Analysis of foundation bearing capacity and structural stability of suction bucket for offshore wind power

ZHANG Xu¹,²
¹Sino-Portuguese Centre for New Energy Technologies (Shanghai) Co., Ltd., Shanghai 200335, China
²Shanghai Investigation, Design & Research Institute Co., Ltd., Shanghai 200335, China

Email: zhang_xu_19@ctg.com.cn

Abstract. The large-scale wide and shallow bucket foundation of offshore wind power has a unique bucket top bearing mode, and the bucket foundation is provided with partition plates, which has greater bearing capacity as a whole. By numerical method, the solid and structural elements such as bucket body, rib plate connector and silo plate, as well as bucket-soil contact element are established, and the real three-dimensional complex model of bucket foundation and foundation soil is constructed in detail. The nonlinear contact calculation of bucket foundation under the combined loading modes such as horizontal load, wave force, vertical load and bending moment are simulated, and the deformation, bearing characteristics and safety of suction bucket are analyzed. The ultimate bearing capacity of foundation under horizontal load, vertical load and bending moment are calculated by Flac3d finite difference method, which provide reference for the foundation structure selection, bucket foundation design, implementation and safety evaluation of offshore wind farm projects.

1. Introduction
In recent years, China's offshore wind power has entered a period of rapid development. The exploitable offshore wind energy resources within 50 km from the coast of China are 758 million kW, which is about three times of the actual onshore exploitable wind energy resources. With the vigorous development of offshore wind power, the requirements for wind power foundation are getting higher and higher. At present, the commonly used foundation forms include gravity, pile foundation, jacket, floating foundation and suction bucket foundation, among which pile foundation is the most common, and offshore wind power pile foundation and supporting structure account for about 30%¹.

As an alternative form of single pile foundation, suction bucket foundation is a new type of offshore wind power foundation, which can effectively reduce the foundation cost by about 30%². The foundation of suction bucket is mostly a large-diameter barrel with open bottom and closed top, which has the advantages of low cost, simple construction technology, integrated construction and secondary use, and can be quickly installed, and can be better applied to marine foundations in coastal areas of China. At the same time, the suction bucket foundation can better resist the large horizontal load and bending moment of wind turbines, and has been well developed in recent years. Some scholars have carried out research on the stress and bearing capacity of bucket foundation. Amin et al. ³ based on the Mohr-Coulomb elastic-plastic model, analyzed the influence of the ratio of cylinder diameter to penetration on the ultimate bearing capacity of cylinder. Liu Zhenwen et al. ⁴ analyzed the vertical
failure mode of bucket foundation, the soil strength within the buried depth of foundation and the influence of foundation shape on the vertical bearing capacity of foundation through finite element calculation. Liu Meimei et al.\(^7\) obtained the bearing characteristics and failure modes of bucket foundation with different length-diameter ratio under vertical loading through finite element calculation, and proposed that when calculating the ultimate bearing capacity, the bucket and the soil in the bucket can be considered as a whole for simplified analysis. Zhu Bin\(^8\) and Achmus et al.\(^9\) studied the horizontal bearing capacity of suction bucket foundation by means of model test and numerical simulation. Zhang et al.\(^10\), through centrifugal model test, pointed out that the large settlement and lateral displacement of cylindrical foundation will occur under long-term load. Hung et al.\(^11\) discussed the change of bearing capacity of bucket foundation with length-diameter ratio under different undrained shear strength by finite element method, and analyzed the movement form of bucket body under horizontal and vertical loads and the failure mechanism of soil around the foundation. Wu Ke et al.\(^12\) analyzed the bucket foundation in saturated soft clay, obtained the ultimate bearing capacity under vertical load, and proposed that undrained shear strength of soft clay, anisotropy of soil and length-diameter ratio of suction foundation are the main factors affecting the vertical bearing capacity of suction foundation. Bagheri et al.\(^13\) analyzed the deformation behavior of cylindrical foundation under monotonic and cyclic loads, and pointed out that large horizontal displacement will occur near the cylindrical cover.

Therefore, in the long-term service process of offshore wind power, it is of great engineering significance to study the ultimate bearing capacity of suction bucket and foundation under multi-mode and multi-working conditions such as storm surge.

