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Analytical study of the failure mode and pullout capacity of suction anchors in clay

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Abstract. Suction anchors are widely adopted in mooring systems. However there are still challenges in predicting the failure mode and ultimate pullout capacity of the anchor. Previously published methods for predicting the inclined pullout capacity of suction anchors are mainly based on experimental data or the FEM analysis. In the present work, an analytical method that is capable of predicting the failure mode and ultimate pullout capacity of the suction anchor in clay under inclined loading is developed. This method is based on a rational mechanical model for suction anchors and the knowledge of the mechanism that the anchor fails in seabed soils. In order to examine the analytical model, the failure angle and pullout capacity of suction anchors from FEM simulation, numerical solution and laboratory tests in uniform and linear cohesive soils are employed to compare with the theoretical predictions and the agreement is satisfactory. An analytical method that can evaluate the optimal position of the attachment point is also proposed in the present study. The present work proves that the failure mode and pullout capacity of suction anchors can be reasonably determined by the developed analytical method.

Keywords: suction anchor; failure mode; pullout capacity; ultimate pullout capacity; inclined loading; analytical model; clay

1. Introduction

The first commercial application of suction anchors was reported by Senpere and Auvergne (1982), in which 12 installations of suction anchors were used for a catenary anchor leg mooring in the North Sea. After that, suction anchors were widely adopted in a variety of offshore engineering applications because of good performances both in pullout capacity and deepwater installation (Christophersen *et al*. 1992, Tjelta 1995, Byrne *et al*. 2002, Dendani and Colliat 2002, Audibert *et al*. 2003). Compared with other types of anchor such as the drag anchor and the gravity-installed anchor, one of the big advantages of the suction anchor is that it can be installed reliably at pre-selected locations with good precision and minimum seafloor disturbance. In addition, for the good performance under different loading conditions, suction anchors can be used as foundations of different mooring systems, e.g., they are applied to TLPs under vertical loading, taut-wire mooring systems under inclined loading and catenary mooring systems under horizontal loading. In order to guarantee the reliability and the economy of the design of suction anchors, the

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study including the pullout capacity and the failure mode of suction anchors is significant and the capacity under different loading conditions should be firstly evaluated.

The research of the pullout capacity of suction anchors under vertical and horizontal loadings has been performed by many researchers by means of field tests, laboratory tests and finite element analysis (Hogervorst 1980, Sukumaran and McCarron 1999, House and Randolph 2001, Cho 2003, Cluky *et al*. 2003, Huang 2003). However, few studies, especially the theoretical analysis, were performed on the capacity of suction anchors under inclined loading. A main reason is that this is very hard to provide a rational mechanical model that can describe the behavior of suction anchors under any loading condition. Several researchers proposed analytical or empirical methods to estimate the inclined pullout capacity of suction anchors. A failure model for skirted anchors with a large penetration depth-to-diameter ratio and loaded at the optimal attachment point was developed by Andersen and Jostad (1999) and suggested by the DNV code (DNV 2005). In this model, the skirted anchor is separated into two parts with a mobilized depth. Active and passive earth pressures are assumed acting on the upper part of the anchor, and the soil may flow around the deep part of the anchor. The pullout capacity can be calculated by adopting appropriate values of parameters, such as the depth to the deep part of the anchor, the active and passive earth pressure coefficients and the roughness factors at the anchor-soil interfaces and the sides of the active and passive zones in the soil. Watson *et al*. (2000) developed a method to analyze the pullout capacity of suction anchors with a 2-dimensional ‘yield envelop’ which is deduced from experimental tests. Within the yield envelope, behavior of the suction anchor is generally assumed to be elastic, and the elastic-plastic response during and after yield is often computed using an associated flow rule. However, experimental data have to be used to determine the coefficients and assess the shape of the yield envelop. Aubeny *et al*. (2003) presented a simplified method of analysis for estimating the lateral pullout capacity of suction anchors based on an upper bound plasticity formulation. The interactional relationship between the ultimate lateral and axial resistance along the side of the anchor caisson was investigated by using the FEM analysis.

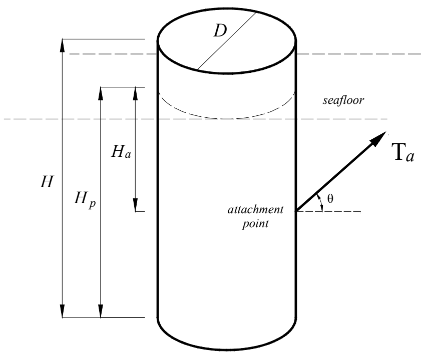
In the present work, an analytical method that is capable of predicting the pullout capacity of suction anchors in clay under inclined loading is developed. A mechanical model is introduced first to describe the behavior of suction anchors under inclined loading. Then a method for predicting the failure mode of the suction anchor under inclined loading is proposed as well, because the displacement direction at anchor failure (or failure direction) will significantly influence the pullout capacity of the anchor. In order to examine the analytical method, the pullout capacity of suction anchors in uniform and linear cohesive soils from the FEM simulation, numerical solution and laboratory tests are employed to compare with the theoretical predictions. Considering that the present analysis is based on the assumption that the inclined external force is applied on the optimal attachment point of the suction anchor, an analytical method that can evaluate the optimal position of the attachment point is also proposed, which forms an important part of the present work.

