Journal of Mines, Metals and Fuels, *73(7): 2197-2206; 2025. DOI: 10.18311/jmmf/2025/49359*

Print ISSN : 0022-2755

Journal of Mines, Metals and Fuels

Contents available at: *www.informaticsjournals.co.in/index.php/jmmf*

Strata Control Challenges and Monitoring Strategies in Indian Coal Mining under Complex Geotechnical Conditions

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Abstract

Strata control plays a critical role in ensuring the safety and stability of undergr ound coal mining operations, especially in India's increasingly complex geo-mining environments. With the growing shift from conventional to mechanised mining methods, the industry faces intensified challenges related to stress redistribution, reduced pillar stability, and frequent occurrences of roof falls. Strata control is a major challenge in underground coal mining and needs special attention throughout the mining operations. Since ancient times, safety has been given top priority in underground coal mines, where accidents related to strata control, like the fall of the roof and sides, have occurred frequently. These accidents and fatality figures have caused concern for the Indian coal mining industry and have drawn attention to focus on advanced technologies for safe extraction in mines. This paper investigates the primary challenges associated with strata control in underground coal mines and emphasises the importance of real-time monitoring and advanced instrumentation in mitigating these risks. It explores the limitations of traditional support systems, the complexities of predicting rock mass behaviour under dynamic conditions, and the inadequacies of conventional monitoring tools in harsh underground conditions. Furthermore, the study advocates for the adoption of integrated, data-driven approaches involving IoT-enabled sensors, wireless monitoring networks, and AI-based predictive analytics to enhance strata management.

Major Findings: *The findings underscore the urgent need for research and development in durable instrumentation, improved data interpretation systems, and the development of adaptive support technologies to ensure safer, more efficient, and sustainable underground mining practices in India.*

Keywords: *Instrumentation, Strata Behaviour, Strata Control, Strata Monitoring*

1.0 Introduction

Minerals are vital assets for a nation's economic development. Extracting these valuable resources from the Earth's crust efficiently and safely is a key responsibility of the mining industry. With the growing demand for economically significant minerals, mineral-based industries across the globe have witnessed rapid industrial expansion. India, as a developing nation, is focused on boosting its economic growth across all sectors[1]. The mining and quarrying sector contributes approximately 2.2%-2.5% to India's Gross Domestic Product (GDP). Among the primary national energy commodities- coal, crude oil, natural gas, and uranium- coal holds a crucial position due to its extensive use in electricity generation and various industrial applications[2].

Coal is one of India's most abundant energy resources and serves as a primary input for the country's industrial

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and power sectors. Two main methods are employed for coal extraction in India: opencast and underground mining. The choice of method depends on several factors, including the depth and quality of the coal seam and the geological characteristics of the area. With the depletion of opencast reserves and their limited applicability at greater depths, the Indian coal industry is increasingly focusing on underground mining methods. These methods allow access to deeper coal seams, which are often of superior quality and present greater long-term potential. To meet the growing energy demand, the Ministry of Coal, Government of India, is promoting underground mining techniques such as powered roof support, longwall mining and Continuous Miner (CM) technology[3]. These methods are seen as essential for large-scale coal production in the future. Continuous Miner technology, in particular, is well-suited for high-speed coal extraction in bord and pillar workings. Many underground coal mines in India have already adopted CM technology for depillaring operations in panels initially developed by conventional mining methods.

Mechanised depillaring using Continuous Miners requires wider galleries—typically ranging from 5.0 m to 6.5 m—and extraction heights of 3.5 m to 5.0 m. As a result, the width-to-height ratio of coal pillars decreases, leading to a reduced Factor of Safety (FoS)[4]. Depending on the geo-mining conditions, depillaring operations may cause several strata-related issues, such as side spalling, roof falls, floor heaving, or even overriding of the roof[5]. Therefore, it is essential to monitor strata deformation, stress distribution, and the load on supports to assess roof stability and the likelihood of ground failure. Since the primary risk arises from the goaf side, remote instrumentation and monitoring become critical due to poor accessibility in these zones[6]. Underground coal mining demands heightened attention from a safety and engineering perspective, especially under complex geo-mining conditions that continue to make operations increasingly challenging. Strata management is a critical component of any underground coal mining method. A successful mining operation depends heavily on a comprehensive understanding of rock mass behaviour and continuous monitoring during depillaring[7].

