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OPTIMIZED DESIGN OF COAL PILLARS IN BOARD AND PILLAR MINING: AN EMPIRICAL AND ANALYTICAL APPROACH

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ABSTRACT

In underground coal mines, we leave some coal in the form of "pillars" to support the roof and prevent the mine from collapsing. If these pillars are too small, the roof can fall and cause accidents. If they are too big, we lose valuable coal. So, designing the right size and shape of pillars is very important. This paper explains how to decide the best pillar size using both simple formulas and computer models. We have studied a real coal mine to understand how pillar size affects safety and how much coal we can take out. We also checked how rock strength, depth of mine, and distance between pillars change the safety of the mine. The results show that by using proper design methods, we can make the mine safer and also get more coal. This study will help mining engineers to plan better pillar designs and avoid accidents in underground coal mines. The primary aim of this study is to develop an effective and optimized approach for the design and sizing of coal pillars in underground coal mines operating under the board and pillar method. In underground coal mining, especially in India, the board and pillar method is one of the most commonly used techniques due to its adaptability to varying seam conditions and simplicity of operation. In this method, a network of roadways (boards) is developed, and coal pillars are left behind to support the mine roof. The correct design of these pillars is critical—oversized pillars lead to resource loss, while undersized pillars can cause mine collapse, threatening safety and productivity. Therefore, the aim is to determine the most suitable pillar dimensions that ensure both maximum coal recovery and long-term mine stability. The study also compares the board and pillar method with the longwall mining method, highlighting differences in resource recovery, safety, and mechanization. While longwall mining offers higher coal recovery through full-seam extraction, it may not be suitable in all geological conditions or existing Indian mines. Therefore, optimizing the board and pillar approach remains essential in many mining scenarios. The final goal is to propose a cost-effective, scientifically validated pillar design methodology tailored for underground coal mines in India, which aligns with current DGMS regulations and enhances both operational safety and economic efficiency.

Keywords: Board and pillar, production, pillar design, coal

1. INTRODUCTION

Underground coal mining remains a crucial method for coal extraction, especially in regions where surface mining is not feasible. Among the underground mining techniques, the board and pillar method are widely adopted due to its adaptability to various geological conditions and relatively simple layout. In this method, large blocks of coal - called pillars - are intentionally left behind to support the mine roof and prevent collapse, while rooms are excavated around them to extract coal. The performance, stability, and safety of this method significantly depend on the proper design, shape, and size of these pillars, making pillar design a critical element of mine planning.

The objective of this study is to explore the design and optimization of pillar dimensions to ensure both maximum coal recovery and structural safety. Poorly designed pillars can lead to catastrophic failures such as roof collapses, ground subsidence, or unsafe working conditions, while overly conservative designs may lead to significant coal loss. Therefore, optimization involves achieving a balance between economics and engineering safety by considering geological data, stress analysis, empirical formulas, and numerical modelling. This research aims to analyses current design practices, evaluate real-world data, and propose optimized pillar

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configurations tailored to specific underground coal mining conditions.

1.1 Underground coal using pillar support in mining

Underground coal mining using pillar support, commonly known as the room and pillar method, is a traditional and widely practiced technique where coal is extracted in a grid-like pattern, leaving behind large pillars of unmined coal to support the roof of the mine. These pillars act as load-bearing structures that prevent roof collapse and ensure the safety of underground operations. This method is particularly effective in shallow to moderately deep coal seams and offers controlled excavation with relatively simple planning and execution.

The stability and safety of the mine heavily depend on the proper design and sizing of the pillars. Factors such as depth of cover, geological conditions, seam thickness, and loading conditions must be considered to determine the optimal pillar dimensions. Although the method may leave some coal unmined within the pillars, it strikes a balance between resource recovery and structural safety. Technological advancements in rock mechanics and mine planning have further improved the efficiency and safety of pillar-supported underground coal mining.

1.2 Underground coal using pillar support in India

In India, underground coal mining using the board and pillar method has been a traditional and widely practiced technique, particularly in the coalfields of Jharkhand, West Bengal, Chhattisgarh, Odisha, and Madhya Pradesh. Due to the geological conditions of Indian coal seams - such as relatively thin seams, irregular shapes, and moderate depths - the room and pillar method has remained more practical compared to mechanized methods like longwall mining. In this system, pillars of coal are left unmined in a calculated pattern to support the roof, providing a simple yet effective way to maintain stability within the mine. Indian mining agencies like Coal India Limited (CIL) and its subsidiaries rely heavily on this method, especially in older and deeper mines where full mechanization is not yet feasible.

However, the board and pillar method in India faces several challenges such as low recovery rates, safety risks due to improper pillar sizing, and limitations in mechanization. To address these issues, efforts are being made to improve pillar design through optimization techniques, updated safety standards, and the use of rock mechanics and numerical modelling tools. The Directorate General of Mines Safety (DGMS) has established strict guidelines for pillar dimensions based on depth, seam thickness, and rock load to prevent collapses. In recent years, the integration of technology, geo-mechanical analysis, and mine planning software has started to modernize pillar design approaches in Indian underground coal mining, aiming to enhance both productivity and worker safety.

2. OBJECTIVES

1. To study the fundamental principles of underground coal mining, with a focus on the Board and Pillar method, and to understand its significance in the Indian mining context.
2. To analyse existing pillar design practices used in Indian and international underground coal mines, and identify limitations related to safety, stability, and coal recovery.
3. To understand the mechanical behaviour of coal pillars under different geological and mining conditions, including depth of cover, seam thickness, roof rock strength, and pillar geometry.
4. To review and apply empirical design formulas (e.g., Bieniawski's, Salamon-Munro) for pillar strength and safety factor evaluation in board and pillar mining layouts.
5. To develop numerical models using software tools such as FLAC3D, Phase2, or similar, for simulating stress distribution, pillar failure, and roof convergence under varied loading conditions.

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6. To optimize pillar dimensions (width, height, and spacing) for achieving the best balance between maximum coal recovery and long-term mine stability.
7. To compare the performance and recovery rates of the Board and Pillar method with the Longwall method, highlighting where each method is most applicable.
8. To examine and incorporate relevant safety guidelines, particularly those issued by the Directorate General of Mines Safety (DGMS), into the pillar design process.
9. To validate the proposed design models through real case studies, mine data, or simulations, and recommend site-specific pillar designs.
10. To provide a set of practical recommendations and design standards for use by mine planners, engineers, and regulatory authorities, ensuring both productivity and worker safety.

3. METHODOLOGY

The methodology adopted in this study involves a systematic approach combining literature review, data collection, analytical calculations, and numerical modeling to design and optimize pillar dimensions in underground coal mines.

