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Cut Out Distance – A Critical Parameter for Mechanized Depillaring by Continuous Miner

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Abstract

India's growing energy demand has intensified the need for efficient and safe coal extraction methods, particularly in underground mining, where mechanized depillaring using Continuous Miner (CM) technology has gained prominence. This study explores the critical role of Cut-Out Distance (COD) in optimizing production and ensuring safety during mechanized depillaring operations. COD, defined as the stable drivage length that can be cut without support, directly impacts productivity, roof stability, and operational safety. Despite its importance, there are no standardized guidelines for determining COD in Indian coal mines, leading to trial-and-error practices that compromise efficiency and safety. This paper reviews global and domestic practices, highlighting the inadequacies in existing methods for COD estimation. It identifies key factors influencing COD, including Rock Mass Rating (RMR), roof elasticity, geological conditions, and machinery capabilities. The work also examines case studies of strata control failures in Indian coal mines, highlighting the consequences of improper strata assessment in mines. The research work advocates for the development of standardized guidelines tailored to Indian mining conditions by integrating numerical simulations and machine learning tools for precise COD estimation. A flow chart of methodology for the development of guidelines is proposed; the findings aim to enhance safety, reduce accidents, and improve productivity, paving the way for sustainable growth in India's underground coal mining sector.

1. Introduction

India, as a developing nation, is actively working to promote economic growth across all sectors. recognizing the critical importance of energy to economic progress; the country places significant emphasis on ensuring energy security. The availability of affordable minerals has driven rapid industrial growth in mineral-based industries [1]. To address rising energy needs, the government has identified fossil fuels, particularly coal, as the primary source for power generation. Coal is a key driver of industrial growth and a cornerstone of India's energy strategy [2]. Among the four main energy resources —oil, natural gas, coal, and uranium —coal has the largest domestic reserves and accounts for the majority of energy production. The vision 2047 of the nation, which is under finalization, clearly indicated that coal continues to remain a major player in the energy supply mix of the nation [3]. The choice of the most cost-effective coal extraction method depends on factors such as seam depth and quality, geological features, and environmental conditions. Coal mining is carried out either through surface or underground methods, depending on technical and economic feasibility. These decisions are guided by regional geology, overburden characteristics, coal seam continuity, thickness, quality, and depth. Additional considerations include the strength of materials for roof and floor stability, topography (elevation and slope), climate, land ownership (affecting land availability and access), surface drainage, groundwater conditions, workforce and material availability, buyer requirements for coal tonnage

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and quality, and the financial investments needed [4].

Minerals located near the surface are typically extracted through surface mining methods. However, due to the limitations of surface/opencast mining, such as land acquisition and environmental related issues, the Indian mining industry is now focusing on underground mining methods that utilize advanced technologies with high production rates [5]. Since opencast reserves in the country are depleted or on the verge of depletion, underground mining has great potential in the long run. Coal seams located at deeper depths are believed to have superior grades. Therefore, only underground mining technologies can access and extract lower seams. Over 96% of India's coal demand is met through the opencast mining method, while underground mining contributes only about 4% to coal production. This disparity arises because coal production from underground mines costs approximately ₹6,000 per tonne compared to ₹1,500–₹1,800 per tonne for opencast mining [6]. The Indian Coal Ministry seeks to increase coal usage to meet the growing energy demand. By prioritizing underground mining, attention would shift to optimizing the use of subsurface deposits. Furthermore, more and more energy should be sourced from environment-friendly mining methods, thereby greatly enhancing the importance and relevance of underground mines. As recommended by the advisory commission, both Longwall mining and Continuous Miner (CM) technology will be utilized, promoted, and further developed to become the primary underground coal mining method for mass production. CM technology is the best alternate method for mass production than Longwall mining in terms of capital expenditure and maintenance cost [7].

To tackle the challenges of low production and productivity in underground mining in India and make it economically feasible, the adoption of appropriate mass-production technologies is essential. Large-scale mechanization in underground coal mines is a viable solution to enhance production, productivity, and safety [8]. Continuous Miner (CM) technology has emerged as a beacon of hope for the underground coal mining industry in India, proving its efficiency in extracting coal seams under local mining conditions. The modern era of Mechanized underground coal mining in India began with the introduction of Continuous Miners in 2003. Since then, the use of Continuous Miners has steadily increased, enhancing mechanization and safety in underground mines. However, most of the underground coal mines still rely heavily on conventional mining methods. It is crucial to fully adopt Continuous Miner technology across all underground coal mines. Several mines (Table 1) have successfully implemented CM technology for development and depillaring operations, and many projects were in the pipeline in the Indian coal mining industry. Coal India Limited (CIL) has prepared a UG vision plan; according to it, CIL has planned to produce 100 Mt from underground mines by the year 2029-30, mainly by introducing CMs in underground mines. At present, 30 Nos of Continuous miners have been deployed in 20 UG mines of CIL with a total capacity of about 14.88Mty. CIL has envisaged a plan for the commissioning of another 110 Nos of CMs with a capacity of about 45.12Mty by 2029-30 [3]. The preference for CM-based mechanization in India's coal mining sector stems from its adaptability to Indian mining conditions, relatively moderate investment costs, and significantly higher production and productivity levels. With its fast and safe extraction capabilities, CM technology is being used to develop and depillar numerous coal seams. Furthermore, several plans are underway to expand the use of CM technology in Indian underground coal mines. The mining community favors this technology not only for its efficiency but also for its superior strata management compared to traditional methods.