2. Mechanical model for suction anchors

As mentioned above, the suction anchor may work in different loading conditions varying from horizontal loading to vertical loading. Thus, a mechanical model which is appropriate for the suction anchor in any loading condition is significant and forms the basis of the theoretical analysis. In the present study, it is assumed that the external force is applied at the optimal attachment point of the suction anchor. In this situation, only transition occurs during anchor failure and the anchor has the maximum pullout capacity. As reported by Keaveny *et al*. (1994), when the external force is attached at the optimal attachment point, the anchor's pullout capacity is almost doubled than attaching the force at the mudline.

2.1 Force equilibrium of the anchor in the failure mode

As illustrated in Fig. 1(a), D is the diameter of the anchor, H is the height of the anchor, H_p is the distance from the seafloor to the anchor bottom, i.e., the penetration depth of the anchor, and H_a is the distance from the seafloor to the attachment point. The equilibrium forces acting on the suction anchor in the failure mode are shown in Fig. 1(b), in which T_a is the chain tension at the attachment point, T_m and T_n are components of T_a along the failure direction and normal to the failure direction, respectively, θ is the angle subtended by the chain to the horizontal at the attachment point and also called the mooring angle, β is the displacement direction to the horizontal at anchor failure and also called the failure direction, F_b is the end bearing in the failure direction of the anchor, F_s is the shear force in the failure direction on the side of the anchor, V_{bot} and H_{bot} are the vertical resistance and the horizontal shear force acting on the bottom of the anchor (including the annulus of the caisson and the bottom of the soil plug inside the caisson), respectively, and W' is the total submerged weight of the anchor and the soil plug inside the caisson.



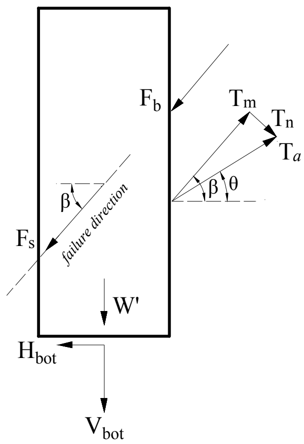


Fig. 1 Geometry and mechanical model of the suction anchor

The force equilibrium in the failure direction is established as

$$T_m = F_b + F_s + (V_{bot} + W')\sin\beta + H_{bot}\cos\beta \tag{1}$$

The ultimate chain tension at the attachment point T_a can then be expressed as

$$T_a = \frac{1}{\cos(\beta-\theta)}\left[F_b + F_s + (V_{bot} + W')\sin\beta + H_{bot}\cos\beta\right] \tag{2}$$

2.2 Expressions of the forces

For saturated clay, the soil strength may be modeled as a frictionless material with cohesion equal to the undrained shear strength which is generally represented as

$$s_u = s_{u0} + kz \tag{3}$$

where, z is the soil depth below the seafloor, s_{u0} is the undrained shear strength at the seafloor (z=0), and k is the gradient of the undrained shear strength with depth.

The end bearing F_b can be calculated adopting the bearing capacity formula for strip footings proposed by Skempton (1951), that is

$$F_b = N_c s_{u,a} A_b \tag{4}$$

where, N_c is the end-bearing factor which will be discussed in detail in the following section, $s_{u,a}$ is the average undrained shear strength at the mid-depth of the anchor, and A_b=$DH_p\cos\beta$ is the effective bearing area in the failure direction of the anchor.

The shear force acting on the anchor is from adhesion of clay. Ignoring variation of the adhesion around the anchor, the shear force can be calculated following the conventional pile design practice, that is

$$F_s = \alpha s_{u,a} A_s \tag{5}$$

where, α is the adhesion factor, and A_s=$2DH_p\beta/\sin\beta$ denotes the effective shear area in the failure direction, which varies with the failure direction. Note that F_s is derived through calculating the shear stress at any point and then integrating over the whole side of the anchor.

When a suction anchor with sealed top cap is under rapid vertical loading (β=$\pi/2$), the saturated soil can be regarded as in an undrained condition and the soil plug inside the caisson will move out with the anchor during pulling out. The reverse end-bearing resistance to the bottom of the anchor can be estimated using the standard bearing capacity approach (Randolph and House 2002) as the following

