressive failure prior to tensile loading [20]. Cavitation is also found in the region beneath the skirt tip during pullout test. The drained capacity of offshore bucket foundations and the ratio of plastic increments are largely influenced by embedment ratio (ratio of current embedded length to the overall length) and the preload ratio (ratio of vertical load to the vertical preload) of the foundation that controls the size of the yield surface for a given load state [21]. The direction of the plastic displacement increments is found to be dependent on the embedment ratio and the preload ratio. With increase in embedment ratio, the direction of these plastic increments is noted to be counterclockwise.

Methods for pullout capacity

Several methods have been developed to determine the ultimate pullout capacity of suction caisson foundations under both drained and undrained conditions.

Drained pullout capacity

Rahman et al. [11] defined drained ultimate pullout capacity (Pu_d) as:

$$Pu_d = 9.1\left(\frac{L}{D}\right)^{0.5372}\left(1-\sin\phi'\right)\sigma'_{v,bottom}(OCR)^{0.5}\tan\phi', \tag{1}$$

where D = caisson diameter, L = caisson length, ϕ' = effective friction angle, $\sigma'_{v,bottom}$ = vertical effective stress at the location of the caisson bottom, and OCR = over-consolidation ratio.

Deng and Carter [8] defined the drained ultimate pullout capacity as:

$$Pu_d = \left[9.48\left(\frac{L}{D}\right)^{-0.18} + 3.792\left(\frac{L}{D}\right)^{0.82}\right]s_{u,tip} \tag{2}$$

where $S_{u,tip}$ = undrained shear strength at caisson tip.

Iskander et al. [1] defined the drained ultimate pullout capacity as:

$$Pu_d = W_c + \pi\left(D_o + D_i\right)\int_0^h \gamma' z K \tan\delta dz, \tag{3}$$

where W_c = caisson weight, D_o = outside caisson diameter, D_i = inside caisson diameter, γ' = effective unit weight of the soil, K = earth pressure coefficient, δ = friction angle of soil on caisson, z = depth, and h = tip penetration of caisson.

Sgardeli [13] defined the drained ultimate pullout capacity by limit equilibrium method as:

$$Pu_d = \frac{1}{2}\pi K \tan\phi' \gamma' \left[DL^2 + (D-2t)\left(L^2 - t^2\right)\right], \tag{4}$$

where t = thickness of caisson wall.

Undrained pullout capacity

Renzi et al. [12] defined the undrained ultimate pullout capacity (Pu_{ud}) as:

$$Pu_{ud} = \pi\alpha DLs_{u,avg} + \frac{\pi}{4}D^2 N_c s_{u,tip}, \tag{5}$$

where N_c = bearing capacity factor = 9, α = skin friction factor = 0.3, and $S_{u,avg}$ = average undrained shear strength.

Christensen et al. [5] defined the undrained ultimate pullout capacity as:

$$Pu_{ud} = \pi\alpha DLs_{u,avg} + \frac{\pi}{4}D^2 N_c s_{u,tip}, \tag{6}$$

where N_c = bearing capacity factor = min {9; 6.2 (1 + 0.35 L/D)}, and α = skin friction factor.

Clukey and Morrison [6] defined the undrained ultimate pullout capacity as:

$$Pu_{ud} = 0.75\pi\alpha DLs_{u,avg} + \frac{\pi}{4}D^2 N_c \xi_s \xi_d s_{u,tip} \tag{7}$$

where N_c = bearing capacity factor = $\pi + 2$, ξ_s = shape factor = 1.2, and ξ_d = depth factor = $1 + 0.18\tan^{-1}(D/L)$.

Deng and Carter [7] defined the undrained ultimate pullout capacity as:

$$Pu_{ud} = 2.7\pi D^2[1 + 0.4(L/D)]s_u \tag{8}$$

where S_u = undrained shear strength.

Rahman et al. [11] defined the undrained ultimate pullout capacity as:

$$Pu_{ud} = N_u d_c s_{u,tip} + \gamma' L \tag{9}$$

where N_u = bearing capacity factor = $8(L/D)^{-0.1833}$, and d_c = embedment factor = $1 + 0.4\tan^{-1}(L/D)$.

Iskander et al. [1] defined the undrained ultimate pullout capacity as:

$$Pu_{ud} = \int_0^h \alpha s_u \pi D_o dz + s_u N_c f \frac{\pi}{4} D_o^2 \tag{10}$$

where α = friction factor, f = bearing capacity correction coefficient, N_c = bearing capacity factor = 9, and z = depth.

Sgardeli [13] defined the undrained ultimate pullout capacity from limit equilibrium method as:

$$Pu_{ud} = A\xi_s\xi_e N_c s_{u,tip} + \frac{1}{2}\pi DLs_{u,tip} \tag{11}$$

where A = area of caisson base, $\xi_s = 1 + 0.5D/D$ = shape factor, $\xi_e = 1 + \sqrt{0.053(L/D)}$ = embedment factor, and N_c = bearing capacity factor.

It has been noted that under the combined action of vertical, lateral and moment loading, tensile pullout is developed on the suction caisson, and a suction pressure is developed beneath the sealed top which provides resistance to pullout. The suction water pressure dissipates if enough time is provided during loading. A prolonged pullout loading may lead to caisson withdrawal. Thus, the ultimate pullout capacity is an important factor for the performance of suction caisson foundation.

