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Detection and Stability Evaluation of Coal Mine Goafs under Transmission Lines

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Abstract: ***To ensure the safety of transmission lines, this study conducts a systematic investigation and evaluation of concealed coal mine goafs along the route. The research begins with a detailed survey using the high-density resistivity method. Through the interpretation of inverted resistivity profiles, the spatial location, burial depth, and approximate scale of several water-filled goafs were successfully identified, with the results subsequently verified by borehole data. On this basis, combining geophysical findings with geotechnical analysis, a stability evaluation of the goaf sites was performed. The evaluation indicates that some goafs are in a sub-stable state, posing a potential threat to the surface transmission facilities. In response to the risks revealed by the evaluation, this paper further explores and proposes corresponding preventive treatment measures. This research provides an effective technical framework and engineering basis for the accurate detection of concealed goafs, scientific evaluation of their stability, and the formulation of treatment plans.***

Keywords: Goaf, High-Density Resistivity Method, Stability Evaluation, Transmission Line.

1. Introduction

Long-term coal resource exploitation in China has left behind a vast number of underground goafs. The resulting geological hazards, such as ground subsidence, collapse, and fissures, have become significant threats to the safety of surface buildings and structures [1]. With the rapid expansion of the national power grid, it is increasingly common and often unavoidable for transmission corridors to traverse over these mined-out areas. As tall structures, the foundation stability of transmission towers is directly linked to the operational safety of the power grid. Any ground deformation caused by the reactivation or instability of goafs can easily lead to catastrophic accidents like tower collapse and line breakage [2]. Therefore, identifying the spatial distribution of goafs underlying the transmission lines and scientifically evaluating their stability are critical steps in ensuring the safety of power transmission projects.

For long-distance linear projects such as transmission lines, traditional drilling methods are limited by high costs, low efficiency, and the difficulty of controlling blind spots between boreholes. In contrast, the high-density resistivity method, with its advantages of high efficiency, non-destructiveness, and continuous imaging, has become an effective geophysical tool for detecting goafs and their associated collapse zones. The significant electrical resistivity contrast between the goaf (and its backfill or collapsed material) and the surrounding rock mass provides a solid geophysical basis for the successful application of this method.

This paper, based on a transmission line project in Hunchun, conducts a systematic study on the engineering challenges posed by tower foundations located over goafs. Firstly, the high-density resistivity method was employed to determine the burial depth, distribution range, and morphology of the goafs along the line. Secondly, integrating this with geological survey data, a quantitative and qualitative stability evaluation of the goafs and the overlying foundations was carried out using key parameters. Finally, based on the evaluation results, targeted foundation treatment and protection measures for the towers were proposed. This research aims to establish a technical framework that integrates “detailed detection, stability evaluation, and engineering treatment,” providing a scientific basis and technical support for the design, construction, and long-term safe operation of transmission lines crossing over coal mine goafs.

2. Project Overview

2.1 Project Background

The proposed project is a 220kV double-circuit transmission line with a total length of approximately 16.3 km, passing through four townships in Hunchun City. The route has a sinuosity coefficient of 1.26. According to preliminary investigations, the 0-4 km section of the line does not pass through any mining areas. However, the 4-16.3 km section traverses two existing coal mine areas. After years of exploitation, these mines were officially closed at the end of 2016 in response to the national policy on reducing coal production capacity. A large number of underground goafs remain, posing a potential threat to the foundation stability of the transmission line.

2.2 Geological Structure

In the tectonic unit classification, the study area belongs to the Hunchun Basin, which is situated within the superimposed tectonic belt of the Northeast China Continental Margin Magmatic Arc-Basin and Range System. As a large Cenozoic fault-depression coal-bearing basin, its formation and evolution were significantly controlled by the regional tectonic stress field, with the overall structural trend oriented at NE 65°. The area has undergone multiple episodes and stages of superimposed tectonic movements, resulting in a relatively complex geological structure. It is primarily characterized by a broad and gentle syncline with a nearly NE-trending axis, plunging towards the SW. The strata on both limbs are gently dipping, with dip angles generally less than 15°, although they steepen locally due to fault drag. Fault structures are well-developed in the region, mainly manifesting as a series of nearly E-W trending normal fault systems. These faults cut deep into the strata and, in some sections, intersect and cut across NE-trending faults, forming a complex arcuate structural zone. This structural framework exerts a certain control over the occurrence of coal seams and the distribution and morphology of the goafs.

