ANALYSIS OF SUBSIDENCE AND STABILITY OF PILLARS IN A COAL MINE

T. Maheswa[1], M. Reddy Var[2], M. Vikra[3], V. Bangaru Ragu[4]

[1,2,3],Students, Department Of Mining, ABR College Of Engineering and Technology, Chinairlapadu, Kanigiri, Andhra Pradesh

Sk. Sabjarvali

Assistant professor, Department Of Mining, ABR College Of Engineering and Technology, Chinairlapadu, Kanigiri, Andhra Pradesh

ABSTRACT

Mining plays a crucial role in human development, with underground mining methods like the Bord and Pillar Method being integral to coal extraction. This method, one of the oldest in mining, relies heavily on the stability and optimal sizing of the pillars. If pillars are too small, they risk collapse; if too large, valuable material is left behind, reducing profitability. The primary objective of this project is to enhance extraction efficiency by improving pillar stability and controlling subsidence. Field observations at the Kumda underground mine revealed stable pillars without side spilling or crushing. Laboratory tests, including uni-axial compressive strength and tri-axial testing, showed the coal's UCS, cohesion, and internal friction angle as 27.9 MPa, 1.85 MPa, and 30°, respectively. Numerical modeling through two-dimensional continuum analysis indicated a maximum stress of 5 MPa on the pillars with a safety factor above 2, confirming pillar stability. Maximum subsidence observed was 1.58 m, with a subsidence factor of 0.63 for depillaring panels, ensuring optimal extraction and stability.

Keywords: Bord and Pillar, coal extraction, pillar stability, subsidence, numerical modeling, safety factor, Kumda mine.

1.Introduction

Mining plays a pivotal role in the extraction of valuable minerals and fuels, contributing significantly to industrial development and economic growth. Among the various underground mining methods, the Bord and Pillar Method is one of the oldest and most commonly used techniques, especially in coal mines. This method involves the creation of tunnels (bords) and leaving behind pillars of coal to support the mine roof. The success of this method hinges on the stability of the pillars and the control of subsidence that occurs as the pillars are gradually removed during the extraction process. The key challenge in Bord and Pillar mining is determining the optimal size and design of the pillars. If the pillars are too small, they risk collapsing under the pressure of the overburden, leading to mine instability. On the other hand, if the pillars are too large, valuable coal is left behind, reducing the profitability of the mine. Therefore, ensuring the stability of the pillars and minimizing subsidence are crucial factors for successful extraction while maintaining safety. This study aims to enhance the pillar stability and subsidence control in underground coal mining through a combination of laboratory testing, empirical modeling, and numerical simulations. Using data from field observations at the Kumda underground mine and laboratory results on coal strength, the study investigates the behavior of coal pillars under different stress conditions and examines the subsidence profiles associated with mining activities. The goal is to optimize pillar design and improve extraction efficiency while minimizing surface displacement, ensuring both safety and economic feasibility in coal mining operations

2.Literature Review

The stability of coal pillars and subsidence in underground coal mining operations has been the focus of extensive research over the years, with several numerical modeling and empirical studies contributing to the understanding of these critical aspects. Amin and Goktan (2006) investigated the stability of rock formations and subsidence behavior in underground coal mines using numerical modeling, emphasizing the role of material properties and geological conditions in influencing pillar integrity and surface displacement. Their findings demonstrated the effectiveness of numerical models in predicting rock behavior and optimizing mining operations. Similarly, Singh and Gupta (2012) explored the stability of coal pillars under varying conditions using numerical methods, highlighting the importance of pillar size and design in ensuring safe mining operations.

Further, Kumar and Reddy (2015) conducted studies on subsidence prediction and numerical modeling in coal mines, focusing on the relationship between pillar stability and surface displacement. They provided insights into how the size and distribution of pillars impact the extent of subsidence in different mining scenarios. Sharma and Meena (2017) also examined pillar stability and subsidence profiles in their numerical analysis, finding that careful planning and modeling of pillar geometry are crucial for minimizing subsidence and ensuring safe extraction.