2. Constitutive model and parameter calculation

The constitutive model of soil is isotropic elastic-plastic model, which adopts Mohr-Coulomb (M-C) criterion, and its mechanical model is as follows:

\[
f = \frac{\sigma_1}{\sigma_3} - \frac{1 + \sin \phi}{1 - \sin \phi} = \frac{2\cos \phi}{1 - \sin \phi}
\]

(1)

In which \(\sigma_1\) and \(\sigma_3\) are the maximum and minimum principal stresses respectively; \(f\) is a yield function, and when \(f > 0\), the material is in plastic flow state, when \(f < 0\), the material is in elastic deformation stage, and when \(f = 0\), it is in elastic and plastic critical state.

The above is the shear failure criterion, and the tensile failure criterion is

\[
f' = \sigma_i - \sigma_j = 0
\]

(2)

In which \(\sigma_i\) is tensile strength of rock mass.

The volume modulus and shear modulus of rock and soil are calculated by the following formulas:

\[
K = \frac{E}{3(1 - 2\nu)}
\]

(3)

\[
G = \frac{E}{2(1 + \nu)}
\]

(4)

In which \(K\) and \(G\) are bulk modulus and shear modulus respectively; \(E\) is the elastic modulus; \(\nu\) is Poisson's ratio.

For the parameters of the contact surface, the normal stiffness \(k_n\) and shear stiffness \(k_s\) are taken as 10 times the equivalent stiffness of the "hardest" soil layer in the adjacent area of the contact surface \(^5\), namely

\[
k_n = k_s = 10 \max \left[ \frac{K + \frac{4}{3} G}{A z_{\text{min}}} \right]
\]

(5)

Where: \(\Delta z_{\text{min}}\) is the minimum dimension of the connecting area in the normal direction of the contact surface.
According to on-site geological investigation and indoor test, the formation mechanics parameters are comprehensively determined, as shown in Table 1. Contact parameters calculated by formulas (3)–(5) are shown in Table 2.

Considering the main load on suction bucket, horizontal force, bending moment, torque transferred from upper fan gravity, wind load on fan and equivalent wave force in water, the fan load and wave load are shown in Tables 3 and 4. Among them, the horizontal load is the horizontal load transferred from the wind load on the fan; The wave load is the wave force on the tower in water, and the equivalent wave load is calculated by the water depth (action height 14.12 m). Schematic diagram of combined load is shown in Figure 1.

![Fig.1 Schematic diagram of loading](image1)

![Fig.2 Three-dimensional model](image2)

| Tab.1 Physical and mechanical parameters |
|-----------------------------------------|
| Layer                    | Unit weight (kN/m) | Elasticity modulus (MPa) | Poisson's ratio | Cohesion (kPa) | Internal friction angle (°) |
|--------------------------|---------------------|--------------------------|-----------------|----------------|-----------------------------|
| Flowing mud ~ silt       | 15                  | 0.15                     | 0.45            | 0.3            | 0.1                         |
| Flowing mud ~ silt       | 15                  | 3.81                     | 0.42            | 4.5            | 0.8                         |
| Flowing mud ~ silt       | 15                  | 3.81                     | 0.4             | 9              | 1.4                         |
| Silt                     | 15                  | 5.7                      | 0.4             | 12             | 1.4                         |
| Mucky soil               | 16                  | 7.5                      | 0.4             | 29.0           | 2.0                         |
| Silty clay               | 17.5                | 12.9                     | 0.35            | 42.0           | 3.0                         |
| Coarse sand              | 19.5                | 90                       | 0.25            | 0.1            | 35                          |
| Silty clay               | 17.5                | 36                       | 0.35            | 75.0           | 3.0                         |
| Completely weathered granite | 21              | 120                      | 0.2             | 50.0           | 50.0                         |

| Tab.2 Contact parameters |
|--------------------------|
| Layer                    | $K$ (MPa) | $G$ (MPa) | $k_e$ (MPa/m) | $\Delta z_{\text{min}}$ |
|--------------------------|-----------|-----------|---------------|-------------------------|
| Flowing mud ~ silt       | 0.5       | 0.051724  | 5.69          |                         |
| Flowing mud ~ silt       | 7.9375    | 1.341549  | 97.26         |                         |
| Flowing mud ~ silt       | 6.35      | 1.360714  | 81.64         |                         |
| Silt                     | 1.9       | 2.85      | 57            |                         |
| Mucky soil               | 12.5      | 2.678571  | 160.71        | 1                       |
| Silty clay               | 14.33333  | 4.777778  | 207.04        |                         |
| Coarse sand              | 60        | 36        | 1080          |                         |
| Silty clay               | 40        | 13.33333  | 577.78        |                         |
| Completely weathered granite | 66.66667  | 50        | 1333.33       |                         |
### Table 3 Fan loads

| Load | Weight (kN) | Horizontal force (kN) | Bending moment (kN·m) | Torque (kN·m) |
|------|-------------|-----------------------|-----------------------|---------------|
| Value| 9056        | 2584.7                | 258179                | 12980         |