2.3 Stratigraphy and Lithology

The stratigraphy in the study area is relatively well-developed. The strata exposed and revealed along the transmission line route, from oldest to newest, primarily include the Paleogene Hunchun Formation (Eh) and the Quaternary System (Q). The Paleogene Hunchun Formation (Eh) serves as the bedrock and the main coal-bearing series, widely distributed at depth. Its lithological assemblage consists mainly of light gray to grayish-white siltstone and silty mudstone, interbedded with medium-to-coarse sandstone and coal seams. The strata generally strike NNE, dip gently to the west, and the rock is well-cemented with relatively high mechanical strength. Unconformably overlying this bedrock are Quaternary (Q) unconsolidated sediments. These are composed of Upper Pleistocene (Qp^3) yellowish silty clay, which is moderately dense and locally interbedded with thin layers of fine-grained sandstone, as well as Holocene (Qh) modern alluvial deposits, which consist of poorly sorted, highly permeable variegated sand, pebbles, and cohesive soils. Given that this study employs the high-density resistivity method for goaf detection, the significant electrical resistivity contrasts between the bedrock and the overlying unconsolidated sediments, as well as between the coal goafs and the surrounding rock mass, provide the necessary geophysical prerequisite for the survey. (Refer to Table 1 for the resistivity parameters of the main rock and soil layers).

Table 1: Resistivity Values and Ranges of Rock and Soil Layers

Rock/Soil Layer	Resistivity (Ω·m)
Quaternary Overburden	20-200
Silty Clay	30-100
Siltstone/Fine Sandstone	300-1200
Coal Seam	800-3000

2.4 Hydrogeology

Based on geological age, lithological assemblages, aquifer media characteristics, and groundwater occurrence types, the aquifers in the study area are classified into four main categories: 1) Quaternary Unconsolidated Rock Pore Phreatic Aquifer: This aquifer is primarily hosted within the sand and gravel layers of alluvial and proluvial deposits. The aquifer thickness generally ranges from 2 to 5 meters. It exhibits good permeability, and its groundwater level is significantly influenced by atmospheric precipitation, showing distinct seasonal fluctuations with rises during the wet season and declines during the dry season. 2) Paleogene (Tertiary) Sandstone Pore-Fissure Confined Aquifer: This aquifer group, controlled by a synclinal structure, is mainly composed of conglomerate, sandstone, and siltstone from the Hunchun Formation. The thickness of a single aquifer layer is typically between 3 and 7 meters, with a cumulative thickness reaching 7 to 10 meters. The aquitard roof is generally buried at depths greater than 120 meters, indicating confined conditions. 3) Cretaceous Clastic Rock Fissure-Pore Interstratal Confined Aquifer: The aquifer medium consists mainly of pyroclastic rocks. The roof of this aquifer is buried at approximately 15.30 meters, and its thickness is about 60 meters. Due to the dense nature of the rock and the uneven development of fractures, its overall water-bearing capacity is relatively poor. 4) Bedrock Fissure Water Aquifer: This category can be further subdivided into two types. The first is the stratified rock fissure phreatic aquifer, composed mainly of Permian sedimentary and metamorphic rocks (e.g., sandstone, siltstone, slate). The fissures are often filled with clay or sand, resulting in moderate water-bearing capacity. The second type is the massive rock fissure phreatic aquifer, with lithology consisting primarily of Late Variscan and Indosinian intrusive rocks (e.g., quartz diorite, plagiogranite). Although structural and weathering fractures are developed, the water-bearing capacity is poor due to the narrow fracture apertures and their infilling with weathering products.

3. Analysis of Geophysical Survey Results

The high-density electrical resistivity tomography (ERT) method was selected as the primary technique for detecting coal mine goafs in this study, owing to its high detection accuracy, strong anti-interference capability, and sensitivity to variations in subsurface electrical properties. A total of 16 ERT survey lines were deployed along the planned transmission line route. Each survey line was approximately 1,000 meters long, resulting in a cumulative survey length of about 16 kilometers.

Through meticulous data processing and inversion calculations, apparent resistivity cross-sections were generated, revealing the geoelectrical structure beneath each survey line. The profiles were systematically numbered based on the direction towards the terminus of the transmission line. The analysis revealed that among the 16 profiles, four (numbered L8, L10, L12, and L15) exhibited distinct low-resistivity anomalies (as shown in Figure 1). The remaining profiles displayed a uniform distribution of apparent resistivity without significant anomalies, indicating that the geological structures in those corresponding areas are relatively intact.