4. LITERATURE REVIEW

Pillar design plays a crucial role in the stability and safety of underground coal mines, particularly in the board and pillar method, which is widely used in India and globally. Over the decades, several researchers and institutions have contributed to the development of pillar design methodologies, ranging from empirical formulas to advanced numerical modeling techniques. This review explores the evolution of these approaches and their application in the real-world mining environment.

4.1 Historical Background of Pillar Design in Underground Coal Mining

The use of pillars in underground coal mining dates back centuries and has been one of the earliest methods to safely extract coal from beneath the earth’s surface. The board and pillar method, also known historically as the room and pillar method, originated in Europe and later spread globally due to its simplicity and flexibility in application. Initially, pillars were designed based purely on experience, trial-and-error, and thumb rules without considering geological variability or rock mechanics. This led to frequent mine collapses, subsidence, and inefficient coal recovery.

With the advent of mining engineering as a scientific discipline in the 19th and 20th centuries, efforts were made to formalize pillar design. Early researchers like Salamon & Munro, Bieniawski, and others introduced empirical equations that considered coal strength, pillar dimensions, and depth of cover. These models significantly improved safety by offering guidelines for designing stable pillar layouts. In India, the board and pillar method has been used extensively since colonial times, particularly in coal-rich regions like Raniganj, Jharia, and Bokaro. Due to the presence of multiple seams, faulted geology, and relatively shallow depths, this method became the backbone of India’s underground coal production.

4.2 Present Status and Modern Developments

In modern times, pillar design has evolved to include empirical, analytical, and numerical modeling techniques, making it far more precise and adaptable to site-specific conditions. Advances in rock mechanics, geotechnical instrumentation, and computer simulation tools have made it possible to design and optimize pillars with greater confidence. Today, mine planners use software such as FLAC3D, UDEC, and Phase2 to simulate stress distribution, pillar load-bearing

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capacity, and potential failure zones.

In India, although longwall mining has been introduced in some areas for higher coal recovery, the board and pillar method still dominates, especially in old mines and in regions with difficult seam geology. Present-day challenges include:

- Optimizing pillar dimensions to improve recovery.
- Preventing accidents due to pillar failure or roof collapse.
- Reducing coal loss while maintaining safety.

Organizations like Coal India Ltd. (CIL) and research bodies such as CIMFR and DGMS are actively working on improving pillar design through updated guidelines, safety regulations, and pilot studies.

4.3 Typical specification

The typical specification for the design and optimization of pillar size in underground (U/G) coal mines focuses on achieving a balance between safety, stability, and maximum coal recovery. Pillars are typically designed based on seam thickness (1.5–4.0 meters), depth of cover (50–500 meters), and geotechnical parameters like the uniaxial compressive strength of coal (5–15 MPa) and surrounding rock. The board and pillar mining method is commonly used, with pillar sizes ranging from 10 to 30 meters and gallery widths of 4.5–6 meters. A factor of safety (FOS) greater than 1.6 is maintained, and the extraction ratio is kept between 55–70% to prevent roof collapse or surface subsidence. Empirical design formulas such as Salamon-Munro and Bieniawski are often supported by numerical modeling using software like FLAC3D or Rocscience for stress and failure prediction. These specifications align with DGMS (India) guidelines and international mining standards.

4.4 Conditions for Operation of Underground Coal Mining (Pillar Support System)

1. Geological Conditions
   - Uniform and continuous coal seam.
   - Moderate seam thickness (1.5 – 4.0 meters)
   - Strong and competent roof and floor strata.
   - Minimal geological disturbances (faults, folds, etc.).
2. Depth of Cover
   - Generally suitable for shallow to moderate depths (up to ~500 meters).
   - Increased pillar size required for deeper seams.
3. Coal Strength and Rock Mechanics
   - Adequate uniaxial compressive strength (UCS) of coal and surrounding rock.
   - Safe Rock Mass Rating (RMR) and Geological Strength Index (GSI).
4. Mine Layout and Design
   - Proper design of panel, galleries, and pillar grid.
   - Safe factor of safety (FOS ≥ 1.6) for pillars.
   - Balanced pillar-to-opening ratio.

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5. Pillar Dimensions

- Square or rectangular pillars of appropriate size.
- Proper inter-pillar spacing (usually 4.5–6 meters).
- Consistent height with seam thickness.

6. Ventilation and Accessibility

- Adequate air circulation for gas dilution and cooling.
- Safe access routes for workers and equipment.

7. Support Systems

- Use of roof bolts, steel props, or hydraulic supports where necessary.
- Regular monitoring of roof conditions and stress on pillars.

8. Drainage and Water Control

- Effective water drainage systems to avoid water accumulation.
- Prevent water-induced weakening of coal and roof strata.

9. Monitoring and Safety

- Real-time monitoring of ground movement and stress changes.
- Periodic inspection of roof, pillar conditions, and ventilation.
- Emergency escape routes and disaster management planning.

10. Compliance with Regulations

- Follow DGMS (India) or MSHA (USA) guidelines.
- Record keeping of design, inspections, and modifications.
- Worker training and safety protocols.

4.5 Classification of Underground Mining Methods Based on Pillar Design

In underground coal mining using the pillar support method, the most commonly followed system of working is the Bord and Pillar method. In this system, the coal seam is developed by driving a series of parallel galleries or “bords” in both the dip and strike directions, leaving behind square or rectangular blocks of coal called pillars. These pillars act as the main support for the roof, ensuring the stability of the underground workings. The development phase focuses on creating a network of roadways and pillars with carefully planned dimensions, based on geological conditions, seam thickness, and depth of cover. The layout is designed to provide ventilation, safe access, and efficient coal transport while maintaining structural integrity.

After the development is completed, and if conditions permit, the operation may proceed to the depillaring or pillar extraction stage. This is done in a systematic manner, often starting from the farthest end and retreating towards the main entry, allowing controlled roof collapse in the goaf area (the void left after coal extraction). Temporary roof supports like hydraulic props or wooden chocks are used during pillar extraction to ensure miner safety. This retreat mining or final extraction stage increases the overall recovery of coal, often boosting the extraction ratio from 40–50% during development to 60–70% after depillaring. The success of this working system

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depends on proper pillar design, effective ventilation, roof control, and strict adherence to safety regulations prescribed by agencies like DGMS in India.

4.6 Working (Advancing):

In the advancing method, galleries or bords are driven from the main entry point towards the boundaries of the panel or mining block. Coal is extracted while leaving behind pillars of coal for support. This phase is also called the development phase, as it prepares the mine layout and infrastructure. It provides better ventilation and transport access since it begins near the intake airways. However, coal recovery is limited (typically 40–50%) as the pillars remain intact during this stage to support the roof.