Aim and scope of the study

In this study, vertical pullout capacity of suction caisson foundation under static loading condition in cohesive soil has been investigated by finite element analysis. The effect of soil shear strength parameters (c and ϕ) and caisson aspect ratio (L/D) on pullout capacity under both drained and undrained conditions has been examined. The caisson aspect ratio has been varied either by changing caisson length keeping caisson diameter constant, or by changing caisson diameter keeping caisson length constant. The influence of cohesion, friction angle and caisson aspect ratio on vertical pullout capacity is shown by developing a mathematical model. The results of the model have been compared with the existing methods.

Numerical modelling

The two-dimensional finite element program PLAXIS 2D [22] has been used to model the pullout behaviour of suction caissons. The caisson foundation has been modelled using 2D-axisymmetric model. The difficulties associated with caisson installation and the effects due to soil rearrangement were not considered in this study. The analysis was performed to investigate the performance of caisson foundation after assuming that the caisson is already placed in the soil domain. Mohr–Coulomb elasto-plastic soil model with 15-node triangular elements was used to model the soil and other volume clusters. This model involves five soil parameters: Young's modulus (E), cohesion (c), soil friction angle (ϕ), Poisson's ratio (ν) and dilatancy angle (ψ). The shear strength of the cohesive soil was assumed to increase linearly with depth as $s_u = 1.5z$ (kPa). Mohr–Coulomb model is a constitutive model with a fixed yield surface, i.e. a yield surface fully defined by model parameters and not affected by plastic straining. For a stress state represented by a point within the yield surface, the behaviour is purely elastic and all strains are reversible. It provides fourth-order interpolation for displacement, and the numerical analysis involves 12 stress points.

The suction caisson was modelled by using plate elements. Perfectly, plastic model for plate element was used. An interface coefficient (R_{inter}) was assumed between the caisson wall and soil. R_{inter} was kept as unity so that the full shear stress of the surrounding soil was transferred to the caisson wall.

Soil domain analysis was necessary for deciding the minimum vertical depth and lateral width, which would not have any boundary effect on the vertical response of the foundation. Standard fixity boundary conditions were considered on the soil domain boundaries. The displacements were restricted only in the normal directions at the bottom and lateral boundaries. Based on the percentage variation in vertical pullout capacity becoming insignificant, finally the soil domain diameter of 5D and depth of 4L were selected to simulate the response of the suction caisson foundation.

Once the soil domain dimensions were fixed, mesh convergence study was carried out to determine the optimum number of elements necessary to represent the soil domain. After assigning all the soil and caisson wall properties as provided, respectively, in Tables 1 and 2, a finite element mesh was generated. In the vicinity of caisson, the soil domain was discretized with finer mesh through local refinement, and the mesh size of the soil domain away from the caisson wall was decided based global refinement. The accuracy of the mesh sizes was considered based on several trials of local and global refinements. Tensile load was applied at the centreline of caisson foundation, and then, the analysis was carried out. The pullout capacity was determined by plotting load–displacement curve for a selected point where the loading effect was assumed to be the maximum.

Table 1 Properties of soil

Properties	Drained pullout	Undrained pullout
Saturated unit weight (γ_{sat})	21 kN/m^3	21 kN/m^3
Unsaturated unit weight (γ_{unsat})	16 kN/m^3	16 kN/m^3
Modulus of elasticity (E)	10,000 kN/m^2	10,000 kN/m^2
R_{inter}	1	1
Poisson's ratio (ν)	0.25	0.49
Internal friction angle (ϕ)	24°	24°
Cohesion intercept (c)	30 kPa	30 kPa
Dilation angle (ψ)	0°	0°

Table 2 Material properties of suction caisson foundation

Properties	Values
Material type	Elastic
Axial 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 (ν)	0.25
Wall thickness (t)	0.03 m
Caisson diameter (D)	20 m

During the course of analysis, firstly the caisson moves downwards under its own weight. When the pullout load is applied, the initial displacement is reversed. This stage of initial displacement is not taken into consideration, and pullout analysis has been carried out considering the initial point of suction caisson foundation where it was placed initially. The analysis was performed for different caisson aspect ratios (L/D) which is the ratio of caisson length to caisson diameter. L/D ratio was varied from 0.5 to 4 (0.5, 1, 1.5, 2, 2.5, 3, 3.4 and 4), by keeping either diameter or length as constant.

Numerical model verification

The model accuracy has been checked by comparing the current results with available experimental results of Iskander et al. [1]. A caisson foundation with diameter of 100 mm and skirt length of 600 mm, embedded in normally consolidated cohesive soil, was modelled, considering the same caisson material and soil properties as used by Iskander et al. [1] in their experiments. Figure 1 depicts the comparison of load–displacement response under undrained condition between the present study and reported experimental results. A good agreement can be noted up to peak value. After the peak load, the plot of Iskander et al. [1] is showing post-peak drop of load indicating that the foundation has failed, whereas for present study, the load increases asymptotically with displacement indicating hardening behaviour of foundation. This is due to the reason that Iskander et al. [1] laboratory pullout analysis is based on displacement controlled method where load–displacement response shows strain softening behaviour. However, in the present study, the pullout capacity is carried out based on load-controlled method, where stress–strain response shows strain hardening behaviour. Nevertheless, the ultimate pullout capacity of the present study and experimental studies of Iskander et al. [1] are comparable. Therefore, it has been decided that numerical models are convincingly able to predict the ultimate pullout capacity of suction caissons foundation for different soil types and drainage conditions within acceptable accuracies.