After the field data acquisition, a systematic preprocessing workflow was applied to the measured potential and current data, which included coordinate transformation, outlier removal, and filtering/smoothing. Subsequently, two-dimensional (2D) inversion was conducted using specialized software to generate four representative apparent resistivity profiles.

The inversion profiles reveal a well-defined geoelectrical structure in the study area. Overall, resistivity tends to increase with depth, and the strata show good lateral continuity with distinct vertical electrical layering. Correlation with regional geological data indicates that the shallow, high-resistivity layer corresponds to the Quaternary overburden, while the intermediate, medium-resistivity zone is attributed to siltstone and fine-grained sandstone interbedded with mudstone. The deeper strata consist of fine-to-coarse-grained sandstone interbedded with coal seams. Crucially, distinct, enclosed low-resistivity anomalies were identified within these deep coal-bearing strata. Given that their apparent resistivity values are significantly lower than that of the surrounding rock mass, these anomalies are interpreted as water-filled goafs.

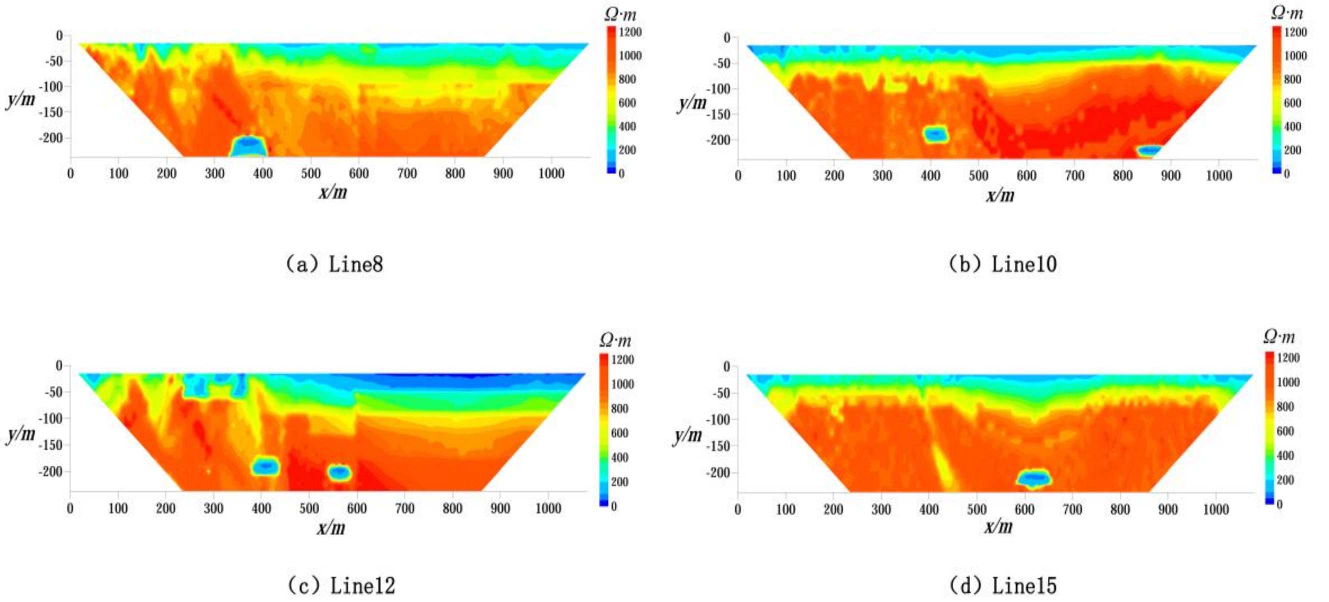

Figure 1: ERT Inversion Profiles of Apparent Resistivity

Detailed analysis of the individual inversion profiles reveals that each survey line successfully captured distinct, well-defined low-resistivity anomalies. For instance, survey line 8 (Figure 1a) identified a single anomaly with a lateral extent of approximately 40 m (horizontal distance 350-390 m) at a depth of about 205 m, with an estimated thickness of 4 m. In contrast, lines 10 and 12 detected dual-goaf features. Line 10 (Figure 1b) located two separate anomalies at depths of 185 m and 215 m, with estimated thicknesses of 3 m and 5 m, respectively. Similarly, line 12 (Figure 1c) identified two anomalies at depths of 185 m and 195 m, with thicknesses of 4 m and 3 m. A final example from line 15 (Figure 1d) shows another anomaly extending 45 m laterally at a depth of 205 m, with an estimated thickness of 3 m. All these identified zones exhibit the characteristic low-resistivity signature of water-saturated geological bodies.

