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SAFETY AND MANAGEMENT ENGINEERING IN THE GLOBAL MINING SECTOR: A REVIEW OF MODERN STRATEGIES AND INTERNATIONAL COMPARISONS

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ABSTRACT

The global mining industry continues to rank among the most hazardous occupational sectors, with persistent high-consequence risks from ground control failures, gas explosions, and human–system interactions, particularly as operations extend beyond 1,000 m depth. This scoping review synthesizes regulatory, technological, and organizational advances in mining safety and management engineering from 2015 to 2025, with emphasis on the accelerating transition toward risk-based “Duty of Care” frameworks and Safety 4.0/5.0 technologies. Drawing on peer-reviewed literature, official fatality statistics, and national regulatory documents from Australia, China, the United States, South Africa, and Canada, we compare the effectiveness of prescriptive versus risk-based regulatory regimes and evaluate the maturity of key engineering controls, including energy-absorbing ground support, real-time IoT hazard monitoring, digital twins, and AI-driven predictive risk models. Results show that jurisdictions adopting mature risk-based legislation (notably Australia) have achieved the lowest fatality rates, while China has recorded substantial absolute reductions through large-scale mechanization and dual-prevention mechanisms supported by big data. The United States retains a predominantly prescriptive model under MSHA yet is rapidly incorporating predictive analytics. Persistent challenges include under-reporting in certain regions, limited integration of behavioral and organizational factors, and escalating geotechnical complexity in ultra-deep mining. The review identifies critical research and implementation gaps and proposes an integrated multi-layered framework that combines adaptive risk-based regulation, high-reliability engineering controls, and human-centered organizational systems to accelerate progress toward zero harm.

Keywords: Mining Safety; Risk-Based Regulation; Digital Twin; Ground Control; Internet of Things; Comparative Analysis.

1 INTRODUCTION

Mining remains one of the most hazardous industrial sectors globally. Despite decades of regulatory and technological progress, the industry continues to record high rates of fatal and permanently disabling injuries, particularly from rockbursts, roof falls, gas outbursts, and mobile equipment incidents. As operations increasingly extend beyond 1,000 m, and in extreme cases approach 4,000 m, the magnitude of high-stress ground failures and the complexity of

emergency response rise sharply [6,15]. Recent multi-country analyses indicate that several thousand mining-related fatalities still occur worldwide each decade, with pronounced disparities between jurisdictions [1,4,25].

Two interrelated transformations have reshaped mining safety and management engineering over the past decade. The first is regulatory. A growing number of jurisdictions have moved, at different speeds and with varying consistency, from rigid prescriptive compliance regimes toward risk-based “Duty of Care” models that require operators to identify, assess, and control risks so far as is reasonably practicable. Australia’s early and relatively comprehensive adoption of this philosophy is widely credited with contributing to sustained reductions in fatality rates [11,12,18]. The second transformation is technological. The emergence of Safety 4.0 and Safety 5.0 concepts, centered on the Internet of Things (IoT), digital twins, artificial intelligence (AI), and real-time analytics, offers the possibility of shifting from reactive incident investigation to proactive and, in some applications, autonomous risk pre-control [14,19,28,33].

Progress, however, remains uneven. Significant differences persist in fatality rates, regulatory maturity, technology adoption, and data transparency across Australia, China, the United States, South Africa, and Canada. Deep mining continues to generate high-consequence events, behavioral and organizational factors are still incompletely integrated into many safety management systems, and under-reporting in certain regions complicates international benchmarking [1,4,8,31].

This scoping review addresses three interrelated questions. First, how have risk-based regulatory frameworks performed relative to traditional prescriptive systems in reducing mining fatalities and serious injuries? Second, what is the current maturity and effectiveness of key engineering and technological controls, particularly energy-absorbing ground support, real-time IoT monitoring, digital twins, and AI-enabled predictive models, across major mining nations? Third, what critical gaps must still be closed if the industry is to make credible progress toward zero harm?

By systematically synthesizing peer-reviewed literature, official fatality and injury statistics, and national regulatory documents primarily covering the period 2015–2025, this paper provides a comparative assessment of safety management approaches and identifies priority directions for research, policy, and engineering practice.

2 METHODS

This paper adopts a scoping review methodology to map the current state of knowledge on safety and management engineering in the global mining sector. The approach follows the Joanna Briggs Institute (JBI) guidance and the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) checklist. The objective is to identify key regulatory models, engineering controls, technological innovations, and performance outcomes across major mining jurisdictions rather than to answer a single narrowly defined effectiveness question.

