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Research on Comprehensive Survey Methods for Mined-out Areas

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Abstract: ***With the continuous expansion of China's railway coverage across the country, railway construction inevitably passes through various underground mineral development areas. Thus, the issue of goaf areas resembles "geological reefs," posing a threat to the safety of railway operations. To more accurately and efficiently detect the location and influence scope of goaf areas, this paper systematically introduces comprehensive investigation methods and techniques, including data collection, field surveys, geophysical exploration, D-InSAR, and drilling. Through systematic comprehensive investigation, not only can the location of goaf areas be accurately determined, but their influence scope can also be delineated, providing assurance for assessing the safety of railway lines traversing goaf areas.***

Keywords: Goaf, Comprehensive survey method, D-InSAR**.**

1. Introduction

China is a country rich in resources, with abundant mineral reserves, particularly in coal resources, which are plentiful in the northwestern regions. In the process of resource extraction and economic development, extensive mined-out areas have been left behind. Due to long-standing mining history, diverse extraction methods, and unregulated exploitation, these mined-out areas exhibit characteristics such as complexity, concealment, multi-period development, and suddenness [1]. The presence of mined-out areas leads to large-scale surface subsidence, damaging surface infrastructure and land, severely affecting land utilization. Therefore, identifying the distribution of mined-out areas and preventing or mitigating secondary disasters are urgent issues that need to be addressed [2].

With the advancement of China's infrastructure development, people have continuously summarized experiences, leading to an improved understanding of comprehensive survey techniques. Shang Peipei et al. precisely identified the spatial distribution of mined-out anomalies by integrating transient electromagnetic and microtremor survey methods, supplemented with drilling verification and borehole television [3]. Feng Deng determined the locations of mined-out areas using two geophysical methods combined with drilling, and conducted stability assessments of these areas [4]. Ma Zhikai et al., through a comprehensive exploration approach involving data collection, geological mapping, engineering geophysical surveys, and drilling verification, clarified the distribution of mined-out areas and obtained geotechnical parameters [5]. Wang Liuwen et al. employed multiple methods, including data collection, geophysical surveys, and drilling, to investigate small coal mine goafs and proposed remediation measures [6]. Most of these approaches primarily rely on geophysical methods, supplemented by drilling for verification.

Railway engineering is a vital public welfare project and serves as a major artery connecting the nation, with high-speed railways, in particular, injecting new momentum into the country's development. High-speed railways impose extremely stringent requirements on substrate deformation. By summarizing various investigation methods for mined-out areas and applying them flexibly according to different conditions, this paper provides comprehensive guidance for precisely delineating the distribution and impact ranges of mined-out areas.

2. Comprehensive Exploration Methods for Mined-out Areas

Due to the influence of various anthropogenic and natural factors, mined-out areas exhibit distinct characteristics. A single survey method can no longer meet the precision requirements for investigating mined-out areas, necessitating the adoption of comprehensive survey techniques to achieve a three-dimensional integrated approach from air, space, and ground.

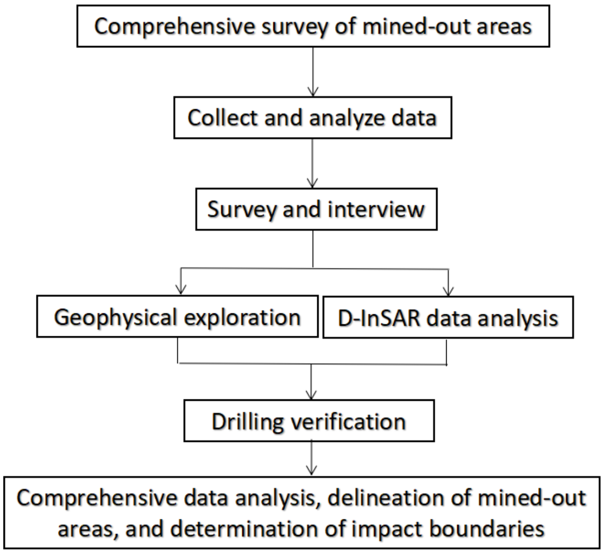

Figure 1: Simplified Flowchart of Comprehensive Survey Methodology for Mined-out Areas

