Numerical study of stability of coal pillars under the influence of line of extraction

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ABSTRACT
In underground coal mining, strata instability is one of the most catastrophic hazards, which involves sudden and violent dynamic failure of the pillars and overlying strata. Despite decades of research, the contributing factors and mechanisms of failure of underground structures are still not completely understood. Hence, it remains challenging to forecast strata failures and quantify their likelihood of occurrence. This paper deals with the scope of application of different line of extraction in problematic conditions, such as when the pillars are surrounded by goaf areas or are overstressed or there are other transportation/coal evacuation issues. In this paper, the effect of line of extraction on pillar stability has been studied in the context of an Indian underground coal mine by way of a comparative analysis through numerical simulation. The stress on the coal pillars during depillaring have been found to be similar for steep-diagonal line and straight line of extraction. However, stress on the pillars in case of steep-diagonal line follows a better trend than straight line of extraction. Overall, the results of this study establish the scope of application of different line of extraction in geo-mining conditions which do not allow implementing straight line of extraction in mechanised depillaring.

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1. Introduction
Coal is the main energy source in India and will remain a critical source for coming years due to dependency on it. Coal contributes nearly 40–50% of electricity generation and is also being used by other iron and steel manufacturing industries (Ghosh et al. 2020; Ali et al. 2021; Cavusoglu et al. 2021a, 2021b). Coal is mainly produced from Opencast and Underground mining. Out of overall coal production, opencast mining contributes nearly 95.64%, whereas underground mining contributes only 4.36% (Provisional Coal Statistics, 2021) as shown in Figure 1. From 1996 to 2021,
we can see a drastic decrease in underground coal production mainly due to a lack of knowledge of strata behavior and skilled engineers and their determined commitment to underground mining. Vice versa, we can observe the drastic increase in opencast production to meet the coal demands of the country. Still, we are not able to meet the complete coal demand. Therefore, the thrust on increasing underground coal production is being felt by coal-producing companies to meet the coal demand. In future, undoubtedly, there will be drastic shift to underground mining due to difficulty in land acquisition for opencast mining, environmental concern, and depletion of shallower deposits.

A sudden shift of underground mining is uncertain in the safety of view due to the complex behavior of overlying strata and lack of understanding of the behavior of strata failure. In underground coal mining, Strata Control is one of the most catastrophic hazards, which involves sudden and violent dynamic failure of the pillars and overlying strata (Xu et al. 2006; 2015; Xue et al. 2020).

Despite decades of research, the contributing factors and mechanisms of pillar failures, rib/snook failures, and roof/side failures are still not completely understood. Hence, it remains challenging to forecast strata failures and quantify their likelihood of occurrence (Yun et al. 2017; Yang et al. 2022; Zhou et al. 2022).

Figure 1. Opencast and Underground Coal production from 1996 to 2020-21.

However, a range of geological, geotechnical, and operational factors are associated with strata behaviour, increasing pillar failure proneness and strata control issues. Coal pillars need to be designed to initiate regular caving and avoid other strata control issues. Overlying strata plays a crucial role in the caving mechanism. Caving is generally delayed in the case of strong and massive roof strata. It takes place after a large overhang. This increases stress acting over surrounding pillars and affects the dynamic loading of supports, leading to sudden and violent failure of pillars.
In weak and moderate roof strata, caving occurs early than the expected time, leading to immediate roof/side falls (Sheorey et al. 1995; Singh et al. 2008; 2008; Peng 2017). Here, an approach has been made to assess mining-induced stress developed during depillaring operations varying line of extraction. Estimation of pillar stress is an essential parameter for proper understanding of strata control, which eventually helps design an adequate support system to address the adverse effects of the caving. Various researchers conduct numerous studies through empirical methods, analytical methods, numerical methods, still there is no permanent solution to ground control issues (Singh et al. 2011; Jaiswal and Shrivastva 2012; Kumar et al. 2018; Das et al. 2019). Line of Extraction plays a crucial role in strata control and operational point of view.

