ISSN Print: 2707-2398 Online: 2707-2401
Environment and Resource – 2025, 7(2)
https://doi.org/10.35534/er.0702033

Research on Ground Pressure Control Technology for Close-distance Coal Seam Mining

Liming Liu[1,2]

1.China Coal Huangjiagou (Linxian) Coal Industry Co., Ltd., Lvliang, Shanxi;
2.Anhui University of Science and Technology, Anhui

Abstract: As the shallow coal resources in China are increasingly depleted, close-distance coal seam mining has become the mainstream mining mode in many mining areas. However, the small spacing of close-distance coal seams leads to significant mutual disturbance during the mining process, resulting in intensified stress concentration and large deformation of surrounding rocks, which seriously restricts the safe and efficient mining of mines. This paper reviews the research status of mining pressure control technologies for close-distance coal seams. It elaborates on the engineering background of close-distance coal seam mining and the core significance of mining pressure control, and summarizes the relevant research progress and existing deficiencies at home and abroad; it also summarizes the principles, application effects and applicable scenarios of four major core mining pressure control technologies, namely, optimization of mining parameters, reinforcement of support, pressure relief control and monitoring and early warning.

Key words: Close-distance coal seam; Ground pressure control; Stress superposition; Support technology; Numerical simulation

1 Introduction

1.1 Research Background

As a fundamental energy source in China's energy structure, coal holds a significant position in the development of the national economy. With long-term large-scale extraction, the shallow and easily accessible coal resources in major coal-producing regions such as eastern and central China are gradually depleting, shifting the focus of mining toward deep and complex geological conditions. Among these challenges, with the continuous growth in energy demand and advancements in mining technology, increasing attention has been paid to the recovery of hard-to-mine coal seams under complex geological conditions. The mining of closely spaced coal seams has emerged as a critical direction for

---

Author's Profile: Liming Liu, Senior Engineer, Ph.D. Candidate.

Article Citation: Liu, L. M. (2025). Research on Ground Pressure Control Technology for Close-distance Coal Seam Mining. *Environment and Resource, 7*(2), 389-402.

the development of the coal industry. Due to their abundant reserves and wide distribution, closely spaced coal seams have become the primary extraction targets in large mining areas such as Huainan, Yanzhou, Xishan, and Shendong. The mining of closely spaced coal seams accounts for a considerable proportion of production in existing mines, and its share in China's total coal output has been increasing year by year, making it a vital support for ensuring energy supply(Yang Daming et al., 2019; Li Shugang et al., 2016).

Closely spaced coal seams typically refer to coal seam groups with small interlayer distances (defined as ≤50 meters according to China's industry standards). Due to the limited interlayer spacing, intense mutual disturbances occur during the extraction of the upper and lower seams, disrupting the original in-situ stress balance and leading to significant complexity and particularity in Ground Pressure manifestations. Field engineering practices have shown that mining closely spaced coal seams is prone to issues such as stress concentration coefficients exceeding 3.0, roof-to-floor convergence of over 500 mm in roadways, and increased frequency of roof collapse. For instance, in a mining area, the superimposed disturbances from upper and lower coal seams during the mining of closely spaced coal seams resulted in large-scale roadway instability, causing direct economic losses exceeding ten million yuan and posing serious threats to the safety of personnel. Therefore, Ground Pressure control has become a core technical challenge that must be addressed in the mining of closely spaced coal seams.

Conducting research on Ground Pressure control for closely spaced coal seams holds significant engineering value and theoretical importance. From an engineering practice perspective, reasonable Ground Pressure control technologies can significantly reduce the probability of Ground Pressure disasters such as roof collapse and roadway instability, ensuring safe mine production. By optimizing control strategies, it is possible to minimize unnecessary support investments, reduce mining costs, and improve the recovery rate of coal resources, thereby achieving efficient resource utilization. From a theoretical application standpoint, research on Ground Pressure control for closely spaced coal seams provides a typical case for the application of advanced geomechanics theories in mining engineering. It promotes the deep integration of core theories such as elastic-plastic mechanics, stress field analysis, and rock mass stability evaluation with engineering practices, enriching the application scenarios and research connotation of geomechanics.

1.2 Research Status

Chinese scholars have conducted extensive targeted research on ground pressure control in closely spaced coal seams, forming a technical system tailored to China's coal seam geological conditions. Academician Qian Minggao's theory of mine ground pressure in longwall mining faces provides core theoretical support for ground pressure control in closely spaced coal seams, clarifying the interaction between surrounding rock and support structures.; Scholars such as Zhang Nong have studied the mutual disturbance effects during the mining of closely spaced coal seam groups through a combination of numerical simulation and field measurements, proposing ground pressure control solutions based on support adaptability, which have been successfully applied in multiple mining areas(Li K et al., 2025), In response to the challenges of mining closely spaced coal seams under goaf areas, Li Shugang and colleagues analyzed the instability mechanisms of roadways and developed combined support technology using bolts, mesh, cables, and grouting, effectively controlling large deformations of the surrounding rock.In terms of numerical simulation applications, domestic scholars widely employ software such as FLAC3D and UDEC to construct three-dimensional mechanical models for mining closely spaced coal seams. These models simulate ground pressure distribution characteristics under various mining parameters, providing an efficient research tool for optimizing control technologies(Hu S X et al., 2016).

