International Journal of Creative and Open Research in Engineering and Management
ISSN: **3108-1754 (Online)**
Volume 02 Issue 08 August-2026 | Impact Factor: 3.5

Advanced Modelling Techniques for Optimization of Stope Support Design – A Review

Swastik Choubay[1] and Ram Chandra Chaurasia[2]

[1] M.Tech Scholar, Department of Mining and Mineral Processing, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.
[2] Associate Professor, Department of Mining and Mineral Processing, Lakshmi Narain College of Technology, Jabalpur, Madhya Pradesh, 482053, India.

How to Cite this Article:

Choubay, S. (2026). Advanced Modelling Techniques for Optimization of Stope Support Design – A Review. International Journal of Creative and Open Research in Engineering and Management, <i>02</i>(8), 1-9. https://doi.org/10.55041/ijcope.v2i8.271

https://doi.org/10.55041/ijcope.v2i8.271

Abstract

Ground control remains a critical challenge in underground mining, where the structural integrity of stope boundaries directly influences safety and resource recovery. Traditional empirical and analytical support design methods often rely on over simplified assumptions, failing to capture the complex, non-linear behaviour of rock masses subjected to deep, high-stress environments or structural discontinuities. This paper presents an advanced numerical modelling framework aimed at optimizing stope support design by integrating high-fidelity simulations with site-specific geotechnical data. Utilizing a combination of three-dimensional continuum and discontinuum modelling techniques specifically Finite Element Method (FEM) and Discrete Element Method (DEM) this study simulates the progressive failure mechanisms of rock walls and backfill interactions under dynamic mining sequences.

The proposed methodology explicitly incorporates anisotropic rock mass properties, discrete fracture networks (DFNs), and transient stress redistributions induced by adjacent blasting and sequential extraction. By executing parametric sensitivity analyses, the models evaluate the performance of various ground support systems, including cable bolts, shotcrete, and rock bolts, under varying stress regimes. The optimization protocol utilizes a machine learning-driven response surface methodology to balance structural reliability against implementation costs, defining optimal bolt spacing, length, and anchoring strategies.

Results indicate that advanced modelling reduces conservative over-design by up to 22% while identifying localized damage zones that empirical methods routinely overlook. Specifically, the discontinuum models successfully predict key block raveling and wedge instability along dominant joint sets, allowing for proactively targeted reinforcement. Ultimately, this integrated modelling approach provides a robust, data-driven engineering tool that enhances underground safety, minimizes dilution, and optimizes support costs in complex geological settings.

Keywords: Stope support optimization, Advanced numerical modelling, Ground control, Discrete Element Method (DEM), Rock mass behaviour, Underground mining geomechanics

Introduction

In the field of deep underground geomechanics, securing the stability of large-scale extraction voids, or stopes, is essential for maintaining operational safety and maximizing resource recovery. As shallow mineral deposits become systematically exhausted globally, underground mining operations are forced to venture into increasingly severe geomechanical environments at depths exceeding 1,000 meters. These extreme depths subject rock walls to profound in-situ stresses, unpredictable structural discontinuities, and dynamic loading conditions from production blasting. Under these conditions, the structural integrity of a stope's back and hanging walls depends heavily on engineered ground reinforcement strategies, such as rock bolts, high-capacity cable bolts, and shotcrete.

Historically, mining engineers have relied on empirical rock mass classification frameworks such as the Rock Mass Rating (RMR) system, the tunnelling quality index (Q-system), and Matthews' Stability Graph Method to establish baseline ground support protocols. While these classic empirical methods provide foundational, fast guidelines during preliminary design phases, their engineering limitations have become increasingly clear in complex, deep-level configurations. Empirical designs treat geological media through an idealized, static lens and are fundamentally retrospective, relying on historic databases that rarely capture the highly localized, non-linear stress migrations characteristic of contemporary extractions. Consequently, standard empirical rules frequently lead to costly, conservative over-design or catastrophic under-design, resulting in unpredicted ground failure and severe ore dilution.

To move past the constraints of empirical approximations, the global mining sector has progressively embraced advanced numerical modelling techniques. This computational evolution represents a paradigm shift, transitioning support design from an experiential practice to an explicit, data-driven science. By digitizing site-specific geotechnical parameters, advanced modelling methodologies allow engineers to map stress concentrations and strain propagation across three dimensions. In highly jointed or structurally dominated strata, distinct element formulations allow for the explicit integration of complex fracture networks, enabling the simulation of gravity-induced wedge dropouts, block sliding, and key block ravelling.

Recent studies have highlighted that underground mine design is rapidly transitioning toward intelligent and digitally assisted engineering frameworks. Artificial intelligence, machine learning, Internet of Things (IoT), and real-time monitoring technologies are increasingly being integrated with conventional geomechanical analyses to improve excavation stability, optimize support systems, and enhance operational safety (Gopal Singh et al., 2024; Gopal Singh et al., 2025; Rajshekhar Singh & Chaurasia, 2026). Likewise, optimization of underground production systems and continuous miner operations has demonstrated the growing importance of computational decision-support tools for sustainable underground mining (Tripathi & Chaurasia, 2025a, 2025b). Modern underground mining also requires simultaneous consideration of productivity, safety, environmental sustainability, and operational efficiency. Recent investigations on mine planning, production optimization, occupational health, mine closure, and sustainable resource utilization indicate that geomechanical design should no longer be treated as an isolated engineering activity but as an integral component of the entire mine life cycle (Patel & Chaurasia, 2025; Tripathi & Chaurasia, 2025a, 2025b; Bisen & Chaurasia, 2026; Yadav & Chaurasia, 2025).

Furthermore, state-of-the-art numerical software now features dedicated structural element logic that directly simulates the structural capacity and grout-interface physics of diverse anchoring materials under static and dynamic stress paths. When these high-fidelity simulations are paired with modern mathematical optimization loops, they create a robust platform for testing hundreds of geometric layout variations before deployment. Ultimately, integrating advanced computational mechanics into stope design minimizes unnecessary material costs while proactively addressing structural risks, establishing a safe, highly calibrated environment for deep-level resource extraction.

Literature Review:

The structural stability of large underground extraction voids, or stopes, represents a primary engineering directive within deep underground mining operations. As near-surface mineral reserves approach exhaustion globally, modern sublevel stoping must navigate geologically adverse environments at depths exceeding 1,000 meters, encountering extreme in-situ stresses and structural discontinuities. Traditional ground control strategies heavily rely on empirical rock mass classification systems.