4.7 Depillaring (Final Extraction Phase):

After the development phase, depillaring is carried out to extract the coal left in the pillars. This is the stage of maximum coal recovery and involves managing the roof over mined-out areas. Depillaring is done using one of the following methods.

a) Depillaring with Stowing (Artificial Support):

- After a pillar is extracted, the void (goaf) is backfilled (stowed) with sand, fly ash, or other materials.
- This method supports the roof, prevents sudden collapse, and minimizes surface subsidence.
- It is suitable in urban or industrial areas where surface damage must be avoided.
- Commonly practiced in Indian coalfields (e.g., Jharia, Raniganj).

b) Depillaring with Caving (Natural Roof Collapse):

- In this method, once the pillar is removed, the roof is allowed to collapse naturally in a controlled manner.
- No artificial support is used in the goaf.
- It is cost-effective and simpler, but leads to surface subsidence, making it suitable only in uninhabited or forest areas.
- Used in longwall mining and some depillaring panels.

Working (Advancing): Initial phase; forms pillars; limited coal extraction.

Depillaring with Stowing: Controlled and safe; costly; reduces subsidence.

Depillaring with Caving: Cheaper; allows subsidence; suitable for rural/remote areas.

5. BOARD AND PILLAR METHOD

The Bord and Pillar method is a widely adopted underground coal mining technique that relies heavily on the design and stability of coal pillars to support the overlying strata. In this method, a network of roadways called bords (or rooms) is excavated in a planned grid-like layout through the coal seam, leaving behind unmined blocks of coal known as pillars. These pillars act as natural supports to maintain the integrity of the mine roof during the initial development phase. The stability of the entire mine largely depends on the size, shape, and strength of these pillars, making pillar design a critical element of this method. The design must consider several factors such as seam depth, coal strength, roof and floor conditions, and safety factor to prevent premature pillar failure, which could lead to roof collapse or surface subsidence.

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Once the development is complete and pillars have fulfilled their primary supporting function, the mine may proceed to the depillaring stage, where the pillars are systematically extracted to recover the remaining coal. This process can be carried out using either stowing (backfilling with sand or fly ash to support the roof) or caving (allowing controlled roof collapse). The success of this stage also depends on the initial pillar design, as improperly sized or weakened pillars can lead to uncontrolled caving and safety hazards. Therefore, in the Bord and Pillar method, pillar design is not only essential for structural stability during development but also influences the efficiency and safety of the depillaring phase, ultimately affecting overall coal recovery and mine sustainability.

6. LONGWALL METHOD

The longwall mining method is a highly mechanized and efficient underground coal mining technique where coal is extracted along a long, continuous face that typically ranges from 100 to 300 meters in length. Unlike the bord and pillar method, longwall mining does not rely on permanent coal pillars to support the roof in the extraction area. Instead, the roof is temporarily held up by hydraulic powered roof supports, which move forward with the mining machine as the coal is extracted. Once the support moves, the roof behind the working face is allowed to collapse in a controlled manner, a process known as caving. This method allows for high coal recovery (up to 90–95 percent) and is particularly suitable for thick, uniform seams at moderate to deep depths.

Although pillar design is not the primary feature of the longwall method, it still plays an important role in the development of gate roads—parallel tunnels that provide access to the longwall face. These gate roads are supported by chain pillars, which are rectangular or square blocks of coal left unmined to ensure the structural stability of the entries throughout the panel’s life. The design of these chain pillars is critical because they must withstand the stress concentrations generated by the advancing longwall face. Key factors such as overburden pressure, coal strength, seam depth, and panel geometry must be considered during the design process. Thus, while longwall mining minimizes the use of pillars in the extraction zone, strategic pillar design remains essential for maintaining safety and infrastructure stability in longwall operations.

7. ROOM AND PILLAR METHOD SYSTEMS – SELECTION CRITERIA AND IMPACT OF PILLAR DESIGNING

The room and pillar method is a widely used underground coal mining system where coal is mined by creating a network of rooms, leaving behind coal pillars to support the roof. Several variations of this method exist, such as conventional room and pillar, batwing pillar design, and panel systems. The choice between room and pillar, batwing board and pillar, or longwall methods depends on multiple factors including coal seam thickness, depth of overburden, geological disturbances, roof and floor strength, expected recovery rate, and surface conditions. For example, in shallow, strong strata conditions, conventional room and pillar is preferred. In weak roof or floor conditions, batwing or split-pillar designs offer added support. Longwall mining is generally selected for thick, deep seams with consistent geology, where higher recovery and mechanization are prioritized.

Pillar designing plays a central role in the success and safety of any underground mining method. In room and pillar systems, the size, shape, and arrangement of pillars directly influence ground stability, ventilation, and coal recovery. Properly designed pillars prevent roof collapse and ensure the safe operation of the mine. If pillars are too small or irregular, it increases the risk of failure, endangering lives and equipment. Oversized pillars, while safer, reduce the amount of coal extracted, lowering the economic efficiency of the mine. In batwing and panel systems, pillar design is modified to reduce stress concentration and support wide openings. Even in longwall mining, where pillars are minimal, chain pillar design along gate roads is essential to maintain stability. Therefore, pillar design not only determines the safety of the mining operation but also affects recovery, cost, and long-term ground control.

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8. DRILLING AND BLASTING IN UNDERGROUND COAL MINING – EFFECT ON PILLAR DESIGNING

In underground coal mining, drilling and blasting is commonly used to fragment coal and rock for easier extraction, especially in non-mechanized or partially mechanized operations. While this method is effective for breaking hard material, it can have a negative impact on the surrounding coal pillars. The shock waves and vibrations produced during blasting can lead to the development of cracks or fractures within the pillar body and along its edges. Over time, this can reduce the strength and stability of the pillars, increasing the risk of failure or roof collapse in the surrounding area.

To reduce these effects, pillar designing must take into account the influence of drilling and blasting activities. Pillars near the blasting zone may need to be larger or reinforced to withstand the stress caused by repeated blasting cycles. Safe drilling patterns, controlled charge quantities, and proper spacing are essential to avoid overbreak, which can reduce the effective width of the pillar. In some cases, a buffer zone is left between the active blasting face and the load-bearing pillars to protect them from direct impact. Overall, careful planning of blasting operations and thoughtful pillar design are closely linked and necessary to ensure the long-term safety and performance of the underground mine.

9. MINING PILLARS USED IN INDIA – SIZE, SHAPE, RETRACTION, AND THEIR EFFECTS

In Indian underground coal mining, particularly in the bord and pillar method, pillars play a vital role in roof support during coal extraction. Their design (size and shape) is based on geological conditions, mining depth, coal seam thickness, strength of coal and surrounding strata, and safety standards set by DGMS (Directorate General of Mines Safety). Pillars are not permanent features in most cases; after initial development, they are partially or fully extracted (depillared) to improve coal recovery.