2.1 Search Strategy and Information Sources

Peer-reviewed literature was retrieved from Scopus, Web of Science Core Collection, and ScienceDirect for the period January 2015 to June 2025. Search strings combined terms related to mining safety (“mine safety”, “mining fatality”, “ground control”, “rockburst”, “coal burst”), regulatory approaches (“risk-based regulation”, “duty of care”, “prescriptive regulation”), and enabling technologies (“Safety 4.0”, “digital twin”, “Internet of Things”, “artificial intelligence”, “predictive risk”). Official fatality and injury statistics, regulatory guidelines, and technical reports were obtained from national authorities, including Safe Work Australia, the Mine Safety and Health Administration (MSHA), the China National Mine Safety Administration, the South African Department of Mineral Resources and Energy, and provincial Canadian regulators.

2.2 Eligibility Criteria and Screening

Documents were included if they addressed at least one of the following: (i) comparative or national-level analysis of mining safety performance or regulation; (ii) engineering controls for high-stress or deep mining environments; (iii) application of IoT, digital twins, or AI to mining hazard monitoring and risk prediction; or (iv) organizational and human-factor aspects of mining safety management. Purely laboratory studies without operational relevance, non-English publications without reliable translation, and opinion pieces lacking empirical or regulatory grounding were excluded.

2.3 Study Selection Process

The study selection process is summarized in the PRISMA-ScR flow diagram (Figure 1).