The three-dimensional integrated exploration of mined-out areas—spanning air, space, and ground—first requires data collection and comprehensive analysis based on regional geological information. Next, field surveys and interviews are conducted along the route to verify the actual conditions of mined-out areas. Subsequently, geophysical exploration is carried out according to the collected data and survey results, selecting appropriate geophysical methods. Geophysical anomaly zones are then verified by drilling to identify mined-out areas. Finally, long-term D-InSAR surface subsidence analysis is performed to delineate subsidence zones, guiding railway route selection to avoid affected areas. A simplified flowchart of the comprehensive exploration methodology for mined-out areas is shown in Figure 1.

2.1 Data Collection

The primary method for investigating mined-out areas is data collection, which involves understanding and grasping the past, present, and future mining conditions of the mining area. This approach not only helps in accurately assessing adverse geological conditions and selecting the optimal route but also ensures route safety while minimizing losses to the mining area to the greatest extent. During the feasibility study stage, collecting information from mining rights management authorities, mining area data, and regional geological data (as shown in Table 1) within the coverage area of the proposed route alternatives can assist in comprehensively analyzing the impact level of mined-out areas on the alternatives, guiding targeted exploration efforts, improving exploration efficiency, and shortening the investigation cycle.

2.2 Field Survey

Survey and interview work serves as the foundation for on-site verification of the impact extent of mined-out areas. By integrating collected mining area data and regional geological information, these investigations help ascertain the damage caused by surface subsidence of mined-out areas to ground structures and the surrounding environment (as shown in Figures 2-3), thereby corroborating the accuracy of the collected data from different perspectives. Simultaneously, this process lays the groundwork for the selection of subsequent geophysical exploration methods and drilling operations.

2.3 Underground Survey

Underground survey is a critical step in mined-out area exploration that shifts the process from "inference" to "confirmation" and from "qualitative assessment" to "quantitative analysis." By conducting on-site measurements in unsealed mine shafts, underground survey offers a level of directness and high precision that surface-based investigations cannot match (As Figure 4 shows).

Table 1: Data Collection Checklist

Data Attribution	Data Type
Information from Mining Rights Regulatory Agencies	Data such as mineral resources distribution maps, mineral resources planning documents, mining area distribution maps, and current mineral resources exploitation and utilization maps.
Mining Area Data	Documents including mining permits, coal mine geological reports, mining and mined-out condition distribution maps (such as mining plan maps, surface-underground correlation maps, cross-sectional diagrams, and composite borehole columnar charts), settlement observation data, and materials on the impact of dewatering near mined-out areas on their deformation.
Regional Data	Data including regional geological maps, structural synoptic maps, topographic and geomorphic maps, seismotectonic maps, geomorphological maps, and related materials.

