Analysis on the Mechanical Characteristics of Onshore Wind Power Generation Foundation Structure

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Abstract. Based on the 3D finite element method, considering the plastic damage model of concrete, the uncoordinated deformation relationship between steel foundation ring and concrete, and the coordinated displacement relationship between steel bars and concrete, this paper conducts a simulation analysis on onshore wind power generation foundation, and studies the stress characteristics of the foundation under ultimate load condition. The results show that the lower part of the steel foundation embedded plate is a weak part, which not only needs to pay attention to the tensile failure, but also needs to prevent the compression failure. Perforated steel bars arranged on the top of steel plates have a obvious stress effect, which obviously strengthens the connection between steel plates and concrete. With the weakening of the connection between steel foundation and concrete, the top displacement and relative displacement of the contact surface between steel plate and concrete gradually increase. With the increase of friction coefficient between steel foundation and concrete, the stress of perforated steel bars and the displacement of foundation ring top surface also decrease. The research results of this paper can provide an important reference for the design and reinforcement of infrastructure.

1. Introduction
With the continuous maturity of wind power technology, wind power generation has become an important way of renewable energy utilization, and the wind turbine foundation is one of the keys to ensure the safe operation of wind turbines. The fan foundation not only bears the gravity load of engine room and tower cylinder, but also bears the huge overturning moment brought by the fan sway. The small displacement of the foundation in the horizontal direction will cause the large horizontal eccentricity at the top of the tower, which will directly affect the safe operation of the fan. The connection between the fan foundation and the tower barrel is mostly based on the embedding method of the foundation ring. The steel foundation ring is embedded into the concrete foundation. The upper part of the steel foundation ring is connected with the bottom tower barrel by flange, and the lower part is connected with the concrete by bolts. Under the action of torque, due to the different properties of steel and concrete materials, the deformation of them is not coordinated, which leads to cracks on the concrete roof and looseness of the interface between the foundation ring and the foundation.
concrete in many projects after the fan operation for a period of time. Therefore, in recent years, infrastructure security has attracted extensive attention [1-2].

The application of finite element method to analyze the basic structure is mostly based on the assumption of linear elasticity [3]. However, without considering the damage of concrete material, the stress concentration phenomenon becomes more serious after the fatigue failure of the foundation, which is not conducive to the real understanding of the mechanical characteristics of the basic structure. In this paper, the plastic damage model of concrete is adopted, considering the uncoordinated relationship between deformation of steel foundation ring and concrete, and the coordinated relationship between displacement of steel foundation ring and concrete, the stress state of concrete and reinforcement around the foundation ring and other stress states are studied, so as to provide a reference for the design of wind turbine foundation and subsequent theoretical research.

2. The analysis model

2.1. Relying on the project
This paper relies on a wind farm in QingHai province a single capacity of 20MW fan foundation. Its basic design section is shown in Figure 1. The total height of reinforced concrete foundation is 3.3m, the bottom is 17.4m in diameter and 1.0m in height. In the middle is a round table with a bottom diameter of 17.4m, a top diameter of 6.8m and a height of 1.3m. The upper part is a cylinder with a diameter of 6.4m and a height of 1.0m. The fan foundation is 0-0.7m of silt and 0.7-20m of pebble bed, and its physical parameters are shown in Table 1.

| Geotechnical | Density of natural (g/cm³) | Compression coefficient (MPa⁻¹) | Compression modulus (MPa) | Cohesion (kPa) | Friction Angle (°) | Characteristic value of bearing capacity (kPa) |
|--------------|-----------------------------|---------------------------------|--------------------------|---------------|------------------|------------------------------------------|
| Pebble bed   | 2.1                         | /                               | 22                       | 0             | 30               | 380                                      |
| Powder soil  | 1.8                         | 0.18                            | 8.0                      | 20            | 20               | 160                                      |

The main loads of the fan are the dead weight of the structure, the aerodynamic action of the blades and the uniform wind load on the tower surface. The load transferred from the superstructure to the fan foundation is simplified into horizontal load, vertical load and bending moment on the top surface of the foundation ring. In the conventional fan design, the extreme load condition is the control condition based on the extreme load condition. The extreme load of this project is shown in Table 2, Y for the vertical. The main body of the foundation is made of concrete C40, the ring steel of the foundation is made of steel Q345, and the reinforcement of the foundation is made of HRB400.