Historically, roof and side falls have been the leading causes of accidents in underground coal mines[8].

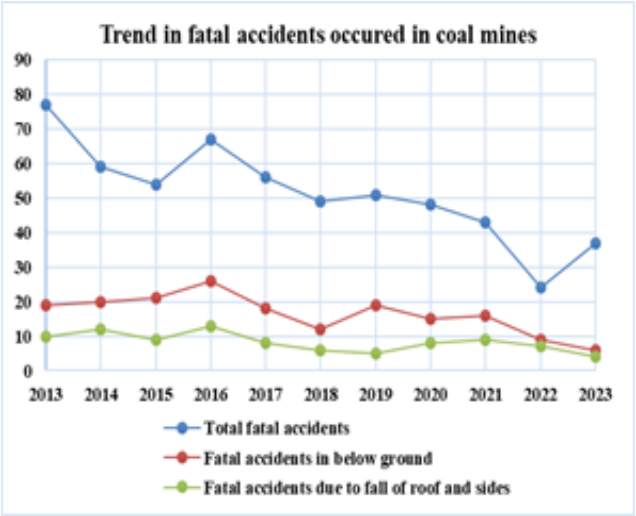


Figure 1. Trend in fatal accidents that occurred in Indian coal mines (2013-2023).

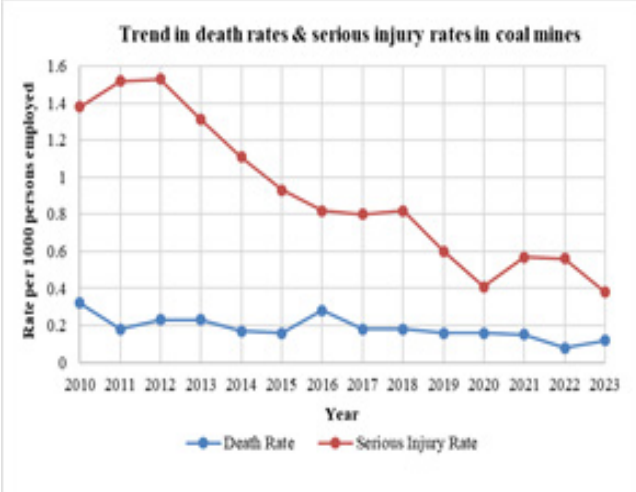


Figure 2. Trend in death rates and serious injury rates in Indian coal mines (2010-2023).

Ensuring safety remains a top priority. Figures 1 and 2 present the trend in fatal accidents that occurred, death rates, and injury rates in Indian coal mines. This shows the importance of strata control and management in underground mines. Effective strata control can be achieved through proper evaluation of rock formations, accurate assessment of the physico-mechanical properties of the host rock, correct determination of required support resistance, appropriate support design, identification of strata anomalies, and the application of suitable

support technologies[9]. However, due to various practical limitations, it is not always feasible to fulfil all these criteria. Thus, reliable instrumentation, real-time monitoring, and appropriate implementation are essential for effective strata management—particularly during the critical depillaring phase[10]. Although several researchers[11-15] have investigated strata control issues in Indian coal mines, this paper aims to explore further the key challenges associated with strata control in underground coal mines. It also discusses potential opportunities for improving safety and performance through systematic monitoring and advanced instrumentation.

2.0 Stress Distribution Around an Opening and Strata Behaviour Mechanism in Underground Mines

In Underground coal mining, whenever an excavation is made, induced stresses are formed due to the excavation. These stresses will redistribute uniformly around the excavation[16]. This uniformity generally occurs because the concentration of vertical stress increases with an increase in the depth of excavation. Excavation or opening made in the underground disturbs the state of original in situ stresses, and the equilibrium state of stresses will be altered, which ultimately results in the loss of support strength of strata exposed due to opening[17]. Consequently, the load carried by the immediate roof/strata is shifted towards both sides of the opening; these loads are also called abutment load or abutment stresses. These abutment stresses are higher than the original stresses. Due to the gravitational force, the immediate roof exposed due to the opening starts sagging, and bed separation occurs in the immediate roof. The rock moves into the opening to adjust itself based on its strength and deformation behaviour. The sagging of strata will come to an end before the roof falls if the nearby roof strata are competent, and the stresses around the excavation/opening eventually come to a new equilibrium. Failure of rock or fracturing in rock mass occurs in hard, brittle rock whenever shear or tangential loads surpass the rock mass strength, Usually, it occurs along the excavation edge, depending on the geometry of the excavation.

