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Stability Assessment of Vertical Remnant Pillars In Cut and Fill Mining Method with Numerical Modelling

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Abstract **-** Cut and fill mining method involves extraction of orebody in horizontal slices in weak rock formations. The void created as a result of excavation is backfilled and vertical pillars are left at intervals if the overlying roof is weak. This method is advantageous in terms of ore recovery and safety, making it a preferred method for steeply dipping orebodies in challenging underground environments. These remnant pillars left intact plays a crucial role in supporting the overlying strata and protecting a safe environment for ore exploitation. The stability of these pillars is important since pillar failure results in catastrophic consequences including subsidence or even loss of lives. Hence, the pillar dimension is one of the important parameters which governs the stability of the overlying strata in cut and fill mining method. The present study focuses on the assessment of vertical pillar stability with 5 m × 5 m dimension left intact throughout the entire depth of orebody in cut and fill post pillar mining method considering three-dimensional finite element analyses. Based on the simulation results obtained from numerical modeling, it was found that the pillar dimension of 5 m × 5 m was stable enough for the considered geo-mining condition with factor of safety above unity.

Keywords**:** Cut and fill mining, Post pillar mining, Pillar stability, Finite Element Analysis

1. Introduction

Underground hard rock mining relies heavily on the stability of pillars to ensure safety and operational efficiency of the mine. Recent studies have developed advanced predictive models and methodologies to assess and enhance pillar stability, addressing the complexities of underground environments. Pillar design significantly impacts the stability of underground metal mining operations, as evidenced by various studies. The stability of pillars is influenced by multiple factors, including working depth, rock mass properties, and pillar dimensions. For instance, when the working depth was increased from 230 m to 290 m, it resulted in a notable decrease in stress concentration factors and an increase in yield around crown pillars, indicating that deeper mining necessitates careful pillar design to prevent failure [1]. Additionally, large-scale laboratory tests have shown that the interaction between pillars and support systems, such as rock bolts, is critical for maintaining stability under load, highlighting the importance of incorporating robust support mechanisms in pillar design [2]. Overall, integrating empirical data, numerical simulations, and innovative support systems is essential for optimizing pillar design and ensuring safe mining operations [3]. While these advancements provide valuable insights into pillar stability, challenges remain in real-time monitoring and adapting to dynamic underground conditions, necessitating ongoing research and advancement in this field.

The most widely practiced underground metal mining methods are sublevel stoping, cut and fill mining, room and pillar mining, block caving and sublevel caving [4]. Amongst all these methods, cut and fill mining is found to be the most suitable non-caving method for ore bodies with steep dipping and/or irregular orebody boundaries, especially in areas surrounded with unstable rock strata [5]. It consists of mining the orebody in horizontal slices followed by filling up the voids with waste materials; thereby, leading to stabilization of the mined-out stope walls [6]. Cut and fill mining provides the advantage of selective mining and also ground stability. With poor roof conditions prevailing in underground mines, pillars penetrate into the roof and floor owing to the overlying vertical stresses [7]. This issue can be countered by cut and fill post-pillar method wherein natural pillars are left intact in between extracted ore at intervals depending on the rock mass conditions, which is particularly useful in high-stress environments. This method of mining tends to provide a safer environment; thereby, reducing the risk of a collapse. However, the dimension of the post pillar is a deciding factor in determination of surrounding underground structures stability while allowing for the valuable mineral extraction. Thus, understanding the pillar stability in underground mines is crucial from safety and operational point of view.

The most widely used approaches to determine the stability of underground structures include analytical, empirical, experimental and numerical methods. Amongst all the methods, numerical methods prove to be more viable for determining the stability of pillars, owing to their different advantages [8]. Recent research has provided valuable insights into the application of cut-and-fill mining method across different mining environments. The stability of the stope and associated drives of a manganese mine situated in the Balaghat district of Madhya Pradesh, India was studied and analyzed with increasing stope [9]. To ensure ongoing stability and validate modelling predictions, continued rock mass deformation monitoring was recommended until the stope was fully extracted. The stability of natural pillars left intact in multilevel cut and fill stopes without reinforcement was analyzed, using ANSYS software to study stress distribution, displacement profiles, and extent of yield zone in varying geo-mining conditions [10]. The study found that stress concentration factors (SCFs) for principal stresses were higher for crown and sill pillars with thicknesses of 4 m and 5 m, respectively at greater depths; indicating a higher possibility of yielding or failure due to shearing effect. The structural parameters for safe and effective recovery of the remnant ore with the overhand horizontal cut and fill method at a lead-zinc mining area in Qi Luo-gou, southern NingNan, were studied using numerical modeling [11]. The simulation results indicated that safe production could be achieved by using the mining process with 3 mining-1 filling or 2 mining-1 filling, with a controlled top height of 10 m and a gap exposure area controlled within 150 – 250 m^2. The literature, however, shows that very few studies have been carried out to analyze the stability of post pillars left intact in cut and fill mining method. Thus, it becomes pertinent to study and analyze the behaviour of post pillars due to subsequent extraction and backfilling of the void area in cut and fill mining method.

