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# Development and Future Outlook of Rail Transit Projects in Mining Subsidence Areas

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**Abstract:** Goaf areas are a significant hazard in mining, posing serious safety risks, and their management is a complex challenge due to their irregular spatial distribution and unpredictable roof collapses. Research on goaf areas focuses on detection technologies, disaster analysis, risk assessment, and remediation techniques. The characteristics of goaf areas vary based on different minerals and mining methods. With the rise of high-speed rail, the stability of foundations beneath high-speed rail lines crossing goaf areas becomes a critical concern, given the dynamic stresses generated by high-speed train operations. The coupling between goaf areas and high-speed rail, and the deformation mechanisms and stability control of foundations in such regions, are emerging as an essential research frontier. The integration of excavation, anchoring, and support technologies, along with an in-depth study of the surrounding rock microstructure under deep mining conditions, is crucial for ensuring the stability of high-speed rail lines in goaf areas.

**Keywords:** Goaf areas, Foundation stability, Deformation mechanisms.

## 1. Introduction

Goaf areas are a critical factor in triggering major accidents. Research on goaf areas can be categorized into four main areas: detection technologies, disaster analysis, risk assessment, and remediation techniques. A goaf consists of the roof and pillars and is a "structure" formed under specific environmental conditions. Its characteristics include strong concealment, irregular spatial distribution, significant variations in spatial forms, and unpredictable roof collapses. Goaf areas have become one of the most significant hazards in mining[1]. These areas are widely distributed and highly varied, with different minerals and mining methods resulting in distinct goaf forms and characteristics. The safety issues caused by goaf areas differ depending on their formation, making their management particularly challenging. In recent years, major accidents triggered by goaf areas have occurred frequently, posing serious threats to mine safety as well as the lives and property of workers. Currently, frontier research includes studying the microstructural features of surrounding rocks under deep mining conditions, as well as the complex effects of goaf clusters and the integration of excavation, anchoring, and support technologies.

High-speed rail is a critical infrastructure being rapidly developed by countries around the world, with significant implications for both economic development and social progress. The most distinguishing feature of high-speed rail compared to traditional rail is the high speed of the trains, which imposes strict control requirements on railbed vibrations and settlements. Additionally, the dynamic stresses generated by high-speed train operations amplify the stresses on the railbed, further accelerating the cyclic accumulation of deformation and performance degradation. The development of high-speed rail has surpassed the traditional scope of geotechnical engineering theories and techniques. Railbed dynamics for high-speed rail have become an international research frontier, involving multiple disciplines such as railway engineering, geotechnical engineering, and structural dynamics[2, 3].

Research on the coupling between goaf areas and high-speed rail has historically been relatively isolated. Therefore, it is necessary to integrate the two fields and conduct in-depth studies on the deformation mechanisms and stability control of foundations in high-speed rail projects crossing underlying goaf areas. Ensuring the stability of both the foundation and subgrade beneath high-speed rail lines in goaf areas is of significant theoretical and practical importance[4].

## 2. Study of Mining-Induced Subsidence Before the Formation of Goaf Areas

Various useful minerals are located at specific positions within the underground rock mass, in contact with the surrounding rocks, and maintaining stress equilibrium. After the extraction of these minerals, the surrounding rock layers lose their support and gradually shift, bend, and fail within the mined area. As the mining face progresses, this process gradually expands outward and upward from the mine, eventually reaching the surface, causing surface subsidence and forming what is known as a subsidence basin. The movement and deformation of the overburden and ground surface is an inevitable result of mining, as it disrupts the original rock's stress state and leads to the establishment of a new equilibrium.

The movement and deformation of the ore layer and surrounding rocks caused by mining is a complex process that occurs over time and space. The affected area of the overburden gradually expands, while the intensity of the damage decreases from the mined cavity to the surface. Based on the destructive characteristics of the overburden rock, the affected regions are generally classified into three main zones: the collapse zone, the fracture zone, and the bending and sinking zone—collectively referred to as the "three zones." From the perspective of rock movement, this classification primarily refers to the spanning zone, the fracture zone, and the bending zone. In the context of coal mining, the process begins with the collapse and compaction of the spanning zone above the coal seam after excavation. This is followed by cracking and separation in the fracture zone, which then extends to the bending zone at the surface, resulting in subsidence. The subsidence curve on the surface typically follows a normal distribution pattern. As a result, the probability integral method is often used to predict ground surface displacement.