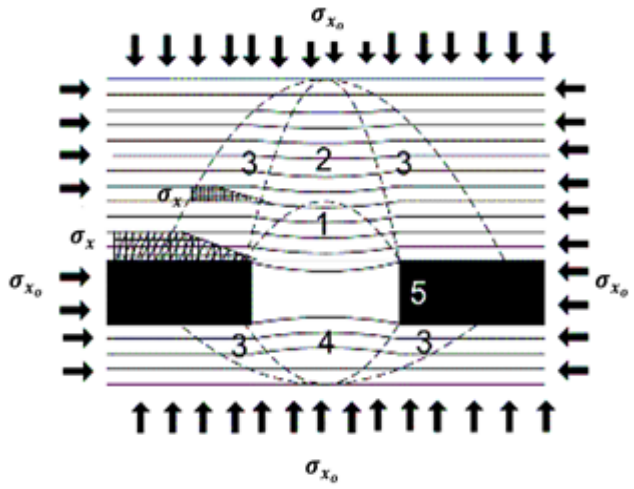


Figure 3. Stress distribution around a rectangular opening in an underground mine.

As discussed earlier, the opening or excavation in the underground creates disturbance in the in situ stresses. This stress disturbance generates five zones (Z1, Z2, Z3, Z4, Z5) around that opening, as shown in the Figure. 3. In these zones, Z1 should be kept stable to uphold the stability of the underground opening. The strata inside the bolting range behave as a solid beam because the roof bolts in this zone cause all the bolted rock mass to deform equally. Spalling can range in severity from slight to excavations collapsing entirely. In brittle rocks, the rock mass may fail with loud noises and result in a rock burst when the rock stresses are very high.

The behaviour of strata in the five zones is as follows:

- Z1- bed separation due to differential sag or clamping
- Z2- Due to gravity roof sags in Z1, Z2 and Sagging of layers can be seen without separation.
- Z3- Vertical and horizontal stresses increase till their unaltered values.
- Z4- Without bed separation, floor heave occurs.
- Z5- Due to the release of horizontal stress, the seam extends toward the excavation.

Various factors influence the strata behaviour mechanism. These include span of opening, profile, magnitude of in situ stresses and induced stresses, and the physico-mechanical properties of rock mass[18]. Understanding the mechanics or behaviour of how the ground moves as a result of mining operations is crucial

before designing effective strata control techniques. In any location, unfavourable geological conditions could further weaken the rock mass's strength. It requires a timely and suitable support system to avoid the roof from collapsing. The depth of the seam, face layout, the way the goaf is treated, and the working thickness of the coal seam are a few mining parameters that have an impact on strata control conditions in underground coal mines.

3.0 Strata Control in Underground Coal Mines

Strata control is a branch of applied rock mechanics that aims to utilise established principles to ensure the safe, site-specific, and sustainable design and operation of underground mining structures according to their intended requirements[19]. Effective strata control is essential for the safe and optimal extraction of mineral reserves in underground mines. The term "strata control" primarily refers to the methods used to maintain the stability of the rock mass surrounding mine openings or excavations, whether operations are ongoing or about to begin.

The main purpose of strata control is to make the strata self-supporting without fail to the possible greatest extent, or if not, to reduce the additional support work required. However, strata control and management within the goaf are usually of no interest. The necessity for strata control may extend into a goaf area for some distance, essentially to the goaf margin. Properties like rock strength (tensile and compressive), modulus of elasticity, Poisson's ratio, etc., as well as details of the expected stress fields under which they will be subjected, are necessary to study strata reactions.