The geophysical interpretations were subsequently validated by borehole data, which showed a strong correlation between the inferred and actual goaf locations. This verification underscores the effectiveness and reliability of the high-density resistivity method for goaf detection. As demonstrated by these case examples, this geophysical technique enables the precise identification and delineation of low-resistivity anomalies associated with water-filled goafs. Interpretation of the inversion profiles allows for the determination of not only their horizontal position and extent but also a reasonably accurate estimation of key parameters, including roof depth and approximate thickness.

4. Stability Evaluation

The presence of coal mine goafs beneath transmission lines introduces significant geohazards by disrupting the in-situ geological equilibrium [3]. The formation of these subterranean voids initiates a process of progressive failure and instability in the goaf roof. This instability propagates upward through the overlying rock mass to the ground surface, manifesting as various forms of surface damage that threaten the structural integrity of the power infrastructure [4]. Key failure mechanisms include: (1) uniform surface subsidence, which lowers tower elevations and compromises safe conductor-to-ground clearance; (2) differential settlement and horizontal displacement, which impose tilting and shear stresses on tower foundations, leading to tower inclination; and (3) the development of tension cracks that can transect foundations, resulting in a complete loss of bearing capacity [5]. This causal chain, extending from subsurface instability to surface-level hazards, is fundamentally governed by the stability of the goaf itself. Consequently, a rigorous evaluation of goaf stability is a critical prerequisite for ensuring the long-term safety and operational reliability of transmission lines in mining areas.

4.1 Goaf Site Stability Evaluation

4.1.1 Stability Assessment Based on Mining Conditions

The duration of surface movement induced by coal mining, denoted as T, is a critical parameter for stability assessment. For the gently inclined coal seams in this project, with an average mining depth of 195 m, the duration of surface movement can be calculated according to Equation (1). This approach is adopted in accordance with the Code for Geotechnical Engineering Investigation of Coal Mine Goafs, which specifies this calculation method for goafs with an average mining depth of less than 400 m.

$$T = 2.5H_0 \tag{1}$$

In the equation, T represents the total duration of surface movement (in days), and H_0 denotes the average mining depth (in meters).

Given that the average mining depth (H_0) of the coal seam in the project area is 195 m, the total duration of surface movement (T) is calculated as:

$T = 2.5 \times 195 = 487.5$ days.

The stability of the goaf site can then be assessed based on the time elapsed since the final mining activities, as detailed in Table 2.

Table 2: Goaf Site Stability Classification Based on Time Since Final Mining

Stability Level	Unstable	Generally Stable	Stable
Time Elapsed Since Final Mining,t (days)	t <0.8T or t ≤365	0.8T≤t ≤1.2T and t >365	t ≥1.2T and t >730

Mining operations in this area ceased completely by the end of 2015. According to the goaf stability classification criteria based on the time since final mining (as presented in Table 2), the elapsed time, t, has significantly exceeded 730 days (two years) and satisfies the condition $t \geq 1.2T$. Therefore, it can be concluded that the surface movement and deformation in the goaf have entered the residual phase, and the site stability is classified as "Stable".

Table 3: Goaf Stability Classification Based on Post-Mining Time under Conditions of Full Roof Caving

Stability Level	Post-Mining Time, t (years)		
	Weak Overburden	Medium-Hard Overburden	Hard Overburden
Stable	t>1.0	t>2.5	t>4.0
Generally Stable	0.6<t≤1.0	1.5<t≤2.5	2.5<t≤4.0
Unstable	t≤0.6	t≤1.5	t≤2.5

The stability classification of the goaf, based on the time required for complete roof caving, is detailed in Table 3. According to geological survey data, the immediate roof of the coal seam beneath the transmission line is primarily composed of medium-to-coarse sandstone and siltstone-to-fine sandstone, with a Uniaxial Compressive Strength (UCS) ranging from 5 to 30 MPa. These properties allow the overlying strata to be classified as "weak rock".

Given that mining activities ceased by the end of 2015, the elapsed time (t) significantly exceeds the one-year threshold (t > 1.0 a). Therefore, based on the post-mining time criterion, the goaf site is assessed as "Stable".

