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Research Article

Analysis of Coal Pillar Strength and Stability in Underground Coal Mines

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Abstract

Coal pillar stability is one of the most significant geotechnical concerns in underground coal mining operations because coal pillars act as the primary support system for overlying strata in bord and pillar workings. Improper pillar design can result in catastrophic failures such as roof collapse, rib spalling, and progressive pillar crushing, thereby threatening mine safety and productivity. The present study investigates the behaviour of coal pillars under varying geological and mining conditions with special emphasis on Indian underground coal mines. Important parameters, including pillar geometry, width-to-height ratio, depth of cover, gallery width, and in situ stress conditions, were evaluated using empirical and analytical approaches. The study comparatively analyses the CMRI, Bieniawski, and Salamon–Munro pillar strength models for assessing pillar stability. Laboratory investigations such as point load testing, Brazilian tensile strength testing, and moisture content analysis were conducted to determine the geomechanical properties of coal samples. The findings reveal that increasing pillar width significantly enhances pillar strength and factor of safety, whereas increasing gallery width leads to greater tributary loading and stress concentration. The study further confirms that the CMRI formula is more reliable for Indian geo-mining conditions due to its calibration with local coalfield characteristics. The outcomes of this research provide a scientific basis for optimising coal pillar design, improving underground mine stability, and minimising ground control hazards in deep underground coal mines.

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1. INTRODUCTION

Coal continues to play a vital role in global energy production and industrial development. In India, underground coal mining remains an important component of the mining sector, especially in coalfields such as Jharia, Raniganj, Bokaro, and Singrauli. Among the various underground mining methods, the bord and pillar system is the most widely practised because of its operational flexibility and comparatively lower capital investment requirements. In this method, coal pillars are intentionally left between excavated galleries to support the overlying rock strata and maintain mine stability during both development and depillaring stages. The stability of these coal pillars is therefore directly related to the safety, productivity, and economic viability of underground mining operations.

Coal pillar failures are among the most serious geotechnical hazards in underground mines. Pillar instability can trigger roof falls, floor heaving, rib spalling, and large-scale collapse, resulting in significant loss of life and infrastructure damage. Consequently, accurate assessment of coal pillar strength and loading conditions is essential for effective mine design and long-term stability planning. Several researchers have contributed to the understanding of pillar mechanics and failure behaviour over the past few decades. Z. T. Bieniawski demonstrated the influence of specimen size on coal strength and established the importance of the size effect in pillar design [1]. Similarly, M. D. G. Salamon and A. H. Munro developed one of the most widely used empirical pillar strength equations through statistical analysis of stable and failed coal pillars [2].

In Indian coal mines, the Central Mining Research Institute (CMRI) developed a pillar strength formula specifically considering Indian geo-mining conditions and extraction practices [4]. This formula remains highly applicable for Indian underground mines due to its consideration of local geological parameters. Research by Sheorey [16], Das [17], and Singh and Singh [18] further contributed to understanding stress redistribution, failure mechanisms, and numerical simulation approaches for coal pillar stability assessment.

Coal pillar design is influenced by several factors, including depth of cover, seam thickness, width-to-height ratio, geological discontinuities, moisture conditions, and in situ stress distribution. The width-to-height ratio is considered one of the most important design parameters because slender pillars are more susceptible to crushing and progressive failure than squat pillars [5,16]. Increasing mining depth also results in higher overburden stress, which significantly affects pillar stability and ground control conditions [20].

Recent advancements in rock mechanics and computational geotechnics have enabled the use of numerical modelling techniques such as finite element and finite difference analysis for underground stability assessment. However, empirical formulas remain widely used in practical mining operations because of their simplicity, reliability, and field applicability [13,14]. The present study, therefore, combines empirical pillar strength analysis with laboratory investigations to evaluate coal pillar stability under representative underground mining conditions.

2. OBJECTIVES OF THE STUDY

The primary objective of this research is to investigate the strength and stability behaviour of coal pillars in underground coal mines using empirical, analytical, and laboratory-based approaches. The study aims to evaluate the influence of pillar geometry, gallery width, and depth of cover on pillar performance and factor of safety. Another important objective is to compare widely accepted pillar strength models, such as the CMRI, Bieniawski, and Salamon–Munro equations, for their applicability under Indian geo-mining conditions. The research also seeks to analyse load distribution using tributary area theory and determine the significance of laboratory-derived coal properties in underground pillar design. Ultimately, the study aims to provide practical recommendations for improving mine safety and optimising pillar dimensions in underground coal mining operations.

3. LITERATURE REVIEW

Coal pillar mechanics has been extensively studied by researchers worldwide due to its direct importance in underground mine safety. Early studies conducted by Bieniawski [1] established that coal strength decreases with increasing specimen size due to the presence of fractures, cleats, and discontinuities. This phenomenon, known as the "size effect," became a fundamental principle in coal pillar design.