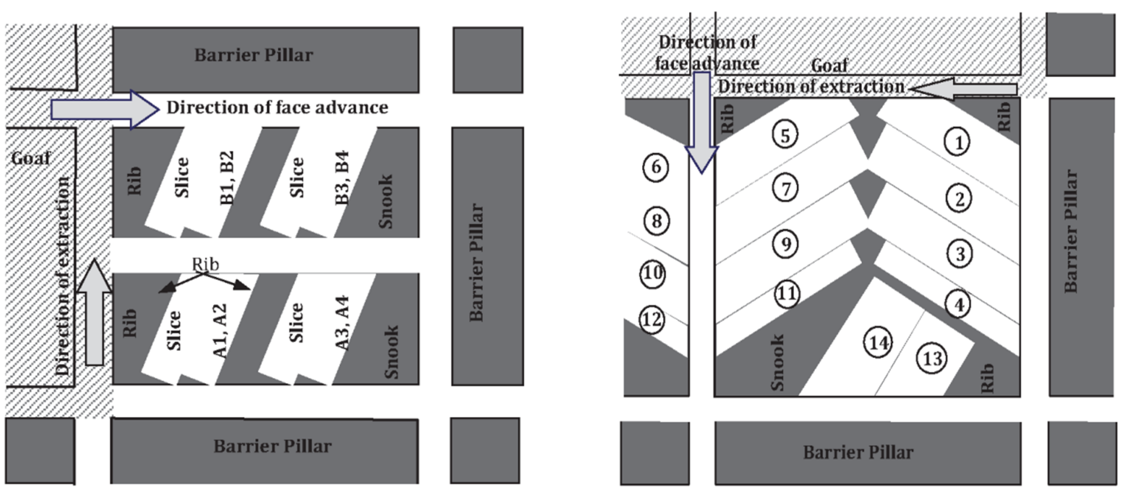
There are two methods of extracting pillars in Indian Mechanized Depillaring (MD) panels: Fishbone/Fish-tail/christmas tree and split and fender/split and slice/pocket and fender as shown in Figure 1. The fishbone/fish-tail/christmas tree method is used for smaller pillars, while the split and fender/split and slice/pocket and fender method is used for larger pillars, according to regulation 111 of the coal mines regulations (2017) [9].

To ensure safe and productive CM operation, critical parameters must be standardized. Cut-Out Distance (COD) is a key parameter in MD operation; COD refers to the length of the stable drivage that can be cut at a time in one place by the CM without installing any support, as shown in Figure 2. Guidelines for cut-out distances need to be established based on different parameters to assist mining engineers during MD operations. The amount of coal that can be cut at one time without installing support directly affects the production rate of the MD system. The size of the gallery or drivage and the distance to which the CM can safely go beyond the last line of the support system determine the amount of coal available for cutting

[10]. Increasing the COD allows the CM to cut more coal continuously, which increases production and productivity and reduces the frequency of machine shifts. COD is a crucial factor in the success of any continuous mining operation.

Table 1. List of coal mines that deployed continuous miner technology in India.

Name of the organization	Name of the subsidiary	Name of the mine
Coal India Limited (CIL)	Central coal fields Limited	Churi benti mine
	Eastern coal fields Limited	Jhanjra mine Sarpi mine kumardih-B project
	South eastern coal fields Limited	Pinoura mine Vindhya mine Churcha R.O. mine Anjan Hill mine NCPH mine Kurja UG mine Beherabandh UG mine Haldibari UG mine Khairaha mine Rani Atari mine Gayathri mine Kapildhara project Bangwar project Vijay west project
	Western coal fields Limited	Tandsi mine Kumbharkhani mine Tawa-II mine Chattarpur – I UG mine
Singareni Collieries Company Limited (SCCL)		GDK-11 Incline mine VK-7 mine Vakilpalli mine Shantikhani mine Kondapuram project PVK-5 mine



(a) Split & Fender/Split & slice/pocket&fender **(b) Fishbone/fish-tail/christmas tree method**

Figure 1. Pillar Extraction Methods in Indian mechanized depillaring panels using CM

The concept of COD plays a critical role in designing ribs and snooks during mining operations. As a geotechnical factor, COD must be optimized to ensure a safe allowable value of roof sagging (SAVRS) during roadway drivages and pillar or fender slicing by Continuous Miner (CM) equipment in mining operations. Research indicates that COD requirements differ between the development and depillaring phases. Depillaring, being a dynamic process, subjects the overlying strata to significantly higher induced stresses compared to development. However, for simplicity and ease of understanding among miners, COD is often maintained at a constant value during both phases. Increasing COD during development can accelerate panel preparation, while reducing it during depillaring enhances safety and productivity. Additionally, pillar size is influenced by COD, as it determines the optimal size of ribs or snooks for maximum coal recovery [11]. Given its critical importance in CM-operated underground coal mines, determining the appropriate COD is essential for ensuring smooth and efficient operations. The future of Indian underground coal mining depends on successful pillar extraction using Continuous Miners. It is crucial to study the stability factors affecting Continuous Miner panel workings in the mines.

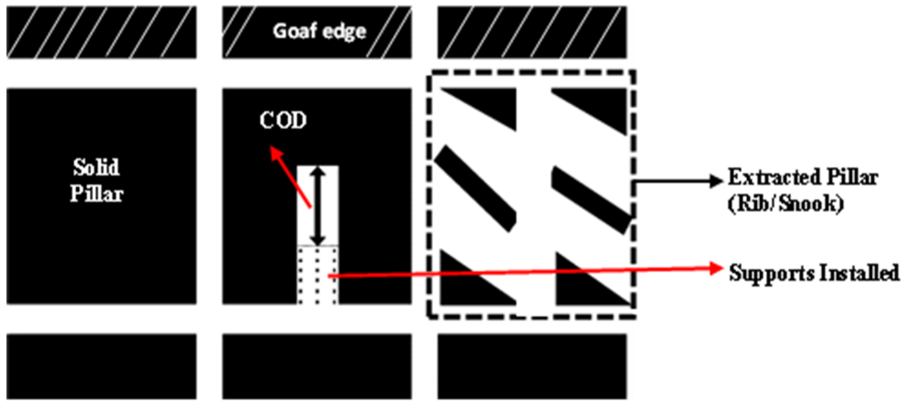


Figure 2. Schematic view of mechanized depillaring workings

2. Literature Review

Safe Cut-Out Distance (COD) is the largest length of unsupported span between the advancing face and the nearest supported area of excavation. COD becomes important during slicing in fender/pillar operation, as the cut-depth decides the productivity of CM in MD. There are other issues like the design of rib/snook studied by [12] and breaker-line support studied by [13], which defines the success of CM-based MD operation. Therefore, it is obvious that COD must be lesser during MD compared to the development of roadways but not quantified in any of the available literature worldwide.

The literature review showed that in the earlier years, when CM was operated by an on-board operator, the COD was limited to 6.0 m, as regulations or guidelines do not allow anybody to go under an unsupported roof. The hidden geological discontinuities like slips, intrusions, cross-stratifications, etc., present in some panels restricted the COD to 4 m from 13 m. The maximum value of COD practised in India is 15 m at a mine [14]. However, the COD values with a remote-controlled CM are 7.8m in the UK, 14m in Australia, 19.5 m in the USA, and 12m in South Africa [15]. South Africa uses the term extended-cut for CM instead of COD. The permissible COD in different countries is also decided mainly by considering human and ventilation issues [15,16]. It reveals that foreign design norms cannot be directly replicated in Indian underground coal mines due to its unique rock mass formations and complex geological conditions. Also, there is no published guideline in India by the mines safety regulatory body (DGMS) in Circulars or the Coal Mines Regulations (2017) to design COD. It has been practised on an error basis since the introduction of CM in 2003 at the Anjan Hill mine [11].