Historically, mining personnel had a limited understanding of how the rock mass behaves around excavations, including the roof, floor, sides, working face, and the strata behind worked-out areas, and how stress redistribution occurs. This lack of knowledge has led to frequent and often serious accidents caused by Roof falls, Significant convergence or relative movement between the roof and floor (including horizontal thrust), Excessive roof flexure in advancing roadways, causing face-front instability, Surface subsidence, which damages surface structures and creates cracks that allow air to reach burning coal seams, Rock bursts triggered by stress concentrations, especially in deep mines, Roof overhangs in goaf areas, leading to overloading of face supports.

Therefore, the study and monitoring of strata behaviour—along with timely interpretation of data—are critical for anticipating and preventing strata or roof failures. These practices significantly enhance both the safety of the mine and the well-being of workers.

3.1 Importance of Strata Monitoring and Instrumentation in Underground Coal Mines

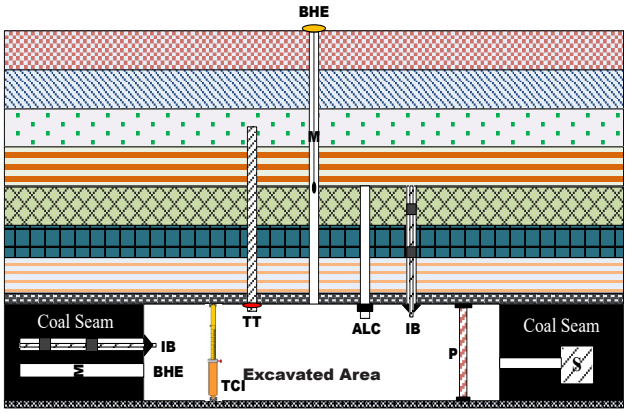
For the survival of underground mining and due to economic, environmental, and safety considerations, it is obvious that underground coal mining needs large-scale mechanisation and automation[20]. Therefore, gradually, underground mines are likely to adopt modern equipment to compete with the arriving global challenges of production, productivity, and safety. The mechanisation and automation of underground mining require matching technology for measurement and monitoring of the strata control parameters. Optimisation of safety and recovery during depillaring involves an extensive and well-planned programme for measurements and control of several strata control parameters through instrumentation and monitoring. Today, along with researchers and scientists, industry professionals should understand the value of underground instrumentation and monitoring for improving production, efficiency, and profitability, as well as the safety of employees and machinery. In a broader context, monitoring may be done for four primary reasons, as stated by Brady and Brown[21] and other researchers:

- To record the regular and changes in the values of geotechnical parameters before the commencement of an engineering project.
- To give an early indication of risk for the development of threshold values or any impending danger for ensuring safe operations.
- To check the validity of design calculations.
- To regulate the execution of ground treatment and remedial works.

For mining, monitoring is generally carried out for all these reasons and also as a preventive measure for ensuring safety. Monitoring for the safety of the mine and workers is a prime responsibility of the engineers who are

involved in mining activity. Engineers should monitor the rock mass response and strata behaviour during mining activity and accordingly should take proper counteractive measures. It is a known fact that rock mass layers are extremely complex media, and it is difficult to predetermine rock mass properties accurately ahead of excavation. Generally, in all mining systems, various characteristics of rock mass response and roof behaviour are predicted by using different models. These models are based on idealisations, assumptions, and some case simplifications.

During a strata control study, the critical parameters to be taken into account for assessing the stability of underground workings are mainly categorised into two types, i.e. constant parameters and variable parameters. Constant parameters are site-specific and include *in-situ* stresses, rock mass classification parameters, physico-mechanical properties, etc. Variable parameters will change as mining operations progress, these parameters must be monitored timely and continuous manner. It includes stress acting on pillars and supports, bed separation, deformation, and the performance and condition of the support system. A strata control study should be planned in such a way that the study should cover the working area, goaf area, and in advance of the face for prediction of roof fall, supports behaviour, roof and floor instability, and goaf behaviour. The instability of the ground is manifested in the form of roof convergence, bed separation, change in stress over the ribs/snooks and pillars, load over the supports, and settlement of the goaf. In order to monitor all these parameters, instruments like Load cells, Convergence indicators, instrumented bolts, Stress meters, Strain bars/meters, borehole extensometers, Dual height tell-tales, Rotary tell-tales, and Auto warning tell-tales are used frequently in underground coal mines. A schematic view of instrumentation for strata monitoring in underground workings is shown in Figure 4.