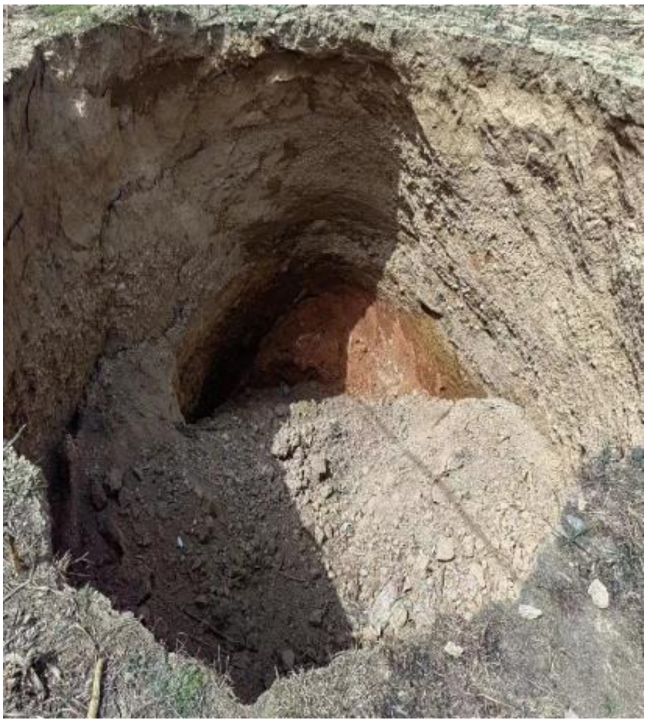

Figure 2: Subsidence Pit Photos

Figure 3: Photos of Cracked Houses

Figure 4: Underground Survey Photo

2.4 Geophysical Prospecting

Given the concealed and diverse nature of mined-out areas, geophysical prospecting has become a widely adopted method for their investigation. To enhance the accuracy of geophysical surveys, multiple methods are often applied in combination, which helps to delineate geophysical anomaly zones more precisely.

The core principle of geophysical prospecting lies in the distinct physical properties exhibited by different underground strata. By performing inversion analysis on data collected from subsurface formations using geophysical instruments and equipment, anomalous physical zones can be detected. Through comparative analysis with other relevant data, the engineering geological conditions of underground rock and soil masses can then be inferred. Therefore, based on the different physical fields utilized, geophysical exploration is generally classified into gravity prospecting, magnetic prospecting, electrical prospecting, seismic prospecting, and radiometric prospecting, among others. The principles and characteristics of these geophysical methods are summarized in Table 2 below.

Table 2: Principles and Characteristics of Common Geophysical Methods for Mined-out Areas

Detection method	Principle	Features
3D seismic method	Using artificial seismic waves as a means, based on the elastic differences in formation lithology, we receive reflected waves to ascertain the underground geological conditions	With high resolution, deep detection depth, and intuitive imaging, it is suitable for use in areas with minimal sound interference and without loose layers.
2D seismic method		
High-density resistivity method	Based on the electrical property differences of underground media, geological issues are interpreted through changes in the underground electric field.	High density of measurement points, rich information, high visibility, high resolution efficiency, and high efficiency
Transient Electromagnetic Method	Based on the magnetic differences of underground media, the distribution patterns of electromagnetic fields in time and space are studied through pulsed magnetic fields.	High fidelity, little influence from terrain, small volume effect, high work efficiency, high resolution, and wide range of application.
Controlled source audio magnetotellurics	Artificial sources are used to emit multi-frequency currents into the ground, measure the orthogonal electromagnetic field components on the surface, and invert the resistivity distribution at different depths underground.	Strong signal, high data quality, moderate depth, and good resolution
ground-penetrating radar	Transmit high-frequency pulsed electromagnetic waves underground, receive reflected signals from different medium interfaces, and detect shallow underground structures by analyzing signal travel time and amplitude.	It has the advantages of high resolution, rapid and economical, flexible and versatile, and intuitive data.
radon measurement method	By measuring the abnormal concentration of radon gas in surface soil or air, we can infer the degree of damage to the stratum structure, and thus predict the location of the mined-out area.	It is not affected by topography, electromagnetic or sound wave interference, and features low cost, portability, flexibility, simplicity, speed, and high work efficiency.
microgravity exploration	By measuring the slight changes in the surface gravity field with high-precision instruments, we can invert the underground density differences and infer the distribution of mined-out areas.	It is immune to common electromagnetic interference, with a compact design and easy operation, making field work straightforward
induced polarization method	By measuring the electrochemical polarization effect (charge and discharge process) generated by the underground medium under the excitation of an artificial electric field, electronic conductors (such as metallic minerals) or ionically conductive media (such as groundwater) can be detected	Sensitive to water-bearing structures, less affected by surrounding rock structure
microseismic detection	Without the need for artificial seismic sources, by analyzing the propagation speed differences of surface wave components in these signals at different frequencies, the shear wave velocity structure of the underground medium can be inversely calculated, thus achieving stratigraphic division from shallow to deep parts and detecting anomalous bodies.	No need for artificial seismic sources, strong anti-interference capability, flexible detection depth, and strong terrain adaptability

