Lateral Bearing Capacity of Modified Suction Caissons Determined by Using the Limit Equilibrium Method

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Received May 19, 2017; revised March 22, 2018; accepted April 12, 2018

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Abstract
The modified suction caisson (MSC) adds a short-skirted structure around the regular suction caissons to increase the lateral bearing capacity and limit the deflection. The MSC is suitable for acting as the offshore wind turbine foundation subjected to larger lateral loads compared with the imposed vertical loads. Determination of the lateral bearing capacity is a key issue for the MSC design. The formula estimating the lateral bearing capacity of the MSC was proposed in terms of the limit equilibrium method and was verified by the test results. Parametric studies on the lateral bearing capacity were also carried out. It was found that the lateral bearing capacity of the MSC increases with the increasing length and radius of the external skirt, and the lateral bearing capacity increases linearly with the increasing coefficient of subgrade reaction. The maximum lateral bearing capacity of the MSC is attained when the ratio of the radii of the internal compartment to the external skirt equals 0.82 and the ratio of the lengths of the external skirt to the internal compartment equals 0.48, provided that the steel usage of the MSC is kept constant.

Key words: modified suction caissons (MSCs), lateral bearing capacity, limit equilibrium method, parametric studies

Citation: Li, D. Y., Ma, S. L., Zhang, Y. K., Chen, F. Q., 2018. Lateral bearing capacity of modified suction caissons determined by using the limit equilibrium method. China Ocean Eng., 32(4): 461–466, doi: https://doi.org/10.1007/s13344-018-0048-3

1 Introduction
Exploring offshore wind energy has been becoming one of the effective ways of solving environmental pollution problems and of handling the energy crisis. The cumulatively installed capacity of the world offshore wind energy was reported to be up to 7.1 GW by 2014 (Lesny, 2010). China is also a country with abundant wind energy resources. It was reported that China will have an offshore wind power capacity of 3.27 GW by 2018 (CICONsulting, 2018). The foundation of the offshore wind turbine is subjected to low vertical loads from the foundation and the superstructures and large lateral loads resulted from wind and wave currents (Houlshby and Byrne, 2000; Byrne and Houlshby, 2003). A regular caisson is a large cylinder structure that is typically made of steel, open at the bottom and closed at the top. The regular suction caissons can be installed by penetrating the seabed under its dead weight (self-weight and ballast) and then by pumping out the entrapped water to the desired depth (Zhang et al., 2013). Suction caissons are available in various water depths, especially in deep waters and have significant advantages of fast installation, cost effectiveness and reuse (Gao et al., 2013). Suction caissons have been extended to act as the foundations of offshore wind turbines and the lateral capacity dominates the offshore wind turbine foundations design.

So far, the lateral bearing capacities of the regular suction caissons in sand or in clay have been investigated by conducting model tests, the numerical simulations and the theoretical method. El-Wakil (2010) carried out 1 g small-scale model tests to study the lateral capacity of the regular suction caissons in sand and concluded that the lateral capacity increases with the increasing aspect ratio. Zhu et al. (2011) investigated the deformation mechanism and soil-structure interaction of the regular suction caisson by performing a series of large-scale model tests in silt. They suggested that the rotation center of the regular suction caissons at failure is at the depth of about four-fifths of the skirt length almost directly below the caisson lid center. El-Sherbiny (2005) found that the rotation center of the regular suction caisson subjected to the lateral load in clay is at a depth of about 2/3–3/4 times the skirt length. Sun et al. (2010) derived the formula of undrained lateral bearing cap...
capacity by using the limit equilibrium method.

To improve the bearing capacity of the regular suction caissons, a modified suction caisson, MSC (Fig. 1), has been put forward by Li et al. (2010). A series of studies on the bearing capacities of MSCs under the vertical, lateral loads and moment were conducted by Li et al. (2014a, 2014b, 2015a). These findings show that the rotation center moves downwards and forwards with the increasing lateral loading, and then tends to be a stable position when the maximum load is approaching. In the limit state, the rotation center depth below the caisson lid decreases with increasing external skirt dimensions. Zhang et al. (2016a, 2016b) carried out the model tests and numerical simulations on the MSCs under load-/displacement-controlled method and their results show that in the displacement-controlled test, the deflection-softening behavior of the load-deflection curves for MSCs is observed, and the softening degree of the load-deflection response increases with the increasing external skirt length or the decreasing loading eccentricity. In addition, it was also found that the lateral load and the resulting overturning moment acting on the MSC are mainly carried by the passive earth pressure zones along the inner and outer shafts of the internal compartment and the external skirt both in the loading and opposite the loading directions and under the external skirt lid in the loading direction. From the viewpoint of theory, the lateral bearing capacities of the MSCs need to be investigated further.