$$V_0 = (N_{c,bot} s_{u,bot} - \sigma_v')A_{bot} \tag{6}$$

where, V_0 is the reverse end-bearing resistance to the anchor bottom under vertical loading, $N_{c,bot}$ denotes the reverse end-bearing factor and will be discussed in detail in the following section, $s_{u,bot}$ is the undrained shear strength at the anchor bottom, $N_{c,bot}s_{u,bot}$ is the net reverse end-bearing stress, $\sigma_v' = \gamma' H_p$ is the effective stress at the anchor bottom in which γ' is the submerged soil weight, and A_{bot}=$0.25\pi D^2$ is the area of the anchor bottom including both the tip of the caisson and the bottom of the soil plug. However, if a suction anchor is under an inclined failure mode (β<$\pi/2$), the net reverse end-bearing resistance reduces with decreasing value of β. Hence, an inclination factor $\lambda=2\beta/\pi$ is introduced to represent the vertical resistance to the anchor bottom in any failure mode

$$V_{bot} = (\lambda N_{c,bot} s_{u,bot} - \sigma_v') A_{bot} \tag{7}$$

When a suction anchor is under horizontal loading (β=0), the horizontal shear force H_0 on the anchor bottom can be expressed as

$$H_0 = s_{u,bot} A_{plug} + \alpha s_{u,bot} A_{annu} \tag{8}$$

where A_{plug} and A_{annu} denote the bottom area of the soil plug and the annulus area of the caisson, respectively. Contrary to the vertical resistance, the horizontal shear force in an inclined failure mode decreases with increasing value of β, and can be expressed as

$$H_{bot} = (1-\lambda)(s_{u,bot} A_{plug} + \alpha s_{u,bot} A_{annu}) \tag{9}$$

2.3 Discussion on the parameters

In the above analysis, selecting a reasonable value of parameters is significant for predicting the pullout capacity of the suction anchor. However, there has not been a clear knowledge of the values of some parameters, especially N_c and $N_{c,bot}$. Hence, it is necessary to discuss them in this section.

2.3.1 End-bearing factor N_c

To the authors' knowledge, there has not been a study published in the literature that recommends the value of the end-bearing factor N_c for the suction anchor which is approximately regarded as a vertically embedded strip footing. However, the lateral bearing capacity of piles or suction anchors under horizontal loading as well as the lateral bearing factor were investigated by several researchers (Randolph and Houlsby 1984, Murff and Hamilton 1993). In purely cohesive soils, the ultimate side resistance p is commonly considered relating to the undrained shear strength s_u by a dimensionless lateral unit resistance factor N_p as $p=N_p s_u$. Thus, the lateral bearing capacity of the suction anchor can be calculated as

$$P = D\int N_p s_u dz \tag{10}$$

Note that the lateral bearing capacity of the anchor can also be expressed as the sum of the end-bearing F_b, the shear force on the anchor side F_s and the shear force on the anchor bottom H_0. Adopting Eqs. (4), (5), (8) and (10), the following expression can be obtained

$$P = D\int N_p s_u dz = (N_c + 2\alpha) s_{u,a} D H_p + \alpha s_{u,bot} A_{annu} + s_{u,bot} A_{plug} \tag{11}$$

The end-bearing factor N_c can then be expressed as

$$N_c = [(D\int N_p s_u dz - \alpha s_{u,bot} A_{annu} - s_{u,bot} A_{plug}) \big/ (s_{u,a} D H_p)] - 2\alpha \qquad (12)$$

Eq. (12) indicates that the value of N_c can be determined if knowing the lateral bearing factor N_p. Murff and Hamilton (1993) developed an upper bound plastic limit approach to lateral bearing capacity of piles and caissons, in which a collapse mechanism comprised of a surface failure wedge, a plain strain flow-around zone and a hemispherical failure surface at the pile tip was assumed. The dimensionless lateral unit resistance factor N_p for soils with uniform and linearly varying undrained shear strength profiles can be expressed as

$$N_p = N_1 - N_2 \exp(-\eta z/D) \qquad (13)$$

where, η=0.25+0.05ρ for ρ<6, η=0.55 for ρ>6, and $\rho=s_{u0}/(kD)$. The parameter N_1 is simply the lateral unit resistance factor far from the free surface, which is also the Randolph-Houlsby (1984) factor for an infinitely long cylindrical pile, i.e., 11.94 and 9.42 for rough and smooth caissons, respectively. Similarly, assuming a plane strain passive earth pressure state at the free surface implies that the difference (N_1-N_2) is 2.82 and 2.0 for rough and smooth caissons, respectively. Note that N_p is a function of depth z in Eq. (13).

In the present study, Eq. (13) is adopted to calculate the value of N_p, and then Eq. (12) is used to obtain the value of N_c.

2.3.2 Reverse bearing factor $N_{c,bot}$

The difference between the suction anchor and the pile is that the former is sealed at the top. In addition, suction anchors that are applied in clays usually have a large aspect ratio (length/diameter). Thus, the negative pressure will be created under the anchor cap and enhance the pullout capacity of the anchor. Consequently, the soil plug inside the caisson accompanies the anchor during the anchor failure.