Salamon and Munro [2] proposed a statistical pillar strength model based on failed and stable pillar cases from South African coal mines. Their work demonstrated that pillar strength depends strongly on the width-to-height ratio and provided an empirical basis for practical pillar design. Hustrulid [5] later reviewed several pillar strength formulas and highlighted the importance of field calibration in empirical design methods.

In India, CMRI developed a pillar strength equation specifically for Indian coal seams and mining conditions [4]. The formula incorporated seam thickness, extraction ratio, and depth parameters, making it highly relevant for Indian underground coal mines. Sheorey [16] proposed theoretical considerations for coal pillar strength and explained the stress distribution behaviour within pillars.

Research by Mark [11] introduced the Analysis of Longwall Pillar Stability (ALPS) methodology, which significantly improved longwall pillar design practices in the United States. Peng [13], Brady and Brown [14], and Hoek and Brown [15] further expanded the understanding of underground rock mechanics and ground control principles. More recent studies by Esterhuizen et al. [19] and Zhang and Canbulat [20] emphasised the application of numerical modelling and deep mining considerations in modern pillar design.

Indian researchers such as Das [17], Singh and Singh [18], and Kishore [8,10,26] have contributed substantially to underground coal pillar design and geotechnical stability assessment under Indian mining conditions. Their studies highlighted the necessity of integrating empirical methods with numerical modelling approaches for improved underground mine planning and safety evaluation.

4. Geological and Geotechnical Considerations

The stability of coal pillars is strongly influenced by geological and geotechnical conditions prevailing within underground mines. Depth of cover is one of the most significant factors because vertical stress increases proportionally with mining depth. Higher overburden pressure generates greater stress concentration around underground excavations, thereby increasing the likelihood of pillar crushing and failure [20].

Coal seam thickness also affects pillar stability because thicker seams produce taller pillars with lower width-to-height ratios. Pillars with low width-to-height ratios generally exhibit reduced confinement and lower strength compared to squat pillars [5]. Geological discontinuities such as joints, cleats, faults, and bedding planes weaken coal mass integrity and facilitate crack propagation under loading conditions [14].

Moisture content is another important parameter influencing coal strength. Increased moisture weakens inter-particle bonding within coal and accelerates weathering processes, thereby reducing pillar strength over time. Variations in in situ horizontal stress conditions can also induce shear failure and rib spalling around underground excavations, particularly in deep mining conditions [19].

5. METHODOLOGY

The methodology adopted in this research involved field data analysis, laboratory investigations, empirical calculations, and stability assessment procedures. Representative mine parameters, including pillar width, gallery width, seam height, depth of cover, and overburden characteristics, were collected and analysed. Empirical pillar strength equations such as the CMRI, Bieniawski, and Salamon–Munro models were used to estimate pillar strength under varying conditions.

The tributary area theory was applied to determine the average stress acting on coal pillars. According to this theory, a pillar supports the weight of the overlying rock mass extending halfway into the surrounding galleries. This method is widely accepted for estimating pillar load in bord and pillar workings [13].

Laboratory tests, including point load testing, Brazilian tensile strength testing, and moisture content analysis, were performed to determine the mechanical properties of coal samples. The experimental data obtained from these tests were subsequently used for pillar stability assessment and factor of safety calculations.

6. Pillar Strength Models

The CMRI formula is one of the most widely accepted empirical approaches for coal pillar design in Indian underground mines. The equation considers seam height, pillar width, and depth of cover while estimating pillar strength under Indian geo-mining conditions [4]. The generalised form of the equation is:

$$S = 0.27\sigma_c h^{-0.36} + \left(\frac{H}{250} + 1\right)\left(\frac{W}{h} - 1\right)$$

where SSS represents pillar strength, W is pillar width, h is seaming height, and H is depth of cover.

Bieniawski [1] proposed another widely used empirical relation based on large-scale in situ tests:

$$S = \sigma_c \left(0.64 + 0.36\frac{W}{h}\right)$$

The Salamon–Munro formula [2], derived from statistical back-analysis of stable and failed pillars, is expressed as:

$$S = 7.176\frac{W^{0.46}}{h^{0.66}}$$

These empirical formulas provide practical approaches for estimating coal pillar strength and are widely used in underground coal mine design.

7. Determination of Pillar Load

The tributary area theory was used in the present study for estimating pillar loading conditions. According to this method, each pillar carries the load of the overlying strata corresponding to its tributary area. For square pillars, the average pillar stress is calculated using:

$$P = \gamma H \left(\frac{W + B}{W}\right)^2$$

where P denotes pillar load, γ is the unit weight of overburden, H represents depth of cover, W is pillar width, and B is gallery width. The method assumes uniform load distribution and remains one of the most practical approaches for underground coal mine design [13].

8. Experimental Investigation

Laboratory investigations were conducted to determine the geomechanical properties of coal samples collected from representative underground mining conditions. Point load testing was performed to determine the point load strength index I50I_{50}I50, which was subsequently converted into uniaxial compressive strength values. Brazilian tensile strength testing was conducted using diametrical loading arrangements to evaluate the indirect tensile strength characteristics of coal specimens.