This paper proposes a three-dimensional limit equilibrium method to analyze the lateral bearing capacity of MSCs. The experimental data presented by Li et al. (2015a) were used to validate the proposed method. Parametric studies were also conducted to investigate the effects of the internal compartment length, external skirt radius, the coefficient of subgrade reaction and the loading eccentricity on the lateral bearing capacity of the MSC.

2 Calculation method for lateral bearing capacity

2.1 Calculation model

Based on the stresses distribution around suction caissons given by Zhang et al. (2016b) and Sun et al. (2010), a three-dimensional model of the MSC was proposed to calculate the lateral bearing capacity, as shown in Fig. 2. To simplify the calculation, the lateral earth pressure and frictional force acting on the bucket wall in Zones I and IV are ignored. In addition, the following assumptions are made.

1. The x-axis is positive to the right; the y-axis is positive to the outside of the plane xoz; and in addition, the z-axis is oriented downwards. Forces and stresses are defined positive parallel to the axis, and the moment is positive in the clockwise direction.

2. The suction caisson and the soil inside the caisson are assumed to be rigid. To simplify the calculation, the MSC subjected to lateral loadings will rotate around the rotation center $O'$ on the z-axis.

3. The lateral soil resistance obeys the Winkler’s assumption. In the $xoz$ plane, the lateral soil resistance $\sigma_{x0}$ along the external skirt wall or the internal compartment wall is depicted as a continuous function with respect to the embedded depth when $\theta=0$ (Fig. 2a).

$$\sigma_{x0} = k_x(z-z_0)\omega; \quad (1)$$

where $z_0$ is the depth of the rotation center $O'$ below the soil surface; $\omega$ is the rotation angle of the MSC. $k_x$ is the lateral coefficient of subgrade reaction which can be obtained by using the “m” method i.e. $k_x = mz$ where $m$ is a proportional constant and determined by the experiments.

4. In the $xoy$ plane, the soil radial resistance $\sigma_r$ is given by

$$\sigma_r = \sigma_{r0}\cos\theta, \quad 0 \leq \theta \leq 2\pi. \quad (2)$$

Therefore, the lateral resistance $\sigma_x$ can be calculated from

$$\sigma_x = \sigma_r\cos\theta = \sigma_{r0}\cos^2\theta. \quad (3)$$

5. The frictional resistance can be written as:

$$\tau_s = f\sigma_r, \quad (4)$$

where $f$ is the coefficient of the friction between the MSC and soil.

6. The vertical soil resistance $\sigma_z$ also obeys the Winkler’s assumption, thus

$$\sigma_{z0} = k_z(z-z_0)\omega, \quad (5)$$

where $k_z$ is the vertical coefficient of subgrade reaction which can be obtained by using the “m” method i.e. $k_z = mz$ where $m$ is a proportional constant and determined by the experiments.

![Fig. 1. Suction caisson model.](image-url)
\[\sigma_s = -k_s x_\omega,\]  
where \(k_s\) is the vertical foundation coefficient and \(k_s = 2k_x\) suggested by Sun et al. (2010) is adopted.

(7) The lateral shear stress at the bottom of MSCs, \(t_b\), can be estimated from

\[t_b = k_t u_t,\]  
where \(k_t\) is the lateral shear coefficient of the MSC, and \(u_t\) is the horizontal displacement of the suction caisson wall under a certain depth. According to Wang and Chi (1997), \(k_t\) is given by

\[k_t = f_k x \approx 2f_k.\]  
The lateral shear stress at the bottom of the internal compartment, \(t_{b1}\), and the lateral shear stress at the bottom of the external skirt, \(t_{b2}\), can be expressed as:

\[t_{b1} = 2f_k x_1(L_0 - z_0)\omega;\]  
\[t_{b2} = 2f_k x_2(z_0 - L_1)\omega,\]  
where \(k_1\) and \(k_2\) are the coefficients of subgrade reaction at the bottom of the internal compartment and the external skirt, respectively.