In the present study, stability assessment of remnant vertical pillars in an underground metal mine is carried out with cut and fill mining as method of extraction. Three-dimensional finite element (FE) analyses have been carried out considering elastic material constitutive behaviour using ANSYS Workbench Version 2023. The simulation results are evaluated in terms of factor of safety and extent of tensile zones around mined out stopes in the 5 m × 5 m vertical pillar, along the pre-defined paths. Based on the study carried out, some important conclusions have been inferred.

2. Details of the Case Study Mine

The case study mine, located in India, is dominated by quartz-chlorite-sericite schists, which are integral to the Dalbhum formation, dating back to the Proterozoic era (1.48-1.58 billion years ago). These schists serve as the host rocks for ore mineralization. The mineralization process is closely associated with structural features including shear zones and faults, primarily influenced by hydrothermal processes. The nature of the mineralization as shown by the synthesis and interpretation of surface and subsurface data, lithological and structural controls, and the geometry of the mineralized horizons all suggest that the ore mineralization in several blocks may have been the expression of a single ore body. The access to the ore deposit is through an 8-degree decline facilitating deployment of trackless mining equipment. The decline access to the ore deposit is at a depth of around 75m via cross-cuts. The principal method of extraction is horizontal cut-and-fill mining with post pillars owing to the steepness of the orebody. The geological strength index (*GSI*) for the mine site is found to vary between 50 and 60; thereby, denoting the rock mass quality to range between fair and good.

3. Material Properties considered for the study

Geo-mechanical properties, including modulus of elasticity (E), Poisson's ratio (ν), uniaxial compressive strength (σ_c) and tensile strength (σ_t) of the intact rock are determined using core samples provided by case study mine and tested in the

Rock Mechanics laboratory. These values represent the intact rock properties. However, the larger rock mass contains local cracks, fractures, and discontinuities, which significantly lower the overall strength of the rock mass. To counter this reduction in rock mass strength, the properties are adjusted using RocData 4.0 software. Table 1 lists the material properties of the rock mass for the orebody, waste rock, and backfill material, which are used as input data for finite element analyses.

Table 1: Material properties considered for numerical models.

Particulars	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio
Orebody	2859	4.16	0.12
Waste Rock	2966	3.12	0.03
Backfill	2200	0.2	0.3

4. Three-dimensional finite element models

Three-dimensional numerical models used in this study incorporate detailed geological data, such as the orientation of the orebody and waste rock, based on geological plans and sections provided by case study mine. To simplify the 3D model, the geological sections are digitized using AutoCAD software to represent the orientation in a simplified manner, and then imported into ANSYS Workbench Version 23.0 [12] for further analysis. Figure 1 illustrates the three-dimensional underground mine model of the orebody used in the study. A 10 m thick rib pillar is left in the orebody (Figure 2) due to the orebody's strike exceeding 100 meters, providing support to the surrounding rock mass.

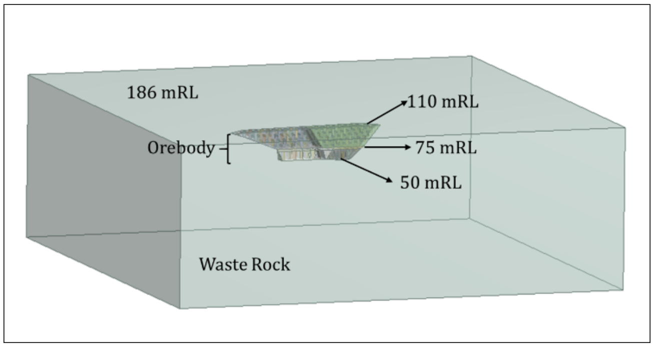

Fig 1: Model geometry showing orebody and waste rock.