In India, pillar sizes typically range from 10 meters × 10 meters to 30 meters × 30 meters, depending on the overburden pressure and depth of the seam. The height of the pillar is usually equal to the thickness of the seam, which ranges between 1.5 to 4.0 meters. The shape is generally square, as it offers uniform load distribution and balanced support in all directions. However, in some cases where panel or gallery layouts are irregular or constrained, rectangular or modified shapes (like barrier or batwing pillars) may be used.

During the depillaring or retraction phase, pillars are extracted in a systematic sequence, starting from the farthest point and retreating toward the mine entrance. This is done using either caving, where the roof is allowed to collapse naturally, or stowing, where goaf areas are filled with sand or fly ash to prevent roof collapse and surface subsidence. The selection of pillar size and extraction method directly affects safety, coal recovery, and cost-efficiency.

10. ADVANTAGES AND DISADVANTAGES OF PILLAR SIZE AND SHAPE

10. 1 Advantages

1. Safety of Mine Workers: Correct pillar size and shape helps support the roof properly. Reduces the chances of roof falls and accidents.
2. Better Stability of Underground Workings: Well-designed pillars keep the mine stable for a long time. Helps in long-term working without collapse.
3. Controlled Ground Pressure: Pillars help balance the load from the overlying rocks. Avoids sudden pressure release or failure.
4. Maximum Coal Recovery (If optimized): Proper size ensures enough coal is taken out while maintaining safety. Avoids unnecessary wastage of coal left in very large pillars.

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5. Helps in Future Planning: Good design makes future extensions or deeper mining possible. Reduces cost of re-support or repairs.

10.2 Disadvantages

1. If Pillars Are Too Small: Not strong enough to hold the roof. Can cause sudden collapse and serious accidents. Higher risk of pillar burst or failure.
2. If Pillars Are Too Large: A lot of coal is left unmined (waste of resources). Reduces overall production and profit. Poor use of space in the mine.
3. Improper Shape (e.g. too long or thin): May cause stress concentration in corners. Leads to pillar spalling or cracking. Unstable under high roof pressure.
4. Difficult for Ventilation and Movement: If pillars are not well-planned, it becomes harder to design ventilation paths and transport systems.

10.3 Pillar Load Estimation – Tributary Area Method

The tributary area method is widely used to estimate the vertical load on a coal pillar. It assumes that each pillar supports the overlying rock directly above it and a portion of the adjacent roof area.

- Formula:

  Load on pillar = Overburden height × Unit weight of overburden × Area supported

  Example: For a 25 m × 25 m pillar with 200 m of overburden at 25 kN/m³ unit weight.

  Load = 25 × 25 × 200 × 25 = 3,125,000 kN
- This method assumes uniform stress distribution, which is a simplification. Actual stress varies due to geology and mining geometry.

10.4 Pillar Strength Calculation – Empirical Formulas

CIL and CMPDI use empirical formulas to calculate the strength of coal pillars based on past data and field experience. The most used formulas include:

- **Salamon-Munro Formula:**

  Used widely in Indian coalfields, particularly for shallow and moderate depth seams.

  $$S = k\left(\frac{w}{h}\right)^{0.5}$$

  where:

  - S = strength of pillar,
  - k = coal strength factor (typically 5–15 MPa),
  - w/h = width-to-height ratio of the pillar.

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- **CMRI Formula (Central Mining Research Institute):**

  Includes correction factors for joint frequency, floor conditions, and depth.

  Used in Indian DGMS-approved mine planning.

These formulas are calibrated with Indian conditions and incorporate coal seam properties, including compressive strength and seam thickness.

10.5 Safety Factor (FOS)

The factor of safety (FOS) is the ratio of pillar strength to the load acting on the pillar:

- FOS = Pillar Strength / Pillar Load
- For Indian conditions, minimum FOS required is 1.6 to 2.0 as per DGMS (Directorate General of Mines Safety) guidelines.
- In risky or deep areas, FOS may be increased to ensure stability and prevent sudden pillar failure.

10.6 Pillar Size and Shape

- Typical Size in India: 10 m × 10 m to 30 m × 30 m.
- Height: Equal to the seam thickness (1.5 m to 4 m).
- Shape: Mostly square, as it provides uniform stress distribution in all directions. Rectangular or modified shapes like batwing or barrier pillars are used in complex or irregular layouts.
- Width-to-Height Ratio (w/h): Maintained at 3:1 or higher to improve confinement and reduce risk of failure.

10.7 Geological Adjustments

CIL mines often experience faults, joints, weak roof or floor conditions, especially in areas like Jharia, Raniganj, and Korba. In such cases:

- Pillar strength is reduced using correction factors:
  - f_1 = joint frequency correction
  - f_2 = floor/roof friction angle
- Pillars are made larger or differently shaped (e.g., barrier pillars or snub pillars) in such zones to handle stress concentration.
- Advanced software like FLAC3D, Phase2, and Rocscience is used to model stress behavior and validate design.

10.8 Final Design Iteration

The final pillar layout is derived after combining:

- Empirical calculations.
- Field surveys (roof test drilling, floor samples).

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- Numerical modeling (for deep or complex mines).
- DGMS safety standards.
- Economic considerations (coal recovery vs. safety).

CIL's mine planners often prepare pillar design flowcharts, which guide the decision-making process from initial coal seam data to final pillar layout and depillaring sequence.

11. UNDERGROUND PILLAR DESIGNING IN OTHER MINES (NON-COAL AND INTERNATIONAL PRACTICES)

Pillar designing is not limited to coal mines; it is a critical aspect of many underground mining operations involving different minerals like limestone, copper, lead, zinc, and salt. The principles of pillar design vary depending on the type of material mined, geological conditions, and mining method used. In non-coal mines and international mining operations, more advanced design techniques and monitoring technologies are often used to optimize safety and recovery.

In metal mines (such as lead, zinc, or copper), pillars are often larger and more irregular in shape compared to those in coal mines due to higher excavation heights and stronger rock masses. The room and pillar method is commonly used in flat-lying deposits, and pillars may be designed based on rock mass classification systems like the RMR (Rock Mass Rating) or Q-system, which account for joint spacing, rock strength, and groundwater conditions. Numerical modeling software such as FLAC3D, Phase2, or UDEC is widely used to simulate stress distribution and assess pillar stability over time. Unlike coal, where pillars are generally left unmined during the development stage, ore pillars in metal mines may be fully or partially extracted later using artificial support or backfilling to maintain stability.