LEGEND

ALC-Anchored Load Cell **BHE**-Bore Hole Extensometer **IB**-Instrumented Bolt **M**-Magnetic ring anchor **P**-Prop Support **S**-Stress cell **TCI** -Telescopic Convergence Indicator **TT**-Tell Tale Instrument

Figure 4. Common instrumentation for strata /roof monitoring in underground coal mines.

3.2 Challenges in Strata Control

Strata control in underground coal mines presents numerous challenges due to the complex and unpredictable nature of geological conditions. One of the primary challenges to productivity and safety in underground coal mining is the strata control problem, which is associated with inequalities related to variability in rock strength and structure, which can lead to sudden roof falls or pillar/rib failures. According to the geo-mining characteristics of the working area, 33% to 43% of the total time is spent on strata control activities in the underground mining cycle. The presence of faults, joints, and weak or moisture-sensitive strata further complicates stability, often rendering traditional support systems inadequate. High-stress conditions at greater depths can cause floor heave or rock bursts, while mining-induced stress redistribution can lead to localised failures. Additionally, the effectiveness of support systems can be compromised by poor design, corrosion, or improper installation. Monitoring and predicting strata behaviour remains difficult due to limitations in real-time data and the delayed nature of ground movements. These challenges not only pose serious safety risks to miners but also impact productivity and operational efficiency.

Generally, efforts are made to project likely rock behaviour in advance by theoretical analysis and modelling by designing different underground structures like the size of the panel, dimensions of pillars/galleries/ribs, caving of roof, etc., for depillaring of a coal seam. However, the exercises may not yield reliable results

due to the difficulties of incorporating the actual characteristics of the rock mass in a real structure despite theoretical assumptions. For assessing the performance of mining structures, depositional situations at the site are also crucial. Whereas various mine sites possess distinct geomining characteristics, it is commonly believed that the behaviour of underground structures during depillaring is site-specific. This explains why the majority of strata control guidelines are based on empirical formulations developed through the measurement and testing of various factors in different mines. But relatively extensive field measurements of the various strata control parameters are necessary for the designing of empirical formulations, though the field measurements of the strata control parameters during depillaring are very challenging. The hazardous nature of the instrumented site during the final extraction of coal makes the job even more difficult. Under the conditions, specialised sensors/instruments/equipment and skilled manpower, along with a proper instrumentation and monitoring plan, should be an integral part of the study. In fact, the strata control study is going to emerge as the most powerful and reliable method for understanding and predicting the ground behaviour parameters that govern the stability of the workings during hazardous operations like depillaring.

Strata monitoring in coal mines faces several significant challenges that impact the ability to predict and manage ground behaviour effectively. One major issue is the limited availability of real-time data, as traditional monitoring methods—like visual inspections or manual instruments—often fail to provide timely warnings of ground movement. Technological limitations in harsh underground environments, such as dust, humidity, and equipment vibration, can lead to sensor malfunctions or inaccurate readings. Data interpretation is another challenge; complex strata behaviour, especially in geologically disturbed areas, can make it difficult to distinguish between normal and dangerous ground movements. The integration of monitoring systems into existing mine operations can also be problematic due to cost, lack of skilled personnel, or compatibility issues. Furthermore, delayed ground movements—such as time-dependent roof sagging or floor heave—are hard to predict without long-term data analysis. These challenges reduce the effectiveness of monitoring programs and increase the risk of unforeseen ground failures.

3.3 Advancements Required in Strata Control Instrumentation and Monitoring in Underground Coal Mines

Strata control monitoring and instrumentation play a vital role in ensuring the safety of personnel and the stability of underground mining operations. However, existing systems often suffer from limitations such as delayed data acquisition, limited coverage, and insufficient integration with predictive technologies. To address these challenges, research is needed to develop advanced, real-time monitoring systems capable of continuously tracking ground movement, stress distribution, and support performance. Emerging technologies like wireless sensor networks, fibre optic sensing, and Internet of Things (IoT)-enabled devices can significantly enhance the precision and responsiveness of strata monitoring. Figure 5 shows the schematic representation of underground excavation with real-time monitoring with advanced technologies. Furthermore, integrating these systems with artificial intelligence and machine learning algorithms could enable predictive analysis, allowing for early warning of potential ground failures[22]. Research should also focus on improving the durability and adaptability of instruments