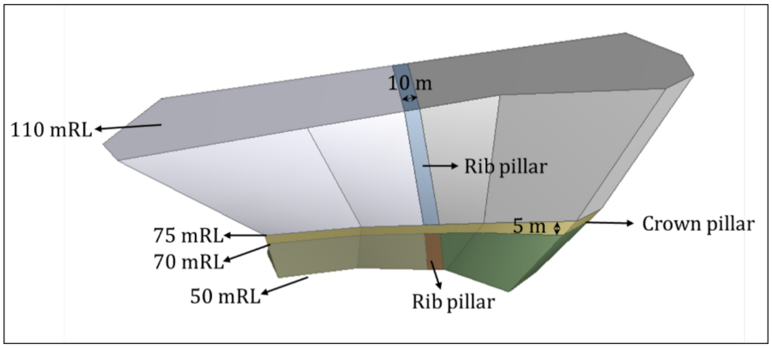

Fig 2: 3D Model showing the rib and crown pillar.

5. Different cases analyzed for the study

Stability of stopes and pillars for the orebody are determined for the worst-case scenario. Four cases have been considered for the present study (as shown in Figure 2): (1) Case 1 where stopes between 75 mRL and 110 mRL (left portion of the rib pillar) are extracted and backfilled except the last 3 m which is mined out leaving unfilled stope in between 107 mRL and 110 mRL, (2) Case 2 where stopes on right portion of the rib pillar between 75 mRL and 110 mRL are mined out and backfilled leaving 3 m unfilled stope (107 mRL – 110 mRL), (3) Case 3 where stopes between 50 mRL and 75 mRL (left portion of the rib pillar) are extracted and backfilled except the last 3 m which is mined out leaving unfilled stope in between 67 mRL and 70 mRL, and (4) Case 4 where stopes on right portion of the rib pillar between 50 mRL and 75 mRL are mined out leaving 5 m × 5 m vertical pillars; and the void space due to extraction is backfilled except the last 3 m (67 mRL - 70 mRL). A crown pillar of 5 m thickness is left between 70 mRL and 75 mRL for Cases 3 and 4. The ground surface is at 186 mRL. Stope dimension is taken as 10 m × 10 m for the three-dimensional numerical model.

6. Loading and Boundary Conditions

Fixed boundary conditions have been applied at the bottom portion of the finite element model, i.e., the bottom portion is constrained in z direction in the Cartesian coordinate system. Moreover, horizontal in situ stresses (σ_{Hmax} and σ_{Hmin}) are applied on the two vertical faces of the finite element model with stresses varying from 0 – 16 MPa, having a uniform increasing trend with depth as shown in Figure 3. The opposite faces are constrained in x and y-direction, respectively. The horizontal to vertical stress ratio K_o (across the strike direction) is assumed to be at 1 and 1.5 for the analyses across and along the strike direction, respectively. In order to impose insitu stresses, gravity loading is applied. The gravitational acceleration is taken to be 9.81 m/s^2 which is applied on the model as body force.

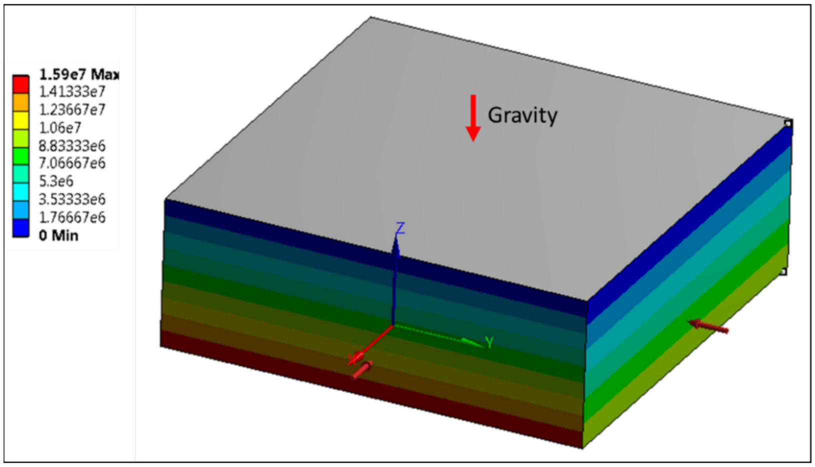

Fig 3: Boundary and loading conditions considered for the 3D model.