In salt and potash mines, which often have soft and plastic rock behavior, pillar design is more complex. These pillars are prone to time-dependent deformation (creep), which can cause gradual loss of strength and eventual collapse. Here, pillar width-to-height ratios are kept very high—sometimes 6:1 or more—to delay failure and ensure long-term stability. Long-term monitoring of pillar convergence and stress is essential in such environments, and designs are often adjusted based on in-situ measurements.

In international coal mines, especially in countries like Australia, South Africa, and the United States, pillar designs are often more refined due to stricter enforcement of geotechnical monitoring. Design standards include detailed analysis of subsidence, gas drainage, and surface protection, particularly near populated areas. Advanced monitoring systems using strain gauges, extensometers, and microseismic sensors are installed to detect stress changes and warn of potential failures.

In summary, pillar design in other underground mines follows the same basic principles of balancing load, strength, and safety, but varies in complexity depending on the material being mined and the mine's location. The use of advanced modeling, instrumentation, and rock mass classification ensures that pillars are not only structurally safe but also allow for optimized mineral recovery.

11.1 Data Collection, Recording and Acquiring in Underground Pillar Designing

In underground mining, particularly in the design of pillars, data collection, recording, and acquiring are essential steps to ensure the stability and safety of the mine. Proper planning and decision-making depend on the quality and accuracy of this data, which includes geological, geotechnical, hydrological, and operational information.

Data collection is the first step, where raw information is gathered from the mining site. This includes geological data such as seam thickness, dip, fault lines, joint patterns, and rock types. Geotechnical data includes coal and rock strength, rock mass classification, joint orientation and spacing, and properties of the roof and floor strata. Other important data includes in-situ stress

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measurements, overburden depth, water table conditions, and mining layout parameters like gallery width, pillar dimensions, and development sequences. These data are obtained through core drilling, geophysical logging, laboratory tests, field mapping, and use of in-situ testing tools like borehole pressure cells and plate load tests.

Recording involves documenting the collected data accurately and systematically. Field observations are usually written in logbooks or recorded in digital devices like tablets or data loggers. Borehole logs, sample test results, and instrument readings are properly formatted and stored in physical or digital formats. High-resolution photographs, mapping sketches, and GPS-based location data also support the documentation process. In mechanized or monitored mines, automated systems continuously record ground movement, stress, and water inflow using sensors and transmitters.

Acquiring and organizing the data refers to compiling all relevant information into a central platform for analysis. This may involve entering data into spreadsheets, databases, or mining software. Geotechnical modeling tools like Phase2, FLAC3D, or Rocscience software are then used to simulate mine behavior under various stress conditions. Geological modeling software helps visualize seam geometry and mine layout in three dimensions. Once organized, the data is used to calculate pillar load, design pillar size and shape, estimate safety factors, and plan mining sequences. In summary, a strong and systematic approach to data collection, recording, and acquiring ensures that pillar design is accurate, safe, and aligned with actual site conditions.

11. 2 Calculation and programming

The above goals could only be achieved if they were pursued in a methodical manner. Knowing everything there is to know about a goal is always the first step. As a result, we must begin with a literature review. In this regard, books, journals, and articles will supply a wealth of information that should be properly researched and learned.

This can be approached by two ways:

- Data collection
- Data analysis

This will be followed by mine visits & collection of data from the field.

Location of seam, depth of seam, seam thickness, and other geological data will be collected, while borehole data, pillar dimensions, and other mining data will be obtained.

- Mine samples will need to be gathered, safely packaged, and delivered to a lab for analysis.
- Different types of experiments will be carried out, including estimating the strength qualities of coal.
- It will be used to compute the safety factor.
- The extraction ratio will be assessed based on the safety factor. We can achieve the experiment's goal by approaching it in the manner described above.

12. PILLAR STRENGTH FORMULAS

➢ CMRI formula

The pillar w/h ratio, the pillar's uniaxial compressive strength, the height of the seam, and the depth of the cover were all factors considered by CMRI when developing a formula for pillar strength.

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

S = Pillar strength (MPa)

σ_c = Uniaxial compressive strength (UCS) (MPa)

h = Working height or seam height (in m)

H = Depth of cover (in m)

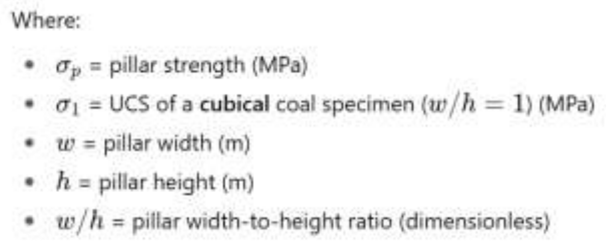
w = Pillar width (in m)

Numerous pillar strength formulas have been proposed, but five formulas are used most commonly (Bieniawski, 1984; Peng, 1986). Each formula specifies its own appropriate factor of safety. These are given below.

- **Obert-Duvall/Wang Formula (Obert and Duvall, 1967)**

This formula is given as:

$$\sigma_p = \sigma_1 \left(0.778 + 0.222\,\frac{w}{h}\right)$$



Where:

- σ_p = pillar strength (MPa)
- σ_1 = UCS of a **cubical** coal specimen ($w/h = 1$) (MPa)
- w = pillar width (m)
- h = pillar height (m)
- w/h = pillar width-to-height ratio (dimensionless)

This equation, according to Obert and Duvall, is applicable for w/h ratios ranging from 0.25 to 4.0, assuming gravity loading.

- **Holland - Gaddy Formula**

Holland & Gaddy, Holland (1964) extended the work by Gaddy (1956) and proposed the following formula:

$$\sigma p = k\ \sqrt{}w\ h$$

The Gaddy factor is k, the pillar dimensions are w and h, and the pillar strength is psi. For the design of coal pillars, Holland advised a safety factor of 2.0, with a range of 1.8 to 2.2.

- **Holland Formula**

In a 1973 publication, Holland proposed a new way of expressing the strength of coal pillars, namely:

$$\sigma p = \sigma 1 * \sqrt{}\ w\ h$$

Where σ1 is the strength of cubical pillars (w = h = 1). In fact, it can be understood as the strength of coal specimens at crucial sizes, and it needs to be determined. A safety factor of 2.0 is recommended.

➢ Salamon-Munro Formula

The following formula for pillar strength was proposed:

$$\sigma p = k * R * w\ 0.46\ h\ 0.66$$

Where, σp the strength is in psi, and the pillar dimensions w and h are in feet. For this calculation, the suggested safety factor is 1.6, with a range of 1.31 to 1.88.k is the UCS of a 1ft3 coal sample (in lb/in2), and R is the long-term Strength factor.

In SI units, the above equation becomes:

$$\sigma p = 0.79 * k * R * w\ 0.46\ h\ 0.66$$

Where, σp the strength is in MPa while w and h are in meters. K is the UCS of 1m3 coal sample (in MPa) and R is the long-term Strength factor.