In more specific applications, Zhou and Zhang (2013) used empirical modeling to assess pillar stability in shallow coal mines, with a particular focus on the interaction between mined areas and surrounding geological formations. Their research underscored the importance of empirical data in improving the accuracy of numerical models. Lee and Kang (2012) conducted simulations to assess subsidence and pillar stability in depillaring operations, finding that numerical models could effectively simulate subsidence profiles and help mitigate risks associated with pillar removal. More recently, Mishra and Srivastava (2019) focused on both numerical and empirical techniques for subsidence prediction in coal mining, contributing to a more comprehensive understanding of the factors that drive subsidence and pillar failure. Pandey and Kumar (2018) also explored pillar stability and subsidence using numerical simulations, further reinforcing the idea that simulation and empirical data play key roles in optimizing pillar design and controlling subsidence in underground coal mining.

3.Methodology

The methodology for this study on pillar stability and subsidence analysis in underground coal mining is based on a combination of field observations, laboratory testing, and numerical modeling to evaluate and enhance the mining process. The following steps outline the methodology employed:

1. Site Selection and Field Observations

The study was conducted at the Kumda underground mine, where the Bord and Pillar mining method is used. Field observations were carried out to assess the stability of the coal pillars, observe any perceptible side spilling or crushing, and monitor subsidence over the extracted panels. Data on the geometry, dimensions, and layout of the mine panels, including the width and depth of the extraction panels, were collected.

2. Laboratory Testing of Coal Samples

Laboratory tests were conducted to determine the mechanical properties of coal, including:

- Uniaxial Compressive Strength (UCS): To measure the strength of the coal when subjected to compressive stress.

- Triaxial Testing: To assess the cohesion (C) and internal friction angle (∅), which are critical parameters for pillar stability analysis.

The results of these tests provided essential material properties for the numerical models used in this study.

Description of the SECL Mine

The mine is located 9 km north from the Bishrampur railway station and 30 km northwest from the district head quarter, Ambikapur (Surguja), Chhatisgarh. The topographical area consists of undulated (bothcultivatedandbaron) land.The elevation in the area ranges from 536 mto 560 ma bove MSL. The drainage of the area is controlled by seasonal Gour bahra nullah flowing west east across the middle of the property. The nullah discharges in Pasang River flowing outside the mine leasehold area.

- The enclosing latitude and longitude of geological block are-Latitude from 230 12' 16" to 230 15' 16" (N)
- Longitude from 82058'58" to83002'53"(E)
- The area is free from major geological disturbances

Table 1: Maximum Subsidence Observed at the Short Wall Panels.

Name of The Short wall Panels	Widths Of Panels (M)	Av. Depths of panels (M)	Maximum Subsidence (CM)	Subsidence factor
63 (1ST Panel)	84	45.5	95	0.41
58L (2ND Panel)	84	38	117	0.50
57L (3RD Panel)	84	35.5	127	0.55
34L (4TH Panel)	104	32	111	0.48
S-7 (5TH Panel)	104	32	158	0.63
S-6 (6TH Panel)	84	30	114	0.45
S-5 (7TH Panel)	84	30	148	**0.59**
46L (8TH Panel)	64	41	116.5	**0.47**

The subsidence factors for the panels are varying from 0.41to0.63 at the mine. The amount of maximum observed subsidence in short wall panel is generally slightly more than the maximum observed subsidence in the long wall panels at the mine and this may be due to the short wall panel was exceptionally high. Before commencement of extraction in this panel the seasonal nallah flowing over the last portion of the panel, which was suitably diverted outside and the overlying strata over the panel of his portion was soft and this may be the reason for such high subsidence in a particular zone.

Shape of the Subsidence Trough

When a subsidence trough is formed at the surface, the central part subsides vertically and the remainder moves inwards and downwards toward the Centre. Points located directly above the Centre of the goaf will subsides vertically and be displaced on an axis parallel to the goaf, where points away from the Centre will be displaced in an elliptical fashion. Since the Centre point is not moving horizontally, while the points on either side of it move inwards toward it ,the central part of the subsidence trough will be subjected to lateral compression. In the Centre of the excavation, the vertical subsidence is maximum whereas the horizontal displacement is zero.

