Study on Critical Factors Influencing Crown Pillar's Stability through Numerical Simulation

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***Abstract*—Mining is a defined process through which valuable minerals are extracted from the earth's crust either using the surface or underground operations. Surface/Open pit mining is the most common approach,used to extract ore from shallow depths. Underground mining, on the other hand, is used to extract deposits at greater depths and when open pit mining is no longer economically feasible or due to lateral extent limitations, the majority of open cast mines must transition from open pit to underground at a certain depth. This transition necessitates the existence of a barrier pillar between the surface and underground mines in order to keep one working area separate from the underground workings and is referred to as a Crown pillar. This barrier pillar is critical throughout the mining operation, and its stability analysis is vital to protect both surface mine slopes and underground my infrastructure. Because of variations in geo-mining conditions, the crown pillar behaves differently than the surface crown,which is commonly leftover barrier at the surface in direct underground mining operations. Stresses reorient around the crown pillar during the underground miningoperations and leads to the occurrence of displacements, which can be evaluated using numerical simulation techniques. This paper focuses on the behaviour of crown pillar and its key factor's influence on its stability by interpreting the stresses and displacements using FLAC3D software.**

***Keywords*—Transition, crown pillar, critical factors, stability analysis, numerical simulation**

I. INTRODUCTION

Mineral deposits at shallower depths are under depletion, and underground mining operations for deposits at greater depths are now unavoidable. The stripping ratio, on the other hand, determines the depth of an open pit mine. Due to land constraints and environmental concerns, mining operations are shifted from surface to underground when an open pit reaches its maximum designed depth and the ore remains at greater depths [1, 2]. Because of the high stripping ratio and limited lateral extent, transition is required and leads to underground mine development, which is more complicated, specialised, and expensive. The "Crown Pillar" is left to isolate ore barriers from both open pit mining and underground mining.

Failure of the Surface Crown or the Crown Pillar, on the other hand, is a large-scale loss that may result in subsidence or sinkhole formation [3]. So, Crown ensuring safe mine operations. The Crown Pillar faces a new challenge in dealing with the change in geo-mining conditions from open pit to underground, and the vertical stresses acting on the pillar increase with increasing depth of mining, forming a critical issue in dealing with crown pillar stability analysis, which is not commonly encountered in the case of surface crown. As a result, when designing the crown pillar, the behaviour of the pillar under these stresses must be thoroughly examined, and if necessary, an additional support system must be provided to ensure the pillar's stability.

The main purpose of this crown pillar is to protect the ground surface and underground mine from subsidence and any material inflows like water, soil and rock into the mine while underground mining activity is going on. In mine closure planning too the evaluation of the stability of crown pillar is one of the most important criteria [4]. As the affect due to failure of this pillar is on large scale, the study on the parameters affecting its stability is utmost important. In addition, infiltration also deteriorates the pillar's stability and so the rock mass quality has to be estimated in prior while designing the pillar. The major factors affecting the stability are found to be as the quality of rockmass and the orebody, the geometry of the open pit and the crown pillar dimensions. These factors can be divided into two sets one which includes the geometric parameters like the orebody dip, overall slope angle of the open pit mine, width and thickness of pillar and depth of open pit mine, while the other set includes the geo-mechanical parameters like cohesion, angle of friction and rockmass quality which indirectly indicates the rockmass rating (RMR) of the rock strata.

II. DESIGN METHODS

To design the crown pillar dimensions there are a few most familiar analytical and empirical approacheswere in use to evaluate the span and thickness of pillar.

- In earlier times, there was a thumb rule for the determination of thickness to span (T/S) ratio. If

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the ratio is 1:1, then it is considered as good rock and for the ratio of 3:1 or more, then the rock is defined as poor. Later it was modified and linked to rockmass and finally it is

$$T/S = 1.55Q^{-0.62}$$

where T is thickness of crown pillar, S is crown pillar span and Q is NGI's rock mass quality index [3, 5].

