Construction and Preliminary Analysis of Three-dimensional Model of Offshore Wind Power Suction Bucket

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Abstract. As a high-rise structure, offshore wind turbines are subjected to huge horizontal loads. Compared with the traditional tubular foundation for offshore wind power, the large-scale tubular foundation with a load-bearing top has a larger load-bearing capacity due to its unique broad-shallow tubular top load-bearing mode. For reasons of towing stability, construction subsidence, fine leveling and structural strength, a subdivision plate is arranged in the concrete cylinder foundation cylinder. We established solid and structural elements through numerical methods, and took into account the tube-soil contact, so as to finely construct a real three-dimensional complex model of this new type of tube-based foundation and soil, which plays an important role in analyzing its deformation and bearing characteristics, as well as the safety and stability of the foundation structure design and practical application.

1. Introduction

With the development of renewable energy in the world, the development of offshore wind energy has become a hot spot nowadays. China's offshore wind power development has also been fully launched. In the construction of offshore wind farms, the cost of infrastructure accounts for a high proportion of the total cost, and the environment is complex, so the research of infrastructure has become the focus and difficulty [1,2]. Since 1980, nearly 500 tubular foundations have been successfully installed in more than 50 countries and regions around the world [3].

Negative pressure bucket foundation, also known as suction bucket foundation, is divided into single bucket and multi-bucket structures. It can be used in shallow sea and deep sea. Among them, the negative pressure bucket in shallow sea is actually the combination of traditional pile foundation and gravity foundation. In deep sea area, it is an anchoring system supported by tension leg floating body. According to seepage theory and bucket foundation negative pressure penetration principle [4], the pile foundation of traditional jacket platform is changed into a bucket foundation with a short and thick rigid open thin-walled cylindrical shell structure, and the bucket foundation is pressed into the seabed to a certain depth by using the dead weight of bucket foundation and the weight of superstructure to form a sealing condition. Then, the inside of bucket foundation is pumped by a pump to cause negative pressure inside and outside the bucket, and the bucket body is pressed into the seabed to a predetermined depth by the pressure difference to achieve the fixed effect. There are many factors to be considered in the design of negative pressure bucket foundation, and the design is difficult. The DNV code recommends that the applicable water depth be 0 ~ 25 m. It can be said that the foundation of negative pressure bucket is still in the research stage, but with the deepening of research, its application in offshore wind power foundation design will be promoted. Like other types
of offshore wind power infrastructure, negative pressure bucket foundation also needs to meet the requirements of foundation stiffness and rotation angle control. Zdravkovic et al. [5] used finite element numerical model to analyze and study the load characteristics of bucket foundation under inclined load. Bransby et al. [6] and Gourvenec et al. [7] studied the bearing capacity of foundation under combined loading conditions by means of model test and numerical calculation. In this paper, the stability analysis of bucket foundation under horizontal load, vertical load and wind, wave and current combined loads are considered.

2. Constitutive Relation
Constitutive relationship of rock and soil mass refers to the constitutive relationship, which is based on the test results of elastic-plastic stress-strain curves of a small number of rock and soil mass, supplements some necessary assumptions according to the plastic theory of rock and soil, and then extends these test results to the stress-strain relationship under complex stress state. The equation to express this stress-strain relationship mathematically is the constitutive model of rock and soil. Because of the diversity and difference of geotechnical materials, they can't be expressed by a unified constitutive model, so many geotechnical constitutive models have been developed. There are 12 models built in FLAC3D software (empty model; Three elastic models (isotropic, transversely isotropic and orthogonally isotropic elastic models); Eight plastic models (Drucker-Prager model, Mohr-Coulomb model, strain hardening/softening model, ubiquitous joint model, bilinear strain hardening/softening ubiquitous joint model, modified Cambridge model, double yield model and Hawke-Brown model)). In this calculation, Mohr-Coulomb model is mainly selected to represent the deformation and failure of rock and soil under stress. Mohr-Coulomb (M-C) criterion is:

$$\sigma_1 = \sigma_3 \frac{1 + \sin \phi}{1 - \sin \phi} + 2c \sqrt{\frac{1 + \sin \phi}{1 - \sin \phi}}$$

(1)

Where, \(\tau_s\) is shear stress, \(c\) is cohesion, \(\phi\) is internal friction angle.

Mohr-Coulomb model adopts ideal plastic material model. When the material is in a yield state, the yield function must satisfy the condition is equal to 0, and the yield function \(f^y\) is:

$$f^y = \sigma_1 - \sigma_3 \frac{1}{N_\phi} + 2c \sqrt{N_\phi} \frac{1 + \sin \phi}{1 - \sin \phi}$$

(2)

The yield function of tensile stress can be written as:

$$f^t = \sigma_1 - \sigma_3$$

(3)

The potential function used in FLAC can be expressed as:

$$g^* = \frac{\sigma_1 - \sigma_3}{1 + \sin \psi} \quad N_\psi = \frac{1 + \sin \psi}{1 - \sin \psi} \quad g^t = \sigma_1 - \sigma_3$$

(4)

Where, \(\psi\) is the dilatancy angle of the material corresponding to shear failure and tensile failure.
(a) yield function \hspace{1cm} (b) plasticity function

**Figure 1.** Complete Plastic Mohr-coulomb Constitutive Model

The potential function is shown in figure 1. The dilatancy angle is defined as the ratio of plastic volumetric strain rate to plastic deformation strain rate (Vermeer and Borst, 1954), which can be written as:

\[
\sin \psi = \frac{\Delta \varepsilon_v}{\Delta \gamma_p}
\]

Where, \( \Delta \varepsilon_v \) is plastic volume strain rate and \( \Delta \gamma_p \) is plastic strain rate (twice plastic shear strain increment).

