Research on Application of Self-locking Anchor Rods in the Improvement of wind turbine generator tower foundation

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Abstract: This article provides a solution to replace the upper equipment while retaining the foundation during the technical transformation of wind power generation. Due to load changes and the damage and defects of the original foundation ring, the connection method to connect the new wind turbine tower and the existing foundation should be redesigned, and the original wind turbine generator tower foundation should be reinforced accordingly. This paper introduces the scheme of using common self-locking anchor rod and prestressed self-locking anchor rod to connect the upper tower and foundation, and compares the advantages and disadvantages of the two schemes. Two schemes for increasing the foundation and strengthening the foundation with prestressed rock bolts are proposed and compared. Both the ordinary bolt scheme and the prestressed bolt can meet the mechanical properties, but the ordinary bolt construction is convenient and economical; the foundation reinforcement using the prestressed rock anchor scheme is more economical and environmentally friendly.

1. Introduction
In 2019, the cumulative installed capacity of wind power nationwide reached 210 million kW, accounting for about 5.5% of the total power generation. During the period from "Twelfth Five-Year" to "Thirteenth Five-Year", the annual installed capacity of wind power will remain around 20 million kW. In 2019, China has launched 3 MW series onshore and 10MW series offshore wind turbines; the longest blade reaches 91 meters; the diameter of the wind wheel has more than doubled in the past ten years, reaching a maximum of 210 meters; the highest domestic hub height exceeds 150 Meters, 160-meter units will soon enter the market.

The early-built wind power plants occupy good wind farm. In general, the design life of domestic wind turbines is 20 years, but the permanent land acquisition term of wind power projects and the basic design life of wind turbines are 50 years. As these wind turbines gradually reach the service life, the transformation of the wind turbines is an inevitable choice. In order to reduce the damage to the land and reduce the generation of garbage, it is necessary to carry out research on the transformation of the wind turbine.
2. Reconstruction of the foundation ring

2.1. foundation ring form

At present, the connection between the topside structure and the foundation is mainly as follows: (a) Embedded high-strength anchor; (b) Embedded foundation ring; (c) Embedded prestressed anchor.

The problems that often occur in embedded foundation rings are cracking of the concrete at the bottom of the foundation ring and mud spillover of the foundation ring under repeated loading [1]. In the past a large number of wind turbine generators were connected to foundation rings at the way of first two methods, and the third method is currently used for high-power wind turbine generators. The bottom of the pre-embedded high-strength prestressed anchor is fixed, and the middle is separated from the base concrete with PVC and other materials. It has a strong deformability and can prevent the anchor from breaking under extreme loads. The improvement of existing wind turbines should reduce the damage to the original structure as much as possible on the basis of the original foundation, it should also avoid the problems of the first two methods as much as possible.

The post-installed fastenings are used in the improvement of the connection between the superstructure and the foundation. The current commonly used post-installed fastenings are chemical planting bars and mechanical anchors. The durability and weather resistance of chemical planting bars are poor, and the service life is generally not more than 30 years. Because of the low elastic modulus of the planting bar, its deformation is large, and its distortions arising from creep is large, which is likely to cause failure. However, the current common mechanical anchors have poor vibration resistance because they do not expand at the bottom and are not effectively anchored. They are generally used to withstand shear loads [2,3]. Wuda Jucheng Structure Co., Ltd. has developed a kind of broaching self-locking anchorage. First, it drills a straight hole in the concrete, and uses a special broaching drill bit to expand the hole at the bottom of the hole into a conical surface, and then installs one end with an unexpanded anchor head. The anchor rod is inserted into the bottom of the hole, and the axial pressure is applied to make the anchor head open and close to the cone surface of the hole bottom. The mechanical bite force of the anchor head and the hole wall (that is, "self-locking") and the friction between the anchor rod and inorganic grout provide anchoring force [4]. In this paper, based on the self-locking anchoring technology, this paper provides a scheme for using a self-locking anchor to build a new foundation connection and strengthen the foundation.