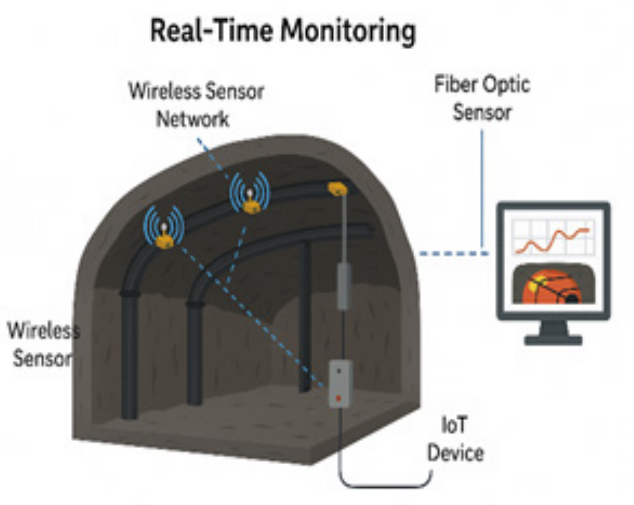


Figure 5. Schematic view of an underground excavation showing real-time monitoring using wireless and fibre optic sensor networks.

to withstand harsh underground environments, as well as developing user-friendly data visualisation tools for better interpretation and timely decision-making. These advancements are critical not only for enhancing miner safety but also for optimising operational efficiency and reducing downtime due to geotechnical hazards.

Despite improvements over the years, several advancements are still needed in strata control instrumentation, as discussed below, to meet modern safety and operational demands.

3.3.1 Real-Time Monitoring and Data Integration

Current instruments often rely on periodic manual readings, which may delay the detection of hazards. Advancements are needed in:

- Real-time monitoring systems that provide continuous data on stress, displacement, and roof movement.
- Wireless sensor networks (WSNs) to transmit data instantly to control rooms.
- Integration with AI and predictive analytics to foresee potential collapses based on data trends.

3.3.2 Durability and Reliability

Instruments used underground are exposed to harsh conditions, including moisture, vibration, and dust. There is a need for:

- Ruggedised and corrosion-resistant sensors.
- Low-maintenance systems with longer operational lifespans.

3.3.3 Automation and Smart Alerts

Automation can significantly enhance response times:

- Automated alert systems that trigger alarms when parameters exceed safety thresholds.
- Remote-controlled or autonomous support systems that can take corrective actions (*e.g.*, bolting or grouting) without human intervention.

3.3.4 Improved Instrument Coverage

Instrumentation needs to cover a wider area with higher spatial resolution:

- Distributed sensing systems using fibre optics or geophones for comprehensive area monitoring.
- Drone and robotic deployments in inaccessible zones.

3.3.5 User-Friendly Interfaces and Data Visualisation

Complex data must be translated into actionable insights:

- Advanced visualisation platforms with 3D models of stress and strata movement.
- User-friendly dashboards for real-time decision-making by engineers and supervisors.

To reduce the risk of roof falls and improve operational efficiency, next-generation strata control instrumentation must focus on real-time, smart, and automated systems. These advancements will play a vital role in transforming underground mining into a safer and more data-driven industry.

4.0 Discussion

The study highlights the critical role of strata control in underground coal mining. The challenges surrounding strata control in underground coal mines, particularly within the Indian context, reflect a complex interplay between geological unpredictability, technological limitations, and operational constraints. As outlined in this study, the increasing adoption of advanced extraction technologies and deeper underground workings has introduced a new dimension of risks, notably related to reduced pillar stability and heightened abutment stresses. While this technology boosts production and efficiency, it also presents significant challenges due to increased exposure of the roof and the consequent stress redistribution around mining excavations. These challenges are exacerbated by variations in geological and geo-mining conditions, which influence the overall stability of underground workings. Despite the mechanisation and modernisation of underground operations, a significant portion of the mining cycle—ranging from 33% to 43% %—is still devoted to strata control activities, underscoring the gravity of the issue.