6. Results and Discussions

Results of the 3D models are assessed along predefined paths in terms of safety factor and extent of tensile zones around mined out stopes. Figure 4 shows the predefined paths (Path 1 – Path 7) considered for Case 1. Path 1-2, 5, 8-9, 12, 16, 18, 21 and 23 lies 1 m above the roof (111 mRL for Case 1 and 2; 71 mRL for Case 3 and 4); whereas path 3-4, 6, 10-11, 13, 17, 19, 22 and 24 are located 1.5 m below the roof i.e. 108.5 mRL for Case 1 and 2, and 68.5 mRL for Case 3 and Case 4. Path 14 -15 passes through the mid-section of the 5 m crown pillar (72.5 mRL); whereas, path 7 and path 20 passes through the mid-potion of the rib pillar. The locations of these paths were selected to highlight the region of the model, which is more relevant to the property being measured.

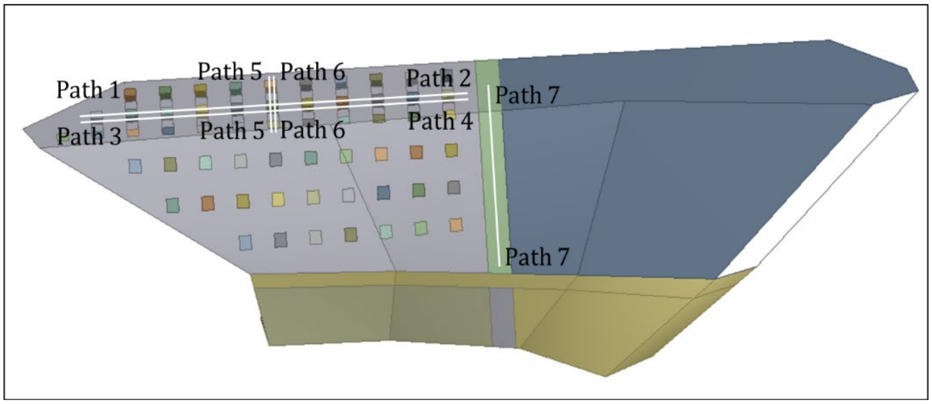

Fig 4: Paths considered for the analysis (Case 1).

Figures 5 - 8 show the safety factor plots for path 1-2-3-4, 5-6, 7, 8-9-10-11 and 12-13 respectively. It is observed that safety factor values vary between 0.6 and 3.5 along path 1-2, 5, 8-9 and 12, which lies at a distance of 1 m above the mined-out stopes. The safety factor falls below unity around the corners of the pillar. For path 1-2, 5, 8-9 and 12, the safety factor varies between 0.5 and 4.0; the minimum value around the corners of the 5 m × 5 m vertical pillar. It is observed that safety factor below unity has occurred at the corner of the pillar. It is quite common since corner of pillar is stressed and may spall. The rib pillar along path 7 shows considerable drop in safety factor as the stopes are mined out and backfilled in the subsequent cases; however, the value is above unity for all the cases.

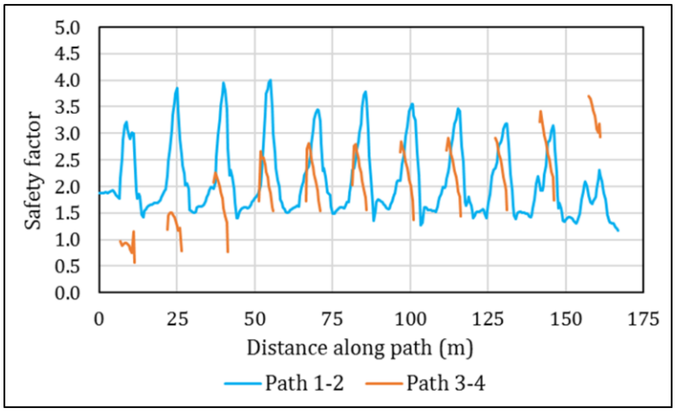

Fig 5: Safety factor along path 1-2 and path 3-4.