Results and discussion

Effect of soil cohesion

Cohesion is the property which holds soil particles together, and this has significant effect on the foundation behaviour. In this analysis, the cohesion value was varied from 5 to 60 kPa, keeping other parameters constant. The typical effects of soil cohesion on pullout response of foundation of 10 m length and 20 m diameter are shown in Figs. 2 and 3, respectively, for drained and undrained conditions against

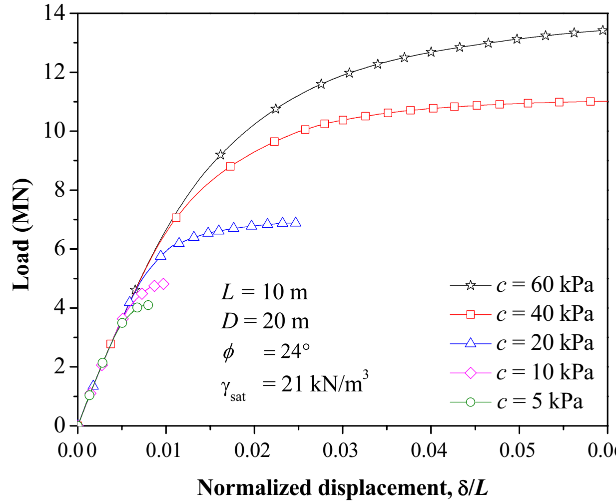

Fig. 2 Effect of soil cohesion on vertical pullout capacity under drained condition

a dimensionless parameter termed as normalized displacement. Normalized displacement (δ/L) is the ratio of caisson displacement (δ) to that of caisson length (L). The ultimate pullout capacity has been considered when either the caisson fails or the load increment with displacement is asymptotic. It has been found that the pullout capacity of the foundation increases with increasing soil cohesion. The pullout capacity under undrained condition is higher than that of drained condition. Also, the failure of foundation under drained condition takes place when only skin friction reaches its ultimate value at relatively smaller caisson displacement compared to that of undrained condition, where failure involves both

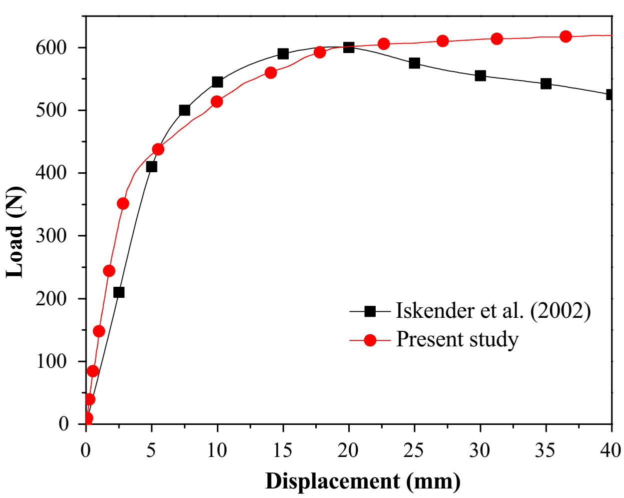

Fig. 1 Comparison of results of the present study with Iskander et al. [1] ($D = 100$ mm, $L = 600$ mm)

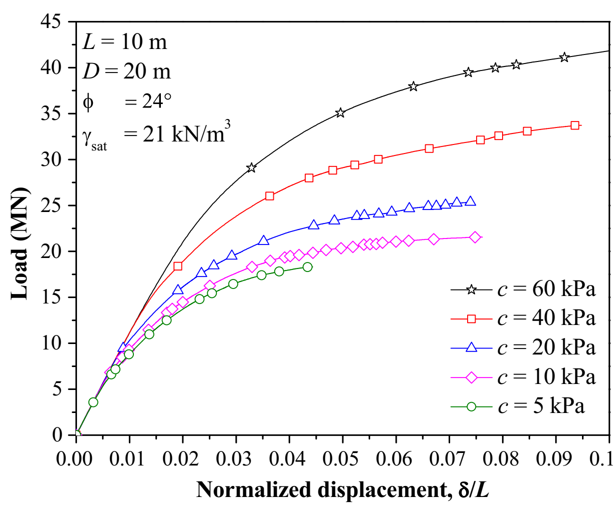

Fig. 3 Effect of soil cohesion on vertical pullout capacity under undrained condition

skin friction and end-bearing failure of foundation involving higher caisson displacement.

The effect of soil cohesion on ultimate pullout capacity under both drained and undrained conditions is summarized in Table 3, along with the ratio of undrained and drained pullout capacity. The ultimate pullout capacity increases with increase in cohesion value. Undrained pullout capacity is found to be at least three times that of the drained condition. Similar trend was found by Iskander et al. [1], in which the undrained pullout capacity of suction caisson foundation was approximately three times the capacity of drained pullout in laboratory model test with *L*/*D* ratio of 6.