Author [17] used the Rock Mass Rating (RMR) developed by [18] for stand-up time and unsupported span of roof and plotted a relationship to estimate COD for a tunnel that has a single opening (as shown in Figure 3). [19] Introduced the Coal Mine Roof Rating (CMRR) to evaluate the lithological factors affecting the structural stability of mine roofs in U.S. coal seams. Using the CMRR values, [20] predicted safe Cut-Out Distances (COD) for coal mines in the U.S.

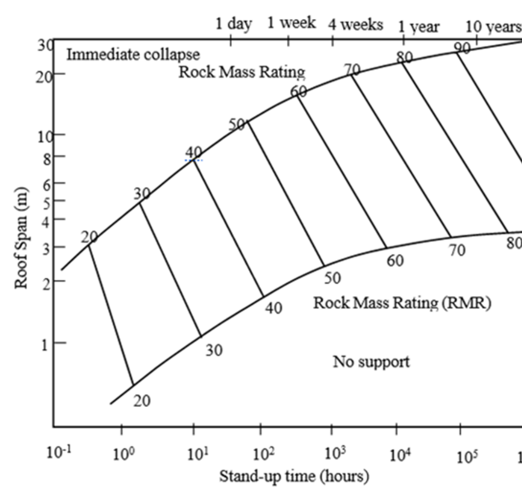


Figure 3. Stand-up time and unsupported span based on RMR and joint factor

Similarly, [21] established a relationship as given in Equation 1 for determining safe COD during the pre-approval phase of a mine, considering CMRR, gallery width, and depth

$$D = 2.47 + 0.172R - 0.046W - 0.0008H \quad (1)$$

Where are:

D - cut out distance (m),

R - coal mine roof rating,

W- width of the gallery (m),

H- depth of cover (m).

[15] applied conventional gravity-loaded beam theory, numerical modeling, and instrumentation across six South African mines to determine COD under various geomining conditions. [22] proposed a method for calculating unsupported roof distances during roadway advancement and applied it in situ to a Chinese mine, concluding that a 6.0m COD was safe for that specific site. [16] utilized the concepts of [17] and [20] to determine gallery width and safe COD for Indian mines. [14] developed a relationship as given in Equation 2 to estimate COD based on the elastic modulus and gallery width, drawing from case studies in Indian coalfields.

$$D = 14.61 + 1.98E - 2.12W \quad (2)$$

Where are:

D - cut out distance (m),

E - elastic modulus (GPa),

W- width of the gallery (m).

It is important to note that COD is highly site-specific and must account for all influencing geomining conditions. A safe COD can be designed effectively through roof deformation studies, as increasing COD is often limited by the risk of instability in surrounding strata, particularly roof formations [23]. Designing COD based on roof convergence addresses most site-specific conditions. [24] studied the effects of COD, gallery width, and RMR on immediate roof convergence and developed a predictive model as given Equation 3. This model helps to estimate roof convergence for safe coal extraction using Continuous Miner (CM) technology and determines COD by setting a threshold convergence value during roadway drivages in coal seams.

$$C = 2.09\, W^{1.23} R^{-0.39} D^{0.11} \quad (3)$$

Where are:

C - convergence of the immediate roof (mm),

W- width of the gallery (m),

R – RMR,

D- COD (m).

COD has been practised in the field based on trial and error [11]. Instrumentation and monitoring are carried out to assess the performance of rock mass behaviour. Unsupported face advance is a major issue in determining the long-term stability of galleries during MD or the development of coal pillars [15]. Around 42 percent of the total roof deflection takes place before the installation of the support in the galleries [25], compromising the support effectiveness. Considering the bandwidth of variation like overlying strata in Indian coalfields, it becomes important to determine the tolerable critical roof sagging before the occurrence of any instability.

The literature review found relatively few published articles on the estimation of a safe COD compared to other geotechnical issues of underground coal mining. The studies conducted by [15,20,21,23] are mainly for COD during development. COD is not an engineering issue during the formation of pillars and galleries but becomes a challenge during the slicing of the fender/pillar. No literature has been found on the design of COD during pillar extraction. The design of the COD provides an opportunity for maximum utilization and availability of the CM for cutting, resulting in increased coal production. Therefore, standardization of this important parameter is required for development and depillaring, respectively.

3. Factors affecting Roof Stability during Mechanized Depillaring

Various factors might contribute to the occurrence of unplanned roof failures in coal mines. In India, several accidents/incidents have occurred in MD workings due to the fall of the roof which resulted in injuries, fatalities, burial of CM, loss of production and productivity and other indirect losses such as cost of compensation, insurance costs, training costs, good will loss, employee moral loss, etc. The cause of roof fall accidents in MD workings is mainly due to the presence of hidden geological discontinuities, working under unsupported areas, high concentration of induced stresses, etc. [14,26]. The stability of a roof is influenced by factors such as span, in-situ stresses, roof profile, pillar dimensions, rock geology, mining method, and support system. Roof falls in coal mines are primarily caused by weak or faulty roof structures, along with local geological changes like faults, joints, clay veins, and slickensides [27]. According to [28], roof falls are also linked to poorly designed support systems, inadequate performance of support components, suboptimal mining practices, limited understanding of stress regimes, and weak roof rock. When designing roof bolting systems, geological factors such as rock type, stratigraphy, and planes of weakness must be carefully considered, which enhances safety in the mine.

4. Parameters Influencing Choice of Cut-out Distance during Mechanized Depillaring

In mechanized depillaring, selecting an optimal cut-out distance is critical to ensure operational safety and efficiency. As discussed previously, COD refers to the length of the stable drivage that can be cut by CM without installing any support; several parameters influence this decision, each of which must be carefully considered:

1. Depth of panel

As the depth increases, the stress concentration around the coal pillars increases, requiring careful management of the cut-out distance to avoid premature collapse. Deeper panels tend to experience higher ground pressures, so according to the depth, the cut-out distance may be varied necessarily to maintain stability.

2. Area of rib/snook

The choice of cut-out distance impacts the final area of the rib/snook of the pillar. For less COD practise, the size of rib/snook left will be high, which ultimately results in loss of coal reserve and also interrupts periodic roof fall results in concentration of stresses. For higher COD, the amount of coal extraction is high and also promotes periodic roof falls.