Despite some progress in domestic and international research, several shortcomings remain. First, there is insufficient adaptability to complex geological conditions, as existing technologies primarily target conventional geological settings and perform poorly in complex conditions such as soft rock or deep mining (burial depth > 800 m) (Zhang J X et al., 2018). Second, theoretical research lacks depth, with the mechanisms of ground pressure control under the coupling of multiple factors (e.g., coal seam spacing, mining sequence, and rock properties) not yet fully understood, and the accuracy of stress calculation models needing improvement(He F L et al., 2023). Third, technological dissemination faces bottlenecks, as advanced technologies such as intelligent monitoring and adaptive support systems are difficult to popularize in small and medium-sized mining areas due to high costs and operational complexity. Fourth, there is inadequate integration with green mining practices. Existing control technologies do not sufficiently incorporate green concepts such as backfill mining and water-preserving mining, making it challenging to meet the requirements of sustainable development.

2 Theoretical Basis

2.1 Definition and Geological Characteristics of Close-distance Coal Seams

There are certain differences in the definition criteria for closely spaced coal seams both domestically and internationally. Internationally, the ratio of the inter-seam distance to the coal seam thickness is typically used as the basis, with a ratio of ≤5 defining the seams as closely spaced(Zhao Y X et al., 2022).

The geological characteristics of closely spaced coal seams have a significant impact on the manifestation of ground pressure. Key influencing factors include inter-seam distance, coal seam thickness, roof and floor lithology, and geological structures. Inter-seam distance is a critical factor determining the intensity of mutual disturbances. The smaller the distance, the more pronounced the superimposed effects of mining disturbances from the upper and lower seams, and the more intense the ground pressure manifestations. Coal seam thickness affects the size of the mining space and the range of stress distribution. Mining thick coal seams tends to expand the roof caving range and increases the difficulty of ground pressure control. The lithology of the roof and floor directly determines the load-bearing capacity of the rock mass. Hard roof and floor strata are prone to high-stress concentration, while weak strata are susceptible to large deformations, both of which increase the complexity of ground pressure control (He F L et al., 2023). Geological structures (such as faults and folds) can compromise the integrity of rock masses, leading to uneven stress distribution and increasing the risk of ground pressure hazards. Therefore, before conducting research on ground pressure control, it is essential to comprehensively understand the geological characteristics of closely spaced coal seams, as this provides a fundamental basis for designing control strategies(Li C et al., 2020).

2.2 Core Influencing Factors of Mine Pressure Behavior

The manifestation of ground pressure in closely spaced coal seams is influenced by both intrinsic and extrinsic factors. Intrinsic factors primarily include inter-seam spacing, lithological parameters, and geological structures. The smaller the inter-seam spacing, the stronger the mutual disturbances and the more intense the ground pressure manifestations(Wu W D et al., 2023). Lithological parameters (such as cohesion, internal friction angle, and elastic modulus) determine the load-bearing capacity of the rock mass. Smaller values of cohesion and internal friction angle make the rock mass more prone to failure, thereby increasing the difficulty of ground pressure control. Geological structures can lead to stress concentration and compromise the integrity of the rock mass, thereby exacerbating the risk of ground pressure disasters.

Extrinsic factors primarily include mining sequence, stope dimensions, coal pillar design parameters, and support schemes. The mining sequence significantly influences ground pressure manifestations: mining “from upper to lower seams” tends to subject the lower seams to intense stress superposition, whereas mining “from lower to upper seams” can reduce the intensity of mutual disturbances through stress release(Hao D Y et al., 2019; Zhang T et al., 2016). The larger the stope dimensions, the wider the range of mining disturbances and the more intense the ground pressure manifestations. The design parameters of coal pillars directly influence stress distribution. Reasonable pillar dimensions can effectively disperse stress and prevent stress concentration. The adaptability of support schemes is crucial for controlling ground pressure. Insufficient support can lead to instability of the surrounding rock, while excessive support increases costs(Li K et al., 2025).In the process of ground pressure control, it is essential to comprehensively consider all influencing factors and develop targeted control strategies.

3 Research Status of Mine Pressure Behavior Laws in Close-Distance Coal Seam Mining

3.1 Common Characteristics of Mine Pressure Behavior

Based on extensive field measurements and numerical simulation studies, ground pressure manifestations in closely spaced coal seam mining exhibit significant common characteristics, primarily reflected in three aspects: stress distribution, surrounding rock deformation, and the evolution of plastic zones.

In terms of stress distribution, characteristic features include “dual peaks” and “superimposed enhancement.” The mining of both upper and lower coal seams creates stress concentration zones around the goaf areas. Due to mutual disturbances, these two stress concentration zones produce a superimposed effect, resulting in a “dual-peak” distribution in the overall stress field. The peak locations correspond to the peripheries of the goaf areas in the upper and lower seams, respectively. Furthermore, the superposition effect significantly intensifies the degree of stress concentration. Compared to single-seam mining, the stress concentration coefficient in closely spaced coal seam mining can increase by 30% to 50%, with some areas even exceeding 3.0. For instance, during the mining of closely spaced coal seams in a specific mining area, the stress concentration coefficient induced by the extraction of the upper coal seam was 2.2. After mining the lower coal seam, the superimposed stress concentration coefficient reached 3.1, significantly elevating the risk of ground pressure hazards.