For the sealed suction anchor under rapid loading in clays, the reverse bearing resistance is assumed acting on the bottom of the anchor. Watson *et al*. (2000) performed a series of centrifuge tests to study the reverse bearing resistance of the suction anchor. The experimental results showed that the anchor capacity was almost the same no matter under compression or tension conditions. Hence, the reverse end-bearing resistance can be estimated using the standard bearing capacity approach. Clukey and Morrison (1993) discussed the results of centrifuge tests on the tensile capacity of suction caissons (L/D≈2) in normally consolidated soils, and the reverse bearing factor was approximately taken as 11. Watson *et al*. (2000) suggested that the bearing resistance in tension be similar in magnitude to that in compression, and the value of the conventional bearing factor N_c be customarily taken as 9. It was observed from the centrifuge data (Martin 2001) that the reverse bearing factor is between 6.5 and 8.5, which is somewhat less than the theoretical value of 9 for an embedment depth of 2 diameters. DNV (2005) stated that the reverse bearing capacity below anchor tip for vertical loading can be calculated with a bearing capacity factor ranging from 6.2 at the surface to 9 at depth greater than 4.5 times the diameter, and can be expressed as $N_{c,bot}$=6.2×[1+0.34×arctan(H_p/D)].

3. Analytical model for predicting the failure mode and ultimate pullout capacity

3.1 Mechanism of anchor failure

A correct understanding of the mechanism of anchor failure is the basis of the analytical model for predicting the failure mode and ultimate pullout capacity of suction anchors. In the theoretical framework of the present study, β is an important parameter that not only reflects the failure mode but also significantly influences the pullout capacity of the suction anchor. Thus, developing a rational method for predicting the value of β is significant in the present study. Once the failure angle β is confirmed, the ultimate pullout capacity can be calculated through the force equilibrium equation, i.e., Eq. (2). Previous work may help us to have an insight into the mechanism of anchor failure. A relevant analytical method was introduced by Liu *et al*. (2012) to predict the movement direction of the drag anchor with an arbitrary fluke section in soils. In the study, a 'movement angle' which represents the movement direction of the drag anchor during penetration was assumed and determined according to an important principle, i.e., the anchor will penetrate with the movement angle that requires the least drag force during anchor penetration.

Obviously, it is the mooring force that leads to the suction anchor failing in soils. Assuming that there are a series of possible failure directions of the anchor, the real failure direction must be the direction in which the soil resistance is easiest to be overcome by the mooring force. In other words, the direction that needs the least mooring force to overcome the soil resistance is the real failure direction.

3.2 Analytical procedure for determining the failure direction and pullout capacity

The above principle that determines the failure direction is applied along with the mechanical model as shown in Fig. 1. Assuming that β is the unknown failure angle with respect to horizontal in the range [0, $\pi/2$], according to the principle that judges the failure direction, the failure direction can then be determined if the variation of T_a with the angle β is clearly known. This can be achieved by investigating the first derivative of T_a with β. The relationship of T_a and β has already been obtained, i.e., Eq. (2). Hence, the first derivative of T_a with β can be obtained as

$$\frac{dT_a}{d\beta}=\frac{1}{\cos^2\left(\beta-\theta\right)}T\left(\beta\right) \tag{14}$$

where,

$T(\beta)=[dF_b/d\beta+dF_s/d\beta+(dV_{bot}/d\beta)\sin\beta+(dH_{bot}/d\beta)\cos\beta]\cos(\beta-\theta)+(F_b+F_s)\sin(\beta-\theta)-H_{bot}\sin\theta$ $+(V_{bot}+W')\cos\theta$, and $0<\beta$, $\theta<\pi/2$.

The variation of T_a with β in [0, $\pi/2$] can be known by investigating the values of T_a at several special points, in other words, the minimum value of T_a can only be reached at these special points. The special points include three types: (a) the boundary points, i.e., β=0 and $\beta=\pi/2$; (b) the points that meet the equation $dT_a/d\beta=0$, i.e., the first derivatives at the points are zero; (c) the points that the first derivatives are non-existent. Employing the expressions of the forces acting on the suction anchor, the equation $dT_a/d\beta=0$ can be solved to identify the last two types of point.

For the suction anchor, the failure angle and the ultimate pullout capacity can be obtained by performing the following analytical procedures:

(1) Accurately express all forces acting on the suction anchor in the assumed failure direction β.