The failure mechanism under varying drainage condition can further be explained based on plastic point generation in the soil domain during pullout. Figure 4a, b shows the generated plastic points at the end of pullout for drained and undrained conditions, respectively. As residual friction force is overcome initially, plastic points start to generate at the top and bottom of the external soil–caisson interface. These plastic points continue to develop at the interface till the full friction capacity is mobilized. In case of drained condition, the plastic points extend only on the soil–caisson interface (Fig. 4a). These points develop more rapidly on the external wall surface and less rapidly on the internal wall surface. Thereafter, only the caisson wall moves upwards without any soil plug, resulting in lower bearing capacity than that under undrained condition. At failure, the soil is fully detached from the caisson wall, and failure is mostly local, i.e. it occurs only near the caisson wall only.

In case of undrained condition, these plastic points shift away from the caisson wall surface. In this way, the failure surface shifts from the caisson vicinity to more extended areas in the surrounding soil with post-failure hardening behaviour. Thereafter, the reverse bearing capacity mechanism starts in case of undrained condition and eventually reaches the soil surface as shown in Fig. 4b. During movement of caisson, both soil and caisson move upwards together up to foundation failure. The soil plug provides added capacity to the foundation prior to failure. Also, the suction developed within the caisson in undrained condition reduces the positive pore pressure. This reduction in pore pressure creates higher effective stress in the soil, and greater normal stresses on the failure surfaces leading to higher shear and frictional forces on the surfaces.

The difference in pullout capacity and failure displacement is due to the difference in failure mechanism, as shown in Fig. 5a, b. The suction developed inside the caisson in undrained condition results in addition of soil plug weight along with the caisson weight, enhancing the overall load-bearing capacity (Fig. 5a). This formation of soil plug causes reverse bearing failure of soil leading to higher pullout capacity during pullout along with higher displacement of foundation from their initial position. Also, the suction

Table 3 Pullout capacity with varying soil cohesion under drained and undrained conditions

c (kPa)	Pu_{d} (MN)	Pu_{ud} (MN)	Pu_{ud}/Pu_{d}
5	4.23	16.3	3.15
10	4.81	20.1	4.18
20	6.88	25.3	3.67
40	11.14	33.7	3.02
60	13.93	46.8	3.36

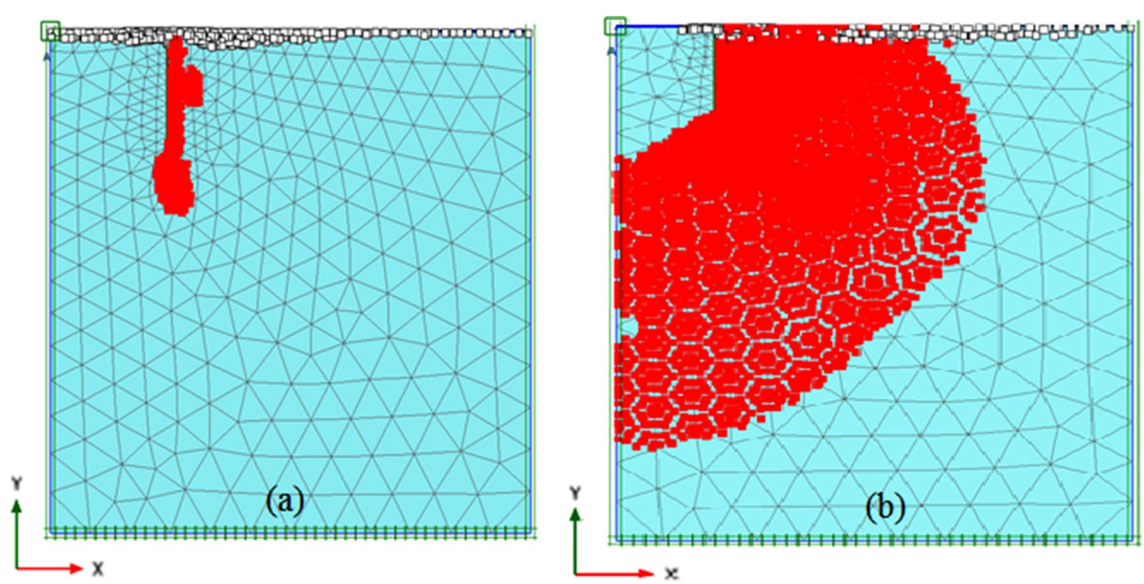

Fig. 4 Plastic points generated at failure: **a** drained condition, **b** undrained condition

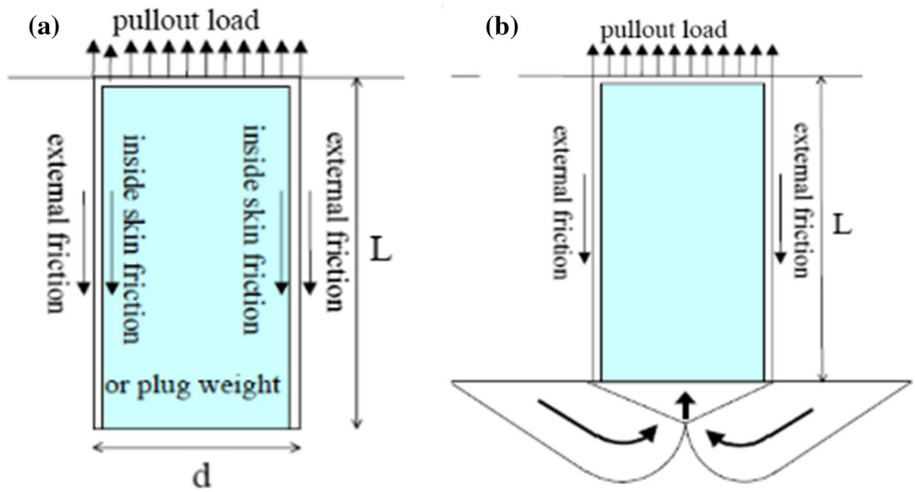

Fig. 5 Soil failure mechanisms during vertical pullout: **a** drained condition, **b** undrained condition

