(REVIEW ARTICLE)

Ground control systems for deep underground mining: Advancing safety and resource recovery in high-stress mining environments

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Abstract

This paper addresses the growing challenges of ground control in deep underground mining environments in the United States, where increasing depths introduce significant safety and operational concerns, including squeezing ground conditions, time-dependent deformation, and seismic activity. We examine the evolution of ground support technologies, focusing on energy-absorbing systems, dynamic surface supports, and innovative materials specifically designed for high-stress conditions. Through analysis of case studies from major U.S. mining operations, we demonstrate the effectiveness of convergence confinement methods and specialized gabion-like systems in enhancing both safety and resource recovery. The integration of artificial intelligence, remote sensing, and IoT-based monitoring systems represents a paradigm shift from reactive to proactive ground management strategies. Our findings indicate that successful ground control requires a multi-faceted approach combining advanced support design, real-time monitoring technologies, and strategic maintenance practices. These advancements significantly contribute to the sustainability and economic viability of deep mining operations, particularly important as the industry increasingly targets critical minerals essential for clean energy transition.

Keywords: Ground Control; High-Stress; Energy-Absorbing; Support; Seismic; Mining

1. Introduction

1.1. Deep Mining Trends in the United States

Ground control systems in deep underground mining are crucial for enhancing safety and optimizing resource recovery, particularly in high-stress environments. The current state of deep underground mining in the U.S. reflects a significant evolution driven by technological advancements and safety considerations. As shallow resources become depleted, the industry is increasingly focused on deep mining, which presents unique challenges and opportunities for innovation. The following sections outline key aspects of this transition. Deep mining operations face risks such as rock bursts, necessitating advanced prediction and prevention techniques [1]. For example, The National Institute for Occupational Safety and Health (NIOSH) emphasizes improved roof support and pillar design to enhance safety in deeper coal mines [2]. Additionally, novel technologies such as the advancements in artificial intelligence, particularly deep learning, are being integrated into mining operations for predictive maintenance, efficiency assessment, and safety enhancements [3]. New engineering technologies, including cooling and rock support techniques, are being developed to facilitate safe and efficient deep mining [1]. The trend towards mining at greater depths is evident, with more reserves increasingly being accessed under challenging conditions [2].

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Ground control systems for deep underground mining play a crucial role in the economic viability of U.S. critical mineral supply chains, particularly as demand for essential minerals like copper, nickel, cobalt, molybdenum surges due to the clean energy transition. These minerals are integral to technologies such as electric vehicles and renewable energy systems, which are expected to see a dramatic increase in demand over the coming decades [4, 5]. Effective ground control systems continue to enhance safety and operational efficiency, thereby reducing costs and environmental impacts associated with mining [6]. For instance, many companies are developing sustainable mining practices that minimize waste and energy consumption, positioning themselves to meet the growing demand [6]. As the U.S. seeks to secure its mineral resources, optimizing these systems will be vital for maintaining a resilient supply chain that can withstand market fluctuations and geopolitical challenges [6, 5].

2. Unique Challenges of High-Stress Mining Environments

2.1. Statistical analysis of depth-related incidents and productivity challenges

Ground control systems face significant challenges related to depth-induced incidents and productivity. As mining operations extend deeper, the geological and environmental conditions become more complex, necessitating advanced ground control strategies to ensure safety and maintain productivity. The depth-related incidents primarily involve seismic events and ground failures, which can severely impact mining operations.