2.2 Calculation of bearing capacity

Based on the assumptions in Section 2.1, the lateral bearing capacity, \(p_w\), can be calculated based on the force and moment equilibrium.

(1) The ultimate lateral earth pressure, \(N\), can be expressed as:

\[N = N_1 + N_2 + N_3 = 2\int_0^{L_1} \int_0^{rac{L}{2}} \sigma_x R d\theta dz + 2\int_0^{L_0} \int_0^{rac{3\pi}{2}} \sigma_x r d\theta dz + 2\int_0^{L_0} \int_{-\frac{3\pi}{2}}^{rac{3\pi}{2}} \sigma_x r d\theta dz,\]  
where \(N_1\) is the force induced by the lateral earth pressure acting on the external skirt in the loading direction; \(N_2\) and \(N_3\) are the forces acting on the internal compartment in the loading and opposite the loading direction; \(r\) is the radius of the internal compartment and \(R\) is the radius of the external skirt.

(2) The friction force acting on the wall of the MSC, \(T\), can be calculated by

\[T = T_1 + T_2 + T_3 = 2\int_0^{L_1} \int_0^{rac{L}{2}} \tau_s R d\theta dz + 2\int_0^{L_1} \int_0^{rac{L}{2}} \tau_s r d\theta dz + 2\int_0^{L_0} \int_{-\frac{3\pi}{2}}^{rac{3\pi}{2}} \tau_s r d\theta dz,\]  
where \(T_1\), \(T_2\) and \(T_3\) are the friction forces shown in Fig. 2a.

(3) Horizontal shear force at the bottom of the MSC caused by rotation, \(T_b\), can be expressed by

\[T_b = T_{b1} + T_{b2} = \int \int t_{b1} ds + \int \int t_{b2} ds,\]  
where \(s_4 = \pi r^2\) and \(s_5 = \pi (R^2 - r^2)\).

(4) The bending moment \(M_{pu}\) about the rotation center, which is induced by lateral loads, can be expressed as:

\[M_{pu} = p_u(z_0 + L_p),\]  
where \(L_p\) is the distance between the loading point and the MSC lid.

(5) The bending moment about the rotation center induced by the earth pressure can be given as:

\[M_N = M_{N1} + M_{N2} + M_{N3} = \int \int \sigma_x(z_0 - z) ds + \int \int \sigma_z(z_0 - z) ds + \int \int \sigma_z(z_0 - z) ds = \int_0^{L_1} \int_0^{rac{L}{2}} \sigma_z(z_0 - z) R d\theta dz + 2\int_0^{L_1} \int_0^{rac{L}{2}} \sigma_z(z_0 - z) r d\theta dz + 2\int_0^{L_0} \int_{-\frac{3\pi}{2}}^{rac{3\pi}{2}} \sigma_z(z_0 - z) r d\theta dz,\]  
(14)

(6) The resisting moment \(M_T\) about Point \(O'\) due to the frictional force acting on the MSC wall can be expressed as:

\[M_T = T_1 R + T_2 r + T_3 (-r).\]  
(15)

(7) The bending moment \(M_T\) about the rotation center, which is produced by the vertical soil resistance on the bottom of the MSC lid, can be written as:

\[M_T = M_{t1} + M_{t2} = \int \int \sigma_t x ds + \int \int \sigma_t x ds,\]  
(16)

where \(M_{t1}\) and \(M_{t2}\) are the bending moments induced by the vertical soil resistance.
(8) The bending moment produced by \( T_b \) is given by
\[
M_{Tb} = T_{b1}(z_0 - L_0) + T_{b2}(z_0 - L_1).
\]

Therefore, the ultimate lateral bearing capacity of the MSC can be evaluated based on the horizontal force and the moment equilibriums:
\[
\begin{align*}
\sum x &= N + T_b + P_u = 0 \\
\sum M &= M_{p} + M_T + M_v + M_{Tb} = 0
\end{align*}
\]