developed during undrained pullout contributes to the load-bearing capacity of foundation. This suction improves the soil resistance characteristics in the vicinity of the foundation system and thus indirectly enhances the overall load-bearing capacity. On the other hand, for drained condition, the load transfer is mainly due to the skin friction on both inside and outside of caisson wall without development of any soil plug within caisson (Fig. 5b). Thus, the failure of foundation takes place when skin friction reaches its ultimate value at relatively smaller caisson displacement leading to the foundation failure than that under undrained condition where failure involves both skin friction and end-bearing failure of foundation.

Effect of soil friction angle

Internal friction angle is the resistance due to interlocking of soil particles which influences the pullout capacity of suction caisson. The friction angle (ϕ) of soil has been varied as 16°, 20°, 24° and 28° by keeping other soil and caisson parameters unchanged. The effect of friction angle on pullout capacity against normalized displacement is shown in Figs. 6 and 7, respectively, under drained and undrained conditions for the caisson foundation of 10 m length and 20 m diameter. The pullout capacity increases with increase in friction angle. The ultimate pullout capacity values are summarized in Table 4 along with the ratio of undrained pullout capacity and drained pullout capacity. The undrained pullout capacity is minimum three times greater than that of drained pullout capacity. This is due to the generation of negative pore pressure, suction and hydraulic gradient under undrained condition which causes higher effective stress and magnifies the effect of soil friction angle. The caisson is also noted to fail at smaller displacement for drained condition than that of undrained condition.

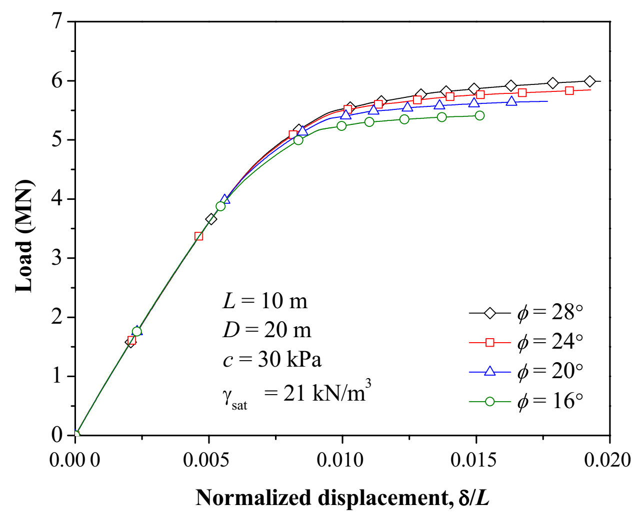

Fig. 6 Effect of soil friction angle on vertical pullout capacity under drained condition

Effect of caisson aspect ratio

The caisson aspect ratio (*L/D*) has been varied in two ways, either by keeping caisson diameter (*D*) constant and varying caisson length, or by keeping caisson length (*L*) constant and varying caisson diameter. For constant diameter case, the diameter was fixed as 20 m and the caisson length was varied from 10 to 60 m (10, 20, 30, 40, 50 and 60 m). In case of constant length, the caisson length was fixed as 10 m and diameter was varied from 2.5 to 20 m (2.5, 5, 10, 15 and 20 m). All the soil parameters were kept constant during this analysis ($c = 30$ kPa and $\phi = 24°$). The effects of *L/D* on pullout capacity under drained and undrained conditions are plotted in Figs. 8 and 9 for constant diameter case and in Figs. 10 and 11 for constant length case, respectively.

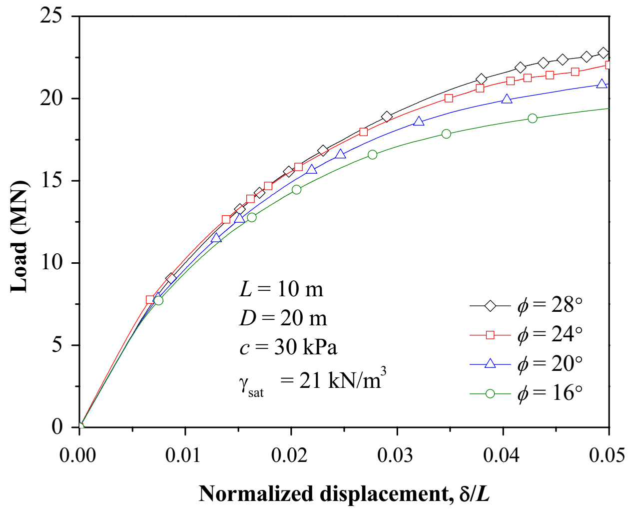

Fig. 7 Effect of soil friction angle on vertical pullout capacity under undrained condition

Table 4 Pullout capacity with varying friction angle under drained and undrained conditions