- Most popularly used design method namely Scaled span approach is developed by Carter for determination of crown pillar thickness and is given by

$$C_s = S\left[\frac{\gamma}{T(1+\ S_R)(1-0.4\cos\theta)}\right]^{0.5}$$

where C_S - scaled span of crown, T - thickness of crown, S_R - span ratio = S/L (crown pillar span/crown pillar strike), γ - specific gravity of the crown & θ - the dip of the foliation or of the underlying stope walls.

By considering the rock mass quality index, an equation to find the critical scaled span was formulated i.e.,

$$S_c = 3.3Q^{0.43}sinh^{0.0016}(Q)$$

where S_C - the critical scaled span & Q - the tunnelling quality index. To attain stable condition, the critical scaled span C_s should be always greater than the scaled span S_c [6, 7]. This empirical Scaled span approach gives better results close to the observational results but its development database includes mostly in dealing with the surface crown case studies.

- An empirical formula also exists for determining the thickness of the crown pillar under the study on the assessment of crown pillar thickness between open pit and block cave mining i.e.,

$$t = \left[\frac{13.22\times C^{0.03}\times\ S^{0.41}\times\ h^{0.56}}{\gamma_{\gamma}^{0.03}\times\ RMR^{0.66}}\right]$$

where, t is thickness of crown pillar; C is cohesion; S is stope span; h is stope height; RMR is rock mass rating; and γ_γ is specific weight of rock [8].

However, these approaches alone are insufficient to design the adequate pillar dimensions and Carter guidelines suggest a coupled approach of numerical and empirical methods will give a better result in design and analysing the stability of the crown pillar [3]. Numerical modelling is generally carried out using the softwares like FLAC3D [9], CPillar where the rock strata is stratified and 3DEC in case of strata with jointed rockmass [10], and this paper highlights the influence of prime factors affecting stability of pillar and the required numerical simulations were done using (Fast Lagrangian Analysis of Continua in 3D) FLAC3D software.

III. NUMERICAL MODELLING IN FLAC3D

To analyse the behaviour of the crown pillar, a case study has been considered and its interpretation is done through numerical simulation technique. The details of site are discussed below.

A. Location and Geology of Site

The case study is carried out at Ramrama Mine in Balaghat, Madhya Pradesh, India. Here, there is transitioning of mine from open pit to underground and the crown pillar of 10m thickness is left and the pillar exists at the shallower depth of 20m and the orebody average width ranges from 8 m to 22m. Pegmatite and Quartz mica schist are found to be the primary rock types and the rockmass comprises of three joint sets. The ore dip is found to be as 55° and the overall slope angle is 28°.

B. Geotechnical Data and Rockmass Characteristics

Borehole data and preserved cores are examined to understand the rockmass characteristics. From the findings the rockmass rating (RMR) of the surrounding rock is found to be as 48 which comes under fair category and the orebody has RMR of 59 which also falls in fair category.

The virgin state of stress termed as insitu stress condition, gets disturbed and redistributed in the surrounding rock mass when an opening is created through excavation process and this may also lead to instability in the cavity formed. The post-excavation states of stress and stability of the ground excavation and the requirements of supports, if any, can be calculated with reasonable accuracy by numerical simulation once the virgin insitu stress situation and rock mass attributes are understood. Therefore, understanding the size, distribution, and orientation of in situ stresses is a crucial input.

In situ stress measurement provides a reliable way to identify a stress field. Since there are no recorded horizontal in- situ stresses for this mine, Sheorey's equation for mean horizontal stresses is used to calculate the horizontal stresses (σ_{hm}) and the final modified equation is given below

$$\sigma_{hm} = 1.792 + 0.011H$$

The vertical stress is calculated from the gravitational load due to self-weight of the overlying strata, i.e.

$$\sigma_{v=}\,\gamma H$$

The rockmass properties used for simulation are mentioned in Table I.