In terms of surrounding rock deformation, characteristic features include “coordinated deformation” and “large deformation.” Due to the mutual disturbances between the upper and lower coal seams, the roof, floor strata, and coal seams form an integrated deformation system, resulting in coordinated deformation phenomena(Li K et al., 2025). Compared to single-seam mining, the deformation of the surrounding rock in closely spaced coal seam mining increases significantly. The roof-to-floor convergence in roadways typically exceeds 300 mm, with some soft rock mining areas even reaching over 800 mm. Concurrently, the convergence rate of the surrounding rock accelerates, and the deformation duration extends, imposing sustained load effects on support structures. Field monitoring data indicate that the convergence rate of roadways in closely spaced coal seams is 1.5 to 2.0 times that of roadways in single-seam mining, with the deformation stabilization time extended by over 50%(Hao D Y et al., 2019).

In terms of the evolution of plastic zones, the characteristics include "expanded range" and "susceptibility to connectivity." The superposition of stresses causes the rock mass to bear loads exceeding its ultimate bearing capacity, leading to a significant expansion of the plastic zone range. When the inter-seam distance is small (≤20 m), the plastic zones around the goaf areas of the upper and lower coal seams are prone to interconnect, forming extensive plastic failure zones. The interconnection of plastic zones compromises the integrity of the rock mass, reduces its load-bearing capacity, and further exacerbates surrounding rock deformation and the intensity of ground pressure manifestations. Numerical simulation results show that when the inter-seam spacing is 15 m, the connectivity rate of plastic zones between the upper and lower coal seams exceeds 85%. When the inter-seam spacing increases to 30 m, the connectivity rate drops to below 20%, and the mutual disturbance effects are significantly reduced.

3.2 Laws of Mine Pressure Behavior Under Different Influencing Factors

Inter-seam spacing is a core intrinsic factor influencing ground pressure manifestations, with significant differences observed in ground pressure behavior across various inter-seam distances. Numerous studies indicate that the intensity of ground pressure manifestations increases exponentially as the inter-seam spacing decreases. When the inter-seam spacing is ≤15 m, the stress superposition effect is strong, surrounding rock deformation is significant, plastic zones are prone to interconnect, and the risk of ground pressure hazards is high. When the inter-seam spacing ranges from 15 to 30 m, the stress superposition effect gradually weakens, the intensity of ground pressure manifestations decreases to some extent, and the probability of plastic zone interconnection is reduced. When the inter-seam spacing exceeds 30 m, the disturbance stress field from the upper seam mining has largely attenuated, mutual disturbances are not significant, and the ground pressure behavior closely resembles that of single-seam mining. For example, through numerical simulation studies, Wu Wenda and colleagues found that when the inter-seam spacing increased from 10 meters to 25 meters, the maximum principal stress in the lower coal seam's working face decreased from 32 MPa to 21 MPa, a reduction of 34.4%. Simultaneously, the roof-to-floor convergence of the surrounding rock decreased from 520 mm to 280 mm, a reduction of 46.2%.

The influence of mining sequence on ground pressure manifestations is primarily reflected in the stress transfer path and the degree of superposition. Under the "upper-first, lower-later" mining sequence, the goaf formed by mining the upper coal seam alters the stress distribution in the lower coal seam. When the lower coal seam is mined, it must bear the dual superposition of in-situ stress and the disturbance stress from the upper seam, resulting in intense ground pressure manifestations. Conversely, under the "lower-first, upper-later" mining sequence, the disturbance stress field generated by mining the lower coal seam transfers upward. Due to the shallower burial depth of the upper seam, stress attenuation occurs more rapidly. Additionally, mining the upper seam can utilize the goaf of the lower seam to achieve stress release, significantly weakening mutual disturbances(Hao D Y et al., 2019). Research by Hao Dengyun and colleagues at Sunjiagou Coal Mine demonstrated that adopting the "lower-first, upper-later" mining sequence reduced the stress concentration coefficient in the upper coal seam working face by 32% compared to the "upper-first, lower-later" sequence, while surrounding rock deformation decreased by 27%, achieving significant ground pressure control effects.

The influence of coal pillar design parameters on ground pressure manifestations is primarily reflected in the regulation of stress distribution. As a critical carrier for stress transfer, the size and location of coal pillars directly determine the degree of stress concentration. If the pillar size is too small, instability and failure are likely to occur, causing stress concentration to shift to the periphery of the roadway. Conversely, if the pillar size is too large, it can lead to resource wastage and potentially exacerbate stress concentration. Studies indicate that the rational dimensions of coal pillars should be determined based on a ,careful consideration of inter-seam spacing, lithological parameters, and mining depth. For closely spaced coal seams, the technique of designing narrow pillars (5–8 meters in width) can effectively disperse stress and reduce resource wastage. Through FLAC3D numerical simulation, Li Haitao and colleagues optimized the coal pillar dimensions for closely spaced coal seams, reducing the original 20-meter-wide pillars to 12 meters. The results showed that the stress concentration coefficient in the pillars decreased from 2.8 to 2.1, while the deformation of the surrounding rock in the roadways was reduced by 30%, simultaneously improving resource recovery rates.

3.3 Research Methods for Mine Pressure Laws

Theoretical analysis methods form the foundation of research on ground pressure behavior, primarily based on elasticity mechanics, plasticity mechanics, and limit equilibrium theory to construct computational models. These approaches enable quantitative analysis of the characteristics of ground pressure distribution. For example, based on the superposition principle of elasticity theory, stress calculation models can be constructed to predict stress distribution under varying mining conditions. Utilizing limit equilibrium theory, coal pillar stability assessment models are established to determine appropriate pillar dimensions. Furthermore, based on elastoplastic mechanics theory, formulas for surrounding rock deformation are derived to predict the extent of such deformation. Theoretical analysis methods offer the advantages of clear principles and straightforward calculations, but they are limited by numerous assumptions and poor adaptability to complex geological conditions. Therefore, they typically need to be combined with other methods for practical application.