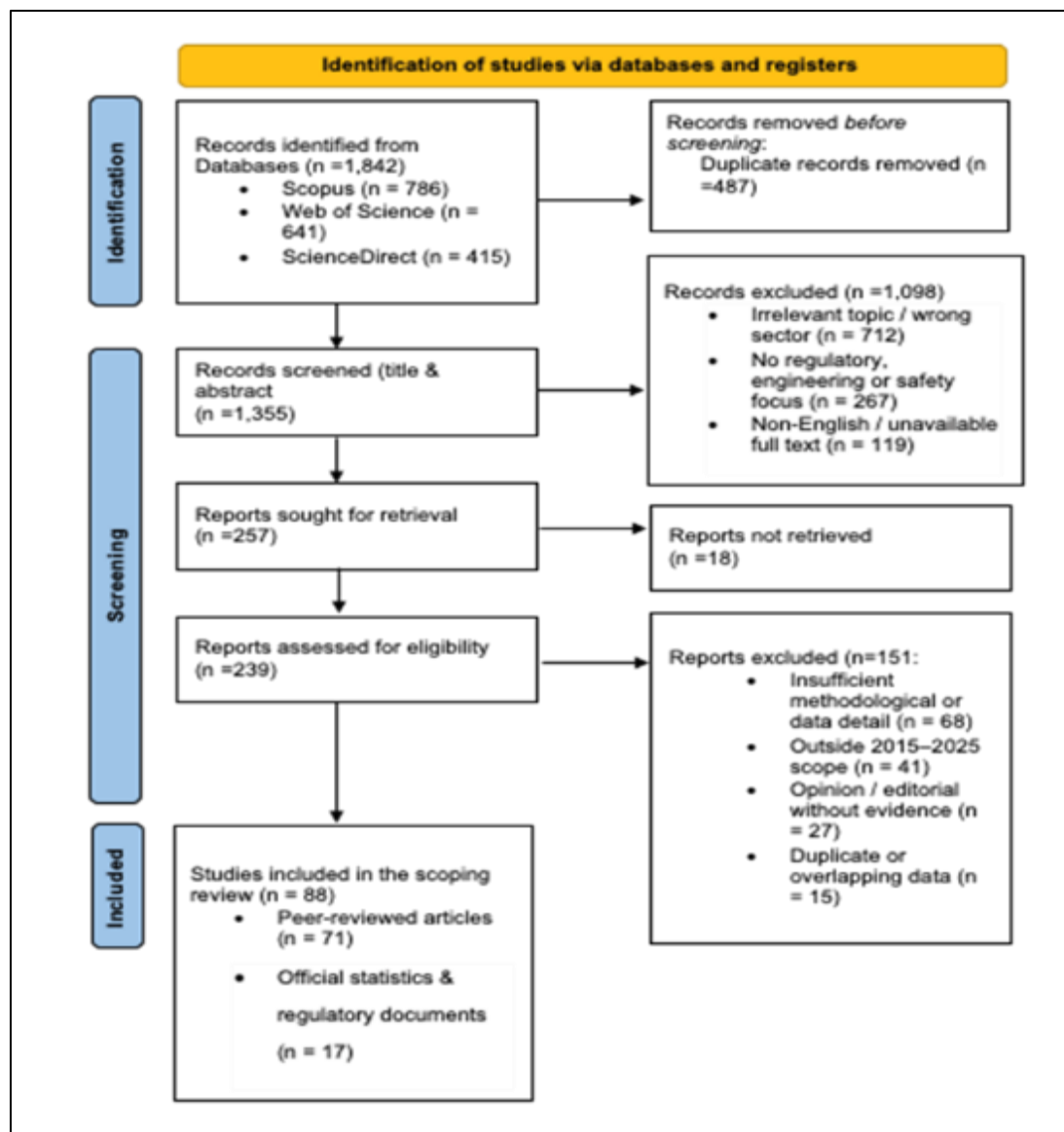


Figure 1: PRISMA-ScR flow diagram of the study selection process

2.4 Data Extraction and Synthesis

Key information extracted from the 88 included sources comprised regulatory philosophy and legal instruments, reported fatality and serious injury trends, description and maturity of engineering and digital controls, and identified implementation barriers. Findings were synthesized narratively and organized thematically around three core domains: (1) risk assessment and regulatory frameworks, (2) engineering and technological controls, and (3) comparative national performance. Quantitative safety indicators were tabulated where consistent multi-year data were available. No formal meta-analysis was performed due to heterogeneity in reporting standards, exposure metrics, and data completeness across countries.

3 REGULATORY FRAMEWORKS AND RISK MANAGEMENT APPROACHES

3.1 Evolution of Regulatory Philosophies

Mining safety regulation has historically been dominated by prescriptive, compliance-based systems that specify detailed technical rules and mandatory practices. While such systems provide clarity and facilitate enforcement, they often struggle to keep pace with technological change and site-specific risk profiles. In contrast, risk-based or “Duty of Care” frameworks require operators to identify hazards, assess risks, and implement controls so far as is reasonably practicable. This approach shifts primary responsibility onto the duty holder and emphasizes proactive risk management rather than mere compliance with fixed standards [11,12,18,29].

Australia pioneered the large-scale adoption of risk-based mining regulation in the late 1990s and early 2000s, particularly in Queensland and New South Wales. The transition coincided with a sustained decline in fatality rates and is frequently cited as a benchmark for regulatory effectiveness [11,12,18]. Other major jurisdictions have moved more gradually. The United States continues to operate primarily under the prescriptive framework of the Federal Mine Safety and Health Act, administered by the Mine Safety and Health Administration (MSHA), although recent initiatives have incorporated elements of risk assessment and predictive analytics [2,8]. China has retained strong centralized oversight while progressively introducing dual-prevention mechanisms and enterprise-level risk grading systems supported by big data [14,19,20]. South Africa and Canada occupy intermediate positions, combining elements of prescription with increasing emphasis on risk management and competency-based systems [1,8,15].

3.2 Core Risk Assessment and Management Models

Several structured risk assessment methodologies have become established in the mining sector:

- Roof Fall Risk Index (RFRI) and related qualitative indices provide systematic tools for evaluating ground control hazards in underground mines [3].
- Major Hazard Risk Assessment (MHRA), often employing techniques such as Workplace Risk Assessment and Control (WRAC), Preliminary Hazard Analysis (PHA), and Failure Mode and Effects Analysis (FMEA), is used to target potential multiple-fatality events [18].
- RISKGATE, an industry-supported body-of-knowledge platform, standardizes the classification and management of priority unwanted events, including geotechnical failures [4,30].
- China's "4+4" safety management model integrates statistical accident patterns with production categories to guide hierarchical risk control [20].

These tools support a cyclical process of hazard identification, risk analysis, control implementation, and ongoing monitoring. Their effectiveness, however, depends heavily on organizational capacity, workforce competence, and the quality of regulatory oversight. In mature risk-based regimes, such tools are embedded within broader Critical Control Management (CCM) systems that focus attention and resources on the most significant risks [30]. In more prescriptive environments, they are often applied selectively or as supplementary measures rather than as the core of the safety management system.

3.3 Implications for Safety Performance

Comparative evidence indicates that jurisdictions with well-implemented risk-based frameworks have generally achieved lower and more stable fatality rates than those relying predominantly on prescriptive controls [11,12,18,32]. Nevertheless, the mere formal adoption of risk-based language is insufficient. Success depends on clear legal accountability, adequate inspectorate capacity, robust verification of critical controls, and a supporting safety culture that prioritizes learning over blame. Where these enabling conditions are weak, even sophisticated risk assessment tools produce limited improvement in actual safety outcomes.

4 ENGINEERING CONTROLS AND TECHNOLOGICAL INNOVATIONS

4.1 Advanced Ground Support for High-Stress Environments

As mining depths increase, conventional rigid support systems frequently prove inadequate against dynamic loading from rockbursts and coal bursts. Contemporary ground control engineering has therefore shifted toward yielding and energy-absorbing support systems capable of deforming under high dynamic loads while maintaining residual capacity [6,15].

Yielding rockbolts (including D-bolts, cone bolts, and other sliding or extruding designs) are engineered to absorb significant kinetic energy through controlled displacement. Laboratory and field evidence shows that well-designed yielding bolts can dissipate tens of kilojoules of energy while retaining substantial residual load-bearing capacity, thereby reducing the likelihood of violent support failure [15].