Deep vein mines, such as the Lucky Friday Mine, experience mining-induced seismic events due to fault slip mechanisms. These often necessitate robust ground support systems to prevent structural failures [7]. In highwall mining, ground falls account for a significant portion of incidents, with large rock falls being particularly hazardous. These incidents frequently lead to severe injuries and significant disruptions to operations [8]. Ensuring effective ground support is essential not only for maintaining the structural integrity of excavations but also for minimizing interruptions to production. To achieve long-term stability, support system designs must often consider both load balance and deformation compatibility [9]. In Arctic mining environments, ground support becomes even more challenging due to the presence of permafrost and groundwater. In these conditions, inflatable bolts and friction bolts are commonly used to address the challenges posed by frozen ground, while deeper mining operations often rely on resin-grouted rebar and cement-grouted cable bolts for added stability [10]. Additionally, a Canadian mine addressed ore pass degradation by employing discrete fracture network (DFN) modeling, which informed the installation of cable bolts and a grizzly to maintain structural integrity [11]. In China, the Jinchuan mine implemented an improved support strategy combining long bolts and floor beams to mitigate large deformations in deep roadways, demonstrating effective control over squeezing failures [12]. These examples illustrate the diverse methodologies employed to ensure safety and stability in challenging underground mining conditions [13, 14]. Although ground control in deep underground mining presents considerable challenges, ongoing advancements in support system design and risk management strategies offer promising pathways toward more effective and reliable solutions.

2.2. Geomechanical principles governing deep mining conditions

The geomechanical principles that govern deep mining are complex, involving the careful management of stress fields, rock pressure, and the dynamic behavior of rock masses. Unlike shallow mining, deep mining is marked by elevated ground stress, higher temperatures, and greater permeability—all of which significantly influence stress distribution and rock fragmentation characteristics [15]. Ventilation is another major concern; it is vital for dissipating heat generated by the geothermal gradient and mining equipment, yet it often clashes with geomechanical limitations such as heightened stress and increased seismic activity. This creates a need to strike a balance between large ventilation conduits and smaller openings that maintain structural stability [16]. To address these challenges, comprehensive geomechanical monitoring is indispensable. It supports the selection of appropriate mining technologies and helps mitigate risks associated with the dynamic and gas-driven failure of rock masses, which can pose serious safety hazards [17]. For example, the development of mining-induced stress fields in the Yuzhnoe complex ore deposit underscores the critical role of numerical modeling in improving both safety and operational efficiency in deep mining [18]. In steep coal beds, the mechanism and intensity of rock pressure manifestations are critical, with successful mining methods relying on effective rock pressure control, which is influenced by geological and mining factors [19]. These principles underscore the need for integrated approaches that consider both geomechanical and operational factors to ensure safe and efficient deep mining practices.

2.3. Rock burst and strain burst phenomena in U.S. geological contexts

Ground control systems in deep underground mining must effectively address the risks posed by rock bursts and strain bursts-particularly in the U.S., where geological conditions make these events especially hazardous. Rock bursts, which involve sudden and violent rock failure, are driven by a combination of high stress environments, specific geological features, and certain mining practices [20, 21]. A notable subtype, coal bursts, often occur in areas with strong overlying strata, abnormal caving behavior, and insufficiently sized pillars, requiring customized prevention strategies [22]. One effective mitigation technique is destress blasting, which helps relieve stress concentrations around mine openings, thereby reducing the likelihood of strain bursts [21]. Moreover, the use of micro-seismic monitoring systems significantly enhances safety by providing real-time data on rock burst activity, enabling timely and informed operational adjustments. These strategies highlight the critical need to combine deep geological insight with innovative engineering practices to manage rock burst hazards in deep mining environments.

2.4. Squeezing ground conditions and time-dependent deformation

In squeezing ground conditions, ground control systems must contend with the significant challenge of time-dependent deformation. These conditions, typically marked by high stress-to-strength ratios and the presence of clay-rich minerals, result in substantial and ongoing deformation even after excavation, requiring durable and adaptive support systems [23, 13]. The Convergence Confinement Method (CCM) is commonly used to analyze tunnel support loads; however, traditional models often neglect the time-dependent behavior of rock masses. This oversight can lead to safety risks and increased project costs if not properly addressed [23, 24].