2.5 Land Subsidence Monitoring- D-InSAR

When railways pass through mined-out areas, they are often subject to multiple external constraints, and mining areas tend to be densely distributed. Therefore, during route selection, it is necessary not only to detect the locations of mined-out areas but also to determine their impact boundaries to ensure that the railway alignment does not undergo significant settlement or deformation. Conventional surface monitoring techniques previously employed mainly included leveling and GPS surveying. Although these methods offer advantages such as simplicity of operation and high precision, they also suffer from drawbacks such as large workloads for observation, lengthy operation cycles, limited data volume, and high monitoring costs.

Differential Interferometric Synthetic Aperture Radar (D-InSAR) technology is an advancement built upon the foundational principles of InSAR technology. It utilizes phase and intensity information provided by Synthetic Aperture Radar (SAR) complex data as its information source to perform differential interferometric measurements. By extracting subtle deformation information of ground targets from one or more interferograms that contain details such as terrain and deformation in the target area, this technology enables precise monitoring of surface changes [7]. It features all-weather capability, multi-polarization, and wide coverage. By analyzing multi-temporal or multi-year satellite imagery data, it can derive surface subsidence information, calculate subsidence rates, delineate subsidence boundaries, and generate subsidence contour maps. This contributes to guiding railway route planning to avoid the impact boundaries of mined-out areas.

2.6 Drilling

Drilling serves as a verification method for the various exploration results mentioned above, representing the most direct and reliable approach to subsurface investigation. It also provides essential data for obtaining strata parameters. Additionally, drilling operations can be combined with other exploration techniques, such as borehole imaging, to achieve detailed verification within boreholes. However, drilling has notable limitations, including its point-specific visibility, significant workload, extended duration, high costs, and substantial risks, often requiring considerable human and material resources. Therefore, in the investigation of mined-out areas, drilling is typically employed for targeted verification based on collected data and geophysical exploration results.

Drilling, when applied to the investigation of mined-out areas, entails relatively high technical requirements and distinctive characteristics. Based on the features revealed during drilling, it can be used to investigate the development conditions of mined-out areas (as shown in Table 3).

Table 3: Field Description of Mined-out Areas and Three-Zone Classification Criteria [8]

collapse zone indicator	**fracture zone marker**	**No hollow mark**
1. Sudden loss of diamond; 2. Buried drill bit, stuck drill bit; 3. The water level at the orifice suddenly disappears; 4. Suction at the orifice; 5. The footage is particularly fast; 6. The core is fragmented and mixed, containing rock powder, coal ash, etc; 7. There is noise during drilling; 8. Visible silt, powdered coal slag, etc; 9. See pit wood, bricks, tiles, etc; 10. There is an upwelling of gas;	1. Sudden severe leakage or a significant increase in leakage volume; 2. The water level in the borehole has significantly decreased; 3. The core exhibits longitudinal cracks or steeply inclined fractures; 4. There is a slight suction phenomenon during drilling; 5. There is gas in the borehole; 6. The core recovery rate is less than 75%;	1. Water flowing backwards through the entire hole; 2. No water consumption or very little water consumption; 3. The core is complete and in the shape of a long column; 4. The core recovery rate is greater than 75%; 5. The footage is stable; 6. The core of the mined ore bed is intact and free from water leakage;

3. Conclusion

When railways encounter mined-out areas, the primary route selection principle is to prioritize avoidance. This paper compiles relevant literature and analyzes various methods for comprehensive exploration of mined-out areas, forming a **"air-space-ground" three-dimensional integrated exploration system** that combines data collection, field surveys and interviews, geophysical prospecting, ground settlement monitoring, and drilling. This system can precisely delineate the extent and impact range of mined-out areas, providing essential guidance for ensuring safety redundancy in railway route selection. Additionally, it offers constructive insights for subsequent mined-out area remediation and land utilization.

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