The stratification of stress zones (Z1 to Z5) around an excavation serves as a valuable conceptual framework for understanding rock mass behaviour. However, actual field scenarios often deviate from theoretical predictions due to the heterogeneity of the rock mass and the complexity

of in-situ stress fields. This disparity underscores the importance of real-time instrumentation and monitoring in supplementing theoretical models. A central theme emerging from the study is the limitation of traditional support systems and monitoring methods under complex geo-mining conditions. Rock mass behaviour remains site-specific and dynamic, often defying predictive models due to the inherent variability in geological conditions. While theoretical and empirical models attempt to forecast strata behaviour, their accuracy is constrained by the difficulty in replicating the true in-situ conditions. This discrepancy often results in unforeseen roof falls, floor heaves, and rib failures, which not only endanger human lives but also hinder productivity.

The current state of instrumentation and monitoring is also insufficient in fully addressing these risks. Challenges such as delayed data acquisition, sensor malfunction due to environmental factors, and difficulties in interpreting complex data patterns limit the responsiveness of strata control systems. This is particularly concerning during the depillaring phase, when ground instability is at its peak and access for manual inspection is restricted. Thus, the integration of advanced instrumentation—such as wireless sensor networks, real-time data systems, and AI-based predictive models—emerges as a critical need.

Moreover, the findings emphasise the importance of holistic strata monitoring strategies that include both constant and variable parameters. A coordinated approach involving robust instrumentation, continuous data monitoring, and real-time interpretation can significantly mitigate ground failure risks. However, the success of such systems relies heavily on the availability of skilled manpower, customised instrumentation plans, and mine-specific risk assessments.

While substantial progress has been made in strata control practices, much remains to be done to meet the evolving demands of underground coal mining in India. While empirical methods have served the industry well, their site-specific limitations and dependency on extensive field measurements limit their applicability across diverse mining scenarios. This necessitates a paradigm shift toward adaptive, real-time strata control systems supported by intelligent instrumentation, data integration, and machine learning-based predictive tools. Future research should focus on developing intelligent, durable, and cost-effective monitoring solutions that are seamlessly integrated into mining operations. Only then can underground coal mining be sustainably scaled while ensuring the highest levels of safety and efficiency.

5.0 Conclusion

Strata control remains a pivotal component in ensuring the safety, efficiency, and sustainability of underground coal mining, particularly in India's increasingly complex geo-mining environments. This study highlights the multifaceted challenges encountered in strata management, ranging from the unpredictability of geological conditions to the limitations of traditional support systems and monitoring instrumentation. As mining operations progress to greater depths and adopt high-production technologies such as Continuous Miners, the associated risks—including roof falls, floor heave, and stress redistribution—become more pronounced, making real-time monitoring and predictive control strategies more essential than ever.

With the increasing shift from conventional to mechanised mining, it is imperative to conduct thorough assessments of stress distribution in and around underground excavations to mitigate the risks of roof falls and ground instability. While theoretical models and empirical guidelines offer valuable initial insights, their effectiveness is often limited by site-specific variability and the challenges of accurately capturing *in situ* rock mass behaviour. Advancing strata control, therefore, necessitates an integrated approach—one that combines field data, robust instrumentation, and adaptive technologies such as AI-driven predictive analytics and IoT-enabled monitoring networks.

Bridging existing gaps in strata management also requires significant investment in durable, reliable sensors, skilled personnel, and user-friendly data visualisation and interpretation tools that support timely, informed decision-making in dynamic mining environments. Despite its challenges, field instrumentation remains indispensable, providing critical real-time insights into strata behaviour and support system performance.

To meet the growing demand for coal while safeguarding miners and infrastructure, the Indian underground coal mining sector must evolve toward a data-driven, technologically advanced framework for strata control. Sustained research, innovation, and

widespread implementation of intelligent monitoring systems will be key to achieving safer, more productive underground operations. There is an urgent need for the mining industry to embrace integrated, data-centric strata control systems that merge traditional rock mechanics with modern sensor technologies and analytics. Future research should focus on enhancing sensor durability, improving remote data transmission capabilities in underground settings, and developing robust algorithms for early warning and decision support. By adopting these innovations, the coal mining industry can advance toward safer, more efficient, and more resilient underground operations.

6.0 Acknowledgement

The authors express their sincere gratitude to the Department of Mining Engineering, National Institute of Technology Raipur, for their valuable support and infrastructure provided throughout this research work.

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