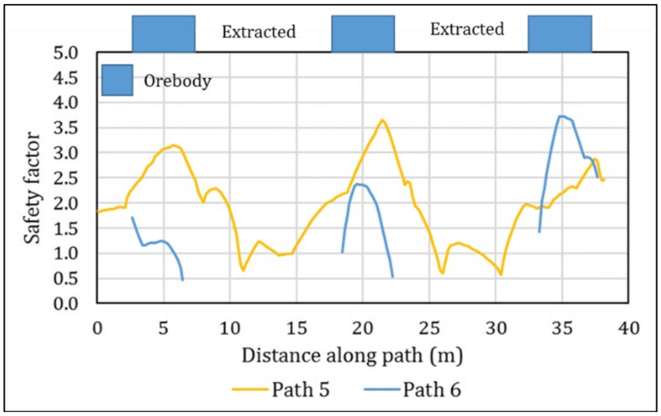

Fig 6: Safety factor along path 5 and 6.

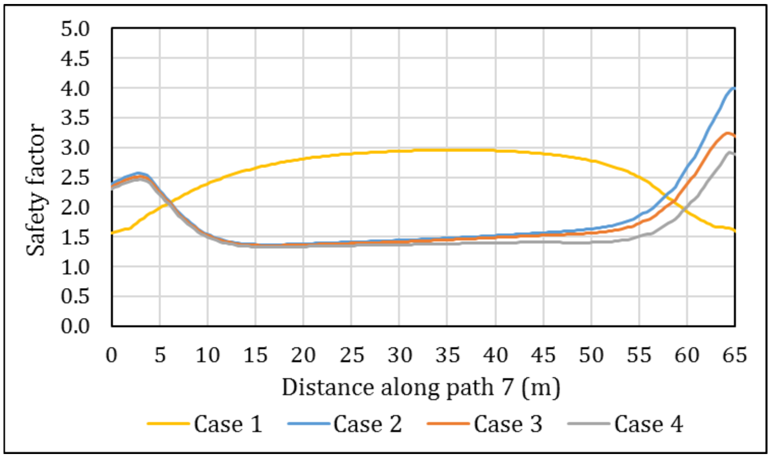

Fig 7: Safety factor along path 7 (Case 1 – 4).

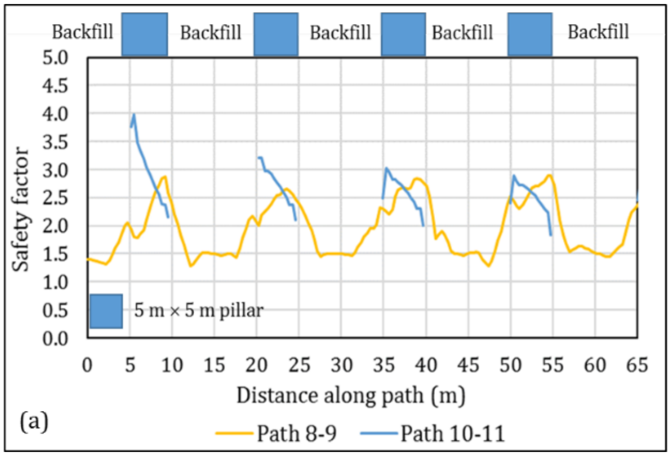

Fig 8: (a) Safety factor along path 8-9-10-11.

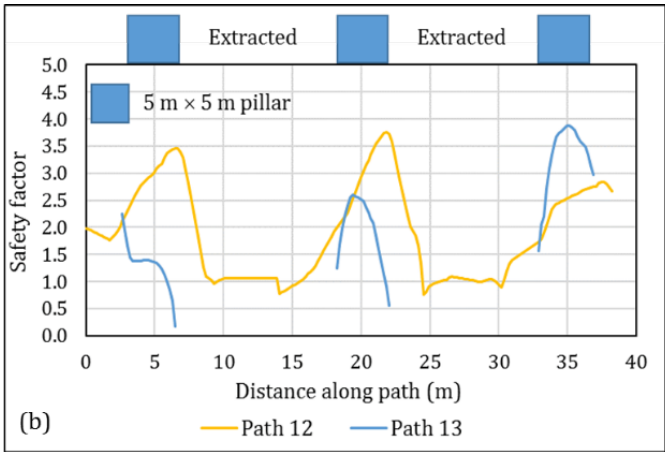

Fig 8: (b) Safety factor along path 12-13.