| Direction | Fy (kN) | Fx(kN) | Mz(kNm) | My(kNm) |
|-----------|---------|--------|---------|---------|
| Load      | 3522.21 | 887.45 | 83309.33| 2394.28 |
2.2. The analysis model
In this paper, finite element analysis software ABAQUS is used to simulate the research object. The damage plasticity model of concrete in ABAQUS is based on the model proposed by Lee, Fenves and Lubliner et al. [4-5]. The model can simulate the softening process and unloading stiffness degradation of concrete materials, and can also simulate the repeated loading process well. In addition, the ABAQUS program has strong implicit and explicit nonlinear computing power, which makes its application effect better. The program can add individual reinforcement units and then embed the reinforcement unit into the concrete unit by embedding. Based on the coordination of the displacement of reinforcement and concrete, the contribution of concrete and reinforcement to the element stiffness matrix is calculated respectively, and then combined to form the comprehensive element stiffness matrix. The bond sliding and dark pin action of concrete and steel are simulated by introducing the stress-strain relationship of concrete. The foundation concrete simulated in this paper adopts C40, and the stress-strain relationship after the material reaches the standard tensile strength (2.39MPa) is shown in Figure 2, while the stress-strain relationship after the material reaches the standard compressive strength (26.8MPa) is shown in Figure 3.

The spring is set at the bottom of the foundation to simulate the effect of the foundation and soil. In addition, considering that the foundation and the foundation ring belong to different materials, the relationship between the two is simulated by means of friction contact, which can reflect the relative sliding and shearing situation. The overall analysis model is shown in Figure 4, and the section of the reinforcement model is shown in Figure 5. The coupling of reference point and top surface motion is established at the center of the top surface of the foundation ring, and then the load is applied to the reference point, and the reinforcement end is restrained at the bottom of the foundation.

3. Mechanical properties of infrastructure

3.1. Mechanical properties of concrete
Under a counterclockwise loop at the top of the bending moment and to the left of the horizontal force, base ring on the right side of regional tension and compression on the left side of the area. Figure 6 concrete on the basis of the plastic strain nephogram of buttock. Figure 7 is cut from the plate at the bottom of the base ring, show the foundation concrete plastic strain nephogram of horizontal section. Figure 8 based ring external plastic strain nephogram horizontal section shape change. Mainly based on plastic deformation area is located in the tension side of buried steel base plate and foundation ring external shape change, although the plastic deformation zone in the tensile zone range is limited, not
present through concrete cases, but in basic loop pressure side, buried plate distance from the center of the bottom plate foundation slab in 0~1.3m in plastic deformation area, studies have shown that buried steel base plate bottom belongs to the weak positions, not only need to pay attention to the tensile failure, also need to prevent compression damage.

3.2. Mechanical properties of reinforcement

The mises stress of overall foundation steel was shown in Figure 9. The most significant areas of the steel were the connection steel of steel plate and concrete, the variation of the lateral body shape of the foundation, and the position near the foundation plate of the lower flange. In order to prevent deformation of the steel foundation ring, holes are generally reserved evenly along the circumference of the steel plate of the foundation ring, and the connection between the steel plate and concrete is strengthened by placing tensile reinforcement bars at the opening. As shown in Figure.10, the reinforcement arranged at the opening of the steel plate is dominated by tensile stress on the tensile side of the foundation ring, the maximum value of which is 239.9MPa. The compressive stress on the tensile side of the foundation ring is all manifested as compressive stress, indicating that the steel plate reinforcement has a good connection effect. As shown in Figure. 11, the stress on the tensile side of the reinforcement at the top of the foundation at the change of the outer body of the foundation is relatively large, and its maximum value is 209.8MPa. In addition, under the lateral steel flange base buried near the plate, because the base ring tension pull up on the side, under the base ring flange ring on both sides of the need to resist large bending moment to the reinforcement of tensile stress, the reinforcement stress is larger, so the parts as shown in Figure 12, the maximum value is 134.3MPa, therefore, in the foundation design of the parts need to configure the sufficient bearing steel.
4. Study on the Interaction surface between foundation ring and concrete