3. Rock Mass Rating (RMR)

Higher RMR values indicate more competent and stable rock, which may allow for larger cut-out distances. Lower RMR values indicate weaker rock, necessitating shorter cut-out distances to reduce the risk of roof failure and pillar collapse during depillaring.

4. Horizontal stress

In regions with high horizontal stresses, the roof and pillars are subjected to additional pressures, which can accelerate roof failure or pillar crushing. Horizontal stress and its direction play an important role in determining the cut-out distance.

5. Elastic modulus and thickness of immediate roof

A high elastic modulus indicates that the roof material is stiff and can resist deformation, allowing for a larger cut-out distance. Conversely, a low elastic modulus (more elastic or deformable roof material) combined with a thin immediate roof requires a shorter cut-out distance to prevent roof falls and maintain integrity during depillaring.

6. Type of roof (nature of strata)

COD can be affected by the nature of the immediate roof, a massive immediate roof can facilitate larger COD as it is hard and competent. Roof: It may allow for larger cut-out distances as it can support itself for longer periods. A laminated/bedded immediate roof allows for shorter COD as the layers present may tend to separate/sag at a faster rate than the massive roof. Softer or highly fractured roofs may require shorter cut-out distances to avoid premature roof falls and ensure proper roof support.

7. Physico-mechanical properties of rock

Stronger rocks with high compressive and tensile strength can support more overlying weight, enabling a larger cut-out distance. Weaker rocks may collapse more easily, necessitating a shorter cut-out distance to minimize roof falls and rib deterioration.

8. Depillaring method

The cut-out distance may vary depending on the depillaring method. Mechanized depillaring by continuous miners mainly includes two types, i.e., split and fender method & fish bone method; COD can be high during depillaring by the split and fender method as this method is adopted for large size pillars. COD can be low in the fishbone method as compared with the split and fender method because it is adopted for smaller size pillars.

9. Machinery adopted

The type and features of the machinery used during mechanized depillaring (continuous miners, shuttle cars, batter haulers, twin bolter, quad bolter, etc.) may influence the choice of cut-out distance. The COD can be affected by the dimension of the machinery if they are not remotely operated because the operator safety is of utmost importance as they are not allowed to enter into unsupported areas.

The selection of the cut-out distance is a balance between maintaining operational efficiency and ensuring mine safety. Shorter cut-out distances may improve roof and pillar stability but can reduce extraction efficiency. On the other hand, larger cut-out distances increase the risk of roof falls but may optimize coal recovery. Hence, the ideal cut-out distance is based on a comprehensive evaluation of geological and operational factors.

5. Case studies of Strata Control Accidents/Incidents that Occurred in Continuous Miner Panels in Indian Coal Mines

The mining industry has long been considered to be one of the most hazardous industries, with significant health and safety risks for its workers. It always remains a dangerous profession globally, and underground mines are more prone to accidents compared to the work environment of opencast mines. Roof fall is a complex problem in underground coal mines, resulting in loss of lives or serious injuries on most occasions, eventually leading to the high cost of medical expenses and compensation and also loss of equipment, idle time of machinery, delay in reaching the normal level of production, etc. [29]. A few case studies of accidents/incidents that occurred [8,20] in CM panels of Indian coal mines are discussed below. According to the statistics provided by the Directorate General of Mines Safety [30], roof and side falls are the leading causes of fatal accidents in Indian underground coal mines. Table 2 highlights the data on fatal and serious accidents resulting from roof and side falls in Indian coal mines from the years 2013 to 2023.

Table 2. Statistics of fatal & serious accidents in Indian coal mines from the year 2013-2023 (DGMS, 2024).

Year	Total No of accidents		Fatal accidents due to roof and side falls	Total number of serious accidents		Serious accidents due to roof and side falls	Rate per 1000 persons employed		Death rate per million tonnes
	Below ground	Total		Below ground	Total		Death rate	Serious injury rate	
2013	19	77	10	336	456	36	0.23	1.31	0.13
2014	20	59	12	250	379	35	0.17	1.11	0.10
2015	21	54	9	185	302	17	0.16	0.93	0.08
2016	26	67	13	178	269	19	0.28	0.82	0.14
2017	18	56	8	190	266	18	0.18	0.8	0.09
2018	12	49	6	174	265	18	0.18	0.82	0.09
2019	19	51	5	127	193	8	0.16	0.6	0.08
2020	15	48	8	68	117	7	0.16	0.41	0.08
2021	16	43	9	108	186	9	0.15	0.57	0.08
2022	9	24	7	94	181	9	0.08	0.56	0.04
2023	6	37	4	55	116	4	0.12	0.38	0.06

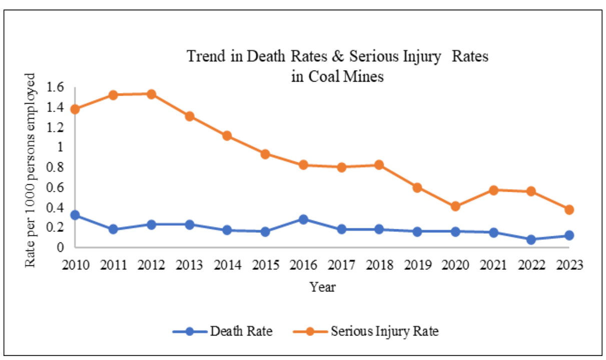


Figure 4. Trend in death rates & serious injury rates in Indian coal mines (2010-2023)

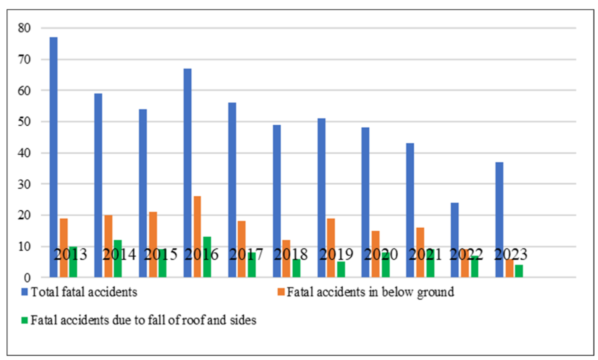


Figure 5. Trend in fatal accidents in Indian coal mines (2013-2023)

5.1. Case Study – I (Mine-A)

Mine A is an underground coal mine started on 15th August 1954 through incline drivage. This mine is operating with continuous miner technology, three incidents occurred in different parts of the mine in three different years due to roof falls, which resulted in fatal accidents, the burial of CM, and damage to CM machinery.