Figure 2 illustrates the dynamic performance of a typical D-bolt (22 mm diameter). The load–displacement response demonstrates a distinct yielding phase under dynamic loading, accompanied by progressive energy absorption. The near-linear relationship between displacement and energy absorption (with a high coefficient of determination) confirms the predictable energy-dissipation behaviour that makes such bolts suitable for burst-prone conditions.

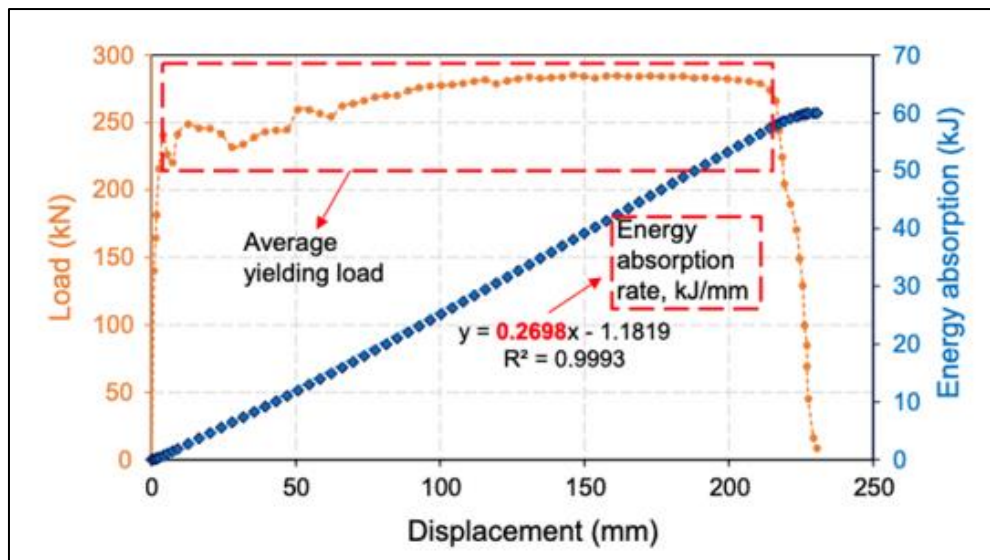


Figure 2: Dynamic test of a 22 mm diameter D-bolt under dynamic loading, showing load–displacement response and cumulative energy absorption.

Complementary support elements include energy-absorbing mesh, yielding props, and hybrid systems that combine high initial stiffness with large deformation capacity. Selection of appropriate support is increasingly guided by quantitative classification schemes that relate energy absorption capacity to expected dynamic demand and reaction pressure. Figure 3 presents a comparative classification of commonly used yielding bolts based on these two key performance parameters. The diagram enables engineers to match support characteristics to site-specific rockburst potential and stress conditions.

Despite these advances, important challenges persist. Performance under repeated dynamic loading, long-term corrosion in aggressive groundwater environments, and consistent installation quality control continue to limit field reliability. In addition, the integration of real-time monitoring with ground support (for example, instrumented bolts that transmit load and displacement data) remains at a relatively early stage of industrial adoption.

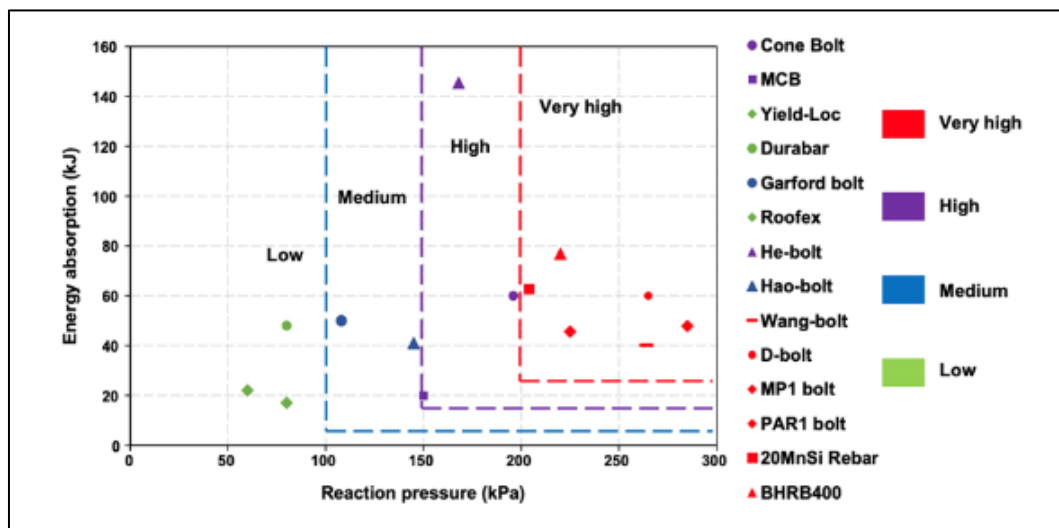


Figure 3: Classification of yielding bolts according to energy absorption capacity and reaction pressure.