4.1. Study on different connection states of action surfaces

Three schemes are selected to study the stress state of different connecting states of steel foundation ring and concrete. Scheme 1 is a steel foundation ring and concrete solid connection, Scheme 2 is a solid connection between the flange at the bottom of the steel foundation ring and concrete, but the side wall of the steel foundation ring is only in frictional contact with concrete (friction coefficient 0.6), and there is no bonding effect, so it can detangle. This scheme simulates that the steel plate will detangle from the concrete laterally due to forces or temperature changes. In scheme 3, both the bottom and the side wall of the steel foundation ring can be detached except for friction contact (friction coefficient 0.6). In this scheme, the lateral wall and the bottom flange of the steel foundation are completely detached, and relative displacement can occur.

As the steel foundation is firmly connected to the concrete in scheme 1, no relative displacement is calculated. As the connection between steel foundation and concrete is broken in scheme 2 and Scheme 3, relative displacement can occur. In both schemes, the maximum relative displacement occurs at the top of the contact surface of steel-concrete foundation, showing relative dislocation. From Scheme 1 to Scheme 3, it can be seen that the connection between steel foundation and concrete gradually weakens, and the displacement at the top of the contact surface between steel foundation and concrete and the relative displacement between steel plate and concrete also gradually increases.

As scheme 3 is the most unfavorable, the vertical displacement of the steel plate is analyzed in Scheme 3, as shown in Figure 13. The maximum displacement is on the top of the steel plate, which is 12.6mm vertically downward on the compression side and 1.92mm vertically upward on the tensile side. Figure 14 shows the vertical displacement cloud map of the peripheral concrete surface corresponding to the position of the steel plate. It is vertically downward at 10.17mm on the compression side and vertically upward at 3.56mm on the tensile side. The vertical dislocation displacement of steel plate and outer concrete on the tensile side is about 1.6mm. In addition, the opening displacement cloud map of the buried plate at the bottom of the steel plate is shown in Figure 15, with the maximum value of 0.61mm on the tensile side. Figure 16 shows the opening displacement cloud diagram of the steel plate and the outer concrete surface, with the maximum value of 0.29mm on the tensile side.

4.2. Influence of different friction coefficients on contact surface

By setting the contact between the foundation ring and the concrete, the possible detach and sliding can be simulated. The contact shear stress is simulated by changing the coulomb friction coefficient.
and the influence of different friction coefficients on the displacement of contact surface is analyzed. Take friction coefficients 0.2, 0.4, 0.6, 0.8 and 1.0 respectively. Figure 17 and 18 respectively show the relationship between the maximum stress of perforated reinforcement with friction coefficient and the maximum vertical displacement of the tensile side of the steel foundation ring with friction coefficient. With the increase of friction coefficient, the maximum stress of perforated reinforcement decreases from 258MPa to 212 MPa, and the maximum vertical displacement of the tensile side of the steel foundation ring decreases from 2.12mm to 1.77mm. With the increase of friction coefficient, the tangential constraint of concrete on the foundation ring increases, the shaking of the foundation ring decreases with the increase of friction shear stress, the stress of perforated reinforcement and the displacement of the top surface of the foundation ring also decrease.

Figure 17. Relationship between maximum stress of perforated reinforcement and friction coefficient.

Figure 18. Relationship between maximum vertical displacement on the tensile side of steel foundation ring and friction coefficient.

5. Conclusion
The research in this paper shows that the concrete at the flange under the foundation ring and the contact surface between steel plate and concrete are all weak parts. Under the action of fatigue reciprocating load, this area may suffer from cavitation damage. The concrete not only needs to pay attention to tensile damage, but also needs to prevent compression damage. In addition, perforated steel bars arranged on the top of steel plates play an obvious role in strengthening the connection between steel plates and concrete. In the design, reinforcement bars should be set here according to the load and foundation layout. With the large-scale use of fan with high wheel hub and large blade, the load borne by fan also increases rapidly and more anchorage force needs to be obtained, which brings greater technical and economic challenges to the design of fan foundation. The research results of this paper can provide important reference for the design and reinforcement of infrastructure.

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