Incident 1: In Mine A, a panel with 20 pillars was developed. Before the accident, the CM was cutting coal, with three pillars already extracted, and the last slice of the fourth pillar was being worked on. Suddenly, a 3 m stone layer collapsed at the junction, trapping six miners, the CM, and a shuttle car. Two miners survived with serious injuries, while four sustained fatal injuries. Rescue operations recovered the victims and machinery. The incident location is shown in Figure 6.

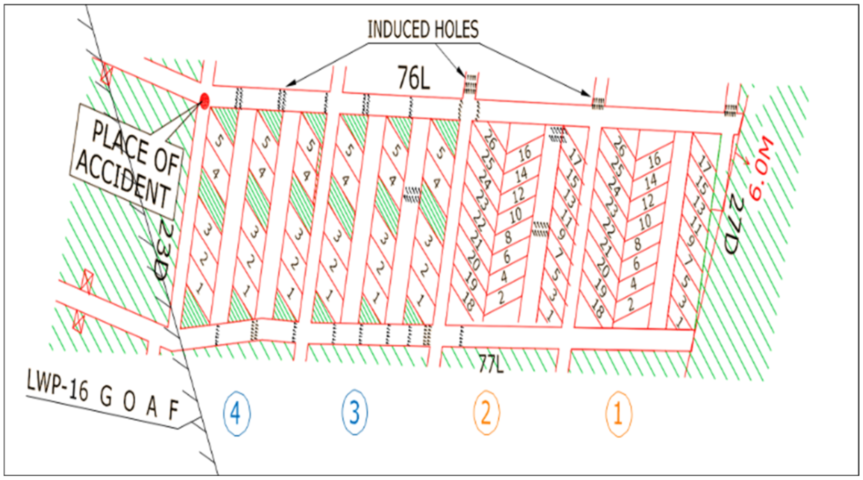


Figure 6. Plan showing location of incident

Incident: 2 pillar No. 13 splitting began and finished in two days. Slicing of fender-A started on the next day after five slices extracted rotary tell-tale showed 13 mm dilation, and a snook of Fender-A was extracted. A 0.10 m fault crack near the goaf edge was observed and bolted effectively. After fender-A's extraction, CM was brought in for fender-B but broke down due to a rear shear cylinder failure, which was replaced. A 13 m rib was left as a precaution due to a crack and fault. On the next day, around 5:30 am, a 3–4 m thick stone fell on the CM during slicing, with no RTT dilation observed on the south side, which is near the place. Recovery began immediately. The puller was grouted, and wooden props were installed as temporary supports. The stone debris was cleared with an LHD, but the first pulling attempt failed. A booster cylinder was added, enabling the CM to be pulled out safely after some movement.

Incident :3 In pillar No. 4, the junction was supported effectively in addition to a prescribed number of bolts as per rules. Slices and snook of fender B were extracted normally. After observing an AWTT reading of 7 mm and signs of a goaf fall; the CM operator was instructed to withdraw the machine. At 3:30 PM, a massive roof fall (10 m length, 8 m width, 4–5 m height) occurred on the CM and in the goaf, covering 80% of the machine. Sounds from the goaf were noted before the fall. Clearing debris revealed that the fall height exceeded 10 m in the goaf, with cable bolts included in the fall. Geological mapping was conducted, and supports such as 2.4 m bolts, w-straps, and wire mesh were installed. To prevent similar incidents, bolting density in junctions should be increased, and scientific studies are needed for support design. The roof fall location is shown in Figure 8.

5.2. Case Study – II (Mine-B)

Mine B is an underground coal mine, where continuous miner technology was introduced in 2010. Two incidents occurred in different parts of the mine in three different years due to roof falls, which resulted in fatal accidents, the burial of CM, and damage to CM machinery. In this mine, two incidents occurred in two different panels in different years, resulting in the burial of CM due to a roof fall in depillaring workings.

Incident :1: In mine B, the fishbone/christmas tree method was used for depillaring. During the second push-out of pillar 49, all of a sudden, a 4–5 m thick roof fall buried the CM, cutting its power supply. Successive roof falls followed, completely burying the CM. The roof near the extraction stage was disturbed by geological discontinuities, but strata monitoring instruments showed no signs of stress or dilation. Visual inspection revealed the final roof height was around 20 m. The fallen roof rock was cleared, the CM was recovered using a puller and arch support, and the CM was operational after power restoration. The exposed snooks near the burial site were intact, and the hidden slip in the area was identified as the cause of the roof fall. The roof fall location is shown in Figure 9.

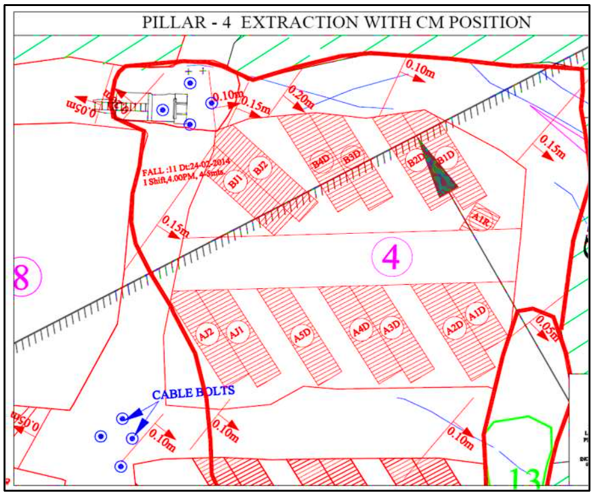


Figure 7. Plan showing location of incident

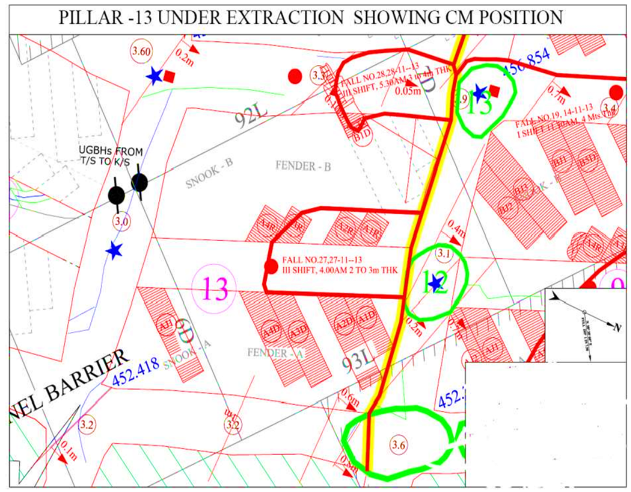


Figure 8. Plan showing location of CM burial due to roof fall

Incident:2 During the first slice extraction of the pillar, the CM was buried due to a roof fall that resulted in an electrical fault, leaving it inoperable under unsupported strata surrounded by discontinuities. Attempts to retrieve the CM with a ram car failed, but it was successfully pulled out using a puller and temporary supports. Tell-tale readings showed roof dilation exceeding the permissible limit of 10 mm, leading to personnel withdrawal. Strata monitoring instruments recorded 0.136 MPa stress, ruling out dynamic loading as the cause. No caving or rib spalling occurred; only 400 m² of hanging area was noted in the goaf. By these observations, the roof fall was attributed to delayed extraction, unsupported strata, and local geology. The Incident location is shown in Figure 10.