The recent roof fall accidents, Srirampur-3 (SRP-3) roof fall accident on 10.11.2021 which took the lives of four workers, and Adriyala Longwall Project (ALP) roof fall accident on 07-03-2022, which took lives of three employees, reminds and warns us about the unsolved mystery of strata control issues. This paper points to study the impact of line of extraction on strata control issues

2. Line of extraction

A line passing through all the corners of stooks under extraction at a time is called the line of extraction (Das 1994). It is sometimes loosely called 'line of face' or 'line of goaf'. A line of extraction should be arranged to facilitate roof control and caving mechanism. There are five types of Line of extraction during depillaring, as shown in Figure 2.

1. Straight line of extraction—Dip
2. Straight line of extraction—Strike
3. Diagonal line of extraction
4. Step-Diagonal line of extraction
5. Steep-Diagonal line of extraction

In a conventional depillaring panel with caving of the Indian coalfields, 60–120 m² area of roof overhang is typically allowed (Singh 2005). The sequence of pillar extraction, i.e., the orientation of the Line of extraction, provides flexibility in controlling the width of extraction, irrespective of the panel width (Das 1994).

In a semi-mechanized depillaring, the diagonal line or step diagonal line of extraction will be maintained in general. Diagonal or step diagonal line of face protects as solid pillars support the working places. The diagonal line of extraction helps in the caving of the roof strata and minimizes goaf flushing into the faces. Recently, Conventional mining is slowly shifted to mechanized mining improving safety, production, and productivity. In mechanized mining, a Straight line of extraction is predominantly practiced to maintain roof control and allows the caving to take in regular. In exceptional cases, a steep line of extraction is followed. Depending upon the given site conditions, a steep diagonal line of extraction is mainly maintained to control the strata movement.
In the caving type of depillaring, a diagonal line of the extraction is more preferred. In the stowing type of depillaring, a step diagonal line of the extraction is preferred. It facilitates water drainage without flooding the working places in the lower level.

Figure 2. Line of Extraction (a) Straight line-Dip, (b) Straight line-Strike, (c) Diagonal line, (d) Step-Diagonal line, and (e) Steep-Diagonal line.
The impact of past experiences of Line of Extraction on Strata Control issues

- In 1976, the first Continuous Miner was introduced in South African Collieries at Usutu Colliery. At Usutu colliery, Greenside colliery, and Ermelo colliery, initially, a straight line of extraction is adopted with Continuous Miner, resulting in severe strata control problems such as high stresses pillars adjacent to the goaf and difficulties in removing the last pillars in the line. It was then changed to the diagonal line. Thus, depillaring with a diagonal line of extraction in these collieries yielded successful results with better strata control (Beukes 1980).
- At Sigma colliery, the first depillaring panel was extracted with a diagonal line of extraction, resulting in high pressures on the lagging pillars and premature fender and bord failures. It was then changed to the straight line, which resulted in successful depillaring.
- At Ermelo colliery, panels extracted in a diagonal line of extraction (long 45°) consists of 11 to 13 roadways caused high tramming distance, resulting in a delay in transportation and production. Then, it changed to short 45° line of extraction consisting of 2 to 4 roadways. And in adverse geological conditions line of extraction even changed to 30° which yielded successful results (Beukes 1992).
- At Venkatesh Khani-7 coal mine, India, initially, a straight line of extraction is followed for panels CMP 5A to CMP7B/2, resulting in high strata control problems such as high stresses and severe floor heaving, higher loads at the face, and some pillars were even left untouched for stability reasons. It was then decided to change the line of extraction from straight to diagonal, which resulted in successful depillaring.

3. Establishment of numerical model

FLAC 3D, numerical modelling software for geotechnical analyses of soil, rock, groundwater, constructs, and ground support is used to study the influence of different line of extraction. The modelling procedure in FLAC 3D is shown in Figure 3. FLAC3D utilizes an explicit finite volume formulation that captures the complex behaviours of models that consist of several stages, show large displacements and strains, exhibit non-linear material behaviour, or are unstable (including cases of yield/failure over large areas or total collapse).

