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Research Article

Analysis of Mine Accidents and Evaluation of Safety Management Practices in Opencast Coal Mines of the Raniganj Coalfield

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Abstract

Coal mining continues to be one of the most hazardous industrial sectors (ILO, 2018; DGMS, 2017). despite continuous advancements in mining technology, mechanization, and occupational safety practices. Opencast coal mines account for a major share of India's coal production (Ministry of Coal, 2024; Coal India Ltd., 2024), with the Raniganj Coalfield being one of the country's oldest and most significant coal-producing regions. This study presents a comprehensive analysis of mine accidents and evaluates the effectiveness of safety management practices in the opencast coal mines of the Raniganj Coalfield. A retrospective analysis of accident records, safety reports, and regulatory documents was conducted to identify accident trends, classify accident types, determine their root causes, and assess existing safety management measures. The study reveals that transportation-related accidents, heavy earth-moving machinery incidents, slope failures, blasting operations, and human errors constitute the major causes of accidents in the study area. The evaluation of safety management practices indicates that while regulatory compliance and technological improvements have contributed to a reduction in accident frequency, challenges remain in hazard identification, risk assessment, safety supervision, workforce competency, and adherence to standard operating procedures. The findings highlight the need for strengthening safety culture, enhancing behavioural safety programs, improving operator training, integrating digital safety monitoring technologies, and adopting proactive risk assessment approaches to minimize workplace hazards. The study provides practical recommendations for improving occupational safety performance and strengthening safety management systems in Indian opencast coal mines, particularly within the Raniganj Coalfield.

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KEYWORDS: Opencast coal mining; Raniganj Coalfield; Mine accidents; Safety management; Accident analysis; Occupational safety; Risk assessment.

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1. INTRODUCTION

Coal remains the backbone of India's energy sector (Ministry of Coal, 2024), contributing significantly to electricity generation, industrial development, and economic growth. To meet the increasing demand for coal, opencast mining has become the dominant mining method (Coal India Limited, 2024) due to its higher productivity, lower production cost, greater recovery of coal reserves, and enhanced mechanization compared with underground mining. The Raniganj Coalfield, one of India's oldest and most important coal-producing regions, plays a vital role in the country's coal production through its numerous opencast mining operations.

Despite continuous advancements in mining technology, heavy earth-moving machinery, blasting techniques, monitoring systems, and regulatory frameworks, opencast coal mining continues to present considerable occupational safety challenges. Mining operations involve complex interactions (ICMM, 2022; SME, 2019) among workers, machinery, geological conditions, and environmental factors, making them susceptible to various types of accidents. Transportation-related incidents involving dumpers and heavy earth-moving machinery (DGMS, 2023), slope instability, blasting accidents, electrical hazards, material handling failures, and unsafe work practices remain among the leading causes of injuries and fatalities in opencast mines. These accidents not only result in loss of human life but also affect productivity, equipment reliability, environmental sustainability, and the overall economic performance of mining operations. Safety management has therefore become (ISO 45001:2018) a fundamental component of modern mining practices. An effective safety management system integrates hazard identification, risk assessment, regulatory compliance, workforce training, safe operating procedures, accident investigation, and continuous monitoring to minimize workplace hazards and improve organizational safety performance. In India, the Directorate General of Mines Safety (DGMS), the Mines Act, 1952, the Mines Rules, 1955, and the Coal Mines Regulations, 2017 provide the statutory framework for ensuring safe mining operations. Nevertheless, accident investigations continue to indicate that deficiencies in risk assessment, human factors, equipment maintenance, safety supervision, and compliance with standard operating procedures remain major contributors to mining accidents.

Several studies have examined accident causation (Kishore et al., 2026; ICMM, 2022) in mining industries using statistical analysis, risk assessment techniques, and human factor evaluation. However, limited research has comprehensively analyzed accident trends while simultaneously evaluating the effectiveness of safety management practices specifically in the opencast coal mines of the Raniganj Coalfield. Such an integrated assessment is essential for identifying recurring accident patterns, evaluating existing safety measures, and developing targeted strategies for accident prevention.