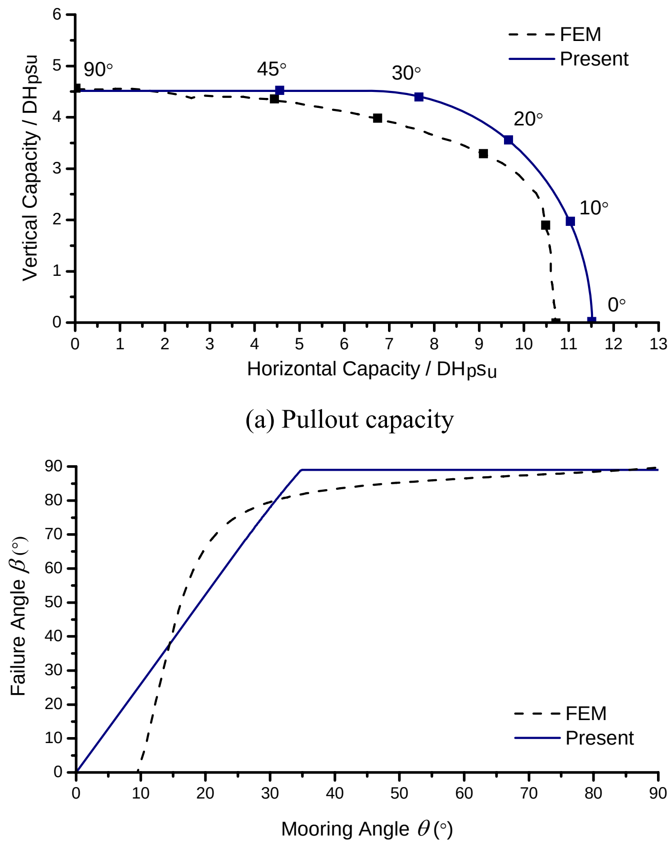
(2) According to Eq. (14), solve the equation $dT_a/d\beta=0$ and obtain the exact points whose first

derivatives are zero.

(3) By analyzing the expression of the first derivative of T_a, obtain the exact points whose first derivatives are non-existent.

(4) Calculate and compare the values of T_a at the three types of point according to Eq. (2). The point or angle with the minimum value of T_a is then the real failure angle β_r. The corresponding T_a is the ultimate pullout capacity of the anchor at that loading condition.

In the present analysis, the failure angle β_r is determined at first. Then the ultimate pullout capacity can be calculated with the known value of β_r. According to the failure angle, the failure mode of the suction anchor falls into three types, i.e., horizontal failure, inclined failure and vertical failure. The failure mode will vary from horizontal failure to inclined failure and finally vertical failure as the mooring angle increases. It was concluded by Clukey *et al*. (2003) that the anchor response to loading angles above 40° to 45° from the horizontal was controlled by the vertical capacity. Unlike the previous work, the present method can clearly analyze the failure mode of the suction anchor under a certain loading condition.



(a) Pullout capacity

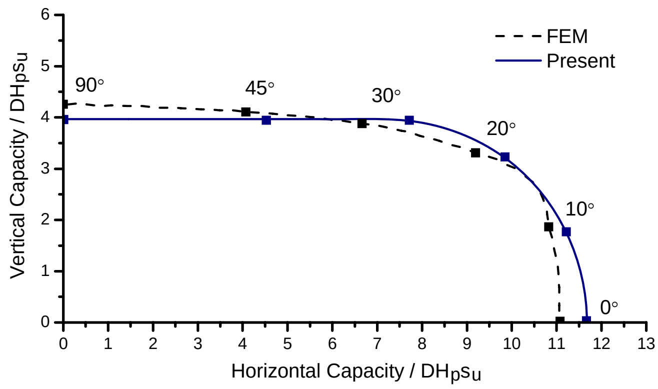
(b) Failure angle

Fig. 2 Comparison with FEM simulations (H_p/D=6)

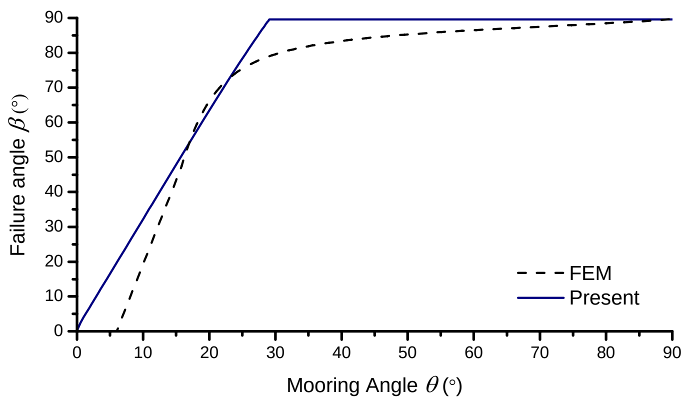
4. Comparative studies

4.1 Comparison with FEM results of Aubeny et al.

A series of finite element simulations performed by Aubeny *et al*. (2003) are selected to examine the present analytical method. Load-control was adopted in their analysis so that the loaded anchor was free to seek its own optimal displacement configuration and all FEM analyses utilized a Prandtl-Reuss material model. Simulations were made for load attachment points at the mid-depth of the anchor (H_a/H_p=0.5). The aspect ratio H_p/D included two values, i.e., 6 and 10. The weight of the anchor was ignored. The simulations considered a uniform soil strength profile (k=0) and the interface of the anchor and the soil was assumed fully rough (α=1). The reverse end-bearing factor $N_{c,bot}$ was recommended in the FEM simulations with a value of 10.5. According to the previously introduced method, the end-bearing factor N_c is determined with the values of 9.39 and 9.60 for H_p/D=6 and 10, respectively. Comparative results of the pullout capacity and the failure angle are presented in Figs. 2 and 3, in which several typical mooring angles are marked in order to make a clear view of the relationship between pullout capacity and mooring angle.