4. Field study

An underground coal mine Venkatesh Khani –7 (VK-7), has been selected for this study. It is between north latitude 17° 27' 07” to 17° 30’ 24” and east longitude 80° 40’ 00” to 80° 41’ 30” as covered in Survey of India topo sheet No.: 65 C/10 & 11 of Kothagudem district in Telangana. The mine was started on 15-08-1954 and has four coal seams: Top seam, Index seam, King seam, and Bottom seam. Continuous Miner was implemented in King seam in 2006. The working method adopted in this seam is the Split and fender method with pillar size 45 m × 45 m, gallery width 6 m, and working height 4.6 m.
Figure 3. Chronology of FLAC 3D model.
The Continuous Miner panel -5B has been taken in this study, which is at a depth of 339 m and monitored during depillaring using vibrating-wire stress cells. The installed stress cells are thoroughly monitored until they go into goaf. A schematic diagram showing the strata Monitoring plan of CMP-5B with relevant dimensions as discussed in this paper (see Figure 4).

The behavior of strata during depillaring face was monitored through field instrumentation. The field instrumentation aims to ensure workmen’s safety and increase the production and productivity of the mine. It provides quantitative figures of strata movement in and around the working to understand the rock mass behavior better. It is also required to give proper attention to durable and robust instruments which are better suitable for the underground mining environment. The calibrated vibrating wire-based stress cells are installed, which suits well for underground mining conditions to monitor the mining-induced vertical stress developed over the pillars/stooks/fenders. It is a reliable and preferred instrument for long-term monitoring due to frequency as output signal rather than the voltage in the case of conventional electrical resistance or piezoelectric transducers. The stress meter is installed into the horizontally drilled borehole in the pillars by setting tool and tightened with wedge and platen assembly. The cross-sectional and side view of vibrating wire stress cell is shown (see Figure 5).

Several boreholes were drilled to estimate the lithology of the area; a borehole, 67LN/16D near to the proposed panel on the dip-most side was considered for the development of the numerical model. The lithology, elastic and mechanical properties of rock layers present in the borehole located at 67LN/16D are presented as histograms (see Figure 6).

The FLAC 3D model was developed with panel length 309 m and panel width 264 m, including the barrier pillars. The pillars and galleries are developed with a width of 45 m and 6 m, respectively. The boundaries and the bottom of the model are constrained by displacement. Vertical stress of 8.52 MPa was applied to the top of the model using the Mohr-Coulomb model.
The field data was collected for the Straight line. With the help of that, a predictor model was formed and validated with the field results. Then the line of extraction was changed to study the stability of pillar and workings, and the stress values were generated. The model so developed with different rock beds. The physico-mechanical properties of coal and overlying strata used in numerical modelling are summarised in Table 1.

The validation of input parameters of the Mohr-Coulomb model was calibrated according to the empirical strength equation for the strength of slender coal pillars proposed by Sheorey, also validated after the depillaring stage with field data collected from the study site using average stress criteria over pillars. The boundary conditions of the model were such that it was laterally confined. The base of the model was fixed and top of the model is set free and was allowed to deform. The boundary conditions and boundaries were placed in such a way that are of interest to sufficiently away from it and do not affect the vertical stress redistribution in the pillars under extraction. The sizes of individual elements were varied to optimise the computational time and memory requirements.

\[
\frac{\sigma_h}{\sigma_v} = \frac{\vartheta}{1 - \vartheta} + \frac{\alpha \times E \times \beta}{(1 - \vartheta) \times \gamma} \left( 1 + \frac{1000}{H} \right)
\]

where \(\sigma_h\) is the in situ horizontal stress (MPa), \(\sigma_v\) is the in situ vertical stress (MPa), \(\vartheta\) is the Poisson ratio, \(\alpha\) is the coefficient of thermal expansion of rock \((30 \times 10^{-6}/\text{C})\), \(E\) is young’s modulus of rock (GPa), \(\beta\) is the thermal gradient \((0.03 \text{ C/m})\), \(\gamma\) is the rock density \((\text{Kg/m}^3)\), and \(H\) is the mining depth (m).