The present study aims to analyze mine accidents in the opencast coal mines of the Raniganj Coalfield and evaluate the effectiveness of existing safety management practices. The study examines accident trends, classifies accident types and their causative factors, assesses the implementation of safety management systems, and identifies gaps in current safety practices. Based on the findings, appropriate engineering, administrative, and behavioural interventions are proposed to strengthen risk management, improve occupational safety performance, and support sustainable mining operations in the Raniganj Coalfield.

2. Study Area

The Raniganj Coalfield is one of India's oldest and most important coal-producing regions, situated in the eastern part of the country, primarily in the Paschim Bardhaman district of West Bengal, with its western extension reaching parts of Jharkhand. Covering an area of approximately 1,530 km², the coalfield contains substantial reserves of bituminous coal and contributes significantly to the nation's coal production. The coalfield is operated mainly by Eastern Coalfields Limited (ECL Annual Report, 2024), a subsidiary of Coal India Limited (CIL), through a combination of underground and opencast mining projects.

The present study focuses exclusively on the opencast coal mines of the Raniganj Coalfield (Coal India Limited, 2024), where mining operations are highly mechanized and involve the deployment of heavy earth-moving machinery (HEMM), including electric rope shovels, hydraulic excavators, dumpers, dozers, draglines, graders, drills, and surface miners. Coal extraction is carried out using controlled drilling and blasting techniques, followed by excavation, loading, transportation, and dumping operations through high-capacity haul roads. These activities expose workers and equipment to various operational hazards, including transportation accidents, machinery-related incidents, slope failures, blasting hazards, electrical accidents, dust exposure, and material handling failures.

The Raniganj Coalfield was selected for this study because of its long mining history, extensive mechanized opencast operations, and the availability of accident records and safety performance data. The diversity of mining activities and operational conditions provides an appropriate basis for analysing accident patterns and evaluating the effectiveness of existing safety management practices.

Mining operations within the study area are governed by statutory provisions and safety regulations enforced by the Directorate General of Mines Safety (DGMS). The principal regulatory framework includes the Mines Act, 1952, the Mines Rules, 1955, the Coal Mines Regulations, 2017, and various DGMS technical circulars, safety guidelines, and standards. These regulations prescribe requirements related to hazard identification, risk assessment, machinery operation, blasting practices, slope stability, occupational health, emergency preparedness, and accident reporting. Compliance with these

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provisions forms the basis for evaluating the safety management practices adopted in the opencast coal mines of the Raniganj Coalfield (Coal India Limited, 2024).

3. OBJECTIVES

The primary objective of this study is to analyse mine accidents and evaluate the effectiveness of safety management practices in the opencast coal mines of the Raniganj Coalfield. Specifically, the study seeks to examine the major types of accidents occurring in these mines, investigate the human, technical, operational, and environmental factors contributing to accident occurrence, and assess the adequacy of the existing safety management systems. Furthermore, the study aims to identify deficiencies and gaps in current safety practices and regulatory implementation that may increase accident risk. Based on the findings, the study proposes appropriate engineering, administrative, and behavioural measures to strengthen safety management systems, reduce accident frequency and severity, and improve occupational safety performance in the opencast coal mines of the Raniganj Coalfield.