ϕ (°)	Pu_d (MN)	Pu_{ud} (MN)	Pu_{ud}/Pu_d
12	5.31	18.3	3.22
16	5.62	20.4	3.47
20	5.83	21.8	3.62
24	5.96	22.9	3.74
28	6.20	23.8	3.76

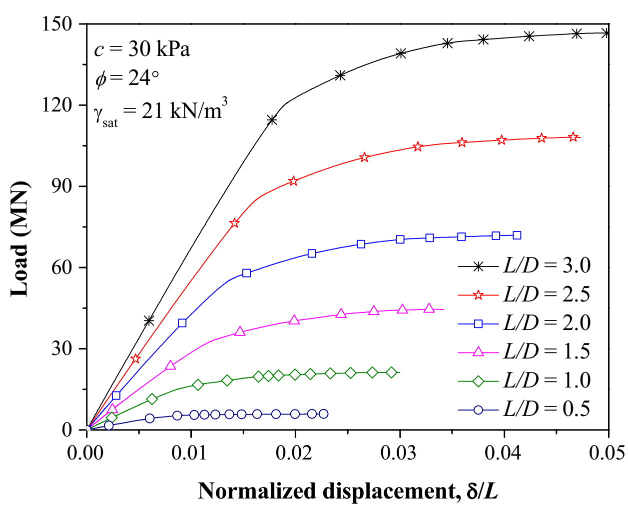

Fig. 8 Effect of caisson aspect ratio on drained pullout capacity when diameter is kept constant

For constant caisson diameter, the increasing caisson length or aspect ratio causes increase in pullout loading and failure displacement (Figs. 8, 9) for both drained and

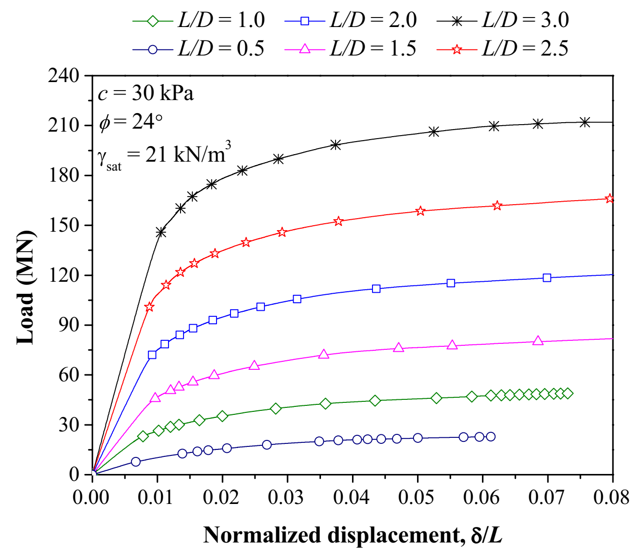

Fig. 9 Effect of caisson aspect ratio on undrained pullout capacity when diameter is kept constant

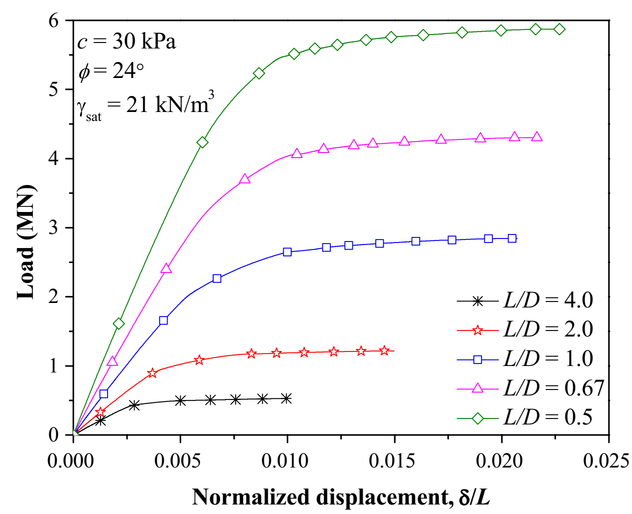

Fig. 10 Effect of caisson aspect ratio on drained pullout capacity when caisson length is kept constant

undrained conditions. This is due to the reason that with increasing caisson length, the overall caisson volume and contact surface area between the soil and foundation are increased, leading to larger soil plug inside the caisson and more frictional resistance between soil and caisson wall. Further, this increase in caisson length leads to increase in average normal force acting on the caisson wall. The increasing caisson length also increases the drainage path and boosts the seepage force which improves the suction effect on the load-bearing capacity of caisson foundation. The ultimate pullout capacity for this case is summarized in Table 5 along with the ratio of undrained and drained

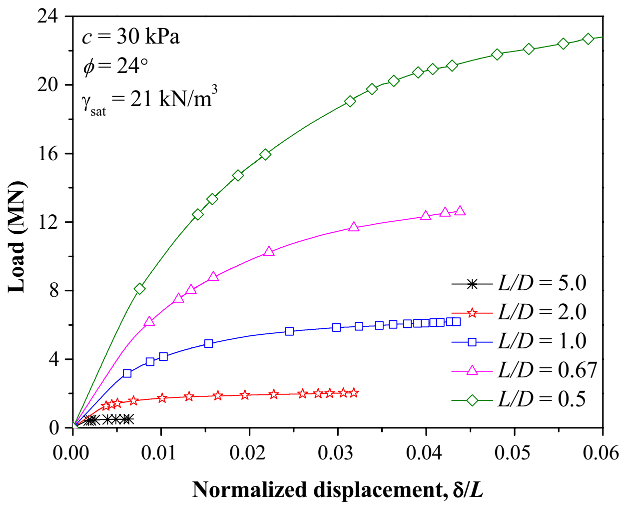

Fig. 11 Effect of caisson aspect ratio on undrained pullout capacity when length is kept constant