The developed model was gravity-loaded, in situ stress conditions (Eq. (1)) were applied to initialize geostatic stresses in the model, and the mining depth was simulated by applying a truncated load at the top surface of the model. The model developed with initialized vertical stress contours was used for further analysis. The galleries were then developed in the equilibrated model (see Figure 7) and were

Figure 5. Vibrating wire-based sensor’s cross-sectional and side view (Mishra et al. 2018).
allowed to re-equilibrate so that the stresses redistribute and the roof converges (Ghosh et al. 2020).

5. Results

Even though numerical modelling is widely accepted globally, even in mining, civil, and other industries, still, numerical simulation is yet to be a fully accepted tool in the mining industry for the performance prediction of an underground structure, mainly due to the difficulties in incorporating the exact geological conditions and unseen findings which didn’t obtain during borehole survey and other unpredictable geological conditions. However, the adoption of the developed calibration approach
(Jaiswal and Shrivastva 2012) was reported to be reasonably reliable. Different models have been developed after the extraction of each pillar by varying the line of extraction. At each extraction stage, nearly 100 models were developed, i.e., 20 models for each Line of Extraction (pillar-wise models) to study its impact on surrounding pillars and all other pillars in the panel, as shown in Figure 8. Here, the extraction stage is known as pillar extraction stage after each pillar is extracted as per different sequences followed in different line of extraction. The stresses acting on the pillars are calculated with average stress criteria in FLAC 3D and noted at each stage. The maximum stresses acting on pillars at each extraction stage vary the extraction line (see Table 2).

6. Discussions

In the developed numerical models, stresses acting on immediate pillars and all other pillars in the panel are calculated using average stress criteria after the extraction of each pillar. i.e., extraction stage. The maximum stress acting on pillars in the Continuous Miner panel after each pillar extraction is shown in Table 2, and a safety rating has been given in Table 3 to different line of extraction based on maximum and minimum stress values observed during extraction in numerical modelling. The maximum stress observed was 16.79 (MPa) for the Step diagonal line of extraction.
Figure 8. Vertical stress acting over pillars (a) after development; Depillaring with (b) Straight line-Dip, (c) Straight line-Strike, (d) Diagonal line, (e) Step-Diagonal ine, and (f) Steep-Diagonal line.
But the minimum stress is the same for different line of extraction since pillar-1 is the first pillar extracted in all different line of extraction. Mining is a hazardous profession and considered as a war against the unpredictable forces of nature. It is always a complicated task for mining engineers to extract minerals. Whenever a complicated operational issue arises, like pillars overlying the goaf area or nearby goaf area are more prone to failure, and overstressed pillars and other strata control issues, mining engineers can opt for different line of extraction better suitable to the existing geological conditions. In special cases like where it is not possible to extract the pillar in a straight line, mining engineers can opt for other line of extraction. This study shows that the Steep-Diagonal line shows equal stress variation to a straight line and follows a better trend than a straight line (see Figure 9). Line of extraction of pillars may be changed in such a way that gravity of goaf forces which can be inclined towards the goaf instead of working area may help in improving condition of goaf edge level galleries, pillars and other strata control issues. In India, for mechanized mining with Continuous Miner, mainly straight line of extraction is being followed to facilitate roof control. Due agreeing with this concept, the Straight line of extraction is more suitable for mechanized mining, but the line of extraction needs to be studied mine to mine along with regular scientific study considering the operational issues. As geological and geo-mining conditions are not the same for all mines. It highly