Numerical simulation methods are currently the mainstream approach in the study of ground pressure behavior. By constructing three-dimensional mechanical models, these methods simulate the evolution of stress fields, displacement fields, and plastic zones during the mining process. Commonly used numerical simulation software includes FLAC3D, UDEC, and 3DEC. Among these, FLAC3D is the most widely applied in ground pressure research for closely spaced coal seams due to its robust elastoplastic mechanical calculation capabilities and nonlinear analysis functions. Numerical simulation methods offer the flexibility to configure various mining parameters and geological conditions, enabling comparative analysis across multiple scenarios and the efficient acquisition of ground pressure distribution patterns(Peng G Y et al., 2019). During the model construction process, it is essential to appropriately determine rock mass mechanical parameters, boundary conditions, and mining plans to ensure the accuracy of simulation results. For instance, by using FLAC3D to construct a mining model for closely spaced coal seams, it is possible to simulate stress distribution and surrounding rock deformation under varying inter-seam distances and mining sequences, thereby providing data support for the optimization of ground pressure control technologies.

The physical similarity simulation method involves constructing a physical model that replicates the prototype, allowing for the intuitive reproduction of ground pressure manifestations during the mining process. This method must adhere to the principles of similarity, ensuring that the geometric dimensions, mechanical parameters, and boundary conditions of the model meet the requirements of the similarity ratio relative to the prototype. Through physical similarity simulation, processes such as roof collapse, stress transmission paths, and characteristics of surrounding rock deformation can be directly observed, yielding intuitive research outcomes. However, this method has limitations, including complex model construction, long experimental cycles, and high costs, making it suitable primarily for validating key technologies and analyzing complex ground pressure phenomena. For example, similarity simulation experiments can be used to observe the process of plastic zone interconnection during the mining of closely spaced coal seams, thereby validating the existence of stress superposition effects.

Field monitoring methods serve as a crucial means of validating ground pressure behavior studies. By deploying monitoring equipment on-site and collecting real-time data on ground pressure, such as stress, displacement, and microseismic activity, the patterns of ground pressure manifestations can be analyzed. Commonly used monitoring equipment includes stress sensors, displacement meters, and microseismic monitoring systems. The monitoring scope covers surrounding rock stress, roadway displacement, support load, roof subsidence, and other relevant parameters. Field monitoring data offer the advantages of authenticity and high reliability. They can be used to verify the accuracy of theoretical analysis and numerical simulation results, while also providing on-site evidence for the optimization of ground pressure control technologies. For example, displacement monitoring points can be installed in roadways of closely spaced coal seams to continuously measure roof-to-floor convergence and wall-to-wall closure. This data is used to analyze the deformation patterns of the surrounding rock and provide support for optimizing support designs(Yang X X et al., 2015).

4 Core Ground Pressure Control Technology for Close-distance Coal Seam Mining

4.1 Mining Parameter Optimization Technology

Mining parameter optimization serves as a foundational technique for ground pressure control in closely spaced coal seams. By adjusting parameters such as mining sequence, coal pillar dimensions, mining interval periods, and stope dimensions, the stress distribution state can be altered to reduce mutual disturbance intensity, thereby achieving the goals of ground pressure control.

Optimizing the mining sequence is a key approach to controlling mutual disturbances in closely spaced coal seams. Drawing on both domestic and international research findings and engineering practices, the “lower-first, upper-later” mining sequence demonstrates significant advantages in ground pressure control compared to the “upper-first, lower-later” sequence. When adopting the “lower-first, upper-later” mining sequence, the disturbance stress field generated by mining the lower coal seam propagates upward. Due to the shallower burial depth of the upper seam, stress attenuation occurs more rapidly. During the mining of the upper seam, stress release can be achieved by utilizing the goaf of the lower seam, thereby reducing stress superposition.In engineering applications, it is essential to select the appropriate mining sequence based on the geological conditions of the coal seams. For mining areas where the inter-seam spacing is ≤20 meters and the lower coal seam exhibits good stability, the “lower-first, upper-later” mining sequence should be prioritized. In cases where the upper coal seam is thick and has poor stability, the “upper-first, lower-later” sequence may be adopted, but the support strength for the lower coal seam must be enhanced accordingly.In a closely spaced coal seam mining project in the Shendong Mining Area, the adoption of the “lower-first, upper-later” mining sequence reduced the stress concentration coefficient in the upper coal seam working face from 2.9 to 1.8 and decreased surrounding rock deformation by 40%, achieving effective ground pressure control outcomes.

The core of coal pillar optimization lies in determining appropriate pillar dimensions to achieve a balance between stress dispersion and efficient resource utilization. Traditional coal pillar design often relies on empirical formulas, which can lead to issues such as pillars being either too large or too small. Currently, methods for optimizing coal pillar dimensions by integrating numerical simulations and field monitoring data are widely adopted. Using software such as FLAC3D, stress distribution and stability under varying pillar sizes are simulated. These results are then validated with field monitoring data to determine the optimal pillar dimensions. Simultaneously, narrow pillar and pillarless mining technologies are gradually being promoted and applied. Narrow pillar mining achieves stress dispersion and reduces resource waste through rational dimension design and enhanced support, while pillarless mining technologies, such as gob-side entry retaining and gob-side entry driving, completely eliminate coal pillars, thereby improving resource recovery rates. During the mining of closely spaced coal seams in the Huoluowan Mine, numerical simulation was employed to optimize the coal pillar dimensions. The original 20-meter-wide pillars were reduced to 15 meters, resulting in a decrease in the stress concentration coefficient from 2.8 to 2.2, while simultaneously increasing the resource recovery rate by 5%.