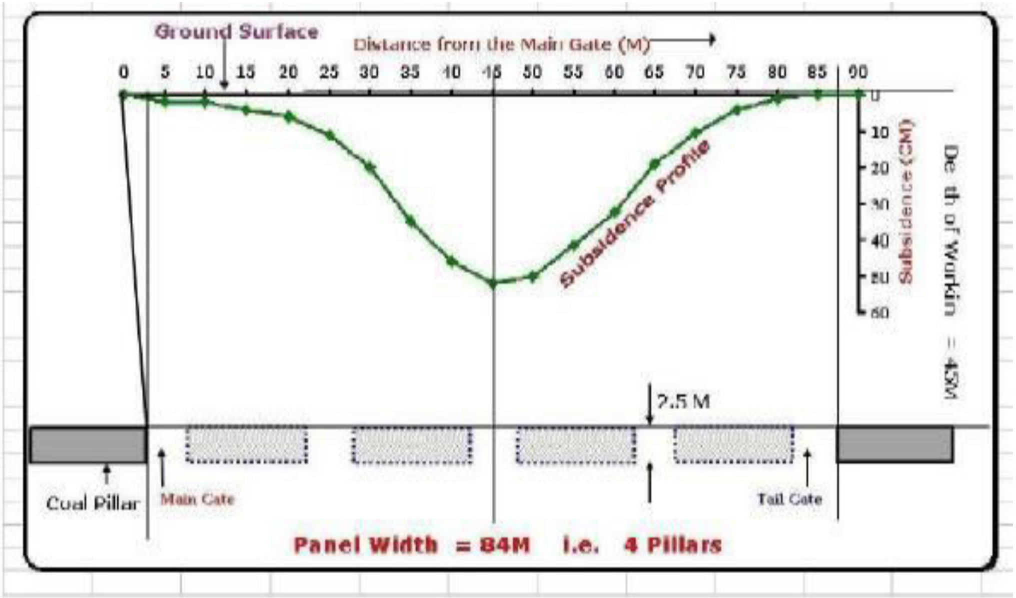

Fig.1(a): Subsidence profile across the Panel ,84m panel width,63LShort wall Panel

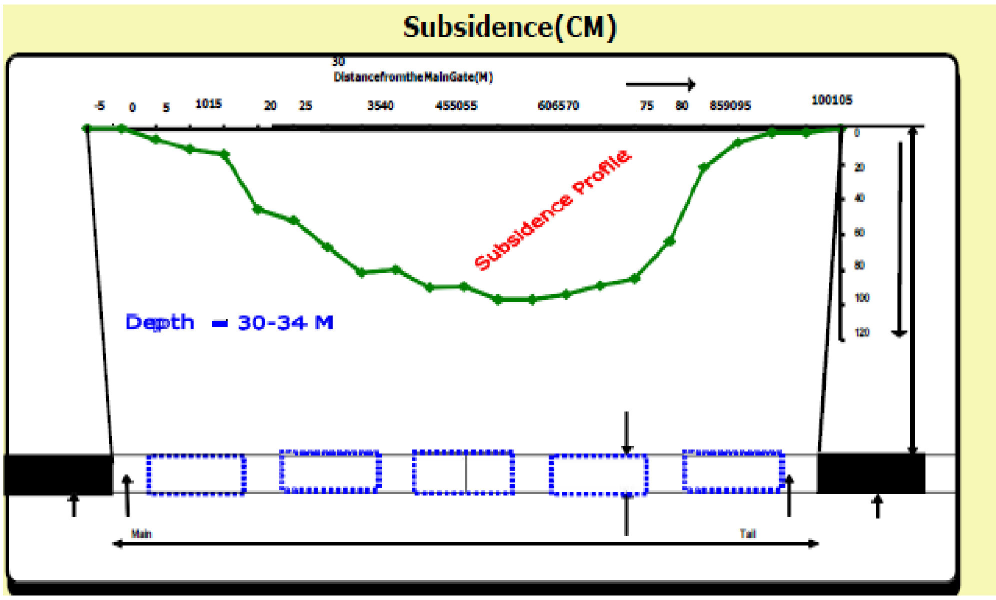

Fig 2: Subsidence Profile across the Panel,104m panel width,34L short wall Panel

The subsidence profile has a part which is convex and where the ground surface is getting elongated and another part is concave where the elongated ground surface is getting compressed. Thus, over the advancing face and the nearby goaf where ground till it was occurring tensile strain develops. The maximum tensile strain develops where the angle of break reaches the ground surface from the edge of the solid face. Further on the goaf side the shape of the subsidence profile changes to concave and the particles on the ground now comes nearer to each other giving rise to compressive strain. After the ground tilt has been fully recovered in an extraction of supercritical width the subsidence profile takes the shape as in the original ground and there is neither tensile nor compressive strain at the central part of the subsidence trough.