TABLE I. ROCKMASS PROPERTIES

Rockmass Property	Orebody	Footwall	Hangwall
Bulk Modulus (K) in GPa	1.6	0.33	0.24
Shear modulus (G) in GPa	0.96	0.2	0.14
Poisson's ratio (v)	0.25	0.25	0.25
Density (Kg/m3)	3900	2800	2800
Cohesion (MPa)	2.5	1.5	1.05
Tension (MPa)	0.6	0.5	0.3
Friction angle (deg)	31	25	25

C. Model Geometry

As per the site conditions the model geometry for a critical section of height 127 m is developed and is extruded to 1m width and the geometry is developed and the developed extrusion pane and model pane are shown in Fig. 1 and Fig. 2 respectively. Cut and fill method of mining is adopted at the site conditions

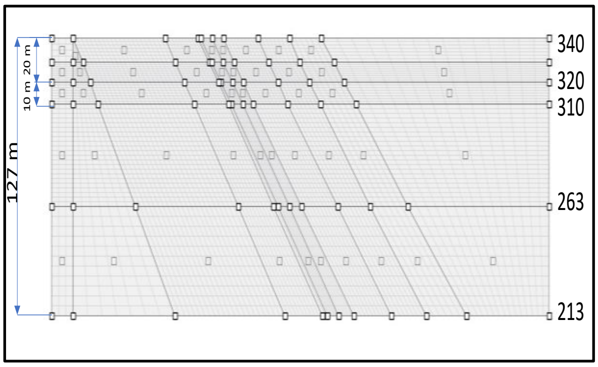

Figure 1. Extrusion pane developed in FLAC3D software.

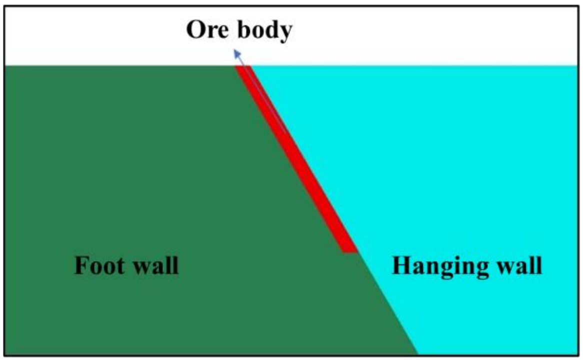

Figure 2. Model pane representation in FLAC3D software.

IV. RESULTS AND DISCUSSION

To study the behaviour of crown pillar in detail, monitoring points P1, P2, P3, P4 and P5 as shown in fig.3 are considered to find the vertical displacements(z) occurring around the pillar and P6, P7 to find horizontal/lateral displacements(x). Considering the two sets of prime factors i.e., geometric parameters and geo-mechanical parametersaffecting the stability of pillar, the simulations were caried out with the variations in these parameters and are discussed below in detail.

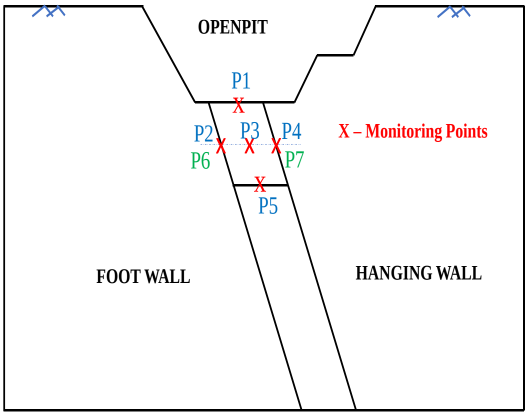

Figure 3. Monitoring points around the Crown pillar.

A. *Geometrical Parametric Variations*

1) *Width/Span variation analysis*

As the orebody width varies from 8 m to 22 m, the influence of varying width is analysed by developing the models for 8 m, 15 m and 22 m spanof pillar and the obtained results the major principal stresses and the displacements are shown in fig.4 andfig. 5 respectively. The stress distribution around the pillar is shown in fig.6.