4. METHODOLOGY

This study employed a systematic descriptive research methodology to analyze mine accidents and evaluate safety management practices in opencast coal mines of the Raniganj Coalfield. The methodology was designed to investigate accident trends, identify operational hazards, assess associated risks, and evaluate the effectiveness of existing safety management systems. Secondary data were collected from Directorate General of Mines Safety (DGMS) accident reports, Ministry of Coal publications, Coal India Limited (CIL) and Eastern Coalfields Limited (ECL) annual reports, technical reports, and relevant peer-reviewed literature. Accident records spanning approximately two decades were systematically reviewed and classified according to accident type, location, severity, causative factors, equipment involved, and time of occurrence. This classification enabled the identification of recurring accident patterns and the major contributors to occupational injuries and fatalities in opencast mining operations. Operational hazards associated with drilling, blasting, excavation, loading, haulage, dumping, maintenance, and electrical installations were identified by analyzing accident records and published literature. Particular attention was given to hazards such as equipment failure, slope instability, vehicle collisions, fly rock, electrical accidents, and unsafe working conditions. A qualitative risk assessment (ISO 31000:2018) was subsequently performed by considering the probability of occurrence, consequence severity, exposure frequency, and effectiveness of existing control measures. A qualitative risk matrix was used to classify identified hazards into low, medium, high, and extreme risk categories, thereby prioritizing hazards requiring immediate engineering or administrative interventions. Finally, the effectiveness of the existing safety management system was evaluated by examining leadership commitment, safety training, personal protective equipment (PPE) compliance, workplace inspections, incident reporting, emergency preparedness, safety audits, and contractor safety management. The integrated findings from accident analysis, hazard identification, risk assessment, and safety management evaluation were used to identify deficiencies in current practices and recommend measures for improving occupational safety and reducing accident risks in opencast coal mining operations.

5. RESULTS AND DISCUSSION

Accident Type	Relative Frequency	Primary Equipment / Location Involved
Haul Road Accidents	High	Dumpers, Haul Trucks, Internal Roads
Machinery Accidents	High	Excavators, Surface Miners, Shovels
Slope Failures	Moderate	Bench Slopes, Highwalls, Waste Dumps
Blasting Incidents	Moderate	Flyrock, Premature Detonation Areas
Fall of Persons	Moderate	Working Benches, Maintenance Platforms
Electrical Accidents	Low	Substations, Trailing Cables

Root Cause Analysis and Evaluation of Safety Management Practices

The root cause analysis revealed that mine accidents in the Raniganj Coalfield were primarily caused by the interaction of human, equipment, environmental, and organizational factors. Human-related causes (DGMS, 2023; Kishore et al., 2026). included unsafe work practices, operator fatigue, inadequate training, poor communication, and non-compliance with standard operating procedures. Equipment-related factors (SME, 2019) involved brake failures, hydraulic malfunctions, poor maintenance, and mechanical defects. Environmental conditions such as poor visibility, excessive dust, heavy rainfall, and slippery haul roads further increased accident risks. Organizational issues (ICMM, 2022), including inadequate supervision, weak safety culture, insufficient hazard reporting, and production pressure, also contributed significantly to accident occurrence.

The evaluation of safety management practices showed that regular toolbox meetings, periodic safety training, PPE compliance, statutory inspections, and emergency preparedness have strengthened workplace safety. However, deficiencies remain, including limited implementation of behaviour-based safety programs, inconsistent contractor supervision, delayed corrective actions, inadequate use of digital monitoring technologies, and poor near-miss reporting. Addressing these gaps through stronger leadership, proactive risk management,

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and improved safety monitoring can significantly reduce accident risks and enhance overall mine safety performance.

6. Risk Assessment Matrix

Based on quantified risk evaluation (R = P x C x E), operational hazards were categorized:

The risk matrix was developed following standard qualitative risk assessment principles (ISO 31000:2018; ISO 45001:2018).

Identified Hazard	Likelihood (P)	Severity (C)	Risk Level
Haul Truck Collision	High	High	Extreme
Bench/Slope Failure	Medium	High	High
Fly Rock Projection	Medium	High	High
Equipment Roll Over	Medium	High	High
Electrical Shock	Low	High	Medium
Slip, Trip and Fall	Medium	Medium	Medium

7. Recommended Safety Improvements

Based on the analysis of mine accidents and the evaluation of existing safety management practices in the opencast coal mines of the Raniganj Coalfield, several engineering, administrative, and emergency preparedness measures are recommended to enhance workplace safety and reduce accident frequency. The implementation of these recommendations will strengthen the existing safety management system while promoting a proactive safety culture across mining operations.