4.2 Real-Time Monitoring, IoT, and Sensor Networks

The deployment of Internet of Things (IoT) architectures has enabled continuous monitoring of multiple hazard indicators, including gas concentrations, strata movement, equipment proximity, and personnel location [13,22]. Modern systems combine distributed sensor networks with wireless communication, edge computing, and centralized visualization platforms. Computer vision and machine-learning algorithms are increasingly applied for real-time detection of unsafe behaviours, equipment interactions, and early signs of ground instability.

These technologies support a shift from periodic inspection to continuous situational awareness. Their effectiveness, however, depends on sensor reliability in harsh underground environments, robust data transmission, and the organizational capacity to respond promptly to alerts. Alert fatigue and false positives remain practical constraints that can undermine operator trust and response discipline.

4.3 Digital Twins and AI-Enabled Predictive Models

Digital twin technology creates virtual replicas of mining systems that can be continuously updated with real-time data, allowing simulation of accident scenarios, testing of control strategies, and predictive assessment of evolving risk conditions [14,28]. When coupled with large AI models and historical incident data, digital twins offer the potential for self-learning safety systems capable of anticipating high-risk states before they fully develop.

AI-powered predictive risk models are also being used to integrate environmental, operational, and human-factor data for early warning and resource allocation [2,22,25]. Early applications show promise in improving the prioritization of inspections and interventions. Most current implementations, however, remain at pilot or early industrial stages. Key limitations include data quality and completeness, model interpretability, integration with existing management systems, and the need for clear accountability when algorithmic recommendations influence safety-critical decisions.

4.4 Synthesis

Engineering and digital controls have advanced substantially, particularly in the design of energy-absorbing ground support, real-time monitoring, and predictive analytics. Their contribution to safety performance is maximized when they are embedded within mature risk-based regulatory frameworks and supported by competent organizations and a learning-oriented safety culture. Technology alone, without corresponding improvements in governance, competence, and human–system integration, yields diminishing returns.

5 COMPARATIVE NATIONAL PERFORMANCE

5.1 Overview of Safety Outcomes

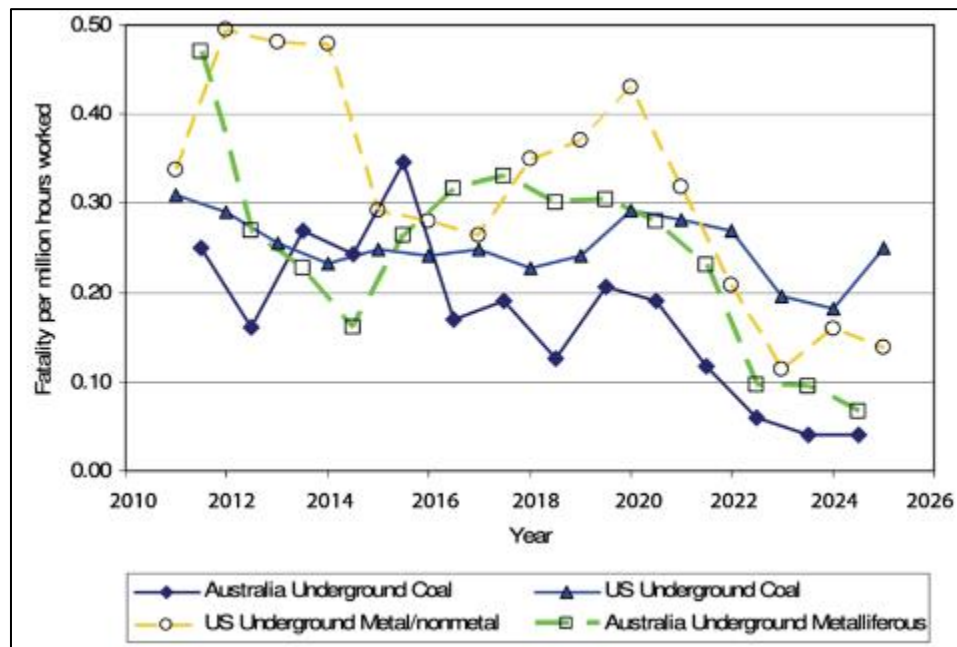


Figure 4: Running three-year underground mine fatality rates for Australia and the United States (coal and metalliferous sectors).

Marked differences in mining safety performance persist across the five jurisdictions. Australia consistently records among the lowest fatality rates globally, reflecting mature risk-based regulation and systematic Critical Control Management [11,12,18]. China has achieved the largest absolute reduction in fatalities through mine consolidation, mechanization, and dual-prevention systems, yet absolute numbers remain higher than in high-income producers [19,25]. The United States shows a long-term decline under MSHA, but with greater year-to-year variability than Australia [1,8,12]. South Africa continues to experience elevated risk, especially in deep gold mining [1,15]. Canada maintains very low absolute fatality numbers but faces the challenge of sustaining vigilance at low incident rates [1].