Geo-mining Details of the Study Site:

Profundity of hard cover of Pancreases working of Balrampur 10 and12mine, SECL in the ascent side were under 15 m at numerous spots having four-path intersections with section measure 4.5x2.8m with columns 20mx20m. Different geomining parameters of the mine are as per the following:

Table 2: Geo Mining Parameters of Balrampur 10 and12 mine

Parameter	Value
Thickness of the Seam	1.8 m to 2.7 m
Gallery Size	4.5 m x 2.7 m
Height of the Exhibition	2.4 m to 2.7 m
Pillar Size	20 m x 20 m
Depth of Working	21 m to 44 m (Hard cover is under 15 m)
Nature of Roof Top & Floor	Shaley Sandstone
Nature of Roof Top & Floor	1 in 51
RMR	56.3
Modulus of Elasticity	1.8 GPa
Tensile Strength	3.11 MPa
Compressive Quality of Coal	27.9 MPa
Density of Coal (kg/m^3)	1400

Fig. 2 shows bore opening segment of BXI 15 of Balrampur, and CBBP-111,112 &113 of Kumda 7&8 Inclines, individually. Top Soil thickness shifted from 2 m to 5 m here while weathered mantle differed from 8 m to 12 m. hard cover in these areas was discovered to be around 6.2 to 15 m.

4. Numerical Modeling Design

The panel elements considered in the model are small, with a size of 1 meter both vertically and horizontally within the pillars. The mesh elements' dimensions increase geometrically from the inner model to the outer boundary, allowing for more accurate readings over the coal seam. This varying mesh size not only improves accuracy but also reduces the simulation and computation time by utilizing larger elements at the boundary. This approach optimizes the model's efficiency without sacrificing the precision of critical areas, particularly the coal seam. The development model is then transformed into an excavation model for further analysis. For simulation purposes, the Mohr-Coulomb failure criteria are applied along with the assumption of plain strain conditions to accurately simulate the behavior of the material under stress. Sandstone elements are used to represent the overburden and floor material, providing realistic geological modeling.

Table 3: Parameters used in the Numerical Modeling

Property	Coal	Sandstone	ClayBand
Bulk Modulus	3.67GPa	6.67GPa	2GPa
Shear Modulus	2.2GPa	4.0GPa	1.4GPa
Density	$1480 kg/m^3$	$2100 kg/m^3$	$1650 kg/m^3$
Tensile Strength	1.86MPa	9.0MPa	6000Pa
Cohesion	1.85MPa	6.75MPa	5000Pa
Friction Angle	30^0	45^0	17^0

The top edge of the model is unconstrained and allowed to move in any direction. The side = edges of the model are constrained to move indirection and left free to move in y direction.

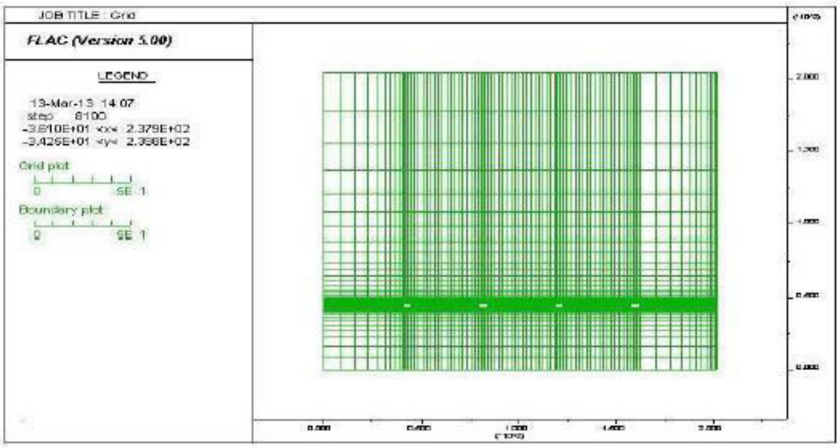

Fig 3: Grid Generation for Development of Galleries and Pillars in the Seams

Stress Distribution over Pillars

The cumulative stress distribution over the pillars and stooks during different stages of excavation is shown in the FLAC simulation of numerical modeling. The model was analyzed under three conditions: with roof support, with both roof and side support, and without any support, to assess the stress distribution across the pillars and stooks. The simulation revealed that the maximum stress of 9 MPa is experienced by the stook located next to the fourth gallery after the excavation of five stooks. The maximum stress over the pillar remains relatively unchanged between the supported and unsupported roof conditions, as the rock load remains constant. However, the stress distribution profile varies significantly, showing higher stress concentration along the sides of the pillars when roof and side support are present. This indicates that while the overall stress remains consistent, the reinforcement provided by the supports alters the stress distribution, particularly at the pillar sides.