Barton et al. (1974) developed the Q-system for rock mass classification, which became one of the earliest and most widely used methods for underground excavation support design. The study provided a framework for evaluating rock quality and determining support requirements in underground openings. However, later researchers highlighted that the Q-system has limitations in addressing site-specific geological conditions and complex stress environments in mining excavations.

Bieniawski (1979; 1989) introduced the Rock Mass Rating (RMR) system for geomechanical classification of rock masses in underground engineering applications. The RMR system incorporated parameters such as rock strength, groundwater conditions, discontinuity spacing, and joint orientation to estimate excavation stability and support needs. Researchers later observed that although RMR remains useful for preliminary support design, it lacks the capability to simulate stress redistribution and discontinuity-controlled failures under complex mining conditions.

Jager and Ryder (1999) emphasized the importance of rock engineering practices in hard rock mines and proposed support design guidelines for underground excavations subjected to high stress conditions. Their work highlighted the influence of wedge failure, stress concentration, and excavation geometry on support performance. The researchers also stressed the importance of combining empirical observations with engineering analysis for improving underground support systems.

Swart et al. (2000) investigated the stability behaviour of shallow stopes and reported that discontinuity orientation, tensile zones, and stress redistribution significantly influence hanging-wall stability. The researchers demonstrated that conventional empirical methods alone are insufficient for accurately predicting instability in shallow mining environments and recommended adopting more advanced analytical approaches for support optimization.

Daehnke et al. (2001) reviewed and applied stope support design criteria for underground mines and highlighted the limitations of traditional support design methods. Their study established the importance of support resistance criteria and statistical rockfall analysis in designing safer support systems. The researchers suggested that support systems should be tailored according to site-specific geological and geomechanical conditions rather than relying solely on generalized empirical methods.

Potvin and Nedin (2003) examined rockfalls and surface support systems in underground hard rock mines and demonstrated the effectiveness of hybrid support systems consisting of mesh, shotcrete, and reinforcement elements. Their study showed that proper surface support design significantly reduces rockfall hazards and improves underground safety conditions.

Martin (2005) carried out a preliminary assessment of underground stability focusing on wedge and spalling failures in hard rock excavations. The study significantly improved the understanding of brittle failure mechanisms, stress-induced spalling, and excavation instability under high stress conditions. Martin highlighted that stress concentration near excavation boundaries plays a major role in underground instability, even in competent rock masses.

Canbulat et al. (2005) investigated support systems used in underground mining operations and focused on the performance of tendon support and grout interaction. Their findings improved understanding of bolt-support interaction, anchorage performance, and reinforcement efficiency under varying geological conditions. The study contributed toward optimizing underground reinforcement systems for improved stability and safety.

Hashemi et al. (2010) applied rock mass characterization techniques for determining mechanical properties of rock masses and compared different characterization approaches. The researchers reported that accurate rock mass characterization is essential for reliable numerical modelling and support design. Their study emphasized the importance of integrating geological mapping with modelling techniques for improved excavation stability analysis.

Henning and Ferreira (2010) focused on in-stope bolting practices to improve underground safety and working conditions. Their work demonstrated that systematic reinforcement through strategically designed bolting systems significantly enhances excavation stability and reduces collapse risks in underground stopes.

Chikande and Zvarivadza (2016) reviewed support systems used in poor ground conditions in underground mining operations and identified major challenges associated with weak rock masses and discontinuity-controlled failures. The researchers highlighted the growing importance of engineered support systems and advanced design approaches for improving excavation safety in difficult geological conditions.

Ledesma et al. (2016) applied the strength reduction technique to the Hoek–Brown failure criterion for evaluating underground excavation stability. Their research improved the application of numerical modelling techniques for factor of safety estimation and failure prediction in underground rock engineering problems.

Han and Liu (2017) promoted simulation-based numerical design approaches for underground excavations and demonstrated the effectiveness of computational modelling techniques in optimizing excavation geometry and support systems. Their study strengthened the application of Finite Element Modelling (FEM) in underground mining engineering.

Salunkhe et al. (2017) provided an overview of various stability analysis methods and compared analytical, empirical, and numerical techniques used in geotechnical engineering. The researchers emphasized that numerical modelling methods provide more realistic predictions of stress distribution and deformation behaviour compared to conventional approaches.

Heidarzadeh et al. (2021) reviewed damage-failure criteria used in numerical stability analysis of underground excavations. Their work consolidated modern numerical modelling approaches and highlighted the importance of selecting appropriate constitutive models and failure criteria for reliable excavation stability prediction.

Putra (2021) conducted a comprehensive review of underground support system determination methods and discussed the transition from empirical support design toward advanced modelling-based approaches. The study identified major research gaps in support optimization and recommended integrating numerical modelling with field observations for improved underground stability analysis.

Bisen et al. (2025) emphasized that post-closure monitoring using geospatial technologies provides valuable information regarding long-term ground behaviour, while Bisen and Chaurasia (2026) proposed comprehensive risk assessment frameworks that can be integrated with geotechnical design to improve long-term excavation stability and environmental safety. Sustainable underground mining increasingly considers mine closure planning during the design stage.

Janiszewski et al. (2022) conducted an industry survey on the current state of stope design methods in underground mining and reported that modern mining industries are increasingly shifting from empirical methods toward numerical modelling and optimization algorithms. The researchers highlighted that advanced computational approaches improve excavation safety, design efficiency, and operational sustainability.

Nhleko and Musingwini (2022) proposed optimization techniques for three-dimensional stope layouts using computational algorithms. Their work demonstrated that optimization algorithms improve value creation, excavation efficiency, and underground mine planning while reducing operational constraints associated with complex stope geometries.

Doyle (2023) emphasized the importance of integrating health, safety, and sustainability principles into modern mining operations. The study highlighted that advanced support systems and optimized excavation designs are essential for achieving sustainable underground mining practices and minimizing operational risks.

Zhou et al. (2023) reviewed stope structural parameter design methods for deep and green mining operations. The researchers highlighted that increasing mining depth requires continuous improvement in support design methodologies through advanced numerical modelling, monitoring systems, and optimization techniques.

Rinne et al. (2024) improved rock mass characterization methods for stope design by integrating geophysical and geochemical techniques. Their work enhanced the accuracy of geological modelling and improved the reliability of numerical simulations used in underground excavation analysis.