Moisture content analysis was carried out using a muffle furnace technique. The average moisture content of the tested samples was found to be approximately 0.292%, indicating comparatively low moisture influence under the investigated conditions. However, long-term exposure to humid underground environments may significantly reduce coal strength and should therefore be considered during mine design and stability assessment [14].

9. RESULTS AND DISCUSSION

Representative calculations were performed for varying pillar widths under constant seam height conditions. The results indicated a substantial increase in pillar strength with increasing pillar width. For example, a pillar width increase from 15 m to 20 m resulted in a significant enhancement in load-bearing capacity and overall factor of safety.

The analysis further demonstrated that gallery width has a major influence on tributary loading conditions. Larger gallery widths increase the tributary area associated with each pillar, thereby increasing vertical stress concentration and reducing stability. This observation is consistent with previous studies conducted by Salamon and Munro [2] and Mark [11].

The width-to-height ratio was found to be one of the most critical parameters governing pillar behaviour. Slender pillars exhibited lower strength and higher susceptibility to crushing failure, whereas squat pillars demonstrated improved confinement and greater stability [5,16]. Increasing the width-to-height ratio, therefore, provides enhanced resistance against progressive failure mechanisms.

The factor of safety was calculated using the ratio of pillar strength to applied stress:

$$FOS = \frac{S}{P}$$

The study indicated that a factor of safety between 1.5 and 2.0 is generally suitable for long-term underground stability under Indian mining conditions [4]. Pillars with lower factors of safety were found to be highly vulnerable to instability and potential collapse.

Comparative analysis of empirical models revealed that the CMRI formula provides more realistic results for Indian coalfields because it was specifically developed considering local geological and mining conditions. The Bieniawski and Salamon–Munro equations also produced reliable estimates but were comparatively less representative for Indian seams under certain conditions.

10. Failure Mechanisms of Coal Pillars

Coal pillar failure generally initiates at pillar ribs due to high stress concentration and gradually propagates toward the pillar core. Common failure mechanisms include crushing, rib spalling, shear failure, progressive yielding, and burst-type failure under deep mining conditions [14,20]. Progressive failure is particularly dangerous because local pillar deterioration may eventually trigger large-scale collapse of underground workings.

The presence of geological discontinuities further accelerates crack propagation and instability. Deep underground mining conditions often generate complex stress redistribution patterns around pillars, leading to sudden failure events if proper design criteria are not maintained [19].

11. Advanced Approaches in Pillar Design

Modern underground coal mine design increasingly incorporates advanced numerical modelling and computational techniques for improved stability assessment. Finite element methods, finite difference methods, and distinct element modelling approaches enable detailed simulation of stress redistribution and failure behaviour around underground excavations [18,19].

Software packages such as FLAC3D, UDEC, and Phase2 are commonly used for underground geotechnical analysis. Probabilistic methods and data-driven approaches are also gaining importance in modern mine planning because they allow uncertainty quantification and risk-based design optimisation [9,26].

Although numerical modelling provides highly detailed insights into pillar behaviour, empirical methods continue to remain essential due to their simplicity, field applicability, and reliability for preliminary design purposes [13].

12. Recommendations

Based on the findings of the present investigation, it is recommended that pillar width should be increased proportionally with mining depth to maintain adequate stability conditions. Gallery widths should be optimised to minimise tributary loading and stress concentration effects. Regular geotechnical monitoring of pillar deformation and roof behaviour should be implemented in underground workings to identify early signs of instability.

The study further recommends integrating empirical pillar design approaches with numerical modelling techniques for a more accurate assessment of underground stability. Moisture control measures should also be adopted because prolonged exposure to humid environments can significantly reduce coal strength over time. Installation of real-time geotechnical instrumentation and stress monitoring systems may substantially improve underground safety and ground control management.

13. CONCLUSION

The present study provides a comprehensive analysis of coal pillar strength and stability in underground coal mines using empirical methods, laboratory investigations, and geotechnical evaluation techniques. The results demonstrate that pillar geometry, width-to-height ratio, gallery width, and depth of cover significantly influence pillar stability and factor of safety. Increasing pillar width improves load-bearing capacity and reduces stress concentration, whereas increasing gallery width increases tributary loading and instability risk.

Among the empirical formulations studied, the CMRI model was found to be the most suitable for Indian underground coal mines because of its calibration with Indian geo-mining conditions. The research also confirmed that moisture content and geological discontinuities adversely affect pillar strength and long-term stability.

The study emphasises the importance of combining empirical methods with advanced numerical modelling techniques for optimised underground pillar design. Proper pillar dimensioning, geotechnical monitoring, and risk-based planning are essential for improving underground mine safety and ensuring sustainable coal extraction practices. The findings of this research can assist mine planners, geotechnical engineers, and researchers in developing safer and more efficient underground coal mining systems.

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