| Extraction stage | Straight line-dip (MPa) | Straight line-strike (MPa) | Diagonal line (MPa) | Step-Diagonal line (MPa) | Steep-diagonal line (MPa) |
|------------------|-------------------------|---------------------------|--------------------|------------------------|--------------------------|
| 1                | 11.27                   | 11.27                     | 11.27              | 11.27                  | 11.27                    |
| 2                | 11.68                   | 11.80                     | 11.80              | 11.80                  | 11.68                    |
| 3                | 12.15                   | 12.23                     | 12.59              | 12.23                  | 12.59                    |
| 4                | 12.40                   | 12.46                     | 13.16              | 13.16                  | 13.12                    |
| 5                | 13.37                   | 12.65                     | 13.17              | 15.45                  | 13.17                    |
| 6                | 13.76                   | 13.50                     | 13.45              | 13.73                  | 13.77                    |
| 7                | 13.60                   | 13.99                     | 14.01              | 14.00                  | 14.06                    |
| 8                | 13.64                   | 14.03                     | 14.29              | 14.03                  | 14.32                    |
| 9                | 14.67                   | 13.65                     | 14.29              | 14.38                  | 14.35                    |
| 10               | 15.10                   | 13.94                     | 14.63              | 14.72                  | 15.11                    |
| 11               | 14.79                   | 14.85                     | 14.80              | 15.17                  | 15.40                    |
| 12               | 14.34                   | 15.49                     | 15.47              | 15.50                  | 15.94                    |
| 13               | 15.33                   | 15.51                     | 15.27              | 15.52                  | 15.31                    |
| 14               | 15.83                   | 14.94                     | 15.38              | 15.69                  | 15.79                    |
| 15               | 15.43                   | 14.77                     | 16.05              | 15.79                  | 16.15                    |
| 16               | 14.75                   | 15.94                     | 16.35              | 16.40                  | 16.69                    |
| 17               | 15.97                   | 16.71                     | 15.92              | 16.78                  | 15.96                    |
| 18               | 16.35                   | 16.77                     | 16.71              | 16.79                  | 16.44                    |
| 19               | 15.77                   | 15.73                     | 15.63              | 15.76                  | 15.79                    |

| Line of extraction       | Maximum stress observed (MPa) | Minimum stress observed (MPa) | Rating |
|--------------------------|-------------------------------|-------------------------------|--------|
| Straight line – Dip      | 16.35                         | 11.27                         | 1      |
| Straight line – Strike   | 16.77                         | 11.27                         | 4      |
| Diagonal line            | 16.71                         | 11.27                         | 3      |
| Step-Diagonal line       | 16.79                         | 11.27                         | 5      |
| Steep-Diagonal line      | 16.44                         | 11.27                         | 2      |
varies from mine to mine due to existing geological conditions and the complexity of overlying strata.

7. Conclusion

Based on the analysis shown in this paper, it was observed that Steep-diagonal line of extraction follows a better trend than Straight line of extraction. Whereas, Step-Diagonal line follows an increasing trend in stress throughout the panel extraction. It was also observed that Diagonal line and Straight line-Strike shows maximum stress values comparatively to other line of extraction. A fall in stress values can be observed in Straight line-Dip and Straight line-Strike after each row of extraction as the pillar under extraction is supported by barrier pillars or may be due to main fall/local fall taken place in goaf after the extraction. This paper establishes the scope of application of different line of extraction in geo-mining conditions which do not allow implementing straight line of extraction. Some examples of such conditions are when the pillars are surrounded by goaf areas or are overstressed or there are transportation/coal evacuation issues. In this paper, a mechanised depillaring panel at an Indian underground coal mine (VK-7) has been studied, and numerical models have been developed as per the actual field conditions of the mine varying the line of extraction. A similar methodology may be applied for the design of a different line of extraction with different site-specific mining conditions. In future, there is a scope for much research yet to be done in this area, where ventilation also plays a key role in different line of extraction.

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**Data availability statement**

The datasets analysed during the current study are available from the corresponding author on reasonable request.

**Disclosure statement**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Code availability**

The Numerical modelling software FLAC 3D is used in this study.

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