By substituting Eqs. (10)–(17) into Eq. (18), the lateral bearing capacity can be presented as:
\[
p_u = \frac{1}{z_0 + L_p} \left( \frac{1}{4} \omega \pi C + 2 f \omega \pi D - m \omega \pi E - f m \omega G \right),
\]
where
\[
C = k_1 r^4 + k_2 (R^4 - r^4);
D = k_3 (L_0 - z_0)^2 r^2 + k_2 (z_0 - L_1)^2 (R^2 - r^2);
E = \left( \frac{L_1^2 z_0}{3} - \frac{L_1^4}{8} - \frac{L_1^2 z_0}{4} \right) r^2 + \left( \frac{L_1^4}{8} + \frac{L_0^2 z_0}{3} - \frac{L_1^2 z_0}{4} + \frac{L_0^2 z_0}{4} \right) r^2.
\]

Therefore, the rotation center depth, \( z_0 \), can be calculated as:
\[
z_0 = \frac{\left( \frac{2}{3} L_0^3 - \frac{2}{3} L_1^3 \right) r + \frac{2}{3} L_1^2 R}{L_1^2 R - r (L_1^2 - L_0^2)}.
\]

2.3 Verification of the proposed method

Eq. (19) is valid for both the MSC and the regular suction caisson. When \( L_1 = 0 \) and \( R = r \), the MSC becomes the regular suction caisson, and then Eq. (19) can be modified as:
\[
p_u = \frac{1024 r^2 f L_0^3 m \pi + 72 L_0^2 m \pi + 1296 m \pi L_0^2 + 1152 f m \omega \pi r^2 L_0^3}{5184 \left( \frac{2}{3} L_0 + L_p \right)}.
\]

It is necessary to verify Eq. (19) by using the model tests carried out by Li et al. (2015a). According to Li et al. (2015a), \( r = 0.06 \) m, \( L_0 = 0.24 \) m, \( R = 0.11 \) m, \( L_1 = 0.09 \) m, \( L_p = 0.18, 0.24, \) and \( 0.3 \) m, \( \omega = 0.02 \) rad, and \( f = 0.3878 \). The Chinese technical code JGJ94-2008 for determining the coefficient of a subgrade reaction suggests a value of \( m = 14–35 \) MN/m⁴ for dense fine sand, 5–14 MN/m⁴ for loose sand and soft clay and 35–100 MN/m⁴ for dense medium-coarse sand and stiff clay (Ministry of Housing and Urban-Rural Development of the People’s Republic of China, 2008). For a simple conservative estimate, the value of \( m \) here is set to 35 MN/m⁴. The results obtained by using Eq. (19) are listed in Table 1. It shows that the calculation results agree very well with the test results.

Previous studies confirmed that the positions of the rotation centers of MSCs are located at the depth of \( (0.54–0.67) L_0 \) below the center of the lid (Li et al., 2015a, 2015b). The relationship between the values of \( z_0 \) and the dimensions of the MSC is given in Eq. (20). Fig. 3 shows a comparison between the theoretical solutions and the experimental results about the position of the center rotation under different \( r/R \) and \( L_1/L_0 \). It can be found that Eq. (20) is

![Fig. 3. Comparisons of the rotation point positions between the calculated and tested results.](image)

| Model No. | \( L_p \) (m) | Test results (Li et al., 2015a) (N) | Calculation results (N) | Relative error (%) |
|-----------|--------------|----------------------------------|------------------------|-------------------|
| 1         | 0.18         | 119                              | 114                    | 4.20              |
| 2         | 0.24         | 102                              | 97                     | 4.17              |
| 3         | 0.30         | 88                               | 84                     | 4.55              |
in good agreement with the experimental results. This leads us to believe that the reliability of the theoretical calculations of the proposed three-dimensional model was verified. It can be concluded that results obtained by using Eq. (20) is in good agreement with the experimental results. It can be seen from Fig. 3 that the normalized depth of the rotation center below the caisson lid $z_0/L_0$ decreases with the increasing $r/R$, however, increases with the increasing $L_1/L_0$. It is concluded that the value of $r/R$ affects the rotation point position greatly.

3 Parametric studies on the lateral bearing capacity

Parametric studies were carried out to investigate the effects of the internal compartment length, the radius of the external skirt, the coefficient of the subgrade reaction and the loading eccentricity on the lateral bearing capacity of the MSC.