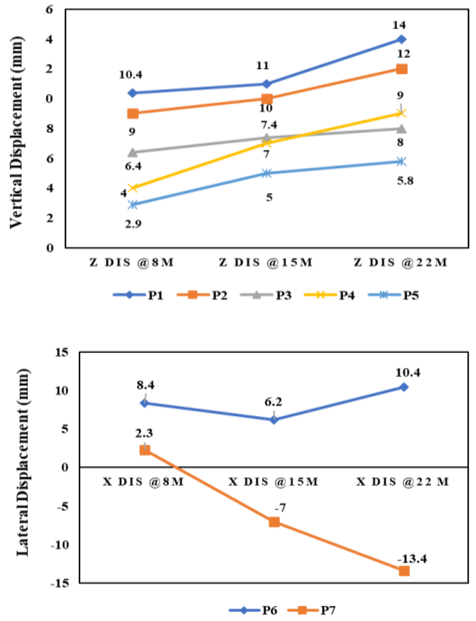

Figure 4. Vertical and Lateral displacements at monitoring points

The vertical displacements (z) are found to beincreasing with increase in the span of pillar and the displacements are found to be more at the top atmonitoring point P1 on pillar in each case i.e., 8 m, 15 m, and 22 m span of pillar. However, the lateraldisplacements (x) are found to be high towards the hangwall side of the pillar i.e., at P7.

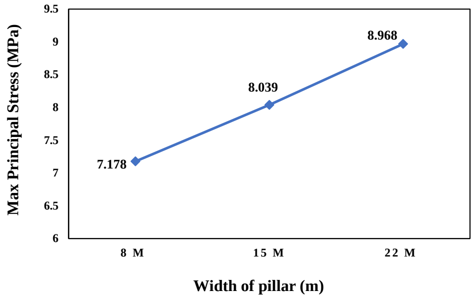

Figure 5. Maximum principal stress generated with variation in span of pillar

The variation of maximum principal stresses clearly indicates the increase in the maximum stress generation around the pillar with increase in width of pillar. The major principal stress is found to be highly concentrated towards the hanging wall side and with the increase in span the amount of stress concentrationin found to be shifting from bottom to top of the pillar.The above results clearly indicates that crown pillar with higher spans need more support requirement to enhance the stability of the pillar. The distribution of principal stresses around the crown pillar for varying width is vividly shown in Fig. 6.