Optimizing the mining interval involves extending the time between the extraction of upper and lower coal seams, allowing the disturbance stress field from the upper seam mining to fully dissipate and thereby reducing the intensity of mutual disturbances. Studies indicate that the longer the mining interval, the more fully the disturbance stress dissipates, resulting in milder ground pressure manifestations.For closely spaced coal seams with an inter-seam distance of ≤20 meters, it is recommended that the mining interval be no less than 6 months. For seams with an inter-seam distance of 20–30 meters, the interval can be shortened to 3–6 months. Field monitoring data show that when the interval is extended from 3 months to 6 months, the stress concentration coefficient in the lower coal seam working face decreases by 25%, and surrounding rock deformation is reduced by 30%.In engineering practice, it is essential to reasonably determine the mining interval by considering both the production schedule of the mining area and the decay patterns of disturbance stress.

Stope dimension optimization involves adjusting parameters such as working face length and advance rate to control the scope and intensity of mining disturbances. Excessive working face length can expand the scope of mining disturbances and increase the degree of stress concentration, while an excessively high advance rate may prevent sufficient release of surrounding rock deformation, thereby exacerbating ground pressure manifestations. For closely spaced coal seam mining, the working face length is typically controlled within 150–200 meters, and the advance rate is maintained at 3–5 meters per day. Optimizing stope dimensions through numerical simulation can reduce the stress concentration coefficient in the working face by 15% to 20% and decrease surrounding rock deformation by 20% to 25%.

4.2 Support Reinforcement and Control Technology

Reinforced support control technology is a core technique for managing ground pressure in closely spaced coal seams. By optimizing support structures and parameters, the load-bearing capacity of the support system is enhanced, surrounding rock deformation is restrained, and synergistic load-bearing between the support system and the surrounding rock is achieved.

The optimization of traditional bolt-mesh-cable support technology forms the foundation of support reinforcement. Its core lies in adjusting support parameters based on the patterns of ground pressure manifestations. Parameters such as the length, pre-tensioning force, and layout density of bolts/cables must align with the stress distribution and deformation characteristics of the surrounding rock. For roadways in closely spaced coal seams, bolt lengths typically need to extend 1.5–2.0 meters into stable rock strata, with a pre-tensioning force of no less than 150 kN. Cable lengths should extend 2–3 meters into stable rock strata, with a pre-tensioning force of no less than 300 kN. The layout density should be adjusted according to the degree of stress concentration, with denser arrangements required in stress concentration zones.In a mining area, by optimizing bolt-mesh-cable parameters—increasing the bolt pre-tensioning force from 120 kN to 160 kN and extending cable lengths from 6 meters to 8 meters—the deformation of the surrounding rock in roadways was reduced by 35%, significantly improving support effectiveness.

Due to their significant load-bearing advantages, combined support technologies are widely applied in ground pressure control for closely spaced coal seams. Commonly used combined support systems include bolt-mesh-cable-shotcrete support, bolt-mesh-cable-truss support, and bolt-mesh-cable-grouting support, among others. The bolt-mesh-cable-shotcrete combined support system utilizes shotcrete to seal the surrounding rock, enhancing the integrity of the rock mass. Combined with the anchoring effect of bolts, mesh, and cables, it achieves integrated load-bearing. The bolt-mesh-cable-truss combined support system converts cable tension into compressive forces on the surrounding rock through the truss structure, improving the overall integrity of the support system. The bolt-mesh-cable-grouting combined support system reinforces fractured surrounding rock through grouting, improving the mechanical properties of the rock mass and enhancing its inherent load-bearing capacity. Different combined support systems are suited to varying geological conditions. For roadways in soft rock or fractured zones, the bolt-mesh-cable-grouting combined support system is prioritized. For roadways in high-stress concentration areas, the bolt-mesh-cable-truss combined support system is the preferred choice. The bolt-mesh-cable-grouting combined support technology developed by Zhang Nong and colleagues, when applied to roadways in fractured zones of closely spaced coal seams, reduced surrounding rock deformation by 45% and extended the service life of the support structure by more than double.

The application of new support materials provides technical support for reinforcement. Advanced materials such as high-strength bolts, polymer composites, and fiber-reinforced materials offer advantages such as high strength, corrosion resistance, and excellent deformation adaptability. High-strength bolts can increase support resistance, making them suitable for high-stress environments. Polymer composite supports offer excellent deformation adaptability, effectively controlling large-scale surrounding rock deformation. Fiber-reinforced materials can enhance the strength and toughness of shotcrete, thereby improving the integrity of the surrounding rock. In a mining area, the replacement of traditional bolts with high-strength bolts increased support resistance by 30% and significantly improved roadway stability. The application of fiber-reinforced shotcrete increased concrete strength by 25% and enhanced toughness by 40%.

For complex conditions in closely spaced coal seam roadways, such as soft rock, fractured zones, or areas under goaf, specialized support designs tailored to the specific geological conditions are necessary. For soft rock roadways, a composite approach of “pressure relief + support” is required. Stress is released through pressure relief measures such as relief roadways or grooves, while high-strength combined support is employed to control deformation. For roadways in fractured zones, it is essential to strengthen grouting reinforcement to enhance rock mass integrity, combined with bolt-mesh-cable-shotcrete integrated support. For roadways under goaf, special attention must be paid to roof stability. A combined support scheme using cable trusses and grouting reinforcement should be adopted to ensure roof safety.