The outer boundary of the subsidence basin in lower seam mining is generally elliptical. Commonly used indices to characterize surface deformation include five key parameters: surface subsidence (W), slope deformation (i), curvature deformation, horizontal movement (U), and horizontal deformation (e). These parameters are used to quantitatively assess the extent of surface deformation.

Liu Baochen[5] introduced the probability integral method, which has become the primary calculation method for predicting mining-induced subsidence. Liu Tianquan[6] conducted in-depth research on the overburden failure patterns and surface movement patterns caused by the mining of coal seams at various dip angles, and established formulas for the collapse zone and water-conducting fracture zone. He Guoqing[7] established a Weibull distribution model for surface subsidence based on the theory of fragmented bodies. Zhou Guoquan[8] proposed the use of the negative exponential function method to calculate surface movement. Wang Jinzhuang[9] developed a typical curve method for predicting surface subsidence at the main fault. Zou Youfeng [10] studied surface subsidence prediction methods. Dai Huayang[11] established a mining-induced subsidence model based on changes in dip angle, called the vector prediction method. Guo Zhangchang[12] applied the probability of fragmented body movement in a random medium to study surface subsidence. Qian Minggao[13] proposed the beam theory of the coal body and the key layer theory, along with the composite key layer theory. Song Zhenqi[14] introduced the transfer rock beam hypothesis. Xie Heping[15] used finite element numerical methods to analyze the rock layer movement patterns. Liu Tianquan[16] studied the rock layer movement and control mechanics issues. Zhang Yuzhuo[17] applied the dislocation theory of rock layer movement and the boundary element method to mining subsidence. Tang Chunan[18] conducted numerical simulations of the overburden subsidence process under mining influence. Deng Kazhong[19] researched the structural effects of rock masses in mining subsidence.

# 3. Study on the Response Characteristics of Mining Void Areas to Dynamic Loads

The study of the dynamic response of railway subgrade under train load can be divided into four main research categories: theoretical analysis, field monitoring, numerical simulation, and model testing. Before the 1970s, the dynamic response of subgrades was primarily studied through theoretical analysis and field experiments. From the late 1990s onwards, as the requirements for the dynamic load on railway subgrade structures increased, both domestically and internationally, researchers began to focus on model testing. Following that, with the rapid development of computer technology, numerical simulation methods became widely used.

Due to the complexity of the coupled train-track-subgrade system, theoretical analysis has significant limitations, and the robustness of its computational results is difficult to control. As a result, field monitoring, model testing, and computer simulations have become more widely applied in the study of the dynamic response of subgrade under railway load. For instance, Jiang Hongguang[20] conducted large-scale model tests on high-speed railway slab track subgrade, where they simulated train vibration loads using excitation signals. Their results revealed that the load-time curve of the track fastening system exhibited an "M"-shaped pattern. Chen Tuo quantitatively studied the dynamic response characteristics of different subgrade structures in permafrost regions under long-term train vibration loads. Based on the varying temperatures and ice content in the Qinghai-Tibet Plateau, different subgrade structures were implemented to reduce or avoid the effects of temperature and engineering disturbances on the underlying permafrost. Real-time strong-motion tests were conducted on typical subgrade structures in the northern section of the Qinghai-Tibet Railway, yielding important results on vibration acceleration attenuation in permafrost areas, contributing to the safety of railway operation.

Chen Renpeng developed a 1:1 scale model of a ballastless track subgrade based on the design and construction standards of the Shanghai-Nanjing Intercity Railway. Through dynamic excitation tests with a single axle, they explored how track slab dynamic strain and subgrade dynamic soil pressure varied with loading frequency, and they derived the relationship between train dynamic loads and operating speed. By integrating the dynamic load amplification factor formulas used in German railways, they proposed a method to determine the dynamic load amplification factors for high-speed railway track structures, offering valuable insights for the design of track-subgrade systems in China.

Wu Longliang analyzed the dynamic response characteristics of subgrade under vibration loads from a spatial perspective. They conducted field excitation response tests based on vibration velocity and acceleration and identified the decay patterns of internal response speed, acceleration, and vertical dynamic response components in various directions. Feng studied the effects of extreme rainfall on the stability of high-speed railway embankments using historical rainfall data from Xuzhou to Shanghai. They estimated the region's maximum rainfall potential and discussed the impact of superstructure, underground fillings, and soil hydraulic properties under extreme storm conditions. Jia Jinzong analyzed the dynamic load magnitude and distribution characteristics of heavy-load railway subgrades using model tests on the Shuohuang Railway with a 30-ton axle load. This study compared the effects of heavy-load trains with those of regular trains, providing significant technical support for the design and evaluation of heavy-load railway subgrade structures.