Figure 4 illustrates the divergence in underground mine fatality rates between Australia and the United States following Australia's shift to risk-based legislation. The sustained downward trajectory in Australia contrasts with the more fluctuating pattern observed in the United States.

Figure 5 presents trends in China from 2016 to 2025, showing a clear decline in the number of major accidents and megaton death rate against a background of rising raw coal production, evidence of the impact of mechanization and improved monitoring systems.

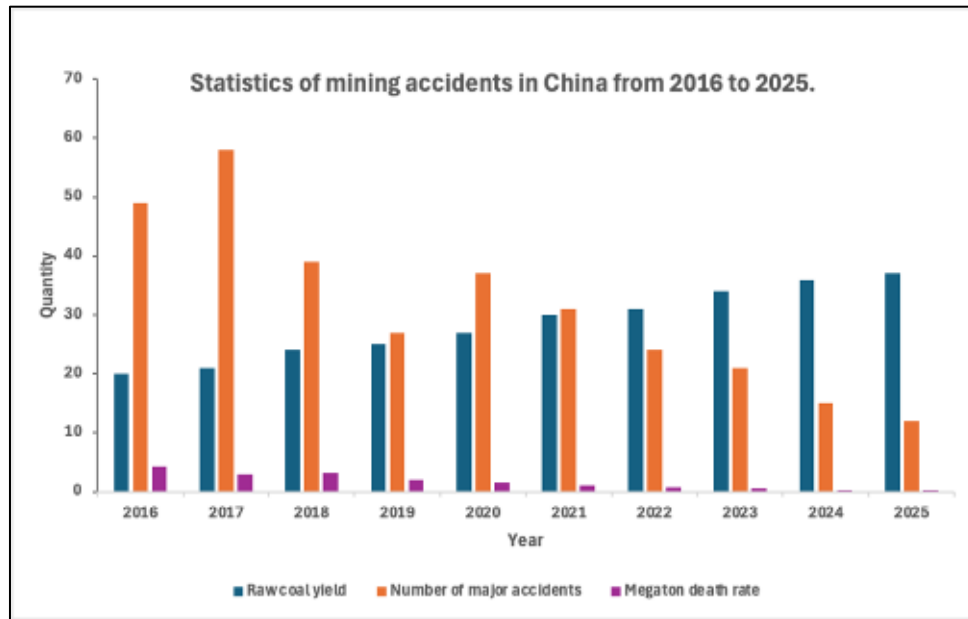


Figure 5: Statistics of mining accidents in China, 2016–2025: raw coal yield, number of major accidents, and megaton death rate.

Long-term U.S. data (Figure 6) confirm a gradual reduction in both the absolute number of occupational mining fatalities and the fatality rate per 100,000 full-time equivalent employees, although the decline has been less consistent than in Australia.