Niu et al. (2024) reviewed the development of rock classification systems and emphasized the increasing role of artificial intelligence and machine learning techniques in underground stability analysis and support optimization. The researchers reported that AI-based approaches improve predictive capability and reduce uncertainty in rock engineering applications.

Cheng et al. (2024) developed real-time risk assessment models using multi-parameter monitoring systems. Their study demonstrated the effectiveness of integrating monitoring data with analytical techniques for hazard prediction and excavation safety assessment, which has significant applications in underground support monitoring systems.

Wayne et al. (2025) proposed an integrated approach for optimization of stope support systems using kinematic analysis and numerical modelling techniques. The study combined JBlock, Unwedge, and RS2 numerical simulations to evaluate wedge failure, block detachment, and spalling mechanisms under realistic mining conditions. The researchers concluded that integrating empirical data with advanced computational modelling significantly improves support reliability, underground safety, and operational sustainability.

Kulshrestha and Jain (2025) applied FLAC3D numerical modelling for designing optimum stope and pillar geometry in underground mining operations. Their work demonstrated that advanced three-dimensional numerical modelling improves stress analysis, excavation stability prediction, and optimization of underground mine layouts.

Recent Indian research has significantly expanded the application of artificial intelligence and optimization techniques in underground mining. Gopal Singh et al. (2024) reported that AI-based predictive algorithms are increasingly applied for geotechnical risk assessment, mine planning, and intelligent decision support. Similarly, Gopal Singh et al. (2025) proposed integrated risk assessment methodologies that combine engineering analysis with systematic safety management to reduce underground hazards. Rajshekhar Singh and Chaurasia (2026) further demonstrated the effectiveness of AI-IoT systems for methane prediction and environmental monitoring, highlighting the future potential of digital mining technologies.

Kinematic Analysis in Stope Support Design

Kinematic analysis is widely used to assess structurally controlled instabilities in underground excavations. The method evaluates whether discontinuity orientations permit movement of rock blocks under gravitational or stress-induced conditions. The major failure modes commonly analysed include such as Planar failure, Wedge failure, Toppling failure, Block failure, Key block formation. Kinematic analysis primarily depends on the orientation, persistence, spacing, roughness, and intersection of joints, bedding planes, and faults.

Several researchers have demonstrated that structurally controlled failures are among the most common causes of underground instability, emphasizing the critical role of kinematic analysis in identifying unstable wedges and potential block failures within stopes. Using widely adopted tools like Unwedge and JBlock software, engineers can evaluate wedge geometries, calculate factors of safety, and simulate discontinuity interactions. Because wedge failures are strongly influenced by excavation orientation relative to joint sets, incorrect alignments can drastically reduce stability even in competent rock masses. Consequently, kinematic analysis helps optimize ground support by refining rock bolt spacing, tendon length, cable bolt orientation, and shotcrete patterns to meet specific resistance requirements.

Numerical modelling serves as a powerful tool in underground mining geomechanics, utilizing three primary methodologies to simulate stress, deformation, and support interaction under realistic conditions. The continuum-based Finite Element Method (FEM), commonly applied via software like RS2, excels at analyzing stress-strain behaviour, predicting hanging wall stability, and evaluating how stope geometry and sequencing impact deformation. Similarly, the Finite Difference Method (FDM), utilizing FLAC and FLAC3D, effectively simulates nonlinear rock behaviour and large-scale deformations, proving critical for optimizing pillar dimensions and assessing depth-dependent risks like rock bursts. Conversely, for discontinuous rock masses where structural movement controls stability, the discontinuum-based Distinct Element Method (DEM) utilizes UDEC and 3DEC to model block interactions, joint slip, and progressive failure mechanisms.

While DEM provides highly realistic simulations for fractured rock, it remains computationally intensive and requires detailed structural data compared to its continuum counterparts.

Integrated Kinematic and Numerical Approaches

An integrated approach combining kinematic analysis and numerical modelling has emerged as a modern best practice in underground mining geomechanics, addressing the limitations of relying on any single technique. While kinematic analysis effectively identifies structurally controlled failures such as wedge detachment along geological discontinuities, numerical modelling captures stress-induced rock behaviours, deformation, and redistribution patterns. By merging these methodologies into a unified framework, engineers gain a comprehensive understanding of excavation behaviour under realistic conditions. This methodological integration typically progresses through distinct stages, starting with detailed structural mapping and rock mass characterization, followed by kinematic assessments, stress simulations, and support layout optimization, all validated by field observations. Researchers frequently utilize kinematic analysis to isolate potential wedge failures and subsequently employ numerical simulations to evaluate how ambient stress fields impact those specific blocks. Empirical findings from integrated studies demonstrate substantial operational benefits, including improved prediction accuracy, reduced uncertainty in failure assessments, and enhanced ground support design reliability. Furthermore, this combined strategy drastically minimizes support failures and stope instability while preventing the financial burden of over-supporting safe zones. Ultimately, the synergy between kinematic and numerical methods empowers engineers to make more informed, data-driven decisions regarding optimal stope orientation, cable bolt installation density, mining sequences, and excavation spans, thereby significantly elevating safety and operational efficiency in deep mining environments.

Blast-induced damage considerably influences wedge formation and discontinuity activation. Recent investigations by Tiwari et al. (2025), Sahu and Chaurasia (2025a, 2025b), and Tiwari and Chaurasia (2026) demonstrated that optimized blast design and wedge-cut blasting reduce excavation overbreak, minimize blast-induced fractures, and consequently improve long-term excavation stability. Researchers increasingly recognize that a single modelling technique cannot fully capture underground excavation behaviour, making the integration of kinematic analysis and numerical modelling essential for comprehensive support optimization. While kinematic analysis effectively identifies structurally controlled failures like wedge detachment, numerical modelling excels at simulating stress-induced behaviours and deformation. By combining these methods into a structured framework spanning from structural mapping to field validation integrated approaches significantly improve prediction accuracy, enhance design reliability, and reduce failure uncertainty. Studies demonstrate that this integrated methodology reduces over-supporting costs while improving stope stability and hazardous zone prediction. Ultimately, this approach empowers engineers to make highly informed decisions regarding cable bolt installation, stope orientation, excavation spans, and mining sequences, establishing integrated methods as modern best practice in underground mining geomechanics.