From an **engineering perspective**, continuous monitoring of high-risk mining activities should be prioritized through the installation of modern slope stability monitoring systems. Radar-based slope monitoring, prism monitoring, and geotechnical instrumentation can provide early warning of slope failures, allowing timely evacuation and preventive action. GPS-enabled fleet management (SME, 2019) systems should be adopted to improve traffic control, optimize haul road usage, and minimize collisions between heavy earth-moving machinery. Advanced collision avoidance systems (ICMM, 2022). incorporating proximity sensors, radar, and vehicle-to-vehicle communication can significantly reduce accidents involving dumpers, excavators, and dozers. Automated dust suppression systems should be installed at drilling, crushing, loading, and haul road locations to reduce respirable dust exposure and improve visibility. Furthermore, fatigue detection systems using artificial intelligence, facial recognition, and wearable sensors should be implemented to continuously monitor operator alertness, thereby reducing accidents caused by human fatigue and loss of concentration.

From an **administrative and organizational standpoint**, strengthening safety leadership at all managerial levels is essential for improving safety performance. Mine management should promote visible leadership through regular workplace inspections, safety interactions, and accountability for safety outcomes. Competency-based training programs should be periodically conducted for equipment operators, blasting personnel, supervisors, and contract workers to ensure that all employees possess the necessary technical knowledge and hazard awareness. Behaviour-Based Safety (BBS) programs should be introduced to identify unsafe acts, reinforce safe work practices, and encourage employee participation in accident prevention. Digital Permit-to-Work (PTW) systems should replace conventional paper-based permits to improve authorization, monitoring, and compliance for hazardous maintenance and operational activities. Since a considerable proportion of mining activities are performed by contractors, contractor safety management should be strengthened through rigorous prequalification, periodic safety audits, competency assessments, and performance-based evaluation.

Improving **risk assessment and hazard identification** practices is equally important. Comprehensive risk assessments should be conducted before commencing drilling, blasting, excavation, transportation, and maintenance operations. Hazard Identification and Risk Assessment (ISO 45001:2018). (HIRA), Job Safety Analysis (JSA), and Failure Mode and Effects Analysis (FMEA) techniques should be systematically integrated into daily operational planning. Lessons learned from previous accidents and near-miss incidents should be incorporated into standard operating procedures, ensuring continuous improvement of the safety management system. Digital reporting platforms should be developed to facilitate timely reporting, investigation, and analysis of accidents and unsafe conditions.

Special emphasis should also be placed on **occupational health management**. Regular health surveillance programs should be conducted for workers exposed to coal dust, noise, vibration, and heat stress. Dust control measures, periodic environmental monitoring, ergonomic improvements, and mandatory use of appropriate personal protective equipment (PPE) should be strictly enforced. Safety awareness campaigns and refresher training programs should be organized regularly to maintain a high level of safety consciousness among employees.

Effective **emergency preparedness and response planning** remain critical components of mine safety management. Periodic mock drills (DGMS, 2017) should be conducted to evaluate emergency response capability for scenarios such as slope failure, fire, explosion, machinery accidents, and inundation. Mine rescue teams should receive continuous specialized training and be equipped with modern rescue equipment and communication devices. Establishing centralized emergency communication systems integrated with wireless networks, GPS tracking, and real-time monitoring will significantly improve coordination during emergencies. Geographic Information System (GIS)-based emergency

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planning should also be adopted to facilitate rapid evacuation planning, resource allocation, and rescue operations. Emergency response plans should be reviewed periodically based on changing mine conditions and lessons learned from accident investigations.