3.1 Influence of length of the external skirt

Fig. 4 shows the relationships between the lateral bearing capacity and the external skirt length under various loading eccentricities. It shows that the lateral bearing capacity of the MSC increases with the increasing external skirt length. When $L_1$ increases from 0.04 m to 0.06 m, an increase of 8.4 N in the lateral bearing capacity was observed under the loading eccentricity of 0.24 m.

3.2 Influence of the external skirt radius

It can be seen from Fig. 5 that the lateral bearing capacity of the MSC depends greatly on the radius of the external skirt. The lateral bearing capacity of the MSC increases with the increase of the radius of the external structure. In addition, the curves shown in Fig. 5 can be best fitted by the exponential functions.

3.3 Influence of the coefficient of subgrade reaction

The value of the coefficient of subgrade reaction, $m$, is determined by experiments. Different values of $m$ were used to obtain $p_{tu}$ by using Eq. (19). It can be seen from Fig. 6 that the lateral bearing capacity increases linearly with the increasing coefficient of the subgrade reaction. The variation of the coefficient of subgrade reaction will lead to the great change in the lateral bearing capacity value.

3.4 Influence of the loading eccentricity

It is well understood that the bearing capacity of the MSCs is significantly influenced by the loading eccentricity primarily because it governs the moment magnitude of the foundation. There are many factors dominate the magnitude of the loading eccentricity, such as the blade length, the wind turbine tower height and the water depth.

When $L_0=0.24$ m, $L_1=0.09$ m, $r=0.06$ m, and $R=0.11$ m, the lateral bearing capacities of the MSC and the regular suction obtained by using Eqs. (19) and (21) under variation loading eccentricities are shown in Fig. 7. It can be concluded that the lateral bearing capacity of the MSC decreases with the increasing loading eccentricity. It also shows that the MSC can increase the lateral bearing capa-

![Fig. 4. Influence of the skirt length on the lateral bearing capacity.](image1)

![Fig. 5. Effect of the external skirt radius on the lateral bearing capacity.](image2)

![Fig. 6. Influence of the coefficient of subgrade reaction.](image3)

![Fig. 7. Influence of the height of the lateral loads.](image4)
city compared with the regular suction caisson under a certain loading eccentricity.

4 Optimum MSC dimensions for the maximum bearing capacity

Provided that the mass of the MSC is kept constant, it is necessary to find the optimum dimensions of the MSC for obtaining the maximum lateral bearing capacity. The mass of the MSC, $m_s$, can be calculated by

$$m_s = \left[ R^2 \pi t_1 + (2RL_0 \pi + 2r \pi L_1) t_2 \right] \rho; \quad (22)$$

where $t_1$ is the thickness of the MSC lid; $t_2$ is the thickness of the external skirt and the internal compartment walls; $\rho$ is the density of the steel. To find the optimum dimension, 294 cases were carried out using Eqs. (19) and (23) based on the following assumptions:

1. $m = 3.5 \times 10^7$ N/m$^4$, $L_0=0.18$ m, $m_s=7.797 \times 10^{-4}$ $\rho$, $t_1=0.01$ m, and $t_2=0.002$ m.
2. $R>r>0$.
3. $(0.67-0.54)L_0>L_1>0$.

It was found that the maximum lateral bearing capacity was obtained ($p_u=146$ N) under the MSC dimensions of $r=0.09$ m, $R=0.11$ m, $L_0=0.23$ m, and $L_1=0.09$ m. Therefore, the optimal dimensions that can be recommended by the practical engineering are:

1. The ratio of the radii of the internal compartment to the external structure is equal to 0.82.
2. The ratio of the lengths of the external structure to the internal compartment equals 0.48.

5 Conclusions

This paper presents a three-dimensional method estimating the lateral bearing capacity of the MSC. The following conclusions can be drawn.

1. The reliability of the proposed method is verified by the model test results. It was found that the theoretical results agree very well with the test results.
2. The lateral bearing capacity increases with the increasing external skirt length and radius and the coefficient of subgrade reaction. The lateral bearing capacity of the MSC follows a linearly relationship with the coefficient of subgrade reaction. However, the lateral bearing capacity decreases with the increase of the loading eccentricity.
3. Provided that the mass of the MSC is kept constant, the optimum dimensions of the MSC for the maximum bearing capacity is obtained as the ratio of the radii of the internal compartment to the external skirt is equal to 0.82 and the ratio of the lengths of the external structure to internal compartment equals 0.48.

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