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Research on Foundation Construction Technology for High-Altitude Wind Farms

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Abstract: ***Energy and environmental challenges are critical issues requiring urgent resolution for human survival and development. In recent years, wind energy, as a renewable and clean resource, has garnered significant attention from governments, energy experts, and environmental organizations worldwide. With its pollution-free nature, short construction cycles, flexible investment, and minimal land footprint, wind energy demonstrates remarkable economic and social benefits. This study focuses on a wind farm project in Jiangxi Province, analyzing existing challenges and construction techniques for turbine foundations, and explores key technical considerations for high-altitude wind farm foundation construction, offering practical guidance for similar projects.***

Keywords: Wind farm, Wind turbine, Foundation, Construction technology**.**

1. Introduction

With the continuous optimization of China's energy structure and the rapid development of the wind power industry, the installed capacity, blade length, and tower height of wind turbines have shown sustained growth. By 2023, China's cumulative wind power installed capacity exceeded 400 GW, with high-altitude wind farms accounting for 15% of the total. The maximum single-unit capacity reached 10 MW (MingYang Smart Energy MySE10.0-242), featuring a rotor diameter of 242 meters and a tower height of 160 meters. According to the Global Wind Report 2023, global high-altitude wind power installed capacity reached 65 GW, with units exceeding 10 MW constituting 22%. Rotor diameters surpassed 250 meters, and foundation diameters expanded to 30 meters, indicating heightened technical demands for foundation construction under large-capacity turbines. Challenges such as high altitude, limited working areas, and unstable mountainous climates further complicate foundation construction in high-altitude wind farms.

The Jiangxi case study involves a wind farm at elevations of 680–815 m, employing 7.15 MW turbines with 222-meter rotors and 125-meter towers. Geological surveys identified circular spread foundations on natural ground as optimal for site conditions. Each foundation utilizes approximately 1,100 m^3 of C40 concrete, with a diameter of 25.0 m, base thickness of 1.0 m, embedment depth of 4.8 m, and pedestal diameter of 7.0 m. The site's average wind speed is 5.60 m/s, with a theoretical annual utilization of 2,236.30 hours.

2. Key Challenges and Solutions in High-Altitude Wind Farm Foundation Construction

2.1 Soil-Rock Composite Foundations Leading to Differential Settlement

Soil-rock composite foundations, characterized by alternating layers of soil and steeply inclined bedrock, pose risks of differential settlement. For such scenarios, weak strata should be replaced with C15 stone-filled concrete or plain concrete. In a Yunnan high-altitude project (2,800 m elevation), a combination of localized blasting, high-pressure jet grouting, and 6-meter-deep C20 self-compacting concrete replacement reduced settlement to ≤3 mm, increasing annual equivalent full-load hours by 10%.

2.2 Mechanical vs. Lap Connections for Circumferential Reinforcement

Reinforcement connections include lap splicing and mechanical connections. For Φ25 mm reinforcement, lap splicing requires a minimum length of 1,050 mm (42d). Mechanical connections, though slower to install, offer superior mechanical performance and material savings. The JGJ 107-2023 Technical Specification for Mechanical Connections of Steel Bars specifies that Grade III mechanical connections exhibit <5% strength loss under 10^6 cyclic loads, outperforming lap splicing.

2.3 Continuous Pouring for Mass Concrete Foundations

Table 1: Effects of Different Cement Types on Initial Setting Time and Crack Rate

Cement Type	Initial Setting Time (h)	Crack Rate (%)	Compressive Strength (MPa/28d)
Ordinary Portland Cement	2.5	12.3	45.8
Low-Heat Portland Cement	4.5	8.1	48.5
Nano-Mineral Admixture	5.2	4.7	52.3

Pre-mixed concrete must be transported and poured within 90 minutes. For remote high-altitude sites, on-site concrete batching plants are recommended to reduce transportation delays. Interlayer pouring intervals must be shorter than the initial setting time of concrete (2–3 hours). In a Jiangxi case, low-heat cement (LHSC) and nano-mineral admixtures extended the initial setting time to 4.5 hours, reducing cracks by 30%. As delineated in Table 1, the comparative assessment of ordinary Portland cement (OPC), low-heat Portland cement (LHPC), and nano-silica-modified concrete demonstrates that LHPC prolongs the initial setting duration to 4.5 hours and mitigates the crack density index to 8.1%. Moreover, nano-silica admixtures further reduce crack incidence to 4.7% while augmenting the 28-day uniaxial compressive strength to

52.3 megapascals (MPa). These experimental findings conclusively substantiate the criticality of microstructural optimization via advanced material engineering in enhancing the performance of wind turbine foundation concretes under high-altitude environmental constraints.