5.3. Case Study – III (Mine-C)

Incident 1 mine C, opened on 1st May 1992, operates at a depth of 28-125 m with shale and shaly sandstone as the roof and floor. The gallery size is 6.0 m x 3.5 m, and pillar sizes are 25 m x 25 m, 25 m x 20 m, and 20 m x 20 m. Continuous Miner (CM) technology was introduced on 10th May 2017. The CM was buried in panel 2 at Location 25LE/47D. It was retrieved on 28th February using pullers, bolts, and wire mesh. The first main fall area was 5625 m², with the hanging roof area before burial at 625 m² and 0 m² after the fall. During slice 5B extraction, a local layer fell on the CM, causing the main fall and burying the machine. The photograph of the CM Burial is shown in Figure 11.

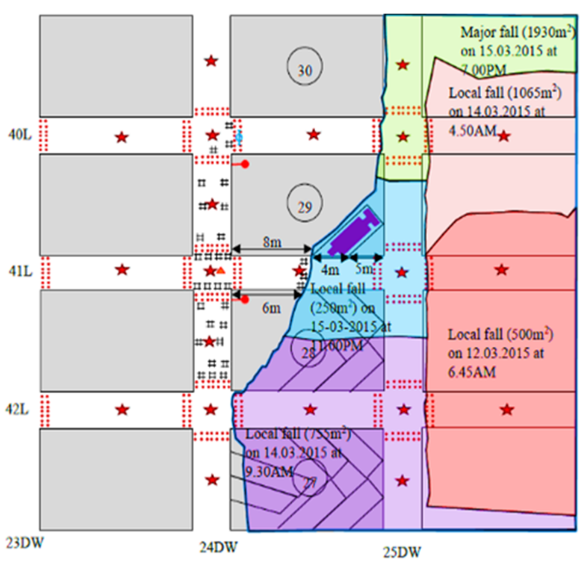


Figure 10. Plan showing location of incident 2

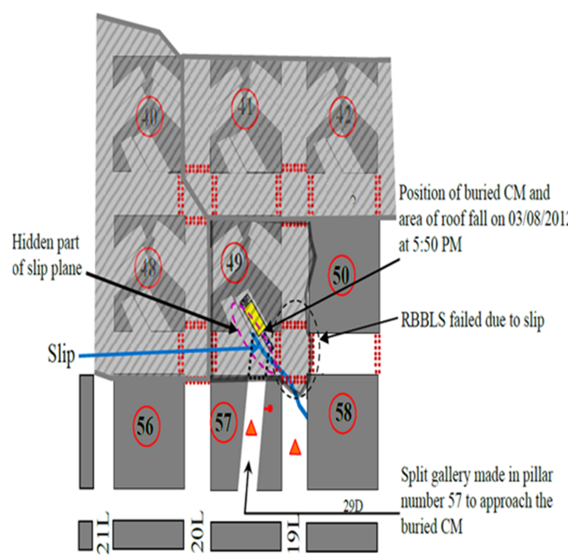


Figure 9. Plan showing location of incident 1

Figure 11. Burial of CM due to roof fall

5.4. Case Study – IV (Mine-D)

Incident 1: During the Depillaring process, CM completed the 3rd slice of fender 2 in pillar No. 2 and began retreating to extract fender 3. A cracking sound from the bearing plate was heard, and as the CM operator tried to retreat under the supervision of mining Sirdar; the roof suddenly collapsed, trapping the CM from the cutter drum to the conveyor boom in the 3rd slice, with a fall area of 990 m², another cracking sound resulted in a second fall, covering the split gallery. Attempts to pull the CM with a heavy-duty chain failed as the D-Link broke due to the load. The team then blasted boulders to reduce the load, and CL-210 was used to clear debris in the 2nd and 3rd shifts, freeing space around the CM. After three days, the CM was successfully retrieved. The fall revealed multiple roof layers, each about 4-5 inches thick, extending up to 2 m. The panel had been a mine sump for 7-8 years, likely weakening the roof.

Incident 2: After splitting 4 meters in pillar 78, sounds were heard in the goaf, followed by heavy bumping, and the CM got stuck. LHD was deployed to clear coal from the pillar sides, but signs of a roof fall were noticed, and the LHD was removed. A roof fall occurred in pillar 76, burying the CM and affecting its power supply. To clear the debris, plaster shooting was done in multiple stages: the first with 16 shots, then 16 more, followed by 18, 17, 9, and 10 shots in successive stages. Each round of plaster shooting was followed by sweeping debris with LHD. After the seventh plaster shooting, the CM was successfully retrieved using a puller. The location of the CM burial is shown in Figure 12.

Incident 3: While depillaring fender C slicing began in pillar-23, leaving an 8m thick snook. Sounds in the goaf indicated a fall to be occurred, and roof fall occurred as the snook was extracted to 5m. While sweeping loose coal, half the body of the CM was trapped by a roof fall, with about 450 m² of debris covering the CM. A puller was used to retrieve the CM, but three heavy-duty rope slings broke. Blasting was done to remove the load, and the puller successfully moved the CM 1.5m, eventually retrieving it. The place of the incident is shown in Figure 13.

It has been observed that even in mechanized depillaring panels utilizing remote-operated continuous miners, numerous strata control issues persist, leading to fatal accidents, serious injuries, or the burial of continuous miners. These incidents are primarily attributed to the following factors: 1) Improper design of coal extraction methods 2) Inadequate support systems 3) Poor planning and design of the ground control plan 4) Lack of regular, cause-specific safety analysis.