2.2. Common self-locking anchor and prestressed self-locking anchor

2.2.1. Calculation parameters of foundation.

![Diagram of the connection between the topside structure and the foundation](image-url)
Taking a 2MW wind turbine generator as an example, it is improved to 3.2MW. The original upper and lower structures are connected by a pre-buried foundation ring with a diameter of 4.2m. The original base has a diameter of 16m at the bottom and a base depth of 2.8m. The rebar is HRB400, the concrete is C40, and the foundation ring material is Q345. The distribution of the soil layer under the foundation is as follows: 0~0.50m is plain fill layer; 0.5m~3.5 m is intense weathering dolomite layer; below 3.5m is medium weathering dolomite layer.

Considering the inherent shortcomings of the embedded foundation ring and having been in service for many years, the existing foundation ring is no longer reliable. There are two schemes to connect the upper and lower structures: the ordinary self-locking anchor scheme and the prestressed self-locking anchor scheme. The superstructure leveling is carried out through the post-grouting (concrete) scheme. Taking into account the changes in the foundation load, the post-grouting part is carried out together with the foundation improvement.

**Table 1. Standard values of bottom load of tower under various load conditions (kN)**

| Load conditions           | Safety factor $\gamma_f$ | $F_z$  | $F_{xy}$ | $M_z$   | $M_{xy}$ |
|---------------------------|--------------------------|--------|----------|---------|----------|
| Frequently occurred earthquake | 1.0                      | -3638.9| 523.53   | 1141.98 | 42959.7  |
| Normal operation           | 1.0                      | -3635.9| 501.3    | 1159.8  | 40956    |
| Extreme load               | 1.0                      | -3527.5| 942      | 3527.7  | 73687    |

### 2.2.2. Common self-locking anchor scheme.

8.8 grade M36 screw with 44mm drilling diameter, 73mm broaching outing diameter (max.), and space twice more than that of broaching outer diameter will be adopted and 188 M36 screws will be arranged. The maximum tension of the anchor bolt under normal load is 156kN, and 297kN under extreme load. The anchor rod length is 3.5m, the bottom is 250mm away from the fundus, and the anchor length including the anchor head is 1000mm. Allowing a certain free length can optimize the deformation performance of the anchor rod under the ultimate load.

### 2.2.3. Prestressed self-locking anchor scheme.

An anchor cable is composed of 5 bundles of 1×7Φs15.2 steel strands, the diameter of the drill hole of the anchor rod is 110mm, the maximum diameter of the broaching hole is 180mm, and the spacing is more than 2 times the diameter of the bottom. It is planned to adopt 80 prestressed anchor cables to fix the foundation ring. If the foundation uncouples from the ground, the single anchoring force is 677kN under normal load and 1236kN under limit load; if the foundation does not uncouple from the ground, the single-hole pull force is 392kN under normal load and 742kN under limit load. The bottom of the anchor is 250mm away from the fundus, and the anchor length including the anchor head is 1000mm. With 800kN prestress of the anchor cable, the foundation ring will not uncouple from the ground under normal load.

### 2.2.4. Scheme comparison

**Table 2. Comparison of tower connection schemes**

| Tower connection scheme | Mechanical properties | Construction convenience | Economy |
|-------------------------|-----------------------|--------------------------|---------|
| Common anchor           | meet the mechanical properties | The drilling hole is small, and the construction is convenient. | good    |
| Prestressed anchor      | Higher rigidity and better mechanical properties | The drilling hole is large, which may obstruct rebars, original foundation rings, etc. | bad     |
3. Improvement of foundation

3.1. Foundation improvement scheme
Prestressed anchor cable scheme: 30 prestressed anchor cables are adopted to reinforce the original foundation. An anchor cable is composed of 8 bundles of 1×7Φs15.2 steel strands. Each anchor cable is prestressed by 760kN, as shown in Figure 3 (a).

Expanded foundation scheme: enlarge the original foundation, the reinforced foundation diameter is 20m, and the reinforcement density is the same as the original foundation, as shown in Figure 3 (b).