Simply put, if the dilatancy angle \( \psi = 0 \), the volume of the material will not change when shear failure occurs. If the dilatancy angle \( \psi > 0 \), the volume will increase after the material is damaged. Finally, the flow criterion defines the magnitude and direction of plastic strain increment, as follows:

\[
\Delta \varepsilon_p = \lambda \frac{\dot{g}^i}{\dot{\varepsilon}^i} (i = 1,2,3)
\]

Where, \( \lambda \) is a multiplier that is not negative.

**3. Three-dimensional Model Building**

Taking an offshore wind power project in Guangdong Province of China as an example, the overall model rendering of the suction bucket is shown in figure 2, and the main structure includes: outer bucket, inner bucket, round plate, sub-warehouse plate and rib connecting piece.

**Figure 2.** Effect diagram of the whole model of suction bucket
According to the actual engineering size of bucket foundation and marine geological conditions, a three-dimensional large-scale field simulation model of suction bucket-stratum is established, and the finite element model is meshed. The numerical 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. The gridding section between suction bucket (including connectors, silo plates, etc.) and stratum is shown in figure 3.

Figure 3. Cross-sectional view of the whole grid
The external loads on the barrel body include vertical load, horizontal load, wave load, bending moment and torque. In order to simulate the contact between real stratum and bucket, a contact surface is set between suction bucket and stratum, as shown in figure 4.

Figure 4. Interface between barrel and formation
4. Stability Analysis
According to the finite element model, based on the Mohr-Coulomb constitutive relation, we used the finite difference method to iteratively calculate the overall deformation and stress of bucket and stratum. Multiple monitoring points are arranged at the nodes or units of bucket and soil, as shown in figure 5, to monitor the displacement evolution characteristics of characteristic points or units in the calculation process.

![Figure 5](image_url)

Figure 5. Arrangement position of monitoring points (units)

Select the upper, middle and lower representative parts, and compare the horizontal deformation characteristics of corresponding bucket top, bucket cover and bucket bottom, that is, the $x$-displacement evolution curves of measuring points 1, 6 and 10. As shown in figure 6, the $x$-displacement generally tends to increase gradually, and the displacement gradually decreases from top to bottom. Because the bucket top is directly affected by horizontal load and bending moment, its displacement is the largest, while the displacement of the bucket bottom is very small.

![Figure 6](image_url)

Figure 6. Evolution characteristics of $x$-displacement of characteristic points

Comparing the vertical deformation characteristics of bucket top, bucket cover and bucket bottom, i.e., $z$-displacement evolution curves of measuring points 1, 6 and 10. As shown in figure 7, $z$-displacement tends to gradually increase, and from top to bottom, the displacement gradually
decreases. The top of bucket is directly subjected to horizontal load and bending moment, so the displacement at the bottom of bucket is the largest, while the displacement at the bottom of bucket is very small.

**Figure 7.** Z-displacement evolution characteristics of characteristic points

According to the displacement calculation result, the mud surface rotation angle of the suction bucket is calculated, \([(105.8 \text{ mm} + 28.6 \text{ mm}) / (36000 \text{ mm})] \times 1000\% = 3.73\%< 4.36\%\), which meets the requirements and is generally stable.

5. Conclusion

Single-column composite tubular foundation is a new type of innovative foundation for offshore wind power projects under complex geological environment in Guangdong and Fujian offshore areas, China. The whole structure is an all-steel structure of "single column + connector + tube". The connecting structure can give full play to the advantages of single pile foundation and traditional tubular structure, and solve the engineering problems of deep water, large waves, shallow bedrock and short construction window in offshore deep water areas. Integral construction on land, rapid sinking and installation at sea, without piling and rock-socketed construction, effectively improving foundation construction efficiency and reducing project cost. Through finite element method, we established a single pile composite tube model, and analyzed the overall stability under multi-load conditions, which provided important reference for the design and construction of composite tube.

6. References

[1] Kuo Y S, Achmus M, Kao C S 2008 Practical design considerations of monopile foundations with respect to scour [C] (Global Wind Power) p 104

[2] LI W 2011 Study on the fuzziness in fatigue life estimation of the foundation of offshore wind turbine (Advanced Materials Research) pp 4741–4745

[3] Zhang S, Zheng Q, Liu X 2004 Finite element analysis of suction penetration seepage field of bucket foundation platform with application to offshore oilfield development (Ocean Engineering) v 31 pp 1591–1599

[4] Li W, Li H J, Zheng Y M, et al 2011 Fatigue life analysis of the foundation structure of offshore wind turbine (Hydro-science and engineering) pp 70–76

[5] Zdravkovic L, Potts D M, JARDINE R J 2001 A parametric study of the pull-out capacity of bucket foundations in soft clay (Géotechnique) v 51 pp 55–67

[6] Bransby M F, Randolph M F 1998 Combined loading of skirted foundations (Géotechnique) v 48 pp 637-655

[7] Gourvenec S, Randolph M F 2003 Effect of strength non-homogeneity on the shape of failure envelopes for combined loading of strip and circular foundations on clay (Géotechnique) v 53 pp 575-586