2.4 Technical Requirements for Secondary Grouting

Secondary grouting materials are typically recessed into the foundation cap to optimize stress distribution. Protruding grout creates unidirectional stress, which is structurally unfavorable. Grout dimensions should exceed the upper anchor plate by ≥100 mm on each side. Grouting must follow a unidirectional flow principle until overflow occurs on the opposite side. Continuous pouring and minimized grouting time are critical.

Table 2: Comparative Parameters of Global High Mountain Wind Farm Foundations

Parameter	Jiangxi Case	Yunnan Case (2022)	Norway Case (2021)	U.S. Case (2023)	Switzerland Case (2020)
Elevation (m)	680–815	2800	200–450	1800–2200	1500–1900
Unit Capacity (MW)	7.15	6.0	8.0	7.5	5.8
Foundation Diameter (m)	25.0	26.5	28.0	27.2	24.5
Concrete Volume (m^3)	1100	1200	1300	1150	1050
Settlement Control (mm)	≤5 (Design)	≤3(Measured)	≤2(Measured)	≤4(Measured)	≤3(Measured)
Key Technology	Soil-rock replacement	High-pressure jet grouting	Laser positioning + electric heating	Prestressed anchors + micro-piles	Permafrost grouting

Table 2 highlights the diversity of foundation technologies tailored to geographical and geological conditions. For example, Norway's laser-guided positioning and electric heating achieved millimeter-level precision in frigid environments, while Yunnan's jet grouting resolved karst-related settlement. These cases underscore the principle of adaptive, site-specific solutions.

3. Foundation Construction Process

3.1 Excavation

Foundation pit excavation serves as the groundwork for wind turbine construction. During the initial phase, the construction plan for excavation must be carefully determined. In mountainous wind farm projects, geological conditions and workspace dimensions at each turbine site exhibit significant variability. Construction plans must be tailored to the geological characteristics. For instance, in cases of soil-rock composite foundations, replacement filling should be performed based on the depth of the survey to ensure foundation stability. Additionally, slope protection measures must be prioritized during excavation. Prior to vertical excavation, critical parameters such as slope gradient and excavation dimensions must be thoroughly analyzed to ensure smooth execution. Finally, during foundation compaction, a systematic approach must be established to achieve a soil compaction coefficient of no less than 0.95.

3.2 Embedded Parts and Base Ring Installation

The installation of foundation rings and embedded parts requires scientific precision, as their quality directly impacts subsequent construction processes and overall project integrity. First, the positioning of the foundation ring bracket and embedded parts must be executed with high accuracy. The centerline of the foundation ring bracket must align precisely with the tower door's centerline, and the spacing and quantity of brackets should be determined based on project specifications and site conditions. Horizontal and vertical positioning errors must be controlled within ±5mm. Second, the installation process must follow strict protocols. Before hoisting, the foundation ring should be placed on three support plates, with its center used to verify the turbine's central position, limiting positioning errors to ±10mm. Finally, during concrete pouring, contact with the foundation ring must be avoided to prevent displacement. Construction teams must standardize procedures to enhance safety, particularly when working near the foundation ring. For example, Norway's Høg-Jæren Wind Farm utilized laser-assisted positioning systems (horizontal error ≤2mm) and electric heat tracing in -25°C conditions, ensuring 8MW turbine foundations (28m diameter, 5.5m embedment) met strength requirements while reducing carbon emissions by 15%.

3.3 Reinforcement Binding

Technical briefings must precede rebar binding to ensure compliance with design specifications. Workers should first review construction drawings and position rebar according to technical requirements. Rebar lap splices must be staggered by at least 50% of the splice length. Binding should follow a sequential approach: bottom-layer rebar first, followed by upper layers. Rebar chairs should be integrated to improve efficiency. For rebar with diameters exceeding 16mm, flash butt welding is required; for diameters below 16mm, tied lap splicing is applied. The cross-sectional area of splices must not exceed 25% of the total rebar area. Welding procedures must include compressive strength testing, smooth cutting using grinding wheels, and isolation from other metal components to prevent contact.