➢ Bieniawski Formula

This formula is based on in situ tests on coal pillars on a massive scale. All of these studies looked into different pillar-strength formulas. The pillar-strength formula can be stated in a normalised form to make the in-situ test results more widely applicable (i.e., not just to the location where the testing were performed).

The Bieniawski equation in its generalised form is:

$$\sigma p = \sigma 1\ [0.64+ 0.36\ w\ h\ ]$$

Where σp is pillar strength, w is pillar width, h is pillar height, and σ1 is the strength of a cubical specimen of critical size or greater (e.g., about 3 ft or 1 m for coal). Bieniawski (1969) and Bieniawski and van Heerden (1975) used large-scale in situ testing on 66 coal specimens with width-to-height ratios ranging from 0.5 to 3.4 to confirm this association.

➢ Pillar load determination

There are several methods for calculating the pillar load or, more accurately, the average pillar stress. The tributary area technique and the elastic deflection theory are the two most common. The tributary area hypothesis is the simplest method for determining the pillar load.

The pillar load can be computed using a number of well-known simplification assumptions:

$$Sp = [1.1H\ (w + B)\ (L + B)\ w * L]$$

Where Sp pillars load or the average pillar stress in psi,

H is is depth below surface in ft,

w is pillar width in ft,

L is pillar length in ft, and B entry width in ft. The term 1.1 H can be replaced by the virgin vertical pressure Sv derived from the overburden weight above the seam γH, where γ is the unit weight of the overburden. The pressure can be considered to increase at a rate of 1.1 psi/ft of depth.

For square pillars, that is, when w = L, Eq. becomes:

$$Sp = H\ [\ (w + B)\ 2\ w2\ ]$$

For inclined seams:

$Sp = H\ [\ (w+B)\ 2\ w2\ ](\mathrm{Cos}\theta+\mathrm{msin}\theta)$

Where,

θ= angle of inclination of seam

m = Poisson’s ratio

If the term extraction e is used (percentage extraction is 100e), which is defined as the ratio of mined-out area to total area, then the extraction e for rectangular pillars is

$e = 1 - [\ \ (w + B)\ ][\ L\ L + B\ ]$

This may also be rewritten as:

Sp=[$H\ (1-e)$]

- **Factor of safety**

Factor of Safety= σp/ Sp.

Where,

σp= Strength of pillar

Sp= Stress of pillar

The above approach of pillar design incorporates the following assumptions:

1. Only vertical pressure, which is continuous throughout the mined region, is applied to the seam. Stress transmission, on the other hand, happens in underground workings with stiff abutments. As a result, some of the vertical pressure may be eased.

2. Each pillar supports the rock column over an area equal to the pillar's cross-sectional area plus a fraction of the room's area, with the latter being shared equally by all neighbouring pillars. However, if the developing area is tiny, this is not true since the pillars in the centre of the excavation are under higher stress than the pillars towards the sides. It is normally only considered valid if the mined-out area exceeds the depth below the surface.

3. The weight is expected to be evenly distributed across the pillar's cross-sectional area. However, study has revealed that:

   a) Stress is not evenly distributed across the cross section of a single pillar, with the highest stress occurring at the corners formed by the intersection of three orthogonal planes, notably the pillar's two sidewalls and the roof or floor.
   b) As the percentage of extraction is increased, the tension on the pillars increases.
   c) The ratio of pillar width to pillar height affects the stress distribution in pillars.

13. Laboratory Techniques

- **Uniaxial compressive testing:**

This is the most popular test for determining the characteristics of any sample. After coring, cutting, and polishing, samples were prepared. The diameter of the sample obtained was 53.2 mm, while the length of the sample used for testing was 78 mm. It was indicated at what load the sample failed. The failure pattern was investigated.

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➢ Protodyakonov Test:

The Impact Strength Index (ISI) is a method of assessing coal strength that has a lot of potential for use in coal cutting and drilling. It also gives a sense of the rock's uniaxial compressive strength.

The impact strength index test was first developed by Protodyakonov to provide insight into the rock's strength, cut ability, and brittleness, and was further enhanced by Evans and Pomeroy (1966).

- This technique is based upon the crushability of rock under standard experimental condition
- This test is performed by a vertical cylinder apparatus which is 30 48 cm in height and has a steel plunger.
- 100 gm of sample is taken of size -4.75 mm to + 3.35 mm is taken in the cylinder
- 50 gm of sample is taken if the sample is coal.
- A plunger is dropped from a height of 65 cm into the cylinder in which the sample is kept.
- The weight of the plunger taken is around 2.4 kg.
- The plunger is dropped 20 times in the cylinder if the sample is rock and 15 times if the sample is coal.
- The crushed sample is collected and is sieved through 0.5 mm sieve.
- The -0.5 mm sample is collected and filled in the volumeter.
- The height “h” in the volumeter is measured.
- Protodyakonov impact strength index is found out by using the following formulae.

  P.S.I = $(20 \times n)/h$

  Where, P.S.I = Protodyakonov strength index n = no of blows h = height in the volumeter Typical Protodyakonov

Method of calculation

- Initial weight of sample =50 g for coal
- Initial weight of sample =100 g for rock
- Height in volumeter = h
- No of blows = n = 15 for coal
- No of blows = n = 20 for rock
- P.S.I = $20 \times n/h$

➢ Point Load Test

Point-load strength index, which is obtained underground on unprepared rock cores, can be used to determine the Uniaxial compressive strength of rock. The ratio of the applied load to the square of the core diameter is used to determine the point-load strength index. The uniaxial compressive strength and the point-load strength index have a strong relationship.

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The relationship is as follows:

Point Load Index: $I_s = P/d^2$

Where d= equivalent core diameter in mm.

$\sigma_c = 24\, I_s$

Where σ_c is the Uniaxial compressive strength and Isis the strength index obtained on NX core (54 mm in diameter).

It should be emphasised that the examined point-load strength index is for NX core, hence the results are only applicable to 54 mm core diameters.

- **Tensile Test**

The maximal stress created in a specimen during a tension test to rupture it is known as tensile strength. Making a rock specimen in the shape of a dumbbell or a dog bone is quite tough. Another option is to use some type of fixing agent, such as epoxy cement/glue, to hold the cylindrical sample at two ends and then apply tensile force to the two ends.

$\sigma_t = P_{max} / A$

Where, σ_t= Tensile strength,

P_{max}= load at failure,

A= area

13.1 Materials and methods

Data collection Bararee Colliery, Dhanbad, Bharat Coking Coal Limited (BCCL) provided the samples. They were then sealed in plastic bags to keep them dry and safe for laboratory examination.