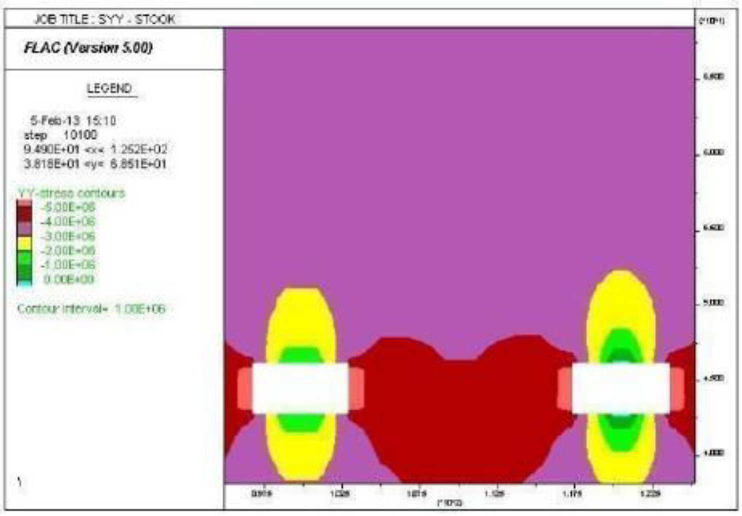

Fig 4.: Stress distribution over the fourth gallery

Stress distribution over the fourth gallery is shown in the Fig 4. The X-axis represents the stress in MPa and Y-axis represents the goaf edge distance in meters. The maximum stress distribution over the pillar/stook shows increasing trend because of load on the pillar/stook due to extraction of adjoining stooks.

Discussions

The investigations into subsidence movement, stress, strength, and safety factors in short wall mining led to the following findings. Subsidence monitoring was critical in shallow depth workings, where its effects were more immediate and severe, helping estimate the overhang in the goaf and the transfer of pressure to the face and adjacent galleries. Subsidence largely depended on the panel geometry, the properties of overlying strata, and geo-technical factors. The observed width-depth ratios ranged from 1.84 to 3.25, with new panels ranging from 1.84 to 2.4. The maximum observed subsidence was 1.58m, with a subsidence factor of 0.42 to 0.63. Surface depression occurred over 6-9 days, with residual subsidence after one year varying from 4.08% to 6.45%. Stress and strain analysis revealed maximum compressive and tensile strains of 69mm/m and 67mm/m, respectively, and the safety factor varied between 3.11 and 5.68. Finally, the maximum stress calculated using FLAC-5.0 software was 5MPa.

CONCLUSIONS

Based on laboratory testing of coal samples, empirical and numerical modeling studies on pillar stability, and subsidence profile analysis in the Kumda underground coal mine, the following conclusions have been drawn:

1. **Field observations** at Kumda mine confirmed the stability of the pillars, with no perceptible side spilling or crushing, indicating the effectiveness of the pillar design under the given geo-mining conditions.

2. **Uniaxial compressive strength (UCS)** and **triaxial testing** of coal samples revealed the coal's UCS to be 27.9 MPa, cohesion (C) to be 1.85 MPa, and the internal friction angle (Ø) to be 30°, providing essential material properties for further stability analysis.

3. **Empirical and numerical modeling**, using two-dimensional continuum analysis, indicated a maximum stress of 5 MPa acting on the pillar, with a safety factor exceeding 2. This modeling outcome corroborates the qualitative observations of pillar stability in the field.

4. A **maximum subsidence** of 1.58 m was observed over the extracted panels, with a subsidence factor of 0.63. The depillaring panels, with dimensions of 64 m by 14 m and 30 m by 45.5 m in width and depth, respectively, showed a controlled and gradual surface displacement, supporting the overall stability of the mining process.

These findings highlight the importance of proper pillar design and continuous monitoring to ensure stability and control subsidence in underground coal mining.

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