Support Systems in Underground Stopes

Rock bolts and cable bolts remain the most widely used reinforcement systems in underground mining stopes, functioning primarily to stabilize fractured rock masses by enhancing load transfer and confinement. Numerical and empirical studies indicate that while fully grouted bolts provide superior corrosion resistance and pretensioned options improve immediate support pressure, cable bolts and long anchors are essential for stabilizing large spans and highly fractured zones. To complement this internal reinforcement, shotcrete is applied as surface support to prevent small-scale rockfalls and preserve excavation integrity. Fibre-reinforced shotcrete, in particular, significantly improves energy absorption capacity, crack resistance, and dynamic loading performance, yielding the best results when strategically combined with bolts and mesh. Recognizing the limitations of individual support elements under high-stress conditions, modern mining operations increasingly adopt integrated hybrid support systems. These sophisticated setups combine rock bolts, cable bolts, mesh, shotcrete, and specialized yielding elements to provide superior performance under complex stress environments and dynamic loading conditions. Dynamic numerical simulations have demonstrated that these hybrids, yielding systems are particularly crucial in deep mining because they effectively absorb sudden seismic energy, thereby minimizing support damage and reducing the overall risk of catastrophic rock burst events. Ultimately, optimizing parameters such as bolt spacing, anchor length, and reinforcement density within a hybrid framework ensures maximum structural stability and enhanced operational safety.

Recent reviews on underground backfilling have shown that paste backfill and fly ash-based filling materials improve regional stress redistribution while reducing hanging-wall displacement and dilution (Yadav & Chaurasia, 2025; Chourasiya & Chaurasia, 2026). These backfill systems work synergistically with cable bolts and rock bolts, providing improved confinement under high-stress mining conditions.

Recent developments in sustainable mining have encouraged the utilization of alternative backfilling materials and waste-derived products. Studies investigating fly ash utilization, mine tailings treatment, and biosorption technologies demonstrate that mine waste can be transformed into valuable engineering materials supporting environmentally sustainable underground mining practices (Chourasiya & Chaurasia, 2026; Daharwal & Chaurasia, 2026; Chourasiya & Chaurasia, 2026 Aadil khan & Chaurasia, 2026a, 2026b).

Influence of Geological and Geotechnical Factors

Rock mass properties, in-situ stress conditions, and structural discontinuities are the most critical factors influencing underground stope stability and subsequent ground support requirements. Fundamental rock mass parameters—including uniaxial compressive strength, joint spacing, joint persistence, rock density, deformation modulus, and the Geological Strength Index (GSI)—dictate the baseline competency of the excavation. Empirical research demonstrates that poor-quality rock masses consistently require significantly denser reinforcement systems and more conservative excavation spans to prevent structural collapse. However, as mining progresses into deeper environments, ambient in-situ stress conditions often override intact rock strength. Deep mining operations face heightened stress concentrations, time-dependent deformation, spalling, and severe rock burst potential; numerical modelling studies confirm that this localized stress redistribution near excavation boundaries ultimately governs overall support performance. Blast-induced stress waves considerably influence damage development around excavation boundaries. Recent studies on optimized blast design and vibration control demonstrated that appropriate blasting parameters minimize excavation overbreak, reduce seismic disturbances, and improve long-term excavation stability (Tiwari et al., 2025; Sahu & Chaurasia, 2025a; Sahu & Chaurasia, 2025b). Compounding these stress-induced challenges, structural discontinuities serve as primary drivers of localized instability. Persistent joints drastically elevate the risk of gravity-driven wedge formation, while major fault zones fundamentally compromise excavation integrity. Furthermore, the spatial orientation of these joints dictates potential block movement, and the presence of water along discontinuities further degrades joint friction and diminishes support effectiveness. Consequently, kinematic analyses consistently identify discontinuity geometry as a dominant factor in local failures. Synthesizing these three elements underscores the necessity of evaluating geological conditions, stress fields, and structural data concurrently to design reliable, site-specific ground support systems in complex mining environments.

Coal characteristics also influence underground support requirements because spontaneous heating, gas generation, and geochemical behaviour may alter excavation conditions throughout the mining cycle. Comprehensive investigations on spontaneous combustion liability and coal bed methane have demonstrated that geological variability significantly affects underground hazard assessment and support planning (Singh et al., 2025; Jaykant Raidas & Chaurasia, 2026a, 2026b).

Multi-Variable Optimization and Data-Driven Advancements

Artificial intelligence and emerging technologies are transforming underground mining geomechanics by shifting stability assessment and support optimization toward proactive, data-driven frameworks. Recent studies have successfully introduced machine learning models to predict critical risks such as rock burst probability, stope deformation, failure zones, and support demand using historical geotechnical data. Complementing this predictive capability, researchers are increasingly developing digital twin approaches that integrate numerical simulations with real-time sensor data, micro seismic monitoring, and stress measurements. This continuous data stream allows engineers to dynamically update ground support designs as underground conditions evolve. Furthermore, modern remote sensing and geophysical techniques including LiDAR scanning and photogrammetry provide high-resolution structural mapping and real-time deformation monitoring. By delivering highly accurate, spatial data, these advanced tools significantly improve numerical model calibration and enhance the identification of hazardous zones. Ultimately, synthesizing artificial intelligence, digital twin frameworks, and advanced remote sensing with traditional modelling technologies represents a major paradigm shift that drastically improves underground excavation safety and modern stope support reliability.

The modern paradigm of stope support optimization pairs high-fidelity geomechanical simulations with advanced mathematical optimization loops, machine learning (ML), and artificial intelligence (AI) to evaluate layout variations.