From the perspective of surface movement and deformation characteristics, the mining of gently inclined coal seams in the study area typically results in a smooth and predictable surface subsidence process, with a low likelihood of sudden collapses or delayed fault-induced subsidences. The tower foundations are located above extensive mined-out areas, yet the overall surface deformation remains fundamentally continuous. Field observations confirm the absence of significant ground fissures, step subsidences, or collapse pits. Consequently, a comprehensive assessment of these macroscopic features indicates that the ground surface in the study area is fundamentally stable.

4.1.2 Site Stability Assessment Based on Surface Movement and Deformation

Based on the criteria in Table 4, combined with relevant survey data and regional experience, the cumulative surface subsidence in the evaluation area over a continuous six-month period is less than 30 mm, with a subsidence rate below 1.0 mm/d. Adhering to the principle of the most unfavorable engineering conditions, the maximum residual tilt after coal seam extraction in the area is 1.05 mm/m, the maximum residual curvature is 0.01×10^{-3} /m, and the maximum residual horizontal strain is 0.83 mm/m. As all residual deformation values fall within the stable range of the evaluation factors, the site is determined to be stable.

Table 4: Site Stability Classification Based on Surface Movement and Deformation Values

Stability Level	Evaluation Factor				Remarks
	Subsidence Rate & Cumulative Subsidence	Tilt Δi/(mm·m^{-1})	Curvature Δk/(mm·m^{-1})	Horizontal Strain $\Delta\epsilon$/(mm·m^{-1})	
Stable	<1.0mm/d,and continuous subsidence for 6 months<30mm	<3	<0.2	<2	All conditions are met
Generally Stable	<1.0mm/d,and continuous subsidence for 6 months.≥30mm	3~10	0.2~0.6	2~6	Any one of the conditions is met
Unstable	≥1.0mm/d	≥10	≥0.6	≥6	Any one of the conditions is met

Considering both the mining conditions and the surface movement and deformation, the stability of the goaf site is comprehensively assessed as "Stable".

4.2 Degree of Impact of Goaf on the Project

The degree of impact of the goaf on the engineering project should be classified based on the stability of the goaf site, the importance and deformation requirements of the proposed project, the characteristics of surface deformation, and the values of surface movement and deformation.

4.2.1 Determination Based on Site Stability, Project Importance, and Deformation Requirements

The proposed power transmission line is a structure with strict deformation requirements. Based on the site stability assessment and the criteria in Table 5, a qualitative analysis of the impact of the goaf on the project was conducted by considering both site stability and the project's importance and deformation requirements. It was determined that the degree of impact from the goaf on the proposed tower foundations is moderate.

Table 5: Qualitative Analysis of the Degree of Impact of Goaf on the Project Based on Site Stability, Project Importance, and Deformation Requirements

Engineering Conditions Degree of Impact Site Stability	Importance and Deformation Requirements of the Proposed Project		
	Important Proposed Project, High Deformation Requirements	General Proposed Project, Moderate Deformation Requirements	Minor Proposed Project, Low Deformation Requirements
Stable	Moderate	Moderate to Low	Low
Generally Stable	High to Moderate	Moderate	Moderate to Low
Unstable	High	High to Moderate	Moderate

4.2.2 Assessment Based on Goaf Characteristics and Reactivation Factors

Based on an analysis of geophysical exploration results, the mining depth to thickness ratio was calculated to be between 43 and 68.3. The goaf areas for each coal seam within the tower foundation site are characterized as mid-to-deep, gently inclined longwall mines where the roof has fully caved. Given these conditions, the caved zone of the goaf is preliminarily judged to be in a generally compacted to fully compacted state. Accordingly, the initial assessment of the goaf's impact on the engineering project is determined to be medium to small.

Table 6: Qualitative Analysis of the Goaf's Impact on the Project Based on Its Characteristics and Reactivation Factors

Degree of Impact	Goaf Characteristics			Reactivation Factors	Remarks
	Mining Depth and Depth-to-Thickness Ratio	Compaction State and Water-Filled Condition	Surface Deformation Characteristics and Development Trends		
High	H＜50m or H/M＜30	Voids present, indicated by sudden drill drops and air rush at the borehole collar during drilling	Discontinuous deformation is ongoing, or the goaf is currently stable but has a high probability of future discontinuous deformation	High probability of reactivation, resulting in a severe impact	Any one of the conditions is met
Medium	50m≤H≤200m or 30≤H/M≤80	Largely compacted; significant loss of drilling fluid occurred in the goaf zone during drilling	Currently stable, but a possibility of future discontinuous deformation exists	Moderate probability of reactivation, resulting in a moderate impact	Any one of the conditions is met
Low	H＞200 or H/M＞80	Fully compacted; no or minor water loss, or indirect water return observed during drilling.	No further discontinuous deformation is expected	Low probability of reactivation, resulting in a minor impact	All conditions are met

Furthermore, mine water inflow during the extraction process was low, and hydraulic connectivity between the aquifers is poor. Since a significant amount of time has passed since mining ceased, the rock and soil mass within the caved zone has likely undergone sufficient softening due to groundwater influence. Therefore, the probability of "reactivation" in the old goaf is considered low.