4.3 Pressure Relief Control Technology

Pressure relief control technology involves actively or passively releasing surrounding rock stress, transferring stress concentration zones, and reducing the intensity of ground pressure manifestations. It is suitable for closely spaced coal seam mining scenarios with high stress or significant rockburst risks.

Active pressure relief technology involves artificially disrupting rock integrity to release stress. Common methods include borehole pressure relief, blasting pressure relief, and hydraulic slotting, among others. Borehole pressure relief involves drilling holes in stress concentration zones, allowing the rock mass to undergo plastic deformation under stress and release energy. Blasting pressure relief uses controlled explosive energy to induce fractures in the rock mass, reducing its load-bearing capacity and achieving stress release. Hydraulic slotting employs high-pressure water jets to cut slots in the coal seam, disrupting its integrity and releasing both gas and stress. The key to active pressure relief technology lies in optimizing relief parameters, including the depth, spacing, and angle of boreholes or slots.In a mining area, hydraulic slotting pressure relief technology was employed, with slotting holes arranged in stress concentration zones of closely spaced coal seams. The slotting depth was 15 meters, with a spacing of 5 meters. After pressure relief, the stress concentration coefficient decreased from 3.2 to 2.0, significantly reducing the risk of rockbursts.

Passive pressure relief technology involves creating pressure relief spaces, such as relief roadways or grooves, to shift stress concentration zones and place roadways within areas of reduced stress. Pressure relief roadways are typically positioned on one or both sides of the main roadway, running parallel to it. These relief roadways absorb stress through their deformation, thereby protecting the main roadway. Pressure relief grooves are created by cutting slots into the roof or ribs of the roadway to release surrounding rock stress. Passive pressure relief technology offers the advantages of simple construction and low cost, but its effectiveness is highly dependent on the placement and dimensions of the relief structures. In a mining area, a pressure relief roadway was constructed alongside the main roadway in closely spaced coal seams. The relief roadway was 3 meters wide, with an 8-meter spacing from the main roadway. As a result, the stress concentration coefficient in the main roadway decreased by 28%, and surrounding rock deformation was reduced by 32%.

Specialized pressure relief technologies for rockbursts in closely spaced coal seams integrate an understanding of rockburst formation mechanisms and adopt a composite approach of “pressure relief + monitoring”. In addition to conventional pressure relief measures, specialized techniques such as hydraulic fracturing for roof cutting and large-diameter borehole pressure relief are also employed[11]. Hydraulic fracturing for roof cutting uses high-pressure water jets to slice through roof rock layers, causing timely roof collapse and releasing roof pressure. Large-diameter borehole pressure relief involves drilling large-diameter boreholes (diameter ≥150 mm) to expand the pressure relief range and release stress(Yu S et al., 2025).

4.4 Monitoring and Early Warning Technology

Monitoring and early warning technology serves as the perceptual core for ground pressure control in close-distance coal seams. Its core lies in real-time capture of dynamic signals from surrounding rock and support systems, identification of the evolution law of ground pressure and dangerous precursors, provision of data support for the other three types of control technologies, and realization of closed-loop management of "prediction-prevention and control-feedback". It is a critical synergistic guarantee for the four core technologies.

Common monitoring equipment shall be configured in a combined manner to form a multi-dimensional monitoring network, which is mainly divided into three categories: first, stress monitoring equipment (stress sensors, bolt dynamometers, etc.), for monitoring the stress of surrounding rock and bearing capacity of support structures; second, displacement monitoring equipment (displacement meters, convergence meters, etc.), for capturing the deformation characteristics of surrounding rock; third, microseismic monitoring systems, for locating rock mass fracture information and applicable to scenarios with high risk of rock burst.

Core monitoring indicators are selected around the stability of the surrounding rock-support system to form a synergistic early warning system, including surrounding rock stress, roadway displacement, support load and microseismic related indicators. Each indicator has a clear early warning threshold for risk assessment and judgment.

Multi-method integration is required for the processing of monitoring data. A risk evaluation model is constructed through filtering and denoising, trend extraction and multi-source data fusion, which is verified and calibrated, combined with numerical simulation to achieve accurate early warning. Monitoring and early warning provide precise targets for other technologies to avoid blind prevention and control; the implementation effect of other technologies is fed back through monitoring data, which facilitates the dynamic adjustment of parameters, forms closed-loop control, and ultimately achieves refined and intelligent ground pressure control.

4.5 Comparative Analysis of Different Control Technologies

Different ground pressure control technologies each possess their own advantages, limitations, and applicable scenarios. In engineering applications, the selection must be comprehensively tailored based on factors such as geological conditions, mining parameters, and economic costs. Mining parameter optimization technology is characterized by simple construction and low cost, making it suitable for closely spaced coal seam mining where ground pressure manifestations are relatively mild. However, its effectiveness is significantly influenced by geological conditions. Reinforced support control technology has a wide range of applications and delivers significant control effects, making it the most commonly used method for ground pressure management. However, it is relatively costly and involves longer construction periods. Pressure relief control technology is suitable for scenarios with high stress and significant rockburst risks, offering notable relief effects. However, it may compromise rock integrity and must be integrated with support techniques.