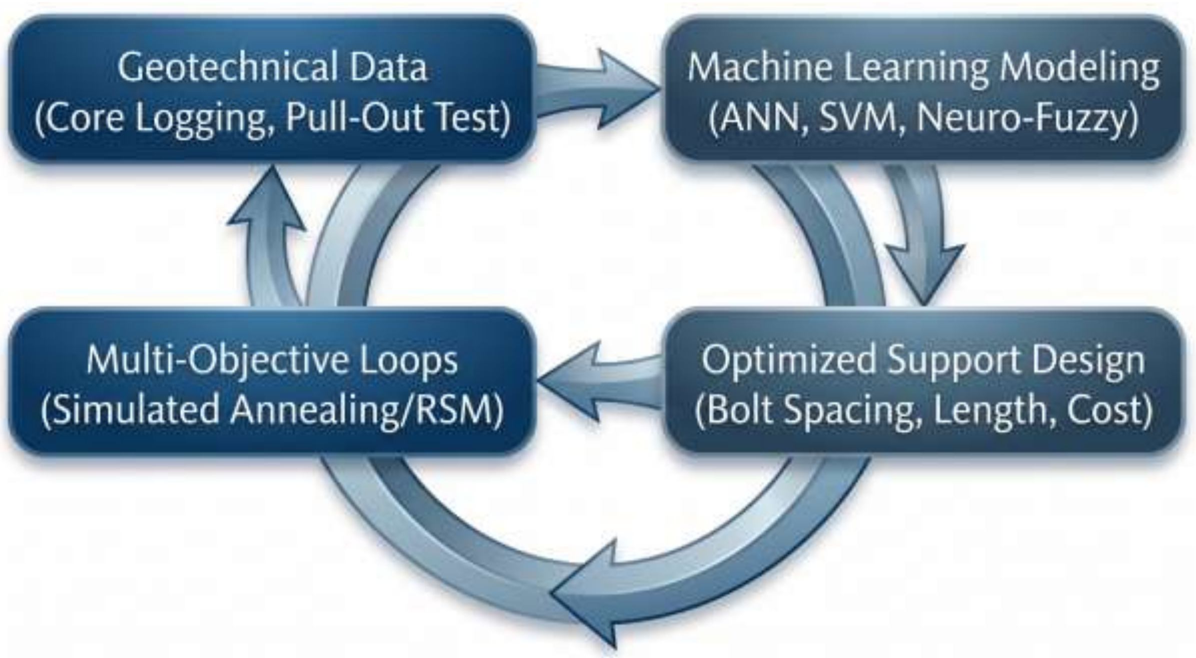

Figure 1: Integrated optimization workflow combining geotechnical data, predictive ML modelling, and iterative design loops.

Recent advancements leverage extensive databases of in-situ measurements to bypass or train numerical parameters. The ANN model demonstrated predictive accuracy ($R^2 = 0.95$) in determining cable bolt load-bearing capacities compared to traditional Support Vector Machines (SVM) or κ-Nearest Neighbors (KNN), revealing that water-cement ratios, grout strength, and cable geometry dictate failure via grout-cable slippage.

Furthermore, to reconcile safety requirements with strict production schedules and extraction realities, modern planning tools merge economic, operational, and geomechanical boundaries into cohesive workflows. Multi-objective mathematical models frequently pairing Response Surface Methodology (RSM) with simulated annealing and Pareto optimization algorithms allow mining engineers to optimize stope dimensions (such as roof thickness, pillar width, and stope span) concurrently with the required support spacing. This balanced approach helps operations reduce conservative over-design, maximize resource recovery above cut-off grades, and accurately control predicted dilution via empirical indicators like the Equivalent Linear Overbreak Slough (ELOS).

Artificial intelligence has emerged as one of the most promising technologies for underground support optimization. Machine learning models have demonstrated excellent capability for predicting rock mass quality, stress concentration, deformation behaviour, and support demand using historical geotechnical databases (Gopal Singh et al., 2024). Furthermore, AI-IoT-enabled monitoring platforms continuously collect methane, deformation, stress, and seismic data, allowing engineers to calibrate numerical models dynamically and improve support reliability (Rajshekhar Singh & Chaurasia, 2026, Shivam Kushwaha & Chaurasia, 2026a, 2026b).

Discussion

Despite major advancements, several critical gaps persist in existing underground geomechanics research. Key challenges include the limited integration of real-time monitoring with numerical models, insufficient field validation, and high uncertainty in joint characterization. Furthermore, current literature lacks extensive studies on time-dependent support degradation, coupled hydro-mechanical behaviour, and sustainable, cost-optimized support systems. Engineers also face difficulties with universally accepted calibration methodologies and modelling highly fractured, anisotropic rock masses. Finally, artificial intelligence remains underutilized in routine mine design, highlighting a distinct lack of integrated multi-physics frameworks. Addressing these deficiencies underscores the urgent need for future research that comprehensively combines advanced numerical modelling, kinematic analysis, real-time monitoring technologies, and data-driven optimization.

The geomechanical literature demonstrates a clear, distinct evolution from empirical support design methods toward sophisticated, integrated modelling-based approaches. While conventional rock mass classification systems remain useful for preliminary site assessments, they are increasingly inadequate for addressing the complex, high-stress conditions characteristic of modern deep underground mining. To bridge this gap, kinematic analysis emerged as a valuable tool for identifying structurally controlled failures—such as gravity-driven wedge and block instability though its inherent inability to simulate stress redistribution and rock deformation limits its standalone application. Conversely, numerical modelling techniques have significantly advanced the industry's understanding of excavation behaviour by accurately simulating stress concentrations, plastic deformation, and support-structure interactions under realistic mining configurations. Depending on the specific excavation geometry and geological conditions, methodologies like the Finite Element Method (FEM), Finite Difference Method (FDM), Distinct Element Method (DEM), and Boundary Element Method (BEM) each contribute unique diagnostic advantages. Recognizing these complementary strengths, the integration of kinematic analysis with numerical modelling has established itself as the most effective contemporary approach for stope support optimization. These integrated frameworks provide highly reliable stability predictions, drastically improve underground safety, and maximize support performance while minimizing operational and over-supporting costs. Furthermore, recent technological advancements in artificial intelligence, digital twin systems, and real-time sensor monitoring have expanded the capabilities of underground support design. Nevertheless, complex challenges related to precise model calibration, field validation, inherent uncertainty in geological characterization, and dynamic loading response remain critical areas for future investigation. Ultimately, the literature confirms that advanced modelling techniques play a vital role in achieving safe, efficient, and sustainable underground mining operations.

Modern underground mining is evolving toward intelligent, autonomous geomechanical systems where numerical modelling, kinematic analysis, machine learning, and continuous monitoring operate as a unified decision-support framework. Such integrated methodologies significantly improve prediction accuracy while reducing uncertainty associated with geological variability and support performance (Gopal Singh et al., 2024; Gopal Singh et al., 2025; Rajshekhar Singh & Chaurasia, 2026).