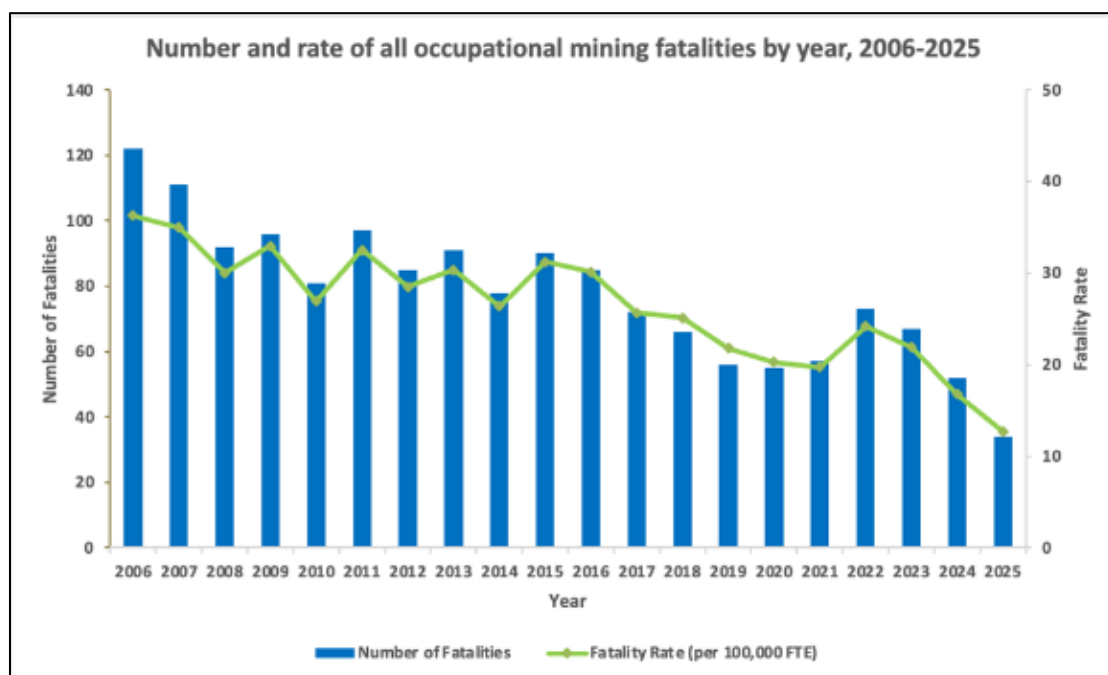


Figure 6: Number and rate of all occupational mining fatalities in the United States by year.

5.2 Regulatory and Performance Comparison

Table 1: Comparative overview of regulatory approaches and safety performance characteristics (2015–2025)

Country	Dominant Regulatory Philosophy	Key Institutional Features	Indicative Fatality Trend (recent decade)	Notable Strengths	Persistent Challenges
Australia	Risk-based / Duty of Care	Strong state regulators; Critical Control Management	Lowest and relatively stable	Mature risk frameworks; high compliance culture	Occupational disease data gaps; risk-assessment fatigue
China	Hybrid (centralized + enterprise risk grading)	Dual-prevention mechanism; rapid digitalization	Sharp absolute decline, still elevated	Mechanization; IoT & digital twin deployment	Data transparency; legacy small-mine risks
United States	Primarily prescriptive (MSHA)	Federal enforcement; growing predictive analytics	Gradual decline with fluctuations	Detailed standards; MINER Act infrastructure	Adversarial culture; slower risk-based transition
South Africa	Mixed (prescription + prevention culture)	Rockburst codes of practice; competency focus	Elevated, especially deep gold	Specialized ground-control knowledge	Inspectorate capacity; extreme depth risks
Canada	Risk-oriented (provincial variation)	Continuous improvement emphasis	Very low absolute numbers	Rockburst support guidance (CRH)	Maintaining vigilance at low base rates

Table 2: Fatality and injury rates in South African gold, platinum, and coal mining (selected years)

Year	Fatality rate (per 10 000 workers)			Injury rate (per 10 000 workers)		
	Gold	Platinum	Coal	Gold	Platinum	Coal
2016	8.9	4.9	3.7	167.4	80.0	35.7
2018	7.5	4.5	5.1	155.2	58.2	39.8
2020	6.5	3.0	2.8	145.5	74.5	31.8
2022	6.9	2.8	2.5	136.9	66.0	33.9
2024	5.1	2.2	2.5	109.8	70.5	41.7

5.3 Cross-Cutting Observations

Three robust patterns emerge. First, mature and well-enforced risk-based regimes are associated with lower and more stable fatality rates. Second, rapid technological deployment can deliver large absolute gains even within hybrid systems, but durability depends on data integrity and organizational capability. Third, ultra-deep mining continues to generate disproportionate high-consequence risk across all countries operating at such depths.

6 DISCUSSION: SYNTHESIS AND IMPLICATIONS

The evidence synthesized in this review supports four central conclusions.

First, regulatory philosophy is consequential. Jurisdictions that have implemented genuine risk-based “Duty of Care” frameworks with strong verification of critical controls (most clearly Australia) have achieved superior and more stable safety outcomes than those relying predominantly on prescriptive rules [11,12,18,32]. Formal adoption of risk-based

language without accompanying enforcement capacity, accountability mechanisms, and organizational competence yields limited benefit.

Second, technology functions as an amplifier rather than a substitute for sound governance. Energy-absorbing ground support, IoT monitoring, digital twins, and AI-enabled predictive models have expanded technical capability [6,14,15,22,28]. Their safety contribution is maximized only when embedded within robust risk management systems and operated by competent personnel. Where these conditions are absent, technological investment risks producing complexity without commensurate risk reduction.

Third, deep and ultra-deep mining remains the most stubborn technical frontier. Despite measurable progress in yielding support systems and real-time geotechnical monitoring, high-stress dynamic failures continue to account for a disproportionate share of fatalities in countries that operate at extreme depth [6,15]. Closing this gap requires continued advances in both support hardware and integrated monitoring–response systems.

Fourth, data limitations constrain learning. Inconsistent definitions, under-reporting, and incomplete exposure data reduce the precision of international comparison and slow the diffusion of effective practices [1,4]. Greater standardization of core safety indicators would materially improve the evidence base for policy and engineering decisions.

Collectively, these findings indicate that progress toward zero harm depends on the simultaneous strengthening of three interdependent layers: (1) risk-based regulatory design with real accountability, (2) high-reliability engineering and digital controls, and (3) organizational and human-factor systems capable of using information effectively. Advances in any single layer while the others remain weak produce diminishing returns.