Recent advancements in CCM have begun to incorporate these time-dependent responses, validated by physical model testing and real-world case studies, such as the Yacambú–Quíbor tunnel in Venezuela, which experienced severe squeezing conditions [24]. In hard rock mines, squeezing is further complicated by structural features like foliation. Research has shown that yielding reinforcement elements can effectively reduce drift convergence under such conditions [25]. Additionally, experimental studies using true-triaxial cells and miniature tunnel boring machines have advanced our understanding of squeezing by replicating realistic stress environments and monitoring deformation over time [23]. These findings underscore the importance of choosing appropriate reinforcement strategies and optimizing installation timing to control large deformations, ensuring both the safety and long-term functionality of underground excavations [25, 23].

2.5. Seismic activity in deep mining environments

Seismic activity in deep mining environments is largely driven by a combination of geological conditions, mining methods, and the mechanical behavior of the rock mass. The extraction of large rock volumes during mining significantly alters the existing stress fields, often triggering induced seismicity, especially in areas with inherent geological weaknesses such as faults and dykes [26, 27]. The design of drill patterns and the presence of unblasted remnants of ore or host rock can further elevate seismic risks, as observed in the Kiirunavaara mine [28]. Environmental factors, including temperature variations and groundwater, also influence stress conditions and rock stability, thereby contributing to the likelihood of seismic events [29]. Continuous monitoring of seismic activity and ground deformation is critical for anticipating and mitigating these risks, as demonstrated in numerous case studies [30]. For example, Deep mining operations, such as those at the Lucky Friday Mine, require specialized ground support systems to manage unique geological and stress conditions. These systems are designed to limit seismic events and maintain the static and dynamic capacity of the support structures [7, 31]. Ultimately, a thorough understanding of the complex interplay between geological, mechanical, and operational factors is essential for effective seismic risk management in deep mining operations.

3. Evolution of Ground Support Systems in U.S. Deep Mining

Current Ground Control Systems (GCS) for deep underground mining face significant limitations, primarily due to the complexities of rock behavior under high stress, seismic events, and the challenges of monitoring ground conditions effectively. High rock stress levels can lead to sudden failures and large-scale deformations, necessitating robust support systems that can adapt to dynamic conditions [32]. Additionally, traditional monitoring methods, such as visual inspections and conventional instrumentation, often yield subjective and limited data, which can hinder timely decision-making and risk management [31]. To address these issues, advancements in support design, such as the implementation of preventive support maintenance (PSM) and innovative systems like gabion panels, can enhance the resilience of excavations [9]. Furthermore, integrating modern technologies like AI, ML, IOT, and remote sensing can provide comprehensive, quantifiable data on ground movements, improving the accuracy of ground behavior assessments and facilitating better-informed operational strategies [5]. Overall, a multifaceted approach that combines

advanced design methodologies, real-time monitoring technologies, and strategic maintenance practices is essential for improving GCS effectiveness in deep mining environments [33].

3.1. Advancing Ground Support Technologies, A Multi-Faceted Approach to Enhanced Safety and Operational Efficiency

The adoption of new ground support systems in U.S. deep mining operations is driven by several interrelated factors, primarily the need to address the challenges posed by high rock stress levels, seismic activity, and the complexities of ground behavior at significant depths. Effective ground control strategies, which include strategic, tactical, and operational design phases, are essential for ensuring safety and efficiency in mining operations [32]. The shift towards advanced support systems, such as roof bolting and innovative deep mixing methods, reflects a response to the evolving demands of the industry, including the need for minimal disruption to adjacent structures and groundwater management [34, 35]. Additionally, the integration of preventive support maintenance and the development of specialized support designs, such as gabion-like systems, enhance excavation health and operational reliability, ultimately reducing costs and production disruptions [36, 37]. These advancements underscore the importance of continuous research and adaptation in ground support technologies to meet the rigorous demands of deep mining environments. Overall, the integration of scientific research and practical applications has been pivotal in enhancing the safety and effectiveness of ground support systems in deep mining [38].

3.2. Classification of Contemporary Support Systems

In the challenging world of deep underground mining, the safety and stability of operations hinge on sophisticated ground control systems. As miners venture deeper beneath the surface, they encounter increasingly complex geological conditions that demand innovative support solutions.