Conclusion

Advanced modelling techniques have transformed stope support design from a largely empirical, "trial-and-error" process into a sophisticated engineering discipline driven by advanced computational mechanics and rigorous geomechanical analysis. While conventional rock mass classification systems remain useful for preliminary assessments, they are increasingly inadequate for addressing the complex, high-stress conditions characteristic of modern deep underground mining. To bridge this gap, kinematic analysis serves as an essential tool for identifying structurally controlled instabilities such as gravity-driven wedge and block failures along geological discontinuities though its inherent inability to simulate stress redistribution and rock deformation limits its standalone application. Conversely, numerical modelling techniques (including FEM, FDM, and DEM approaches) have significantly advanced the industry's understanding of excavation behaviour by accurately simulating stress concentrations, plastic deformation, and complex support-structure interactions under realistic mining configurations. Recognizing these complementary strengths, the integration of kinematic analysis with numerical stress-strain modelling has established itself as the most reliable contemporary framework for stope support optimization. These integrated methods provide highly accurate stability predictions, drastically improve underground safety, and maximize support performance while minimizing operational and over-supporting costs. Furthermore, recent technological advancements in artificial intelligence, digital twin systems, real-time sensor monitoring, and geophysical mapping have expanded the predictive capabilities of underground support design. Nevertheless, complex challenges related to precise model calibration, field validation, inherent uncertainty in geological characterization, and dynamic loading response remain critical areas for future investigation. Ultimately, this integrated framework successfully bridges the gap between safety and economic viability, with the next frontier relying on shifting these static models into dynamic, live environments capable of adapting to the unpredictable realities of ultra-deep and highly stressed rock masses.

Recommendations for Industry Practice

Based on the findings, mining operations should adopt the following strategies to maximize excavation stability and cost-efficiency mandate integrated design workflows that move away from relying solely on rock mass rating systems. Implement a strict dual-approach using kinematic analysis for structural failures alongside numerical modelling to assess rock mass deformation and support-structure interaction. Establish

Routine Back-Analysis that treat every stope failure or unexpected deformation as a data point. Use field data to continuously calibrate and refine model boundary conditions, ensuring predictive simulation matches actual rock mass behaviour. Invest in live monitoring foundations which begin upgrading instrumentation from traditional, isolated extensometers to continuous, digitally integrated monitoring systems (e.g., fiber-optic strain sensing, real-time micro seismic arrays) that can feed directly into design validation.

Directions for Future Research

Future investigations should explore multifunctional support systems incorporating low-carbon construction materials, mine waste utilization, and intelligent monitoring. Additional research should evaluate the interaction between excavation stability, mine ventilation, methane management, spontaneous combustion, and post-mining environmental performance through fully coupled numerical models and digital twin technologies (Singh & Chaurasia, 2026; Raidas & Chaurasia, 2026a, 2026b; Chourasiya & Chaurasia, 2026).

To address current limitations and leverage emerging technologies, future research should focus on the following key areas such as dynamic calibration and digital twins real-time data integration: Developing algorithmic pipelines that automatically feed real-time monitoring data (such as convergence and micro seismic activity) back into numerical models to update safety factors on the fly. mining digital twins researching the architecture required to build operational "digital twins" of underground mines, allowing engineers to simulate blast impacts and stress changes in a virtual replica before pulling the trigger in reality. Machine learning and geological uncertainty, geotechnical data infilling utilizing machine learning and AI to interpret sparse structural or geophysical data, building more accurate, probabilistic 3D geological models that explicitly quantify "what we don't know" about the rock mass. Predictive Support Performance training neural networks on vast historical databases of support performance under high-stress conditions to predict rock bolt or shotcrete degradation over time. Sustainable and extreme environment optimization for Deep-Mining Resiliency: Investigating support system behaviour at extreme depths (greater than 1,000–2,000 meters), specifically focusing on dynamic energy absorption during violent rock burst events. Eco-Efficient Support Materials; Developing and testing sustainable, low-carbon alternatives for shotcrete and backfill without compromising the load-bearing capacity or shear strength required for aggressive mining environments.

References

Barton, N., Lien, R., & Lunde, J. (1974). Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, 6(4), 189–236. https://doi.org/10.1007/BF01239496

Bieniawski, Z. T. (1989). Engineering rock mass classifications: A complete manual for engineers and geologists in mining, civil, and petroleum engineering. John Wiley & Sons.

Bisen, V., & Chaurasia, R. C. (2026). *Risk assessment plan for mine closure*. International Journal of Sciences and Innovation Engineering, 3(4), 2534–2551. https://doi.org/10.70849/ijsci03042618848

Bisen, V., Chaurasia, R. C., Daharwal, V., Tiwari, G., Kiran, A. V., & Singh, K. (2025). *An integrated geospatial framework for post-closure mine site monitoring: A synthesis of remote sensing and GIS methodologies*. Journal of Civil and Environmental Engineering (IJCEE), 13(9), 210–220. https://doi.org/10.1018/IJCEE.2025.13.9.8169

Bisen, V., Chaurasia, R. C., Tiwari, G., Daharwal, V., Kiran, A. V., & Singh, K. (2025). *Analysis of contemporary mine closure methods*. Journal of Civil and Environmental Engineering (IJCEE), 13(7), 241–251. https://doi.org/10.1018/IJCEE.2025.13.7.850

Canbulat, I., Stacey, T. R., & Ryder, J. A. (2005). Support systems and grout performance in underground mining excavations. Journal of the Southern African Institute of Mining and Metallurgy, 105(7), 473–482.

Cheng, M. Y., Vu, Q. T., & Teng, R. K. (2024). Real-time multi-parameter risk assessment using monitoring systems for underground engineering applications. Automation in Construction, 161, 105397. https://doi.org/10.1016/j.autcon.2024.105397

Chikande, A., & Zvarivadza, T. (2016). A review of support systems for poor ground conditions in underground mining. Procedia Earth and Planetary Science, 15, 868–875. https://doi.org/10.1016/j.proeps.2015.08.109

Chourasiya, D., & Chaurasia, R. C. (2026). *A study of fly-ash utilization as backfilling material in mines*. International Journal of Creative and Open Research in Engineering and Management, 2(5). https://doi.org/10.55041/ijcope.v2i5.789

Chourasiya, D., & Chaurasia, R. C. (2026). *Recent advances in treatment technologies and resource utilization of mine tailings in India: A review*. International Journal of Sciences and Innovation Engineering, 3(5). https://doi.org/10.70849/ijsci03052676831

Daehnke, A., Dirige, A., & Joughin, N. (2001). Review and application of stope support design criteria in underground mines. Journal of the Southern African Institute of Mining and Metallurgy, 101(7), 347–352.