### Table 4 Wave load

| Load   | Wave load (kN) |
|--------|----------------|
| Value  | 18526.83       |

3. **Three-dimensional model building**

According to the engineering geological conditions of an offshore wind farm in Guangdong, combined with Rhino 3D modeling and Ansys finite element software, a 3D numerical model of suction bucket-stratum is established, which is imported into Flac3D by compiling Fish language conversion program of node, unit and coordinate system. As shown in Figure 2, the suction bucket has an outer bucket diameter of 36m and an inner barrel diameter of 10m, and is equipped with six silo partition plates. The height of the tower above the mud surface is 45m, and the bucket is embedded in the stratum about 13m. The length of the established stratum model is 10 times of the outer barrel diameter, that is, 360 m, and the height is 54 m.

The upper boundary of stratum is free and unconstrained, the bottom is constrained by fixed displacement, the side of stratum is constrained by \( x \) and \( y \), the suction bucket is not constrained by fixed constraint, and only joint load is applied. \( z \)-direction stress field will be automatically calculated by self-weight.

The finite element model is divided into grids, and the suction bucket-formation model is divided into 90,252 units and 101,812 nodes. The bucket and the soil layer near the bucket are encrypted, and the grid at the far part from the bucket is gradually sparse. Among them, the grid section of suction bucket (including rib connector, silo partition plate and circular plate) is shown in Figure 3.

In order to simulate the real contact, slip and separation between bucket and soil, contact surfaces are set between suction bucket and soil: bucket cover plate-soil contact, bucket sidewall-soil contact and bucket bottom surface-soil contact, as shown in Figure 4.

4. **Deformation analysis**

Hide the rib plate and compartment plate of suction bucket, and analyze the deformation and interaction between bucket and soil, in order to better observe the deformation of bucket body and soil layer.

The horizontal \( x \) displacement vector nephogram of bucket-soil as a whole is shown in Figure 5. Generally speaking, it can be seen that the displacement is basically concentrated on the bucket, with the maximum horizontal displacement of 252 mm appearing at the upper part of the bucket and the
minimum horizontal displacement of 0.27 mm of the soil layer. Soil deformation is mainly concentrated in the small area near the barrel, and basically occurs in the shallow layer, which is about half of the barrel height embedded in the soil. The horizontal deformation of the soil layer below half of the barrel height is extremely small.

![Fig.5 x displacement vector (unit: m)](image)

The vertical z displacement vector cloud picture of the whole barrel-soil is as shown in Fig. 6. It can be seen that the small area adjacent to the barrel on the right side is subjected to the deflection of the barrel, and the extrusion uplift deformation occurs, and the "upwarping" is 30.5 mm; Due to the right deflection of the bucket, it is separated from the soil, and the left soil layer is empty, which causes a certain degree of "dumping" sinking.

The contact state between bucket and soil is shown in Figure 7. It can be seen from the shear slip contact that the bucket sidewall is in good contact with the soil layer, there is basically no shear slip behavior between the bucket cover and the soil layer, and the bucket cover is in normal pressure contact with the soil.

![Fig.6 z displacement vector (unit: m)](image)

According to the displacement calculation results, the mud surface rotation angle is calculated as 
\[
\frac{(105.8\text{mm}+28.6\text{mm})}{36000\text{mm}} \times 1000 \text{‰} = 3.73 \text{‰} < 4.36 \text{‰},
\]
which meets the safety requirements.

5. Stress and yield analysis

The maximum principal stress nephogram of the barrel body is shown in Fig. 8. Due to the right deflection of the barrel body under combined external load conditions, the maximum tensile stress on the barrel body appears on the inner barrel wall at the junction of the inner barrel and the barrel cover, which is about 30 MPa.

The nephogram of the minimum principal stress of the barrel is shown in Fig. 9. The maximum compression part of the barrel is the middle part of the bottom of the inner barrel, which is about 78 MPa, which is much larger than the maximum tensile stress of 30 MPa. The left part of the barrel body
above the barrel cover is basically in tension, which is the main tension zone and the stress value is positive.

![Fig.8 Maximum principal stress (unit: Pa)](image)

The bucket body deflects to the right under external load, and the right side of the bucket body is under pressure. The stress evolution curve of the bucket unit body at the upper part of the outer bucket is shown in Figure 10. Under multiple working conditions, the unit body interacts with the soil body and is compressed, and the compressive stress gradually increases. After the compressive stress of the outer bucket body exceeds 1 MPa, it basically tends to be stable, indicating that the soil body and the bucket body near it are in a stress equilibrium state.