Case studies highlight that the longstanding problem of strata control failures remains unresolved. Identifying the root causes of failure mechanisms and addressing them with appropriate engineering controls is crucial. Accidents in underground operations, which contribute only 4% of total coal production, are already alarming. If underground coal production were to increase to 50%, the implications for national safety standards would be severe. The adoption of Continuous Miner Technology in Indian underground coal mines is growing rapidly. Therefore, it is essential to understand the various parameters influencing strata behavior and the stability of Continuous Miner panel workings. With the increasing use of Continuous Miners, the frequency of ground control accidents in underground coal mines is also rising, necessitating immediate action.

No comprehensive study has been conducted in Indian mines to predict mining-induced stresses in mechanized depillaring operations. While numerical simulation tools are available for stress prediction, their application faces limitations such as the lack of sufficient geo-mining data to develop accurate models. Additionally, the daily use of numerical simulation tools in every underground coal mine is impractical. However, integrating numerical simulations with machine learning tools could help develop predictive models and equations that practicing mining engineers can readily apply.

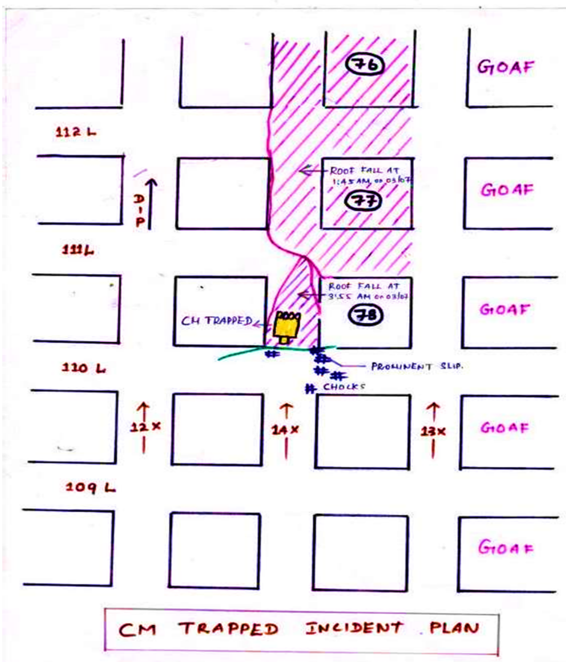


Figure 12. Plan showing location of incident 2

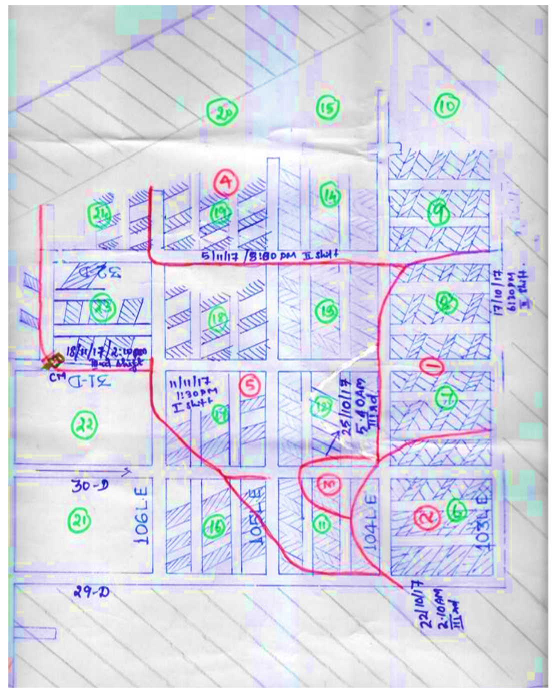


Figure 13. Plan showing location of incident 3

6. Discussion

The investigation into Cut-Out Distance (COD) as a critical parameter in mechanized depillaring using Continuous Miner (CM) technology provides valuable insights into the challenges and opportunities for improving underground coal mining in India. The findings emphasize the pivotal role of COD in balancing productivity, safety, and operational efficiency while highlighting the significant gaps in current practices and the absence of standardized guidelines tailored to Indian geo-mining conditions. This discussion synthesizes the key observations from the study, evaluates their implications, and proposes directions for future research and implementation.

One of the significant revelations of this study is the variability of COD requirements between the development and depillaring phases of underground mining. During development, a larger COD can accelerate panel preparation and enhance productivity by allowing the CM to cut more coal continuously without frequent support installation. Conversely, during depillaring, a shorter COD is often necessary to mitigate the induced stresses and ensure roof stability, as this phase involves dynamic extraction processes that increase the risk of strata failure. The lack of differentiation in COD application between these phases, as noted in the study, reflects a practical simplification for miners but compromises both safety and efficiency. This highlights the need for a dynamic, phase-specific approach to COD determination, which could optimize coal recovery while minimizing risks.

This research work effectively identifies the multiplicity of factors influencing COD, including Rock Mass Rating (RMR), roof elasticity, depth of panel, horizontal stress, and the physico-mechanical properties of the rock. These parameters collectively dictate the stability of unsupported spans and the allowable roof sagging during CM operations. The statistics from DGMS underscore the urgency of addressing roof and side falls, which remain the leading cause of fatal accidents in Indian underground coal mines. The trend of declining death rates from 0.23 per 1000 persons employed in 2013 to 0.12 in 2023 is encouraging, yet the persistence of serious injuries and equipment losses in CM panels signals an ongoing safety crisis. As underground mining scales up to meet India's energy demands- targeting 100 Mt by 2029-30 per Coal India Limited's vision risks could escalate without standardized COD guidelines and improved ground control practices. The case studies of strata control failures in Indian coal mines, such as Mine-A, Mine-B, Mine-C, and Mine-D, vividly illustrate the consequences of neglecting these factors. Incidents involving roof falls, CM burials, and fatalities highlight how geological discontinuities, inadequate support systems, and improper COD estimation exacerbate risks. These examples reinforce the argument that trial-and-error approaches, prevalent since the introduction of CM technology in India in 2003, are insufficient for managing the complex interplay of geotechnical variables in mechanized depillaring.

Globally, COD practices vary significantly, as evidenced by the literature review. For instance, the permissible COD ranges from 7.8 m in the UK to 19.5 m in the USA, reflecting differences in geological conditions, regulatory frameworks, and technological capabilities. In India, the maximum recorded COD of 15 m [14] contrasts with these international benchmarks, suggesting that Indian mines operate under unique constraints that preclude the direct adoption of foreign standards. The absence of guidelines from the DGMS or the Coal Mines Regulations (2017) further compounds this issue, leaving mining engineers reliant on empirical relationships such as those proposed by [11,17,20,21,24], which are primarily designed for development rather than depillaring. This gap in depillaring specific research represents a critical oversight, given that pillar extraction is the most hazardous and production-intensive phase of CM operations.