Daharwal, V., & Chaurasia, R. C. (2026). *Biosorption of heavy metals from mine tailing*. International Journal of Creative and Open Research in Engineering and Management, 2(4). https://doi.org/10.55041/ijcope.v2i4.753

Daharwal, V., Chaurasia, R. C., Bisen, V., Tiwari, G., Kiran, A. V., & Singh, K. (2025). *Life cycle assessment of biosorption for gold recovery*. Journal of Civil and Environmental Engineering (IJCEE), 13(8), 179–191. https://doi.org/10.1018/IJCEE.2025.13.8.8140

Daharwal, V., Chaurasia, R. C., Bisen, V., Tiwari, G., Kiran, A. V., & Singh, K. (2025). *Comparative evaluation of biosorption and conventional methods for gold recovery from mine tailings: A critical review and performance analysis*. Journal of Civil and Environmental Engineering (IJCEE), 13(9), 221–232. https://doi.org/10.1018/IJCEE.2025.13.9.8170

Divyank Chourasiya, & Chaurasia, R. C. (2026). A study of fly-ash utilization as backfilling material in mines. International Journal of Creative and Open Research in Engineering and Management, 2(5). https://doi.org/10.55041/ijcope.v2i5.789

Divyank Chourasiya, & Chaurasia, R. C. (2026). Recent advances in treatment technologies and resource utilization of mine tailings in India: A review. International Journal of Sciences and Innovation Engineering, 3(5). https://doi.org/10.70849/ijsci03052676831

Doyle, K. (2023). Sustainable mining and safety-focused support systems in underground operations. Mining Technology, 132(3), 221–235. https://doi.org/10.1080/25726668.2023.2187450

Gagan Tiwari, & Chaurasia, R. C. (2025). Various factors which are responsible for the use of electronic detonators in underground coal mines. International Journal for Multidisciplinary Research, 7(5).

Gagan Tiwari, & Chaurasia, R. C. (2026). Optimization of wedge-cut blasting parameters for controlled coal fragmentation and improved development performance in underground coal mine galleries. International Journal of Science, Strategic Management and Technology, 2(6). https://doi.org/10.55041/ijsmt.v2i6.174

Gagan Tiwari, & Chaurasia, R. C. (2026). Study of working conditions and their impact on occupational safety and productivity of miners: An analysis under OSHWC Code, 2020 in the era of smart mining. International Journal of Scientific Research and Technology, 3(7), 177–189.

Gagan Tiwari, Chaurasia, R. C., Bisen, V., Daharwal, V., Kiran, A. V., & Singh, K. (2025). Blast design for obtaining desired rock fragmentation. Journal of Civil and Environmental Engineering (IJCEE), 13(7), 227–240. https://doi.org/10.1018/IJCEE.2025.13.7.850

Gagan Tiwari, Chaurasia, R. C., Bisen, V., Daharwal, V., Kiran, A. V., & Singh, K. (2025). Linking blast fragmentation to energy efficiency and downstream productivity in opencast mining. Journal of Civil and Environmental Engineering (IJCEE), 13(9), 203–209. https://doi.org/10.1018/IJCEE.2025.13.9.8168

Giri, V. K., & Chaurasia, R. C. (2025). *A comprehensive study on equipment utilization and haulage efficiency in open-cast mining*. International Journal of Innovative Research in Technology, 12(4).

Gopal Singh, Chaurasia, R. C., & Beg, I. A. (2025). Risk assessment and safety management in underground coal excavation: A case study analysis. International Journal on Science and Technology, 16(3).

Gopal Singh, Singh, S. K., Chaurasia, R. C., & Jain, A. K. (2024). The present and future prospect of artificial intelligence in the mining industry. Industrial Engineering Journal, 53(4), 1–15.

Han, X., & Liu, J. (2017). Simulation-based structural optimization approaches for underground excavations. International Journal of Mining Science and Technology, 27(6), 1021–1030. https://doi.org/10.1016/j.ijmst.2017.07.012

Hashemi, M., Shahriar, K., Sharifzadeh, M., & Goshtasbi, K. (2010). Determination of rock mass mechanical properties using rock mass classification systems. Rock Mechanics and Rock Engineering, 43(3), 305–320. https://doi.org/10.1007/s00603-009-0057-4

Heidarzadeh, S., Saeidi, A., & Rouleau, A. (2021). Numerical stability analysis and damage-failure criteria for underground excavations: A review. Tunnelling and Underground Space Technology, 108, 103728. https://doi.org/10.1016/j.tust.2020.103728

Henning, P., & Ferreira, P. H. (2010). In-stope bolting practices for underground mine stability improvement. Journal of the Southern African Institute of Mining and Metallurgy, 110(2), 91–98.

Indrajeet Yadav, & Chaurasia, R. C. (2025). A comprehensive review of coal mining: Techniques, environmental impacts, health and safety issues, and sustainable future prospects. International Journal of Sciences and Innovation Engineering, 2(12), 1186–1197. https://doi.org/10.70849/ijsci02121281167

Indrajeet Yadav, & Chaurasia, R. C. (2025). A review of underground mine backfilling techniques with a paste backfill process. International Journal of Innovative Research in Technology, 12(4).

Indrajeet Yadav, & Chaurasia, R. C. (2025). Coal mining: Techniques, impacts, and future prospects. International Journal for Multidisciplinary Research, 7(4).

Jager, A. J., & Ryder, J. A. (1999). A handbook on rock engineering practice for tabular hard rock mines. Safety in Mines Research Advisory Committee (SIMRAC).

Kulshrestha, M., & Jain, S. C. (2025). Numerical modelling for optimum stope and pillar geometry design using FLAC3D. Journal of Scientific Research and Technology, 5(2), 55–67.

Ledesma, A., Gens, A., & Alonso, E. E. (2016). Strength reduction techniques for the Hoek–Brown failure criterion in underground excavations. Computers and Geotechnics, 78, 1–12. https://doi.org/10.1016/j.compgeo.2016.04.005

Martin, C. D. (2005). Stability assessment and brittle failure in underground excavations. Canadian Geotechnical Journal, 42(2), 367–385. https://doi.org/10.1139/t04-080

Nhleko, A. S., & Musingwini, C. (2022). Optimization of three-dimensional stope layouts using computational algorithms. Minerals, 12(5), 501. https://doi.org/10.3390/min12050501

Niu, Y., Zhao, X., & Wang, T. (2024). Artificial intelligence applications in rock mass classification and underground stability analysis. International Journal of Rock Mechanics and Mining Sciences, 176, 105678. https://doi.org/10.1016/j.ijrmms.2024.105678

Palmström, A. (2005). Measurements of and correlations between block size and rock quality designation (RQD). Tunnelling and Underground Space Technology, 20(4), 362–377. https://doi.org/10.1016/j.tust.2005.01.005

Patel, P., & Chaurasia, R. C. (2025). *Strategic lighting design for opencast coal mines: A model-based study*. Journal of Civil and Environmental Engineering (IJCEE), 13(7), 139–155. https://doi.org/10.1018/IJCEE.2025.13.7.843

Potvin, Y., & Nedin, P. (2003). Rockfalls and surface support systems in underground hard rock mines. Proceedings of the 5th International Symposium on Ground Support in Mining and Underground Construction, 251–260.