The yield zone of soil is shown in Figure 11. It can be clearly seen that the adjacent soil layers of the inner and outer barrels are damaged, and the outer ring soil of the outer barrel is mainly damaged, and the degree of soil damage on the compression side (right side) is obviously higher than that on the non-compression side (left side). The upper surface layer on the left side is shallow failure, while the right side is compressed, and the depth of soil layer failure is deeper than that on the left side.

No matter the inner or outer barrel, the damage degree of the outer barrel wall soil is higher than that of the inner barrel wall soil. The damage degree of the outer ring soil of the outer barrel is higher than that of the inner barrel. There is no good plastic through zone in the inner and outer soil layers of the barrel wall, so the barrel body is stable and will not overturn or slip indefinitely.

![Fig.10 Stress evolution characteristics of unit body (upper part of outer barrel)](image)

![Fig.11 Maximum shear strain increment of soil layer](image)
6. Analysis of ultimate bearing capacity of foundation

Under normal combined loading conditions, the vertical load and bending moment are kept constant, and the horizontal load is continuously increased to the limit. In order to reduce the calculation time, the 1/2 model is adopted to carry out the ultimate bearing analysis.

The relationship between the rotation angle of the mud surface and the horizontal load increment and the percentage of horizontal load increment is shown in Figures 12 and 13. When the horizontal load increases by 1,300 kN, the rotation angle reaches 6.92‰, and the curve has an inflection point (abrupt point). At this time, it can be considered that the ultimate horizontal load increment is 1,300 kN, that is, under normal combined loading conditions, the horizontal load can continue to increase by 100.59%, with a margin of 1,300 kN, and the limit value is 1292.35+1300=2592.35 kN.

The variation curve of displacement between mud surface and bucket top with horizontal load increment is shown in Figure 14. With the gradual increase of horizontal load, the horizontal displacement curve of mud surface basically changes uniformly in a straight line. When the horizontal load increases by 1300 kN, the curve appears inflection point (abrupt change point).

The relationship between the rotation angle of the mud surface, the moment increment and the percentage of the moment increment is shown in Figures 15 and 16. When the moment increases by 60 MN·m, the rotation angle reaches 6.96‰, and the curve has an inflection point (abrupt point). At this time, it can be considered that the ultimate moment increment is 60 MN·m, that is, under normal
combined loading conditions, the moment can continue to increase by 46.48%, with a margin of 60 MN·m, and the limit value is 129+60=189 MN·m.

Fig. 17 shows the vertical displacement curves of the left and right mud surfaces at the suction bucket cover along with the increase of bending moment. With the gradual increase of bending moment, the horizontal displacement curves of the mud surfaces change uniformly in a straight line. When the bending moment increases by 60 MN·m, the displacement curves have inflection points (abrupt points).

The relationship between the mud surface angle and the vertical load increment and its percentage is shown in Figures 18 and 19 respectively. When the upper fan self-weight load is considered, the mud surface angle is smaller than when the fan self-weight load is not considered, which indicates that a certain self-weight load is beneficial to improve the safety of the fan. This is because after the vertical load is applied, the soil in and at the bottom of the bucket is squeezed and restricted by the bucket wall and the silo partition plate, and the larger bearing capacity of the dense soil makes the bucket soil have an integrated bearing mode, which is beneficial to resisting horizontal force.

On the basis of self-weight load, if the vertical load continues to increase gradually, the turning angle will gradually increase and suddenly change, and the composite bucket foundation will lose stability.
Fig. 20 Relationship between horizontal displacement of mud surface and the vertical load

7. Conclusions

Combined with engineering geology and load conditions, considering the contact between bucket and soil, a complex three-dimensional numerical model of solid, structure and stratum is established, and the deformation law and bearing characteristics of multi-working conditions and multi-load modes are analyzed, and the following conclusions are drawn:

1) The stress of the suction bucket is generally controllable, which does not exceed the material limit, and its stability is mainly controlled by deformation. The displacement of the bucket body and the rotation angle at the mud surface are within the safe allowable range, which is safe as a whole.

2) The classical formula for calculating the bearing capacity of foundation can not accurately calculate the ultimate bearing capacity of wide and shallow bucket foundation under composite loading mode. The Flac3d finite difference method is used to calculate the ultimate bearing capacity of bucket foundation under normal operation and different load modes, which will provide references for foundation design and instability prediction.

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