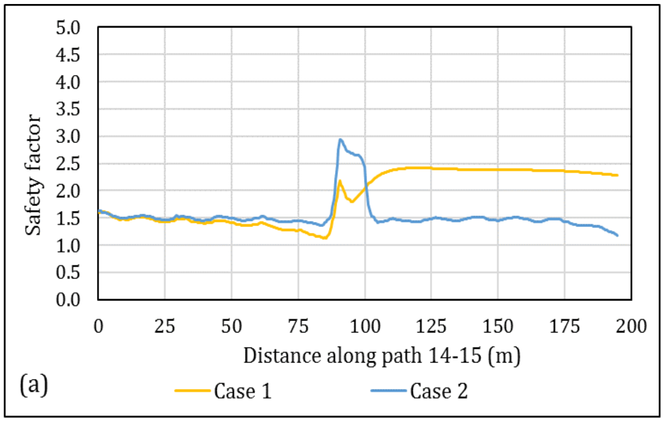

Fig 9: (a) Safety factor along path 14-15 for cases 1-2.

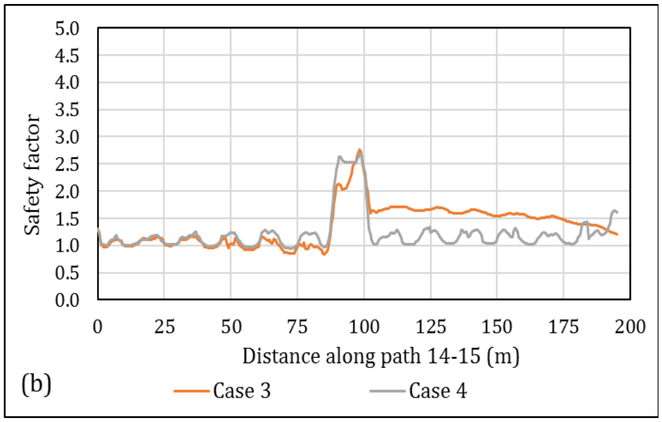

Fig 9: (b) Safety factor along path 14-15 for cases 1-2.

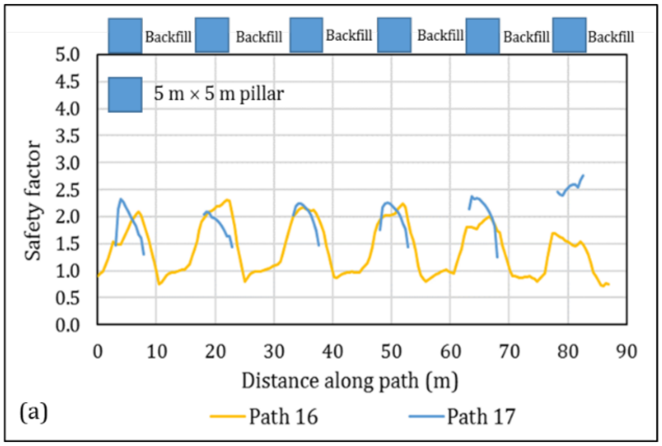

Fig 10: (a) Safety factor along path 16-17.

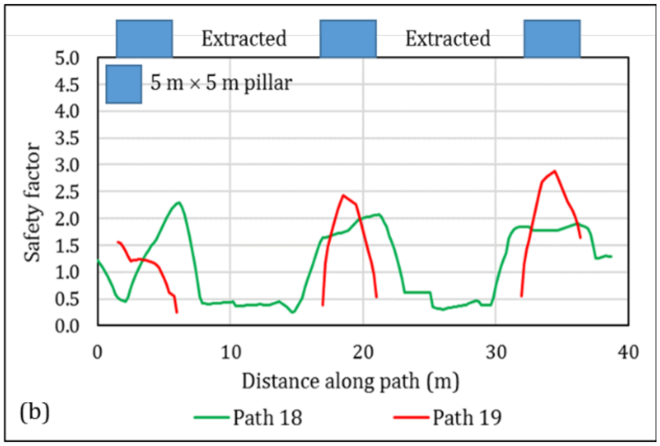

Fig 10: (b) Safety factor along path 18-19.