The story of modern ground control begins with terminology and frameworks. Thompson and colleagues established a formal classification scheme in 2012 that brought much-needed consistency to the field, distinguishing between surface supports that protect exposed rock surfaces and reinforcement systems that strengthen the rock mass from within [39]. This standardization created a common language for engineers and miners alike, facilitating more effective design and testing protocols.

3.2.1. Ground Support Terminology and Frameworks

Ground control strategies have evolved to address different phases of mining operations. Behrooz's research in 2020 revealed three distinct design stages: strategic planning for long-term stability, tactical implementation to address immediate challenges, and operational adjustments to manage day-to-day conditions [32]. Each stage requires specialized approaches, particularly when confronting high rock stress or unexpected seismic events. The integration of monitoring systems has become crucial, allowing for continuous assessment and timely rehabilitation when needed.

3.2.2. Support Systems for Weak Rock Mass

Weak rock conditions present their own narrative of challenges. Foo's work in 2011 demonstrated how thin spray-on liners and other innovative solutions have transformed operations in poor ground conditions [40]. These advancements have opened possibilities for mining in previously inaccessible or prohibitively dangerous areas, expanding the industry's reach while maintaining safety standards.

3.2.3. High-Stress Ground Conditions

The story grows more intense when considering high-stress environments. Ghorbani's 2020 research highlighted the critical importance of energy-absorbing rock bolts in these scenarios [14]. These specialized systems dissipate energy from rock bursts and accommodate ground movement in squeezing conditions. The selection of appropriate supports has become increasingly sophisticated, taking into account various factors from rock mass characteristics to the geometry of excavations.

3.2.4. Geotechnical Risk Classification

Risk assessment frameworks complete this narrative of evolution. Mishra and Rinne proposed a classification system in 2015 that categorizes operations based on geotechnical risk levels, considering both mining methods and rock mass properties [41]. This system serves as an essential preliminary tool, guiding engineers toward appropriate support selections before problems arise.

The story of ground control systems continues to unfold. The dynamic nature of underground environments demands continuous adaptation and innovation. As mining operations push deeper and encounter new challenges, support strategies must evolve accordingly, writing new chapters in the ongoing narrative of underground safety and stability.

4. Technologies for High-Stress Environments

Our discussion continues to explore how advanced technologies such as thermal insulation materials, intelligent monitoring systems, and predictive modeling technologies are transforming traditional approaches to ground control. Investigating the integration of artificial intelligence with geospatial techniques, the development of energy-absorbing support systems, and the application of photogrammetric monitoring will enhance the safety and operational efficiency in deep mining operations. By focusing on these technological innovations, we aim to demonstrate how modern mining operations are evolving from reactive to proactive ground management strategies

4.1. Energy-Absorbing Rock Bolts and Anchors

Energy-absorbing rock bolts and anchors significantly enhance ground control systems in deep underground mining operations by effectively managing the dynamic hazards associated with high geo-stress environments. These systems mitigate deformation and reduce the extent of plastic zones in surrounding rock, thereby preventing incidents such as rock bursts and collapses [42]. The energy-absorbing mechanism operates through structural slip and material deformation, allowing bolts to dissipate energy from rock movements, which is crucial under both static and dynamic loads [43, 44]. Recent advancements, including the development of new bolt designs, have demonstrated improved anchorage performance and energy absorption capabilities, with tests showing increases in peak pullout force and energy absorption by over 200% in various rock conditions. Furthermore, innovative designs like the deformation-controlled rockbolt (DC-bolt) have been validated to limit rock surface movement, providing robust support in challenging geological conditions [45]. Overall, these enhancements contribute to safer and more efficient mining operations.