- **Storage & transportation of samples**
  - The samples taken at the site are preserved in a separate location.
  - Plastic bags are used to store some of the samples that will be taken to the lab for testing.
  - Samples are typically transported in trucks, lorries, and other vehicles.
  - Wooden boxes are used to store samples gathered in plastic bags that prevent the samples from interacting with the outside environment.
  - When transporting coal samples, wooden boxes are frequently recommended because they protect the samples from sunlight.
  - If the coal samples are exposed directly to the sun's heat during transit, they may catch fire. As a result, wooden boxes effectively safeguard the samples.

The samples are expected to reveal important information about the sub surface’s geological, physical, and engineering characteristics. Coring was done prior to doing laboratory research. Suitable cores with the appropriate L/D ratio were obtained for several investigations. The cores were then polished with corundum powder and prepared for testing.

13.1 Laboratory data analysis

- **Uniaxial compressive strength test:**

The length of the sample used for testing was 78.4 mm, and the sample diameter was 54.2 mm. As the sample goes off before showing any reading on the scale, the average UCS value of the sample was not able to be determined.

- **Point Load test:**

The sample length used for testing was 72.9mm and the diameter of the sample taken was 54.2mm. The $l\ d$ ratio is 1.345. The breaking load (P) was 1kN.
Therefore, I_{50}= 1000 54.2 2 = 0.340N/mm2 .

Therefore, σ_c=24*I50 =24* 0.349 = 8.16MPa.

- **Brazilian test:**

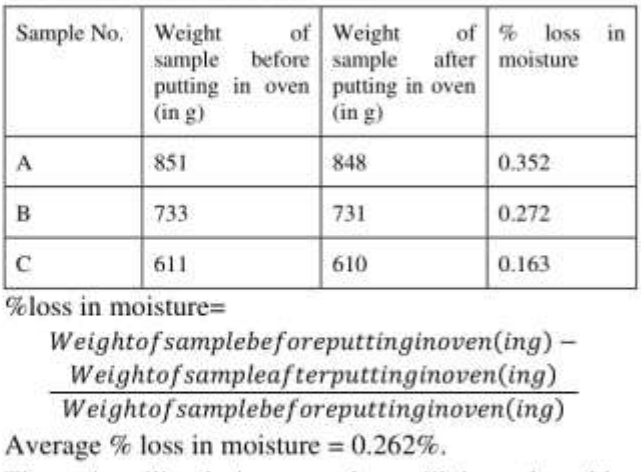
The sample length used for testing was 31.8mm and the diameter of the sample taken was 54.2mm. The $l\ d$ ratio is 0.586. The breaking load (P) was 3kN.
Therefore, Tensile Strength, $\sigma t = 2P\ /dt = 2*3000\ 3.14*54.2*31.8$ N/mm2. = 1.10N/mm2.

- **Moisture test:**

This test was carried out on three samples of varying weight. The presence of moisture in the sample taken from mines was determined by baking it at 1050°C to 1100°C for 5 hours. By interacting with mineral/coal surfaces and changing their surface characteristics and bonding nature, moisture in rock can affect uniaxial compressive strength.

Moisture-induced reduction in Uniaxial compressive strength has been documented by a number of researchers. Because the amount of reduction varies depending on the rock type and test settings, it's best to figure out the Uniaxial compressive strength of rock under the moisture conditions that will be faced in the field. This test was done on Nov. 1, 2025.

Table 1 Moisture test result



Sample No.	Weight of sample before putting in oven (in g)	Weight of sample after putting in oven (in g)	% loss in moisture
A	851	848	0.352
B	733	731	0.272
C	611	610	0.163

%loss in moisture=

$$\frac{Weightofsamplebeforeputtinginoven(ing) - Weightofsampleafterputtinginoven(ing)}{Weightofsamplebeforeputtinginoven(ing)}$$

Average % loss in moisture = 0.262%.
The entire pillar design procedure will depend on this much moisture content.

14. Test results & discussions

The results of the numerous tests performed on the produced sample reveal that the coal sample is extremely soft.

- **Compressive strength test result**

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This test fails because the coal was too soft, and it fails before any value is revealed.

- **Point load test result**

Table 2 for point load test result

S. No.	Length of Sample L (in mm.)	Diameter r of Sample D (in mm.)	L/D	Failure load (in KN)	I50 (in N/mm^2)	σc = 24*I50 (in MPa)
1.	72.9	54.2	1.345	1	0.340	8.16

Because the compressive strength test failed due to the soft nature of coal, only one sample was subjected to a point load test. The average strength obtained was 8.16 MPa.

- **Tensile strength test result**

Table 3 Tensile test results

S. No.	Length of Sample L(in mm.)	Diameter of Sample D (in mm.)	L/D	Failure load (in KN)	σt
1.	31.8	54.2	0.586	3	1.10

The coal sample's average tensile strength was found to be 1.10 MPa. This discrepancy in compressive and tensile strength appears to be related to the fact that during coring, a fracture in the coal sample may have occurred.

According to the aforementioned test results, the coal we're working with is soft and friable. As a result, we must be extremely cautious when planning and deciding on pillar sizes.

- **Moisture test result**

Table 4 Moisture test results

Sample No.	Weight of sample before putting in oven (in g)	Weight of sample after putting in oven (in g)	% loss in moisture	% Average
A	851	848	0.352	0.262
B	733	731	0.272	
C	611	610	0.163	

At this moisture content, the different calculations have been completed. The moisture content in the mine, on the other hand, does not remain consistent and might fluctuate. As a result, consideration must be exercised when designing a coal pillar.

➢ Further extrapolation from results

The table below was created using the CMRI formula to calculate the Factor of Safety.

This is an Indian method for determining the safety factor of coal pillars.

$$S = (0.27 * \sigma c * h - o.36) + ((250 + 1) * (w\ h - 1))$$

The Strength value calculated from this formula is compared with the original strength values and the Factor of Safety has been calculated. The graphs for factor of safety versus width of the pillar have been plotted for various dimensions of gallery width.

P1= Load on the pillar if gallery width is 3m.

P2= Load on the pillar if gallery width is 3.6m.

P3= Load on the pillar if gallery width is 4.2m.

P4= Load on the pillar if gallery width is 4.8m.

F1= Factor of Safety at gallery width 3m.

F2=Factor of Safety at gallery width 3.6m.

F3=Factor of Safety at gallery width 4.2m.

F4=Factor of Safety at gallery width 4.8m.