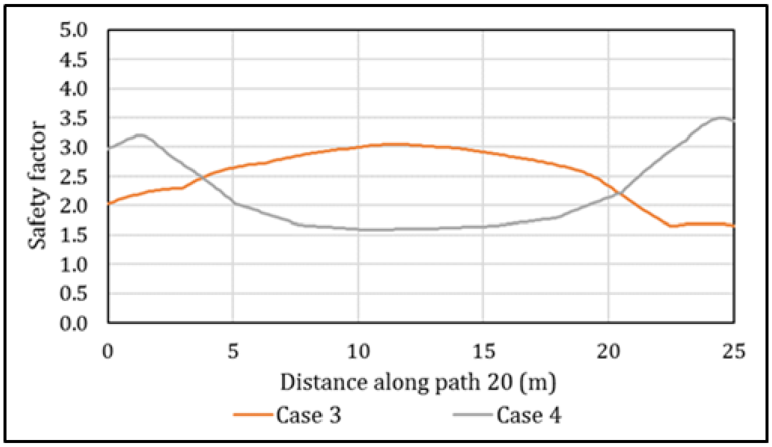

Fig 11: Safety factor along path 20 (Case 3 – 4).

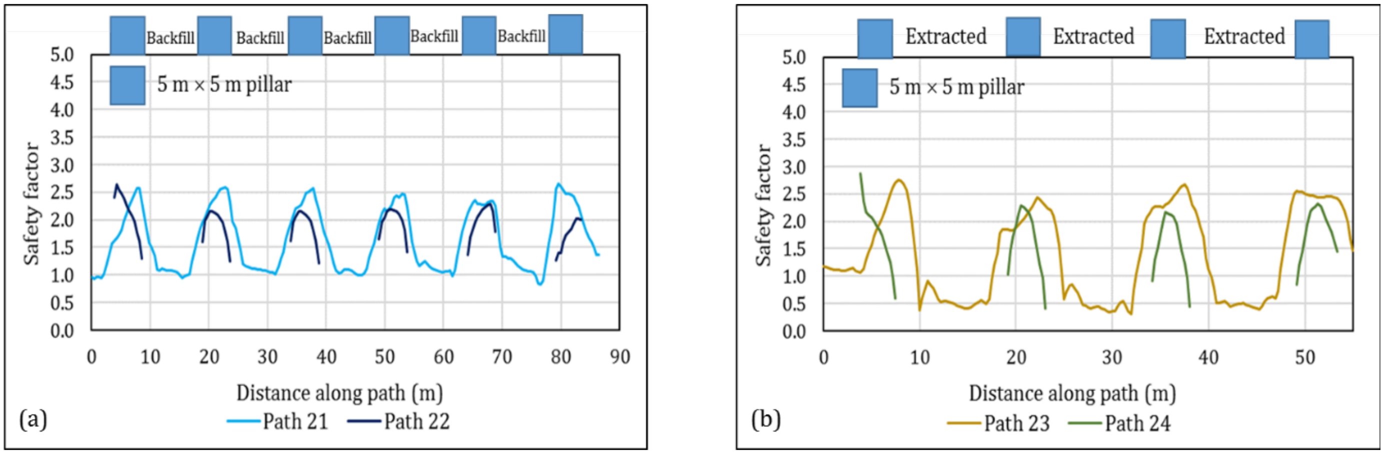

Fig 12: (a) Safety factor along path 21-22.

Fig 12: (b) Safety factor along path 23-24.

Figures 9 – 12 show the safety factor plots for path 14-15 (Case 1-2), 14-15 (Case 3-4), 16-17, 18-19, 20, 21-22 and 23-24 respectively. The average safety factor value in the crown pillar along path 14-15 vary between 1.1 and 1.5 for the different cases considered; thereby, indicating that it is stable. The safety factor values are found to be maximum at the mid-portion of the vertical pillar and reduces towards the corners of the pillar. The safety factor values in the 5 m × 5 m vertical pillar vary in the range 0.9 – 2.3 along path 16-17; 0.6 – 2.7 along path 18-19; 0.9 – 2.5 along path 21-22; and, 0.5 – 2.7 along path 23-24. It is observed that the rib pillar (50 mRL – 70 mRL) shows drop in safety factor (Figure 11) from 3 (Case 3) to 1.75 (Case 4). It can be attributed to the fact that stress redistribution takes place due to backfilling around the mined-out stopes.