4.2. Dynamic Surface Support Systems

Dynamic ground control systems in underground mining encompass several key components and functionalities aimed at ensuring safety and operational efficiency. These systems integrate advanced technologies such as remote mining head assemblies that utilize high-intensity electrical pulses for ore extraction, alongside logic control and sensor systems for real-time monitoring of mining conditions [46]. Safety is further enhanced through comprehensive monitoring systems that include ground control centers, underground monitoring stations, and environmental sensors, all interconnected via robust communication networks [46, 47]. Additionally, ground support schemes are critical, particularly in deep mining environments, where they must accommodate dynamic loading and seismic activity, ensuring energy dissipation and effective load transfer [48]. The proactive ground control management systems implemented in Australian coal mines exemplify the structured approach necessary to mitigate ground failure risks, emphasizing the importance of coordinated efforts across all operational levels [49]. Collectively, these components form a cohesive framework that addresses the multifaceted challenges of underground mining.

4.3. Innovative Materials and Technologies

Innovative materials for deep underground mining applications are increasingly focused on addressing the challenges posed by high temperatures, stress, and the need for sustainable practices. One promising development is a new type of thermal insulation shotcrete material that incorporates coal fly ash, tailings, and basalt fiber, achieving a compressive strength of 16.26 MPa and a thermal conductivity of 0.228561 W/(m·k) [50]. This material not only enhances thermal insulation but also utilizes solid waste, contributing to environmental sustainability. Additionally, foam fiber insulation materials have been developed, demonstrating a thermal conductivity of 0.1164 W/(m·K) and effectively reducing heat dissipation in high-temperature environments [51]. These advancements, alongside intelligent mining technologies that enhance operational efficiency and safety, represent a significant shift towards more effective and sustainable deep mining practices [52, 1]

4.4. Monitoring Systems for Ground Behavior Prediction

Recent advancements in technology have significantly enhanced the accuracy of ground behavior prediction in deep underground mining through the integration of artificial intelligence (AI), Internet of Things (IoT), and advanced geospatial techniques. Deep learning applications, particularly using Convolutional Neural Networks (CNN) and Feedforward Neural Networks (FNN), have been employed to model and forecast ground deformations caused by mining activities, achieving high accuracy in predictions (up to 94.23% for accident scenarios) [3, 53, 54]. Additionally, the development of a comprehensive positioning and navigation system utilizing IoT has improved personnel safety by

enabling real-time monitoring of underground conditions, thus facilitating timely evacuations during hazardous situations [55]. Furthermore, innovative computational tools for predicting land subsidence have demonstrated effective forecasting capabilities, with metrics indicating strong correlation and low error rates in predictions [56]. Collectively, these technologies represent a transformative shift towards more precise and proactive management of underground mining environments.

4.5. Remote sensing

Remote sensing has emerged as a transformative tool in ground control systems for underground mining, offering significant advantages over traditional monitoring methods. Conventional techniques, such as visual inspections and geotechnical instrumentation, often yield limited data and can be costly and time-consuming [57]. In contrast, photogrammetric systems provide millimeter-level accuracy and full tensor descriptions of ground movements, enhancing the understanding of deformation and support conditions in complex mining environments. Case studies, such as those conducted at the Lucky Friday mine, demonstrate the effectiveness of remote sensing in monitoring rock mass movements and support corrosion, while also integrating data from various sources for comprehensive analysis [31]. Additionally, advancements in UAV-based remote sensing have further expanded its applicability, enabling efficient 3D mapping and monitoring of large-scale mining areas [58]. Overall, remote sensing represents a robust, efficient, and precise method for enhancing safety and operational efficiency in underground mining ground control systems.

5. Conclusion

In conclusion, the paper underscores the critical role of advanced ground control systems in ensuring safety and efficiency in deep underground mining. The challenges posed by high-stress environments, including time-dependent deformation and weak rock conditions, necessitate the adoption of innovative support strategies. The review indicate that effective ground control not only mitigates risks associated with mining-induced seismic events but also enhances operational reliability and reduces costs. Continuous research and collaboration among industry stakeholders are essential for developing and implementing these advanced technologies. As the mining industry evolves, the integration of scientific insights with practical solutions will be pivotal in addressing the complexities of deep mining, ultimately leading to safer and more productive operations. The advancements discussed in this paper pave the way for future innovations that can further enhance the safety and effectiveness of ground support systems in challenging mining environments

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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