(a) Pullout capacity

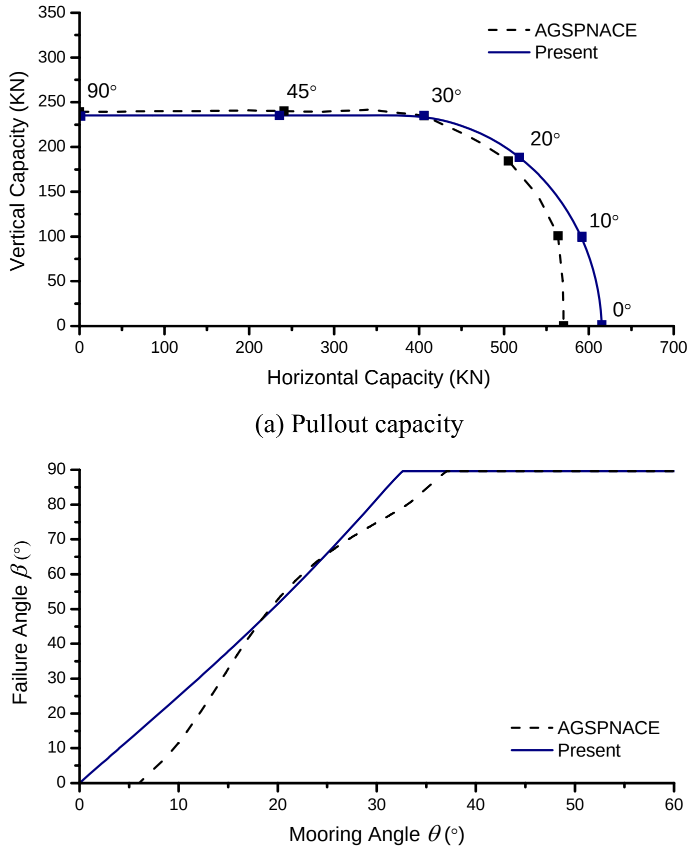


(b) Failure angle

Fig. 3 Comparison with FEM simulations (H_p/D=10)

As observed in Figs. 2(a) and 3(a), the agreement of the pullout capacity between the analytical and FEM results is generally good. The present analytical method can well reflect the relationship between the horizontal and vertical capacities of the suction anchor under different loading conditions. It should be noted that, under vertical loading, the bearing capacity of the anchor bottom takes 30.47% and 20.83% of the total capacity of the anchor with H_p/D=6 and 10, respectively. In other words, the shear resistance to the anchor provides the major part of the total capacity for a very long suction anchor in clays with a uniform strength.

According to the associated flow rule, the gradient of the yield locus determines the failure direction of the suction anchor. Thus, the failure angle can also be obtained from the FEM simulation results of the pullout capacity, and is compared with the directly calculated failure angle of the present method. It is observed from Figs. 2(b) and 3(b) that the general trends of the two curves are identical. However, the analytical failure angles present a piecewise linear variation with the mooring angle.



(a) Pullout capacity

(b) Failure angle

Fig. 4 Comparison with AGSPANC

4.2 Comparison with AGSPANC of Randolph and House

A numerical simulation work on pullout capacity of suction anchors under inclined loading in clay with linearly increasing strength was performed by Randolph and House (2002) using the software AGSPANC (Advanced Geomechanics 2001). AGSPANC comprises a spreadsheet for data input and optimization of the parameters defining the mechanisms. Numerical integrations are carried in a Fortran routine called from the spreadsheet. In the numerical simulation, a suction anchor with diameter of 5 m and length of 30 m was adopted. The weight of the anchor was ignored. The shear strength of the clay at the seafloor was 10 kPa and the gradient of shear strength with depth was 1.8 kPa/m (s_u=10+1.8z). It was recommended in the simulation that α=0.7 and $N_{c,bot}$=9. In the theoretical calculation, N_c is determined with the value of 9.46 according to the proposed method. The comparative results of the pullout capacity and failure angle are presented in Fig. 4.

It is found from Fig. 4 that, not only the pullout capacity but also the failure angle, the agreement between the analytical and numerical results is generally good. When the mooring angle exceeds a certain value, the pullout capacity of the anchor is controlled by the vertical capacity, especially when the mooring angle is larger than 32°, the vertical capacity holds at the maximum level. It is clear from the analytical cure in Fig. 4(b) that the failure angle is 90° when the mooring angle is larger than 32°, which indicates that the failure mode of the suction anchor is vertical failure.