3.2. Force analysis
Abaqus is used for calculation, the upper part of the prestressed anchor cable is connected to the foundation platform by “Embedded region”, and the bottom of the prestressed anchor cable is connected to the soil layer by “Embedded region”. The deformation of the soil layer is included in the calculation.

(a) Prestressed anchor cable scheme
Through finite element calculation, the stress, internal force and deformation of the foundation under extreme load conditions are greater than those in normal operation conditions and frequently occurred earthquake conditions, so this article mainly studies the stress conditions of the foundation under extreme load conditions. The base stress is shown in Table 3, and the base stress nephograms under extreme load are shown in Figures 4 and 5.

**Table 3. Base stress(kPa)**

| Load conditions                      | $p_{\text{max}}$ | $1.2f_a$ | $1.2f_{\text{Ed}}$ |
|--------------------------------------|------------------|----------|---------------------|
| Pre-stressed anchor cable scheme     | 1691             | 4500     |                     |
| Frequently occurred earthquake       |                  |          |                     |
| Pre-stressed anchor cable scheme     | 1907             |          | 3000                |
| Extreme load                         |                  |          |                     |
| Expanded foundation scheme           | 565              |          | 4500                |
| Frequently occurred earthquake       |                  |          |                     |
| Expanded foundation scheme           | 676              |          | 3000                |
| Extreme load                         |                  |          |                     |
See Table 4 for the radial and annular reinforcement area of the foundation under extreme loads, and Table 5 for the maximum crack width.

Table 4. Reinforcement area under the extreme load (mm²)

| Plan      | Radial bottom reinforcement | Radial top reinforcement | Annular bottom reinforcement | Annular top reinforcement |  |
|-----------|-----------------------------|--------------------------|-----------------------------|--------------------------|---|
| Calculation of reinforcement area | Prestressed anchor cable scheme | 5801                      | 4394                        | 2703                      | 1983 |
|           | Expanded foundation scheme  | 6489                      | 4145                        | 4113                      | 2300 |
| Actual reinforcement area           | 7061                      | 6243                      | 4399                        | 4399                      |   |

Table 5. Maximum crack width under extreme load

| Plan                          | Bottom tension | Top tension |
|-------------------------------|----------------|-------------|
|                               | $\sigma$ (MPa) | $w_{\text{max}}$ (mm) | $\sigma$ (MPa) | $w_{\text{max}}$ (mm) |
| Prestressed anchor cable scheme | 211.12          | 0.270       | 164.46         | 0.100       |
| Expand foundation scheme      | 190.05          | 0.189       | 152.85         | 0.093       |

It can be seen from Table 4 and Table 5 that foundation of the prestressed anchor cable scheme and the expanded foundation scheme both accord with requirement of criterion, but the prestressed anchor cable scheme is more economical than the expanded foundation scheme, and the amount of excavation and concrete is small, as shown in Figure 6. The foundation diameter of the prestressed anchor cable scheme is small, and many wind turbine sites do not have the construction conditions for large diameter wind turbines. The prestressed anchor cable scheme has obvious advantages in terms of construction difficulty and environmental friendly, and it is also superior to the expanded base scheme because it does not require additional land acquisition.

Table 6. Economic comparison of the two schemes

| Improvement scheme                          | Foundation diameter(m) | Excavation volume (m³) | Concrete amount (m³) |
|---------------------------------------------|------------------------|------------------------|----------------------|
| Prestressed anchor cable scheme             | 8                      | 402                    | 69                   |
| Expand foundation scheme                    | 10                     | 942                    | 322                  |
4. Conclusion

- Due to load changes and the damages and defects of the original foundation ring, the connection method of the new wind turbine generator tower and the existing foundation should be redesigned, and the original foundation should be improved.
- Ordinary self-locking anchors and prestressed self-locking anchors can both connect the new wind turbine generator tower with the existing foundation. Compared with prestressed self-locking anchors, ordinary self-locking anchors have slightly worse mechanical properties, but the construction is less difficult and more economical.
- Prestressed anchor cable scheme and expand foundation scheme can both bear increased load, but prestressed anchor cable scheme is more economical and more environmental friendly.

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