Table 5 Pullout capacity with varying *L/D* for constant caisson diameter under drained and undrained conditions

L/D	Pu_d (MN)	Pu_{ud} (MN)	Pu_{ud}/Pu_d
0.5	5.9	22.9	3.88
1.0	21.2	48.9	2.31
1.5	44.6	84.7	1.89
2.0	71.9	128.1	1.78
2.5	108.2	182.9	1.69
3.0	146.7	212.0	1.44

pullout capacity. For any aspect ratio, the pullout capacity under undrained condition is greater than that of drained condition. Also, the ratio of undrained and drained pullout capacity decreases with increasing aspect ratio, i.e. increasing caisson length.

When the caisson length ($L = 10$ m) is kept constant and aspect ratio (*L/D*) is varied by changing *D*, the pullout capacity is found to increase with decreasing aspect ratio along with increasing failure displacement. For fixed caisson length, with decreasing aspect ratio, the caisson diameter increases (Figs. 10, 11). This increasing caisson diameter increases the surface area and overall volume of caisson. This leads to the increase in surficial friction force and cohesive resistance between soil and interface area of caisson wall along with larger soil plug, resulting in higher pullout capacity. However, the pullout capacity with increasing caisson length is much higher than that of increasing caisson diameter. Thus, it can be said that increasing caisson length is more beneficial for increasing the pullout capacity of suction caisson foundation keeping caisson diameter constant than that of increasing diameter by keeping caisson length constant. The summary of pullout capacity for this condition is given in Table 6 along with the ratio of undrained and drained pullout capacity. It can be noted that both pullout capacity and pullout ratio decrease with increasing aspect ratio, i.e. decreasing caisson diameter.

Comparing the above-mentioned two cases of varying caisson aspect ratio, it can be noted that the pullout capacity with increasing aspect ratio is much higher in case of increasing length by keeping diameter constant than that of decreasing diameter by keeping length constant (Tables 5, 6). For both conditions, at any caisson aspect ratio, undrained pullout capacity is higher than that of drained pullout capacity. This is due to the effect of generated pore pressure during undrained condition. The generated extra pore water pressure contributes in holding the soil plug within caisson.

Mathematical model

Based on the results of the current study, multiple regression statistical analysis was carried out to develop models for predicting the vertical pullout capacity of suction caisson foundation under both drained and undrained conditions. Regression analysis is a statistical tool for the investigation of relationship between dependent and independent variables. The vertical pullout capacity is a function of soil shear strength parameters (c and ϕ) and caisson aspect ratio (*L/D*). In multiple regression analysis, the relationship between the dependent variable (P_u) and the independent variables (*L/D*, ϕ, c) can be presented as follows:

$$y_i = a_o + a_1 x_{i1} + a_2 x_{i2} + \cdots + a_k x_{ik}, \tag{12}$$

where $i = 1, 2, 3, \ldots, n$ is the number of observations, y_i is dependent variable, $x_{i1}, x_{i2}, \ldots, x_{ik}$ are independent variables, and $a_0, a_1, a_2, \ldots, a_k$ are regression coefficients. The mathematical models developed are as:

Table 6 Pullout capacity with varying *L/D* for constant caisson length under undrained and drained conditions

L/D	Pu_d (MN)	Pu_{ud} (MN)	Pu_{ud}/Pu_d
0.5	5.9	22.9	3.88
0.67	4.30	12.6	2.93
1.0	2.84	6.18	2.17
2.0	1.21	2.03	1.67
2.5	0.89	1.36	1.53
4.0	0.54	0.70	1.29

Under drained condition

$$\log_{10}\left(Pu_{\mathrm{d}}\right) = 0.95 + 0.413\log_{10}(c) + 0.273\log_{10}(\tan\phi) + 1.729\log_{10}\left(\frac{L}{D}\right) \tag{13}$$

$$\Rightarrow Pu_{\mathrm{d}} = 8.91(c)^{0.413}(\tan\phi)^{0.273}\left(\frac{L}{D}\right)^{1.729}$$

Under undrained condition

$$\log_{10}\left(Pu_{\mathrm{ud}}\right) = 1.257 + 0.476\log_{10}(c) + 0.262\log_{10}(\tan\phi) + 1.268\log_{10}\left(\frac{L}{D}\right) \tag{14}$$

$$\Rightarrow Pu_{\mathrm{ud}} = 18.07(c)^{0.476}(\tan\phi)^{0.262}\left(\frac{L}{D}\right)^{1.268}$$

The respective values of R^2 for Eqs. 13 and 14 are 0.95 and 0.94, while the values of standard error are 0.054 and 0.053, respectively, indicating excellent quality of fit for the models.