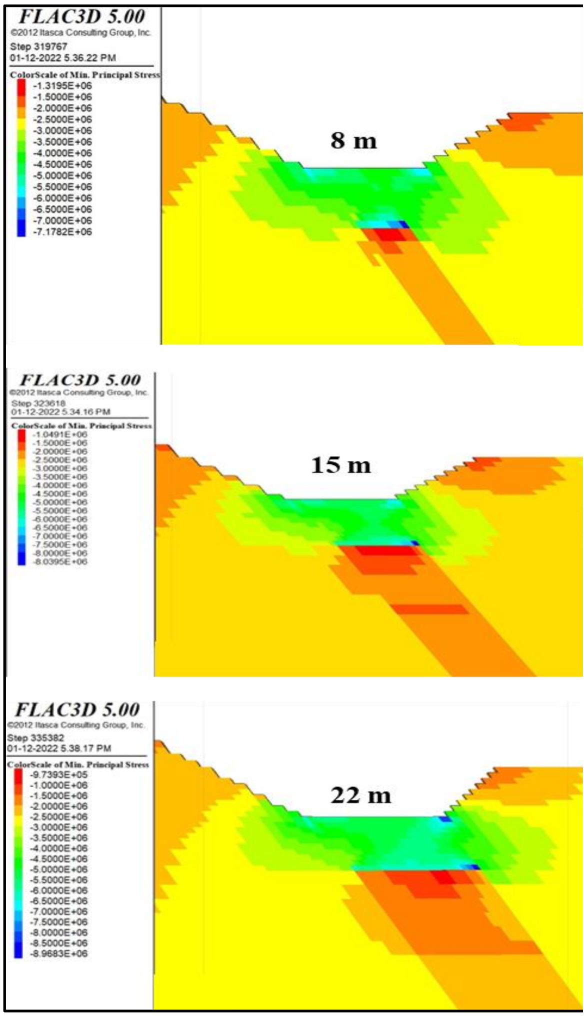

Figure 6. Principal stress distribution around the pillar

2) *Thickness variation analysis*

The effect of thickness on stability is analysed by increase the pillar thickness from 10m to 15m and the stresses and displacements around the pillar are interpreted and the results are shown in Fig.7 and Fig. 8.

The results indicate that the amount of displacements are found to be very low with increase in the pillar thickness. However, the stresses are also interpreted and the amount of maximum principal stress (Smax) generation is found to be low and the variation is shown in fig.7. and as the pillar comprises of orebody, it’s necessary to determine the optimum thickness of the pillar.

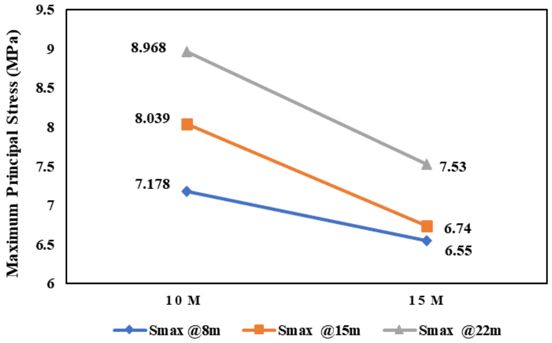

Figure 7. Maximum principal stress generated for 10 m and 15 m thickness pillar

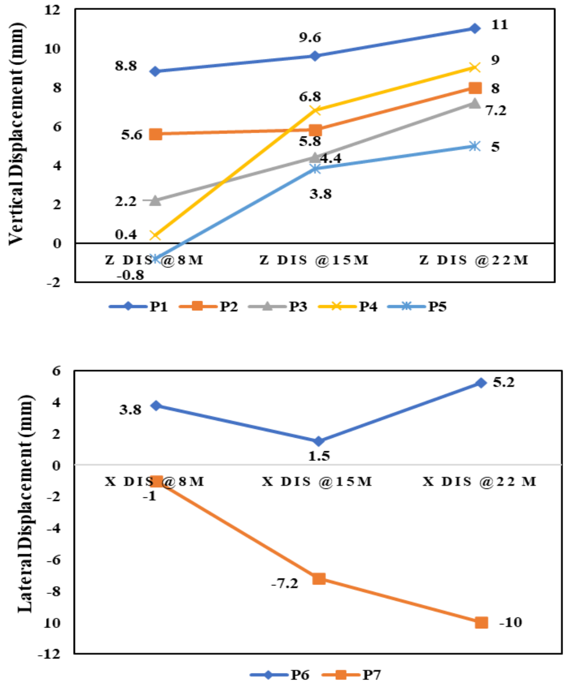

Figure 8. Vertical and Lateral displacements for 15 m thickness pillar

3) *Slope angle variation analysis*

The influence of overall slope angle is analysed by varying the slope angle from 28^o to 38^o and 45^o. The variation in stress is analysed and the obtained resultsare shown in fig.9. The results declare that the amountof stress is generation is low for 38^o in each case of span. The results highlight that with increase in slope angle upto 45^o the pillar’s stability is more as the amount of stresses generating is low compared to 28^o.