Overall, the implementation of these engineering, administrative, occupational health, and emergency preparedness measures will substantially improve safety performance, reduce accident frequency and severity, and contribute toward achieving a sustainable zero-harm safety culture in the opencast coal mines of the Raniganj Coalfield.

8. Future Scope

The present study provides valuable insights into accident trends and safety management practices in the opencast coal mines of the Raniganj Coalfield; however, considerable scope exists for further research to enhance mine safety through advanced technologies and data-driven approaches. Future investigations should focus on integrating modern digital technologies with conventional safety management systems to develop predictive and preventive safety strategies.

One promising area of future research is the application of Artificial Intelligence (AI) and Machine Learning (ML) for accident prediction and risk assessment. Historical accident databases, operational parameters, weather conditions, production records, equipment utilization, and human performance indicators can be utilized to develop predictive models capable of identifying high-risk situations before accidents occur. AI-based (Kishore et al., 2026) decision support systems can assist mine managers in implementing timely preventive measures and optimizing safety interventions.

The development of real-time risk assessment models using big data analytics represents another important research direction. By integrating data from sensors, machinery, environmental monitoring systems, and workforce activities, dynamic risk assessment frameworks can continuously evaluate workplace hazards and provide early warning alerts. Such systems can significantly improve decision-making under changing mining conditions.

Future studies may also explore the use of Internet of Things (IoT)-enabled smart mining systems**.** Smart sensors installed on heavy earth-moving machinery, haul roads, slopes, conveyors, and electrical installations can continuously monitor equipment condition, environmental parameters, and operational performance. The integration of IoT devices with centralized monitoring platforms can facilitate predictive maintenance, reduce equipment failures, and improve operational safety.

The application of drone technology (Unmanned Aerial Vehicles) offers significant potential for enhancing my safety. Drones equipped with high-resolution cameras, LiDAR, thermal imaging, and multispectral sensors can be used for slope inspection, overburden dump monitoring, volumetric surveys, environmental assessment, and post-blast inspections without exposing personnel to hazardous conditions. Drone-based monitoring can substantially improve the efficiency and accuracy of safety inspections in large opencast mines.

Another important area for future research involves digital twin technology**,** where a virtual representation of the mine is continuously updated using real-time operational data. Digital twins can simulate mining operations, evaluate different safety scenarios, predict equipment failures, and support emergency response planning, thereby improving overall mine safety management.

Further research should also investigate human factors engineering by examining the influence of fatigue, workload, organizational culture, communication, leadership, and behavioural aspects on accident occurrence. Advanced behavioural safety models can provide deeper insights into human error mechanisms and facilitate the development of targeted intervention strategies.

Long-term comparative studies involving different subsidiaries of Coal India Limited and other major coal-producing regions may also be undertaken to benchmark safety performance and identify best safety management practices. Comparative analyses between mechanized and semi-mechanized opencast mines would provide useful information regarding the effectiveness of different safety technologies and management systems.

Finally, future research should focus on developing integrated Safety Management Systems (SMS) combining AI, GIS, IoT, cloud computing, and real-time environmental monitoring to create intelligent mining environments capable of continuously identifying hazards, predicting accidents, and supporting evidence-based safety decisions. Such technology-driven safety frameworks will play a crucial role in improving occupational safety, enhancing operational efficiency, and achieving sustainable mining practices in the opencast coal mines of the Raniganj Coalfield.

9. CONCLUSION

The study demonstrates that accident occurrence in opencast coal mines is influenced by technical, human, environmental, and organizational factors. Although safety standards have improved significantly in recent years, opportunities remain for strengthening proactive risk management and behavioural safety. The integration of advanced monitoring technologies, digital safety management systems, and competency-based training can substantially reduce accident frequency and improve overall operational safety. The findings provide practical guidance (DGMS, 2017; ISO 45001:2018) for mine managers, safety professionals, and policymakers working to enhance occupational health and safety in the Raniganj Coalfield and similar opencast mining operations.

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