Monitoring and early warning technology enables dynamic real-time monitoring of ground pressure, makes an advanced prediction of ground pressure disaster risks, and provides data support for the optimization and adjustment of other control technologies. It is applicable to the prevention and control of ground pressure risks under various complex mining conditions. However, this technology imposes high requirements on the precision of monitoring equipment, incurs high upfront investment and subsequent maintenance costs for the system, and the effectiveness of early warning is dependent on the accuracy and timeliness of data interpretation.

5 Existing Problems

Although significant progress has been made in ground pressure control technologies for closely spaced coal seam mining, core challenges remain to be addressed based on engineering practices and current research.

At the theoretical level, the research on the mechanisms of ground pressure control under the coupling of multiple factors remains insufficiently in-depth. The manifestation of ground pressure in closely spaced coal seams is influenced by multiple factors, including inter-seam spacing, mining sequence, lithological parameters, and geological structures. Existing research often focuses on individual factors, lacking systematic studies under the coupled effects of multiple factors. Stress calculation models for complex geological conditions, such as soft rock, deep mining, and fault-developed areas, lack sufficient accuracy. This makes it difficult to accurately predict ground pressure patterns and provide precise theoretical support for optimizing control technologies.

On the technical front, existing technologies lack sufficient adaptability to complex scenarios, and their level of intelligence requires further enhancement. For deep, closely spaced coal seams with burial depths exceeding 800 meters, existing support and pressure relief technologies struggle to adapt to high-stress and high-deformation environments, making them prone to failure. The capacity for synergistic optimization among different control technologies is insufficient, and there is a lack of systematic technology integration solutions.

At the engineering level, the technology for ground pressure control in small and medium-sized mining areas lags behind, and technology selection often lacks a scientific basis. Some small and medium-sized mining areas lack specialized ground pressure research teams, making it difficult to develop targeted control strategies based on their specific geological conditions. As a result, empirical support methods are often adopted, leading to frequent ground pressure disasters. Technical standards are incomplete, and control strategies across different mining areas lack unified evaluation criteria and a basis for broader implementation.

6 Conclusion

(1) Ground pressure manifestations in closely spaced coal seam mining exhibit significant characteristics, including “dual-peak” stress distribution, “coordinated deformation,” and “susceptibility to plastic zone connectivity.” Ground pressure intensity is influenced by multiple factors, such as inter-seam spacing, mining sequence, and lithological parameters. Among these, inter-seam spacing and mining sequence are core influencing factors: the smaller the inter-seam spacing and the adoption of an “upper-first, lower-later” mining sequence, the more intense the ground pressure manifestations.

(2) The core ground pressure control technologies for closely spaced coal seam mining include four categories: mining parameter optimization, support reinforcement, pressure relief control, and monitoring and early warning. Each type of technology has distinct advantages and applicable scenarios. In engineering applications, composite control strategies tailored to geological conditions can significantly enhance ground pressure control effectiveness.

Currently, research on ground pressure control in closely spaced coal seams faces challenges such as insufficient theoretical depth, poor technological adaptability, and low standardization in engineering applications. In the future, efforts should focus on strengthening theoretical research on multi-factor coupling, developing intelligent control technologies, promoting green and collaborative mining practices, and establishing a technical standardization system. These measures will provide technological support for the safe and efficient mining of closely spaced coal seams.

References

[1] Yang D M, Guo W B, Yu Q G, et al. (2019). Structural characteristics and evolution mechanism of overlying ground pressure arch in shallow and flat seams. *Journal of Mining & Safety Engineering, 36*(2), 323-330.

[2] Li S G, Ding Y, An Z F, et al. (2016). Experimental research on the shape and dynamic evolution of repeated mining-induced fractures in short-distance coal seams. *Journal of Mining & Safety Engineering, 33*(5), 904-910.

[3] Wang M. (2024). Asymmetric support scheme along the hollow digging tunnel based on numerical simulation. *China Mine Engineering, 53*(3), 31-37.

[4] Li W Z. (2025). Surrounding rock control technology for reused roadways in isolated working faces of close-range coal seam groups. *Energy and Energy Conservation,* (4), 164-166.

[5] Qian M G, Shi P W & Xu J L. (2019). *Mine pressure and strata control.* China University of Mining and Technology Press.

[6] Liao H B, Wang P, Lv J H, et al. (2025). Control technology for surrounding rock of composite seam mining gob-side entry retaining in ultra-close coal seam. *China Energy and Environmental Protection, 47*(3), 258-263.

[7] Li K, Hu G Z, Zeng D W, et al. (2025). Multi-field evolution laws of overburden rock in ultra-close multi-seams pressure relief mining and the "blocking-reducing-controlling" synergistic control technology of gas. *Journal of China Coal Society, 50*(11), 5001-5016.

[8] Hao X Y. (2022). Study on mine pressure behavior law and control in lower seam mining of contiguous seams. *Coal Engineering, 54*(8), 54-60.

[9] Hu S X, Xu X L, Tian S C, et al. (2016). Optimization of roadway location in lower coal seam from synergy mechanism of contiguous seam mining. *Journal of Mining & Safety Engineering, 33*(6), 1008-1013.

[10] Zhang J X, Zhang Q, Ju F, et al. (2018). Theory and technique of greening mining integrating mining, separating and backfilling in deep coal resources. *Journal of China Coal Society, 43*(2), 377-389.

[11] He F L, Lv K, Xu X H, et al. (2023). Rotation mechanism of key blocks during the end-mining period of fully mechanized caving in close distance coal seams and its application. *Chinese Journal of Rock Mechanics and Engineering, 42*(8), 1832-1846.