Figures 13 – 14 show the extent of tensile zone around the excavated/mined out stopes and backfilled area for Case 1 and 2, respectively. It is clear that tensile stress will develop around the corners of the vertical pillar around the backfilled/excavated stopes. The results show that on an average 0.45 MPa tensile stress may occur around the corners and edges of the vertical intact pillar for all the models, which is nominal. Similar results are also obtained for Case 3 and 4, respectively. Backfilling of mined out stopes has contributed to a greater extent in minimizing the tensile zone around the stopes. It may be also noted that the safety factor values obtained from the numerical simulation are without any artificial support. Artificial supports such as rock bolt will further improve the safety factor values in the roof.

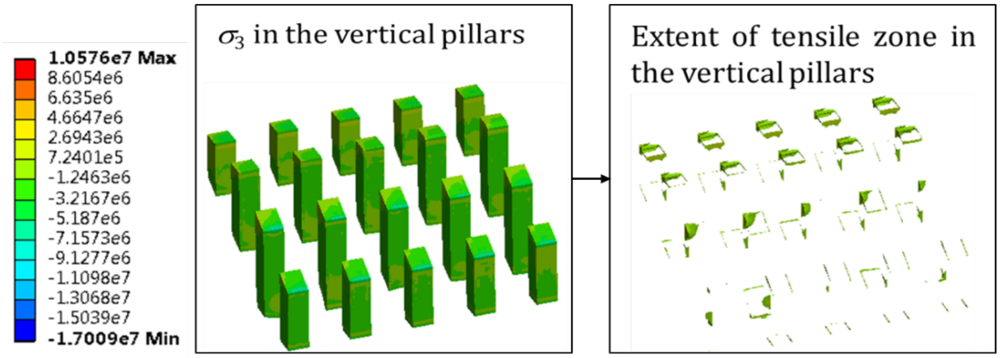

Fig 13: Extent of tensile zone around vertical pillars (Case 1).

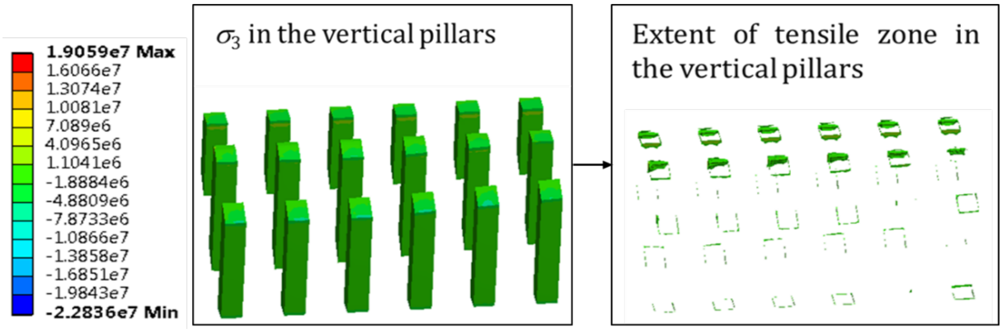

Fig 14: Extent of tensile zone around vertical pillars (Case 2).

7. Conclusion

In the present study, three-dimensional finite element analyses for an underground mine with cut and fill mining method has been carried out to evaluate the stability of remnant vertical pillars around the excavated or mined-out stope. The simulation results are assessed in terms of safety factor and extent of the tensile zone within the 5 m × 5 m vertical pillar, along different predefined paths. It is observed that vertical square pillars with 5 m sides and rooms sized 10 m × 10 m are found to be stable. The results show that on an average 0.2 – 0.65 MPa tensile stress may occur around the corners and edges of the vertical intact pillar, which is nominal and may result in spalling. Backfilling of mined out stopes has contributed to a greater extent in minimizing the tensile zone around the stopes. The safety factor values for the 5 m crown pillar between 70 mRL and 75 mRL are also above unity. It may be also noted that the safety factor values obtained from the numerical simulation are considered without any artificial support such as rock bolts, which may further improve the safety factor. Also, the worst-case scenario having *GSI* value of 50 is considered for the simulation purpose; however, the average *GSI* value in the mine is around 50 to 60.

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