Shen Quan used FLAC3D finite difference software to study the dynamic response of a novel embankment structure (with a new drainage layer) under train loads. Field test results were used to validate the numerical study. This new drainage structure aims to control moisture content changes in expansive soil subgrades and was applied in the remediation of expansive soil sections of the Yunnan-Guizhou high-speed railway.

Zhang Junying employed both similar material simulation experiments and numerical simulations to study the stress distribution of subgrade under additional loads after the mining area's surface was loaded. Their study revealed the interaction between additional surface loads and the overlying strata, which is essential for reinforced design in mining areas.

In summary, the study of dynamic responses of railway subgrades under load has evolved significantly from theoretical methods to the widespread use of numerical simulation, model testing, and field monitoring. These research developments have played an important role in enhancing the safety, reliability, and efficiency of modern railway infrastructure.

# 4. Methods for Evaluating the Stability of Mining-Affected Sites

In recent years, many scholars have conducted extensive quantitative or qualitative studies on the stability of mining-affected sites from different perspectives. Liang Jianping combined a large amount of field data and established a surface subsidence prediction model for road tunnels crossing mining voids, based on hyperbolic and grey prediction models. They applied error absolute value weighting and the minimum criterion, using MATLAB software to calculate the weighted average. Yang Feng, taking the Wuyun Expressway as an example, first selected six major factors and 19 sub-factors to build a second-level fuzzy comprehensive evaluation model. They then used the scaling method and eigenvector method to determine the weights of the evaluation factors. Afterward, they combined the Delphi method and scatter plot analysis to study the membership of each evaluation factor, ultimately assessing the stability of the construction site of the Wuyun Expressway. This research enriched the safety evaluation system for highway construction over old coal mining voids and provided new ideas for related research fields, with broad guiding significance.

High-speed railway line engineering requires high smoothness and stability to ensure smooth operation of high-speed trains and passenger comfort. Du Yanliang conducted a comprehensive analysis and evaluation of key technical issues in the safety monitoring of ballastless track structures, including subgrade engineering, ballastless track structure, bridge engineering, and environmental monitoring. They verified the scientific and practical feasibility of the system they developed, providing a basis for scientifically evaluating the quality of high-speed railway line projects and guiding equipment maintenance and repair plans. Wang Zhengshuai analyzed the time-varying law of probability integral parameters after the collapse of old mining voids and established a comprehensive relationship between surface deformation parameters and geological, mining, and environmental factors using actual surface movement observation data. By comparing the residual settlement deformation of the surface and critical deformation values for buildings, they assessed the stability of foundations above old mining voids.

Deng Kazhong analyzed the residual subsidence mechanism of old mining voids and identified the primary cause of residual settlement as the fracture-induced voids in the mining area. They established a method for calculating the residual subsidence coefficient based on stress-strain relationships and the height calculation method for fractured rock masses, and analyzed the relationship between the residual subsidence coefficient and cover rock lithology, mining thickness, depth, and building load. Zheng Zhilong relied on the reinforcement project of the foundation pile and slab structure in the mining area along the Hefei-Fuzhou High-Speed Railway. Using on-site monitoring techniques, they analyzed the load transfer, deformation mechanisms, and characteristics of the reinforced railway foundation in mining areas.

Chen et al. summarized the engineering problems caused by extreme climate conditions, such as heavy rainfall, persistent drought, extreme low or high temperatures, and the long-term dynamic load effects on subgrade settlements, mud pumping, slab cracking, excessive voids under the slab, and corrosion of reinforced concrete structures. Zhao Shiyun monitored the ground temperature and deformation in different sub-layers of the subgrade along the Shenyang-Harbin High-Speed Railway, establishing a monitoring system to support the evaluation of seasonal frost-susceptible railway subgrade deformation.

Other scholars have adopted various methods such as numerical simulation, field investigations, and geophysical exploration to assess the stability of mining-affected sites and to improve safety evaluation systems and engineering practices for construction in mining areas. These methods have contributed to the development of new evaluation models and the application of advanced monitoring technologies, ensuring the safety and stability of infrastructure projects above mining voids.

# 5. Conclusion

The dynamic response of mining subsidence sites involves several critical aspects, including the stability of the foundation within the subsidence area, the "activation" of the subsidence area under dynamic and static load effects, and the deformation control of subsidence sites. The study of subsidence area stability is a complex system engineering issue, extending from mining damage studies. It is the result of the integration of mining engineering, civil engineering, geological engineering, control science and engineering, and transportation engineering.

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