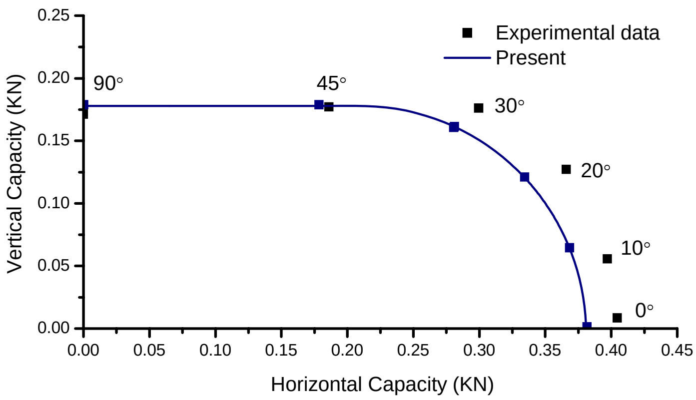
4.3 Comparison with model tests of EI-Sherbiny

A series of laboratory tests were conducted by EI-Sherbiny (2005) to study the performance of suction anchors under different loading conditions. The factors influencing the pullout capacity such as the attachment position, the method of installation (installed using deadweight or suction) and the setup time were taken into account in the study. The experiments were performed using 0.10m diameter model anchors inserted to a depth of 0.81m in normally consolidated kaolin clay. The strength of the soil was tested by four different methods (T-bar, Ball penetration test, Cone penetration test and Vane shear test). The average soil strength profile was s_u=0.04+0.91z (kPa). The pullout capacity and the displacement of attachment point of the anchor subjected to inclined loadings (with angles of 0°, 10°, 20°, 30°, 45° and 90°) were detected. The weights of the anchor and the equipments attached on the anchor were deducted from the experimental data. It was recommended in the experimental study that α=0.78 and $N_{c,bot}$=15. The value of N_c is determined as 9.49 according to the proposed method. The comparative results of the pullout capacity and failure angle are shown in Fig. 5.

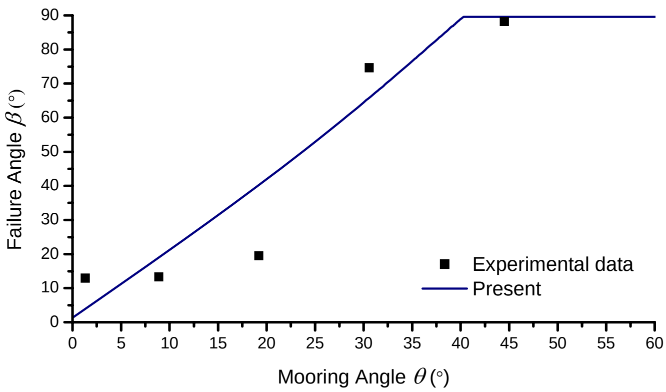
It is observed from Fig. 5 that, the general trends of experimental data agree with the analytical predictions. Comparing with the cases in clay with a uniform strength (Aubeny *et al*. 2003), the present capacity of the anchor bottom under vertical loading takes 54.48% of the total capacity. It indicates that the reverse end-bearing capacity contributes a considerable proportion of the total capacity of the anchor in clays with linearly increasing strength.

5. Method for predicting the optimal attachment point

Both experimental data and numerical simulations indicate the fact that, the ultimate pullout capacity of suction anchors is generally achieved when the failure mode is pure translation without rotation. The translation performance of the suction anchor is related to the attachment point of the mooring force. If the mooring force is applied at a point where only anchor translation occurs during the failure process, the point is defined as the 'optimal attachment point'. In order to make full use of the pullout capacity of suction anchors, the optimal attachment point is worthy of being further investigated by a theoretical method, which could not be found in the literature.



(a) Pullout capacity



(b) Failure angle

Fig. 5 Comparison with model tests

The location of the optimal attachment point can be regarded as the depth where the resultant overturning moment of the anchor is zero. The analytical method for predicting the optimal attachment point is illustrated in Fig. 6, in which the dashed line is the symmetrical axis of the anchor, Point O denotes the optimal attachment point, and A and B are two points at the symmetrical axis. Point A is at the depth of the centroid of the soil profile, and the distance of A to the seafloor is *l*. Point B is the intersection of the applied mooring force and the symmetrical axis of the anchor, and the distance of B to the seafloor is *L*. Considering that the end bearing F_b, the shear force F_s and the vertical resistance V_{bot} approximately pass through Point A, the overturning moment of all forces to Point A will be dominated by T_a and H_{bot}. Hence, in order to simplify the analysis, the location of the optimal attachment point can be calculated by making the resultant overturning moment to point A equal zero, as the following

$$\Sigma M_A = 0 \tag{15}$$

Eq. (15) can be further expressed as

$$(L-l)T_a\cos\theta - (H_p - l)H_{bot} = 0 \tag{16}$$

By considering the geometrical relationship between Point B and Point O, i.e., $\tan\theta=2(L-H_a)/D$, the location of the optimal attachment point can be expressed as

$$H_a = l + \frac{H_{bot}}{T_a\cos\theta}(H_p - l) - \frac{D}{2}\tan\theta \tag{17}$$

where $l=[H_p(s_{u0}/2+kH_p/3)]/(s_{u0}+kH_p/2)$.