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S.No.	*WIDTH (in m)*	*STRENGHT (in MPa)*	*P1(B=3.0) (in MPa)*	*P2(B=3.6) (in MPa)*	*P3(B=4.2) (in MPa)*	*P4(B=4.8) (in MPa)*	*F1*	*F2*	*F3*	*F4*
	05	2.859	17.024	19.673	22.514	25.546	0.167	0.145	0.127	0.111
	10	6.299	11.238	12.299	13.409	14.566	0.560	0.512	0.469	0.432
	12	7.675	10.390	11.238	12.119	13.034	0.739	0.683	0.633	0.588
	15	9.739	09.579	10.225	10.895	11.566	1.013	0.952	0.893	0.840
	17	11.115	09.204	09.764	10.341	10.935	1.207	1.138	1.074	1.016
	18	11.803	09.053	09.576	10.115	10.669	1.304	1.232	1.166	1.106
	20	13.179	08.794	09.259	09.736	10.225	1.498	1.423	1.353	1.288
	22	14.555	08.587	09.004	09.431	09.868	1.695	1.616	1.543	1.475
	24	15.931	08.416	08.794	09.181	09.576	1.892	1.811	1.735	1.663
	25	16.619	08.341	08.703	09.072	09.448	1.992	1.909	1.831	1.759
	26	17.307	08.273	08.619	08.971	09.332	2.092	2.008	1.929	1.854
	27	17.995	08.209	08.541	08.879	09.224	2.192	2.106	2.026	1.950
	28	18.683	08.151	08.469	08.794	09.125	2.292	2.292	2.124	2.047
	30	20.059	08.046	08.341	08.642	08.948	2.492	2.492	2.321	2.241
	31	20.747	07.999	08.284	08.574	08.868	2.593	2.504	2.419	2.339
	32	21.435	07.955	08.230	08.510	08.794	2.694	2.604	2.518	2.437
	33	22.123	07.914	08.180	08.450	08.725	2.795	2.704	2.618	2.554
	34	22.811	07.875	08.132	08.394	08.660	2.896	2.741	2.717	2.634
	35	23.499	07.838	08.088	08.341	08.599	2.997	2.905	2.817	2.732
	36	24.187	07.804	08.046	08.292	08.541	3.099	3.006	2.916	2.831
	37	24.875	07.772	08.007	08.245	08.487	3.200	3.106	3.017	2.931
	37.5	25.219	07.756	07.988	08.223	08.461	3.251	3.157	3.075	2.980
	38	25.563	07.741	07.969	08.201	08.436	3.300	3.207	3.117	3.030
	40	26.939	07.684	07.900	08.119	08.341	3.505	3.410	3.318	3.229
	45	30.379	07.566	07.756	07.900	08.144	4.015	3.916	3.821	3.730

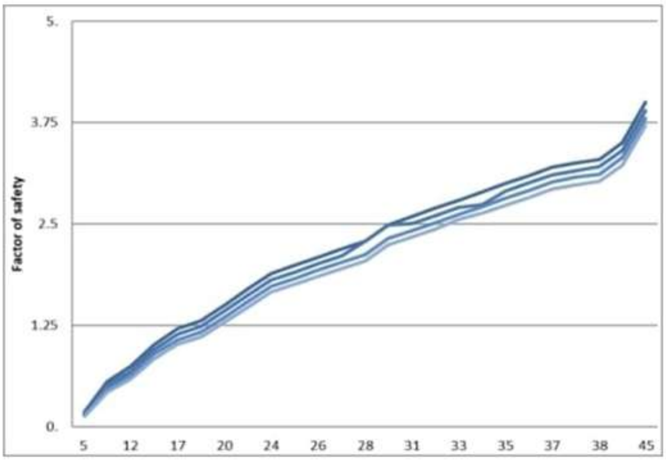

Figure 1 Graph showing comparisons for various FOS with width of pillar.

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The investigation's goal was to assess the pillar design in an underground coal mine. The following conclusions have been reached as a result of this research.

- The CMRI pillar design formulas were assessed, and the best width/height ratio of the pillar was determined, resulting in maximal extraction and a sufficient safety factor for workings.
- The standard Bord and pillar approach was used, with all pillars assumed to be square in shape. Throughout the mine, the gallery width and working height remained constant, and the safety factor was assessed by adjusting other geotechnical factors.
- When compared to the typical safety factor of 1.5 -2 for Indian mining circumstances, the safety factors computed using the CMRI technique were found to be on the higher side.
- When safety factors were calculated using the DGMS criteria for minimum pillar dimension for all approaches, they ranged from 0.70 to 4.02 at various depths and aperture widths.
- For each strategy, simple linear equations were created to aid the mine operator in determining the economic extraction percentage for a sufficient safety factor while maintaining overall safety.

15. CONCLUSIONS

The most important aspect of successful Bord and Pillar mining is choosing the right pillar size. The mine will collapse if the pillars are too small. If the pillars are excessively large, substantial amounts of valuable material will be left behind, lowering the mine's profitability. The safety factor is the most critical criterion to consider while building a pillar.

According to the CMRI technique, the observed safety factor for the coal pillar is 3.17. 18.10 percent was calculated as the extraction percentage. Due to panelling, the average life span of a coal pillar is 3-4 years. As a result, the suggested safety factor for coal pillars is 1.5-2. The observed safety factor, however, is 3.17.

So, it gives a possibility of decreasing the safety factor to around 2. This would increase the extraction percentage without compromising the safety factor.

16. DISCUSSIONS

Following conclusions were drawn from the study:

- For all techniques, the safety factor of a fixed width to height ratio diminishes as depth increases.
- For a fixed depth of mining of 266 m, the safety factor falls and the extraction percentage increases for all techniques as the w/h ratio lowers.
- At various w/h ratios, the Obert – Duvall technique revealed the maximum safety factor for a depth of cover of 120 m.
- When the width to height ratio of the pillar was reduced from 18.292 to 11.504, the extraction percentage increased from 16.3 percent to 25.64 percent for all approaches at 200 m depth cover.
- The safety factor increases as the w/h ratio grows for all approaches at a given depth of cover.
- The safety factor for CMRI formula is maximum at a depth of 266 m, with a width to height ratio of 13.33, with a value of 3.168, as the pillar strength is calculated as 25.76 MPa, while the load on the pillar is 8.13 MPa.

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- For various width-to-height ratios and varied depths of cover, the Bieniawski technique yields a safety factor ranging from 0.697 to 1.4936.
- Using the CMRI technique, the safety factor ranged from 1.84 to 6.84 for various width-to height ratios and different depths of cover.
- The safety factor for the CMRI approach ranged from 2.78 to 3.60 when using regulation 99 of the CMRI regulations 1957 for a minimum width to height ratio at various depths of cover. The Bieniawski technique had a safety factor of 0.70 to 1.35.
- The safety factors produced via CMRI and the Obert-Duvall technique are on the upper side when compared to the stability conditions in Indian mines, which require a safety factor of 1.5– 2

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