Consequently, a qualitative analysis based on the goaf's characteristics and reactivation factors confirms that the overall impact of the old goaf on the engineering project is medium to small.

4.2.3 Evaluation Based on Residual Surface Deformation Values of the Goaf

Analysis based on the evaluation criteria in Table 7 indicates that for each tower foundation within the goaf's zone of influence, the values for residual tilt, residual horizontal deformation, and residual curvature all meet the standard for a 'low' degree of impact. The subsidence values, ranging from 20 to 60 mm, also fall within the criteria for 'low' impact.

Table 7: Determination of the Goaf's Impact on the Project Based on Residual Surface Deformation Values

Degree of Impact	Residual Surface Deformation				Remarks
	Subsidence Δw/(mm)	Tilt Δi/(mm·m^{-1})	Curvature Δk/(mm·m^{-1})	Horizontal Strain $\Delta \epsilon$/(mm·m^{-1})	
High	≥200	≥10	≥0.6	≥6	Any one of the conditions is met
Medium	100-200	3-10	0.2-0.6	2-6	Any one of the conditions is met
Low	<100	<3	<0.2	<2	All conditions are met

A comprehensive evaluation was conducted by integrating several key indicators: overall site stability, the importance and deformation requirements of the proposed project, surface deformation characteristics, and the measured residual surface deformation values. Based on this integrated assessment, the impact of the goaf on the proposed transmission line is determined to be minor to moderate.

5. Mitigation Recommendations

Given the complexity of geological conditions within a coal mine goaf and the delayed nature of surface deformation, relying solely on site selection and avoidance during the preliminary design phase is often insufficient to completely eliminate the associated risks [6]. To ensure the long-term safety and stability of the transmission line operating over the goaf, it is essential to adopt appropriate measures during both the engineering design and subsequent operational and maintenance (O&M) phases. These measures should aim to eliminate or mitigate the damage to transmission facilities caused by non-uniform surface settlement [7]. Specific recommendations are as follows.

5.1 Optimize Foundation Structural Design

To counteract the potential for non-uniform settlement over the goaf, a foundation structure combining a "large raft foundation with a flexible cushion layer" is recommended. By implementing a large-area reinforced concrete raft, the contact area between the foundation and the subgrade is effectively increased. This reduces the bearing stress at the base and enhances the overall anti-overturning capacity of the structure.

Concurrently, a sliding layer composed of pebbles and sand should be installed between the foundation base and the concrete raft. The excellent flowability and permeability of this layer permit slight relative sliding between the foundation and the subgrade. This mechanism serves to release the additional stresses induced by horizontal surface deformation and facilitates future realignment and adjustments in the event of settlement.

5.2 Incorporate a Pre-designed Adjustable Alignment Mechanism

Considering the continuous nature of surface deformation over a goaf, the transmission line design must reserve sufficient allowance for alignment correction. Specific strategies include appropriately increasing the exposed length of anchor bolts for use with steel shims, installing a dedicated adjustable transition structure between the foundation top and the tower leg base, or preparing replaceable, heightened tower leg base plates for future use. The core principle of these measures is to establish an “adjustable block” or “shimming” system. This system ensures that if the tower tilts, live-line reinforcement and attitude adjustments can be performed without a power outage, thereby maximizing the continuity and reliability of the power grid supply.

5.3 Establish a Multi-dimensional Monitoring Network

The implementation of mitigation measures relies on precise data support. It is recommended to install online tower tilt monitoring sensors at key tower locations to enable real-time surveillance of the tower’s attitude. Concurrently, conventional manual inspections and precision surveying should be intensified, focusing on monitoring crack development, subsidence rates on the goaf surface, and the differential settlement of tower foundations. By comparing and analyzing real-time data against long-term observational data, precursor information of geological hazards can be captured in a timely manner. This provides valuable lead time for the operations and maintenance department to implement emergency interventions, thereby effectively mitigating or avoiding economic losses resulting from surface collapse.

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