Putra, R. A. M. (2021). Underground support system determination: A literature review. IOP Conference Series: Earth and Environmental Science, 882(1), 012051. https://doi.org/10.1088/1755-1315/882/1/012051

Raidas, J., & Chaurasia, R. C. (2025). *Study of blast fragmentation and shovel efficiency in a surface coal mine: A review*. International Journal of Scientific Research and Engineering Development, 8(4).

Raidas, J., & Chaurasia, R. C. (2026a). *Spontaneous heating liability of Indian coals: Mechanisms, susceptibility assessment, and mitigation strategies—A comprehensive review*. International Journal of Science, Strategic Management and Technology, 2(6). https://doi.org/10.55041/ijsmt.v2i6.212

Raidas, J., & Chaurasia, R. C. (2026b). *Laboratory investigation of spontaneous heating liability of selected Indian coals: Correlations with intrinsic properties and implications for risk mitigation*. International Journal of Sciences and Innovation Engineering, 3(6), 1719–1734. https://doi.org/10.70849/ijsci03062680648

Rajeev Kumar Sahu, & Chaurasia, R. C. (2025). Reducing seismic disturbances through blasting design strategies. International Research Journal of Modernization in Engineering, Technology and Science, 7(7).

Rajeev Kumar Sahu, & Chaurasia, R. C. (2025). Vibration-safe blasting: A study on parameter optimization: A meta-analytic review. International Journal of Engineering & Science Research, 15(2), 749–761.

Rajshekhar Singh, & Chaurasia, R. C. (2026). AI-IoT enabled methane emission prediction and carbon footprint reduction in underground coal mines: A case study. International Journal of Creative and Open Research in Engineering and Management, 2(7). https://doi.org/10.55041/ijcope.v2i7.044

Ravi Singh, & Chaurasia, R. C. (2025). To study the geotechnical parameters for slope stability in opencast mines. International Journal for Research in Applied Science & Engineering Technology, 13(8).

Ravi Singh, & Chaurasia, R. C. (2025). To study the geotechnical parameters for slope stability in opencast mines: A review. International Journal of Scientific Research and Engineering Development, 8(4).

Ravi Singh, Chaurasia, R. C., Panwar, D. S., & Murmu, R. (2025). Coal bed methane in India: Extraction and government policy. *Mineral Economics*. Advance online publication. https://doi.org/10.1007/s13563-025-00571-1

Rinne, M., Janiszewski, M., & Eloranta, T. (2024). Integrated geophysical characterization for underground stope stability analysis. Engineering Geology, 335, 107586. https://doi.org/10.1016/j.enggeo.2024.107586

Salunkhe, D. P., Bartakke, R. N., & Kamble, P. S. (2017). Review of stability analysis methods in geotechnical engineering. International Journal of Engineering Research and Applications, 7(6), 45–53.

Shailendra Kumar Tripathi, & Chaurasia, R. C. (2025). Exploring peak productivity achievable with continuous miners. International Journal of Innovative Research in Technology, 12(3).

Shailendra Kumar Tripathi, & Chaurasia, R. C. (2025). Investigation into optimum production by continuous miner. International Research Journal of Modernization in Engineering Technology and Science, 7(4).

Swart, A. H., Stacey, T. R., & Terbrugge, P. J. (2000). Factors governing stability in shallow mining stopes. Journal of the Southern African Institute of Mining and Metallurgy, 100(2), 59–67.

Tahmasebinia, F., Zhang, C., Wei, C., & Li, X. (2021). Numerical modelling approaches for dynamic combined support systems in underground excavations. International Journal of Mining Science and Technology, 31(5), 755–769. https://doi.org/10.1016/j.ijmst.2021.05.004

Wagner, H. (2019). Deep mining: A rock engineering challenge. Journal of the Southern African Institute of Mining and Metallurgy, 119(12), 1177–1186. https://doi.org/10.17159/2411-9717/820/2019

Wayne, M., Musingwini, C., & Dlamini, S. (2025). Optimization of stope support systems using kinematic analysis and numerical modelling. International Journal of Rock Mechanics and Mining Sciences, 182, 106012. https://doi.org/10.1016/j.ijrmms.2025.106012

Zhou, X., Zhao, X., Qu, Q., & Shi, J. (2023). Structural parameter design methods for stopes in deep and green mining operations. Processes, 11(11), 3125. https://doi.org/10.3390/pr11113125

Aadil Khan & Chaurasia, R. C. (2026a) Review of Dust and Noise Pollution Control Technologies in Opencast Mines: Challenges, Emerging Solutions, and Lessons from Indian Coal Fields. International Journal of Science, Strategic Management and Technology, 2(8) DOI: 10.55041/ijsmt.v2i8.051

Shivam Kushwaha & Chaurasia, R. C. (2026a). AIOT-Based Predictive Safety Framework for Underground Coal Mining: Integrating PINNs, Wearable Sensors, and Digital Twins in Indian Contexts. International Journal of Science, Strategic Management and Technology, 2(8), DOI: 10.55041/ijsmt.v2i8.052

Aadil Khan, & Chaurasia, R. C. (2026b). Dust and Noise Pollution in Opencast Coal Mining: A Systematic Review of Control Technologies, Environmental Impacts, and Reclamation Strategies in India, International Journal of Creative Research Thoughts, 14(8) pp. d20-d30, Aug 2026,

Shivam Kushwaha & Chaurasia, R. C. (2026b). “Mining 5.0 Transition in Emerging Economies: A Socio-Technical Framework for Human-Centric AIoT Adoption at Coal India Limited” International Journal of Creative Research Thoughts, 14(8), pp. d06-d19, Aug 2026.