7 FUTURE DIRECTIONS AND RESEARCH GAPS

Achieving sustained progress toward zero harm in the mining sector requires coordinated advances across regulatory design, engineering controls, digital technologies, and human–organizational systems. The evidence reviewed in this paper points to several high-priority directions for research and practice.

7.1 Strengthening Risk-Based Regulation and Critical Control Management

Further work is needed to identify the institutional conditions under which risk-based “Duty of Care” frameworks deliver durable safety gains. Comparative studies that examine inspectorate capacity, verification practices, enforcement consistency, and the practical operation of Critical Control Management systems would help distinguish formal adoption from effective implementation. Research should also address the risk of “assessment fatigue” and the dilution of focus that can accompany the proliferation of risk registers, with particular attention to methods for maintaining emphasis on the highest-consequence hazards.

7.2 Advancing Ground Control for Ultra-Deep Mining

As a growing number of operations exceed 1,000 m and some approach or surpass 3,000–4,000 m, the demand for reliable energy-absorbing support systems will intensify. Priority research areas include the performance of yielding bolts and hybrid support systems under repeated dynamic loading, long-term durability in corrosive environments, and the integration of instrumented support with real-time monitoring and automated response protocols. Quantitative design methods that link expected dynamic demand to support energy absorption and reaction pressure capacity require further validation across a wider range of geological conditions.

7.3 Maturing Digital and AI-Enabled Safety Systems

Digital twins and AI-based predictive models remain predominantly at pilot or early industrial stages. Key research needs include improving data quality and completeness, enhancing model interpretability and trustworthiness, establishing clear accountability frameworks for algorithmic recommendations, and evaluating the actual contribution of these technologies to reductions in high-consequence events. Studies that examine human–AI interaction, alert management, and the organizational conditions required for effective use of real-time risk information are particularly important if these tools are to move beyond demonstration projects.

7.4 Integrating Human and Organizational Factors

Behavioral, cultural, and organizational determinants of safety performance remain under-represented in many formal management systems. Future research should apply contemporary psychological and organizational models to the design of user-centred monitoring systems, competence development programs, and learning-oriented incident

investigation processes. Greater attention to psychological safety, frontline engagement, and the practical barriers to reporting and learning would strengthen the human layer of multi-layered safety systems.

7.5 Improving Data Transparency and International Comparability

Inconsistent definitions, incomplete exposure data, and under-reporting continue to limit the precision of cross-national learning. Collaborative efforts to standardize core indicators (fatality rates, serious injury rates, exposure metrics, and leading indicators of critical control effectiveness) would substantially improve the evidence base available to regulators, operators, and researchers. Open, high-resolution datasets would also enable more rigorous evaluation of the relative contributions of regulatory, technological, and organizational interventions.

Addressing these gaps in a coordinated manner offers the most credible pathway for translating the substantial technical and regulatory progress already achieved into further, sustained reductions in mining harm.

8 CONCLUSION

Safety and management engineering in the global mining sector is undergoing a significant transition. The shift from predominantly prescriptive regulatory regimes toward risk-based “Duty of Care” frameworks, combined with the rapid development of Safety 4.0 and Safety 5.0 technologies, has expanded the means available to prevent high-consequence events. Comparative evidence from Australia, China, the United States, South Africa, and Canada demonstrate that jurisdictions with mature, well-implemented risk-based systems have generally achieved lower and more stable fatality rates, while large-scale technological deployment, particularly in China, has produced substantial absolute reductions in harm.

Engineering advances in energy-absorbing ground support, real-time IoT monitoring, digital twins, and AI-enabled predictive models have strengthened technical capability, especially in high-stress and deep mining environments. Yet these tools deliver their greatest benefit only when embedded within robust regulatory frameworks and supported by competent organizations capable of acting on the information they generate. Technology and regulation alone are insufficient; durable progress also requires systematic attention to human and organizational factors, data integrity, and continuous learning.

Persistent challenges remain. Ultra-deep mining continues to generate disproportionate geotechnical risk, data transparency and comparability limitations hinder international learning, and behavioral and cultural dimensions of safety are still incompletely integrated into many formal management systems. Closing these gaps will require coordinated advances across three interdependent layers: risk-based governance with real accountability, high-reliability engineering and digital controls, and human–organizational systems that enable effective use of information and sustained learning.

The goal of zero harm is ambitious but no longer purely aspirational. Realizing it depends on treating safety as a dynamic, multi-layered system rather than a set of isolated technical or legal requirements. The evidence synthesized in this review indicates that the most promising pathway lies in the deliberate integration of these layers, supported by rigorous evaluation, transparent data, and a commitment to continuous improvement across the global mining industry.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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