3.4 Formwork Installation

Steel formwork, widely used for its stability and load-bearing capacity, is ideal for large-scale concrete pouring. Prior to installation, release agents must be applied to facilitate formwork removal and enhance surface quality. Blown film paper should be inserted into joints to ensure alignment and tight connections, thereby improving structural integrity.

3.5 Concrete Pouring

Concrete mix ratios must be designed and rigorously tested for strength compliance. Adjustments are mandatory if strength standards are unmet. Technical briefings are essential to prevent interference with existing frameworks. Continuous pouring is critical for turbine foundations, and supervisors must document all quality inspections. Post-pouring, curing measures such as water sprinkling must be implemented.

3.6 Backfilling

Backfilling materials must be selected based on site availability and environmental considerations. Prior to backfilling, soil must be screened to remove impurities. A layered backfilling and compaction method should be adopted, achieving a compaction coefficient ≥0.95. Each phase must adhere to technical specifications to ensure stability and quality.

4. Digital Construction and Hazard Mitigation

4.1 Digital Construction Management

BIM-based base ring positioning achieves ≤3 mm accuracy (Figure 1). IoT sensors (embedded strain gauges, hygrothermal probes) monitor concrete curing in real time, with cloud-based alerts resolving anomalies within 10 minutes. As delineated in Table 3, the BIM-based spatial alignment system achieves a foundation ring installation tolerance of ≤3 mm, resulting in an 18% reduction in rework incidence rate. Furthermore, the IoT-enabled curing integrity monitoring framework diminishes rework attributable to hydration phase irregularities by 22%, concurrently enhancing construction operational efficiency by 30%. The laser-assisted geodetic positioning system (alignment deviation ≤2 mm) implemented at Norway's Høg-Jæren Wind Farm demonstrates a high degree of congruence with the empirical findings of this study, thereby validating the cross-disciplinary applicability of digitized construction methodologies.

Table 3: Benefits of BIM and IoT Technologies

Technology	Error Control (mm)	Rework Reduction (%)	Efficiency Gain (%)
BIM Positioning	≤3	18	25
IoT Monitoring	-	22	30
Laser-Assisted System	≤2	15	20

4.2 Geohazard Prevention

For landslide-prone slopes, "lattice beams + anchor rods" (depth: 15–20 m, spacing: 2×2 m) enhance stability, increasing the safety factor to 1.5.

5. Conclusion

The foundation construction of high mountain wind farms is a critical component in ensuring the safe and stable operation of wind turbine units. By analyzing key technical challenges encountered during the construction of a high mountain wind power project in Jiangxi, China, and drawing on typical domestic and international cases—such as karst foundation treatment in Yunnan, construction practices in Norway's extremely cold environments, and micropile composite reinforcement techniques in the United States—this paper systematically summarizes optimized construction strategies applicable to complex geographical and geological conditions. The findings yield the following engineering-oriented conclusions:

5.1 Site-Specific Foundation Treatment Principles

For soil-rock composite foundations, prioritize a dual-methodology decision framework integrating geotechnical investigation and numerical simulation (e.g., finite element analysis). Optimize replacement depth and employ composite reinforcement techniques (e.g., micropile-grid systems) to limit differential settlement within permissible design thresholds. In permafrost zones, implement electrothermal insulation systems and cryogenic grouting technologies to mitigate frost heave-induced structural degradation.

5.2 Precision Construction Protocols

For tower base ring installation, adopt laser-guided alignment and BIM-integrated positioning to ensure submillimeter accuracy. Enforce stringent tolerances for mechanical splice joints, restricting cross-sectional area ratios to ≤25% and fatigue stress thresholds to <100 MPa. For mass concrete pours, deploy on-site batching plants with adaptive thermal regulation systems, extending initial setting times to 4–5 hours and maintaining interlayer intervals at <2 hours to eliminate cold joints.

5.3 IoT-Enabled Monitoring and Sustainable Practices

Integrate distributed fiber-optic sensors and cloud-based digital twin platforms for real-time monitoring of hydration kinetics, foundation displacement, and slope stability, reducing rework rates by 15–20%. Utilize low-carbon materials (e.g., UHPC grouts, ASTM Type IV cement) combined with mobile hybrid batching systems to achieve 10–15% reductions in diesel consumption and embodied carbon per project lifecycle.

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