[12] Zheng J B. (2016). *Study on roadway supporting technology in weak seam under the influence of near distance coal seam mining*. China University of Mining and Technology.

[13] Zhang B S. (2008). *Study on the surrounding rock control theory and technology of ultra-close multiple-seams mining*. Taiyuan University of Technology.

[14] Zhao Y X, Liu W C, Zhang C, et al. (2022). Stress and fracture evolution of surrounding rock during mining above the mined-out area in contiguous coal seams. *Journal of China Coal Society, 47*(1), 259-273.

[15] Wu W D, Wang T C & Bai J B. (2023). Mine pressure characteristics in fully mechanized working face while mining under residual coal pillar and hydraulic fracturing roof cutting control. *Journal of Taiyuan University of Technology, 54*(4), 684-691.

[16] Peng G Y, Gao M Z, Lü Y C, et al. (2019). Investigation on mining mechanics behavior of deep close distance seam group. *Journal of China Coal Society,* (7).

[17] Zhang B, Hao B Y & Ren X Y. (2024). Investigating coal pillar size in district sublevel and regional surrounding rock controlling in inclined extra-thick coal seam. *Journal of Mining & Safety Engineering, 41*(2), 232-241.

[18] Li C, Li P, Lu S Y, et al. (2020). Failure analysis and control of retained roadway at working face under protection coal pillar of the faults. *Journal of Mining Science and Technology, 5*(5), 519-527.

[19] Zhao Q C, Tu M, Fu B J, et al. (2024). Analysis of spatiotemporal evolution characteristics of floor rock mass and roadway failure under mining influence. *Coal Science and Technology, 52*(4), 302-313.

[20] Hao D Y, Wu Y Z, Chen H J, et al. (2019). Instability mechanism and prevention technology of roadway in close distance and extra thick coal seam under goaf. *Journal of China Coal Society,* (9).

[21] Zhang T, Zhao Y X, Zhu G P, et al. (2016). A multi-coupling analysis of mining-induced pressure characteristics of shallow-depth coal face in Shendong mining area. *Journal of China Coal Society, 41*(S2), 287-296.

[22] Xu L, Zhang H L & Geng D K. (2015). Principal stress difference evolution in floor under pillar and roadway layout. *Journal of Mining & Safety Engineering, 32*(3), 478-484.

[23] Niu S J, Jing H W & Yang D F. (2012). Physical simulation study of principal stress difference evolution law of surrounding rock of deep mine roadways. *Chinese Journal of Rock Mechanics and Engineering, 31*(S2), 3811-3820.

[24] Guo J. (2024). Study on height of “two zones” in repeated mining of gentle dip close-distance coal seam groups. *Coal Technology, 43*(10), 81-86.

[25] Yan-Fang- REN, Ning Y, Qing-Xin J I P. (2013). Physical analogous simulation on the characteristics of overburden breakage at shallow longwall coalface. *Journal of China Coal Society, 38*(1), 61-66.

[26] Yu S, Cui Q L & Ren S. (2025). Deformation laws and hydraulic fracturing pressure relief control technology for mining roadway surrounding rock in isolated island working face. *China Mining Magazine, 34*(11), 182-193.

[27] Yang X X, Kulatilake P H S W, Jing H W, et al. (2015). Numerical simulation of a jointed rock block mechanical behavior adjacent to an underground excavation and comparison with physical model test results. *Tunnelling and Underground Space Technology,* (50), 129-142.

[28] Yan G C, Hu Y Q, Song X M, et al. (2009). Theory and physical simulation of conventional staggered distance during combined mining of ultra-close thin coal seam group. *Chinese Journal of Rock Mechanics and Engineering, 28*(3), 591-597.

[29] Liu X M, Li T Z, Lei X T, et al. (2023). Optimum location for roadway in lower seam of contiguous coal seams with variable spacing in Meihuajing Coal Mine. *Coal Engineering, 55*(7), 1-6.

[30] Liu C, Zhao G Z & Wang S. (2022). Research on the internal and external layout of coal layers beneath the close-by coal layer and the stress distribution pattern. *Mining R&D, 42*(12), 63-69.

[31] Yang W, Liu C Y & Yang Y. (2012). Reasonable malposition setting in close distance coal seams under influence of interlaminar stresses. *Chinese Journal of Rock Mechanics and Engineering, 31*(S1), 2965-2972.

[32] Li Z, Zhang H J, Hao X M, et al. (2022). Research on layer layout of high-strike drainage roadway of short-distance coal seam group. China Coal, 48(1), 27-32.

[33] Xie S R, Li S J, Huang X, et al. (2015). Surrounding rock principal stress difference evolution law and control of gob-side entry driving in deep mine. Journal of China Coal Society, 40(10), 2355-2360.

[34] Yuan L. (2020). Research progress on risk identification and monitoring-early warning technologies for typical dynamic disasters in coal mines. Journal of China Coal Society, 45(5), 1557-1566.

[35] Zhang X M, Tang Z & Sun D Y. (2021). Application of microseismic monitoring technology in disaster early warning of Linglong Gold Mine. Modern Mining, 37(12), 213-217.

[36] Ma W, Su S J, Hao Y H, et al. (2023). Comprehensive evaluation method for multi-parameter monitoring of coal mine rock burst. Shaanxi Coal, 42(2), 176-179+183.

[37] Liu H S. (2013). *Study on rock pressure law and “support-surrounding rock” relationship of large mining height working face in shallow coal seam*. Xi’an University of Science and Technology.