Comparison of results

The pullout capacity values calculated by models developed in this study are compared in Figs. 12 and 13, with those obtained by the available methods mentioned in "Methods for pullout capacity" section, respectively, for drained and undrained conditions. The pullout capacity under drained condition (Fig. 12) is showing very good agreement with that of Sgardeli [13]. The method developed by Sgardeli [13] to predict the net ultimate pullout capacity of suction caisson foundation under drained condition as in Eq. 4 is based on limit equilibrium method, where the pullout capacity is the frictional resistance occurring on the exterior and interior caisson wall surfaces during pullout loading. The pullout capacity obtained as per Iskander et al. [1] and Deng and Carter [7] is on the lower side that of the present results; however, the pullout capacity calculated by Rahman et al. [11] is on the higher side.

For undrained condition (Fig. 13), pullout capacity by Iskander et al. [1] and Sgardeli [13] is higher than the present results at all aspect ratios used in this study, except for $L/D = 3$, in which the pullout capacity of Iskandar et al. [1] and the present study are nearly the same. It has been noted that the undrained pullout capacity by Iskandar method is much greater than that of the present study at lower aspect ratio, and the value gradually decreases with increasing caisson aspect ratio and comes close to that of the present study at higher aspect ratio of 2.5 and 3. The present analysis results show higher undrained pullout capacity values than those obtained by Christensen et al. [5], Clukey and Morrison [6], Deng and Carter [7], Rahman et al. [11] and Renzi et al. [12].

The variation in results of the current study with available methods is due to the reason that the pullout capacity of existing methods is dependent only on the caisson aspect ratio and shear strength (S_{u}) of the soil. While in present analysis, several soil parameters (c, ϕ, ν, γ_{sat}) and soil–foundation interface parameter (R_{inter}) have also been considered along with caisson aspect ratio and shear strength (S_{u}) of the soil. There is also no proper matching among the results of different methods. This is due to the reason that the bearing capacity factor, shape factor, external skin friction factor, depth factor and embedment factor for different methods have been calculated in different ways and have different values. Also, methods developed by analytical approach might have used different soil models in their analysis. Overall, it

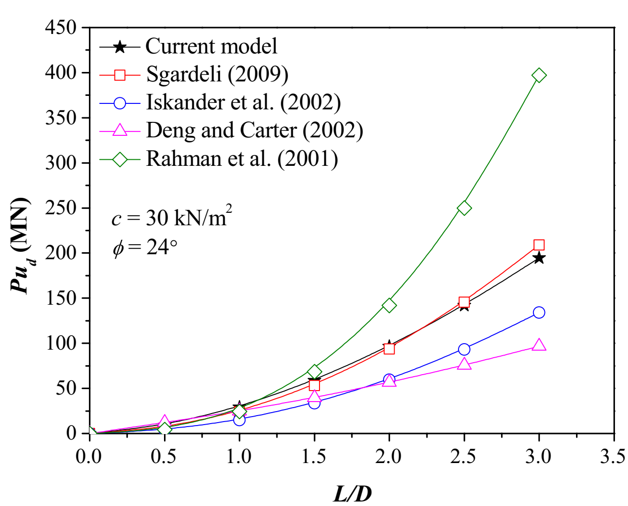

Fig. 12 Comparison of drained pullout capacity calculated by different methods

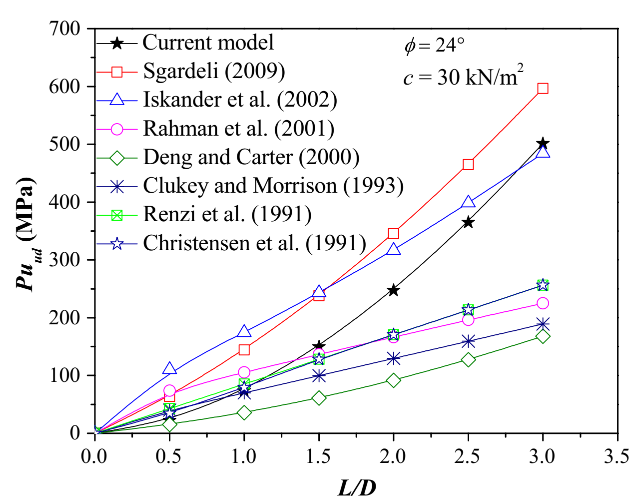

Fig. 13 Comparison of undrained pullout capacity calculated by different methods

can be said that the current model has resulted in reasonably good prediction of pullout capacity particularly under drained conditions and can be used for predicting the pullout capacity of suction caisson foundation in cohesive soil. Under undrained condition, the pullout capacity curve by the current model is showing some different trend, especially at higher aspect ratio, and this model needs some further investigation under undrained condition.

Conclusions

From the numerical analysis of vertical pullout capacity of suction caisson foundation in cohesive soil under both drained and undrained conditions with varying soil cohesion, soil friction angle and caisson aspect ratio, the following major findings can be highlighted:

- For any caisson aspect ratio and drainage condition, the vertical pullout capacity of suction caisson foundation increases with increasing soil cohesion and friction angle.
- The upper and lower limits of vertical pullout capacity of suction caisson foundation depend on the undrained and drained conditions, respectively.
- The foundation under drained condition fails easily as it requires comparatively less deformation than that under undrained condition.
- For any friction angle and cohesion of soil, with constant caisson diameter and increasing caisson aspect ratio, the vertical pullout capacity increases and the ratio of undrained and drained pullout capacity decreases. In contrast, with constant caisson length and increasing caisson aspect ratio, both the vertical pullout capacity and the ratio of undrained and drained pullout capacity decrease.

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