Eq. (17) gives an approximate method to simply evaluate the optimal attachment point. Since the shear force on the anchor bottom is a smaller value to the applied mooring force, the major factors that influence the optimal attachment point are the mooring angle θ and the centroid depth of the soil profile L. When the mooring angle is relatively large, the position of the optimal attachment point is near the top of the suction anchor. The fact indicates that when the suction anchor is used as the foundation of TLPs, attaching the mooring chain to the top of the suction anchor is reasonable. Nevertheless, if the suction anchor is used in the taut-wire mooring system or the catenary mooring system, where the mooring angle is generally less than 45°, the optimal attachment point will be in the range of 0.45-0.65 times the insertion depth. These conclusions basically agree with the relative numerical or experimental studies (Keaveny *et al*. 1994, Tjelta 2001, Aubeny *et al*. 2003, Clukey *et al*. 2003).

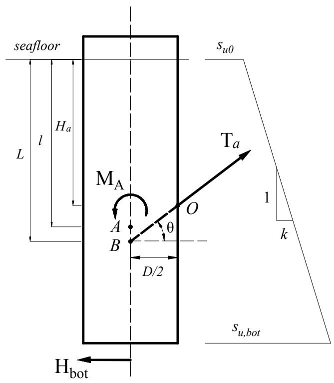


Fig. 6 Analytical method for predicting the optimal attachment point

6. Conclusions

In this paper, efforts are made to develop an analytical method that is capable of predicting the failure mode and pullout capacity of suction anchors in clay under inclined loading. Based on a rational mechanical model for the suction anchor and a reasonable assumption that the real failure direction of the anchor must be the direction in which the soil resistance is easiest to be overcome by the mooring force, the failure angle and the pullout capacity of suction anchors can be theoretically analyzed.

Three failure modes are usually defined by the failure direction as horizontal failure, inclined failure and vertical failure. The failure modes are closely related to the angle of the mooring force. Determining the critical mooring angle of the inclined failure is important, because the pullout capacity will be controlled by the pullout capacity of the anchor under vertical loading if the mooring angle exceeds the critical one. The present analytical method can reasonably determine the critical mooring angle, which is especially meaningful for assessing the reliability of suction anchors. Unlike the conventional methods that use an assumed relationship between the vertical and horizontal capacities to calculate the inclined capacity of suction anchors, the failure angle and the pullout capacity of the anchor under inclined loading as well as the vertical and horizontal capacities can all be easily determined through the present analytical method.

In the comparative study, the predicted failure angle and pullout capacity of suction anchors generally agree with the FEM simulation, numerical solution and laboratory tests in cohesive soils with uniform or linear undrained shear strengths. This confirms the effectivity and veracity of the present analytical method. The prediction results demonstrate that the end-bearing factor has much influence on the pullout capacity of suction anchors. Hence, more profound studies on the end-bearing factor of suction anchors should be performed in the future.

Being a necessary part of the present work, an analytical method for predicting the optimal attachment point of suction anchors under various loading conditions is proposed. The parametric analysis indicates that, when the mooring angle is relatively large, the position of the optimal attachment point is near the top of the suction anchor. And if the suction anchor is used in the taut-wire mooring system or the catenary mooring system, where the mooring angle is generally less than 45°, the optimal attachment point will be in the range of 0.45-0.65 times the insertion depth of the anchor. These conclusions basically agree with the studies of other researchers. However, the present theoretical method is simpler and more efficient to analyze the optimal attachment points.

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Nomenclature

A_{annu} annulus area of the caisson
A_b effective bearing area of the suction anchor in the failure direction
A_{bot} area of the anchor bottom including both the tip of the caisson and the bottom of the soil plug
A_{plug} bottom area of the soil plug inside the anchor caisson
A_s effective shear area of the suction anchor in the failure direction
D diameter of the suction anchor
F_b end bearing in the failure direction of the anchor
F_s shear force in the failure direction acting on the side of the anchor
H height of the suction anchor
H_a distance from seafloor to the optimal attachment point
H_{bot} horizontal shear force acting on the bottom of the suction anchor
H_p distance from seafloor to the bottom of the suction anchor
k gradient of the undrained shear strength with depth
N_c end-bearing factor
$N_{c,bot}$ reverse end-bearing factor
N_p lateral unit resistance factor
s_u undrained shear strength of clay
$s_{u,a}$ average undrained shear strength at the mid-depth of the anchor
$s_{u,bot}$ undrained shear strength at the anchor bottom
s_{u0} undrained shear strength at the seafloor
T_a chain tension at the optimal attachment point
T_m component of T_a in the failure direction
T_n component of T_a in the normal to the failure direction
V_{bot} vertical resistance acting on the bottom of the anchor
W' total submerged weight of the anchor and the soil plug inside the caisson
z soil depth below seafloor
α adhesion factor
β failure direction (failure angle to the horizontal)
β_r real failure direction
σ_v' effective stress at the anchor bottom
γ' submerged soil weight
λ inclination factor
θ mooring angle (angle subtended by the chain to the horizontal at optimal attachment point)