The integration of numerical simulations and machine learning tools offers a promising pathway for addressing these challenges. Numerical modeling can simulate stress distributions and roof convergence under varying COD scenarios, while machine learning can analyze historical data from Indian mines to predict safe COD values based on site-specific conditions. However, the study acknowledges practical limitations, such as the scarcity of comprehensive geo-mining data and the infeasibility of daily simulations in operational mines. Overcoming these barriers will require concerted efforts to collect high-quality field data and develop user-friendly predictive models that mining engineers can apply without extensive computational expertise. A flow chart of methodology for the development of guidelines for estimation of COD is suggested for future research.

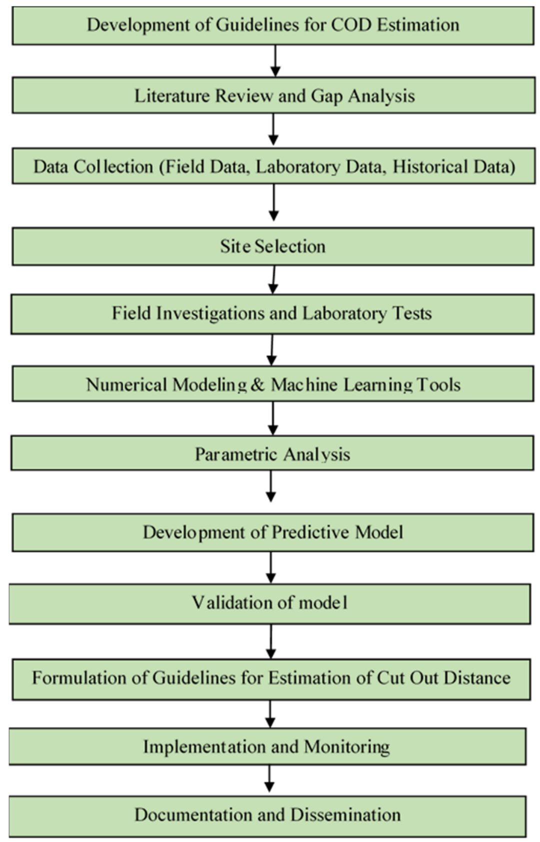


Figure 14. Proposed flow chart of methodology for development of guidelines for COD estimation

7. Conclusions

The work underscores the critical importance of optimizing Cut-Out Distance (COD) in mechanized depillaring operations to enhance safety, productivity, and efficiency in underground coal mining. Continuous Miner (CM) technology has emerged as a significant advancement in the Indian coal mining industry, driving improvements in both mechanization and safety. However, there are currently no published guidelines from regulatory bodies either in India or internationally for estimating COD in mechanized depillaring operations. This absence of standardized guidelines presents a major challenge, resulting in inconsistent practices and an increased risk of strata control failures. A review of existing literature reveals that the Indian coal mining industry lacks a standardized method for COD estimation. In most cases, COD is determined through a trial-and-error approach, without the support of a structured methodology. This practice is often unreliable and may not be suitable for varying geological and operational conditions, potentially leading to accidents and safety incidents. The absence of a standard methodology for COD estimation represents a missed opportunity for improving safety and productivity in the mining sector. While empirical models and global practices provide a foundation, their application to the specific context of depillaring operations in India remains limited and underexplored.

Therefore, there is a pressing need to develop a scientific, standardized approach for COD estimation, tailored to the unique geological and operational conditions of Indian underground coal mines. Such an approach would enable mining engineers to make informed decisions, reduce reliance on trial-and-error methods, and minimize the risk of accidents. The integration of advanced technologies, along with regulatory support and industry collaboration, can help bridge this gap, ultimately enhancing both safety and productivity. Future research should focus on field-based validation of predictive models, in-depth studies of COD design specific to depillaring, and the development of real-time monitoring systems. These efforts are essential for establishing robust standards that address the unique challenges of Indian underground coal mining and ensuring the sector's sustainable growth.

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فاصله برش - یک پارامتر حیاتی برای حفاری مکانیزه توسط دستگاه ماینر پیوسته

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پایداری سقف

چکیده

تقاضای رو به رشد انرژی در هند، نیاز به روش‌های استخراج زغال‌سنگ کارآمد و ایمن را، به‌ویژه در معادن زیرزمینی، که در آن عملیات لایه‌برداری مکانیزه با استفاده از فناوری Continuous Miner (CM) اهمیت یافته است، تشدید کرده است. این مطالعه به بررسی نقش حیاتی فاصله برش (COD) در بهینه‌سازی تولید و تضمین ایمنی در طول عملیات لایه‌برداری مکانیزه می‌پردازد. COD، که به عنوان طول حفاری پایدار که می‌تواند بدون پشتیبانی برش داده شود، تعریف می‌شود، مستقیماً بر بهره‌وری، پایداری سقف و ایمنی عملیاتی تأثیر می‌گذارد. علیرغم اهمیت آن، هیچ دستورالعمل استانداردی برای تعیین COD در معادن زغال‌سنگ هند وجود ندارد که منجر به شیوه‌های آزمون و خطا می‌شود که کارایی و ایمنی را به خطر می‌اندازد. این مقاله به بررسی شیوه‌های جهانی و داخلی می‌پردازد و نارسایی‌های روش‌های موجود برای تخمین COD را برجسته می‌کند. این مقاله عوامل کلیدی مؤثر بر COD، از جمله رتبه‌بندی توده سنگ (RMR)، خاصیت ارتجاعی سقف، شرایط زمین‌شناسی و قابلیت‌های ماشین‌آلات را شناسایی می‌کند. این کار همچنین مطالعات موردی شکست‌های کنترل لایه‌ها در معادن زغال‌سنگ هند را بررسی می‌کند و پیامدهای ارزیابی نادرست لایه‌ها در معادن را برجسته می‌کند. این کار تحقیقاتی از توسعه دستورالعمل‌های استاندارد متناسب با شرایط معدنکاری هند با ادغام شبیه‌سازی‌های عددی و ابزارهای یادگیری ماشین برای تخمین دقیق COD حمایت می‌کند. نمودار جریان روش‌شناسی برای توسعه دستورالعمل‌ها ارائه شده است؛ این یافته‌ها با هدف افزایش ایمنی، کاهش حوادث و بهبود بهره‌وری، زمینه را برای رشد پایدار در بخش معدن زغال سنگ زیرزمینی هند فراهم می‌کنند.

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