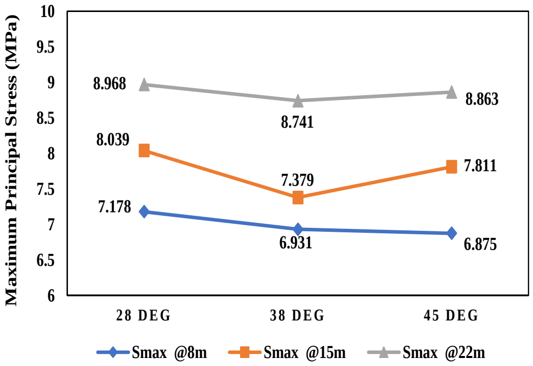

Figure 9. Maximum principal stress generated with slope angle variation

4) *Ore dip variation*

The ore-dip variation analyses are carried out by varying the dip original dip of 55° to 70° and 85°. The results are interpreted for these variations in dip angle and the evolved results are in Fig.10. The results indicate that the with increase in dip of orebody stress concentration is high around the pillar and it is also found that the stresses are reorienting towards the top of the pillar.

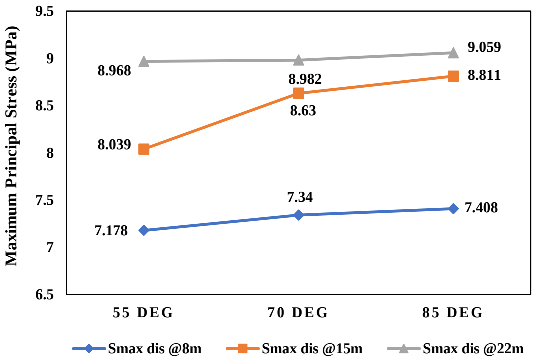

Figure 10. Maximum principal stress generated with ore-dipvariation

5) *Open cast depth variation*

At the site conditions the open pit depth was found to be 20 m and to study the influence of depth of open pit, it is increased to 50 m and 100 m and the results are analysed and the stress variation is shown in Fig. 11. The results clearly indicate that very large-scale variation is found in increasing magnitude of stress with variation in depth. Further, with increase in span of the pillar the amount of stress generated is also high. This shows that pillar with larger span at greater depth has to be provided with additional supports to maintain the pillar stable.

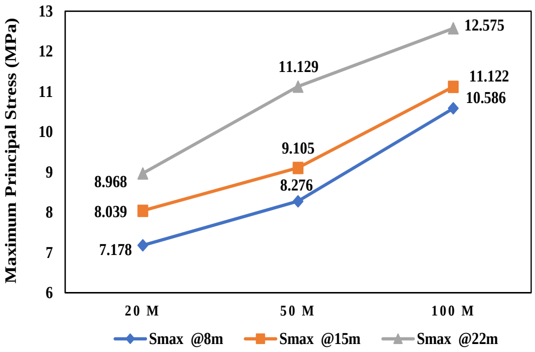

Figure 11 . Maximum principal stress generated with open pit depth variation

B. *Geo-Mechanical Parametric Variation*

The effect due to variation in geo-mechanical parameters is carried out by taking the rockmass parameters which are taken from literature mentioned in Table II, are considered for numerical simulation. As per these properties the rock condition falls under the good category having rockmass rating (RMR) as 62 and the variation analyses is carried out for the behaviour of rock under fair category versus good category.

TABLE II. ROCKMASS PROPERTIES CONSIDERED FOR GEO-MECHANICAL PARAMETRIC VARIATION

Rockmass Property	Orebody	Wall rock
Bulk Modulus (K) in GPa	3.46	2.72
Shear modulus (G) in GPa	2.08	1.63
Poisson's ratio (ν)	0.25	0.25
Density (Kg/m^3)	3900	2800
Cohesion (MPa)	2.4	1.8
Tension (MPa)	0.34	0.2
Friction angle (deg)	41	40

With the mentioned properties in Table II, numerical simulation is carried out for the site conditions and the results are analysed and the displacements are found to be low in case of good category condition and the results of vertical and lateral displacements with width variation are shown in Fig. 12.

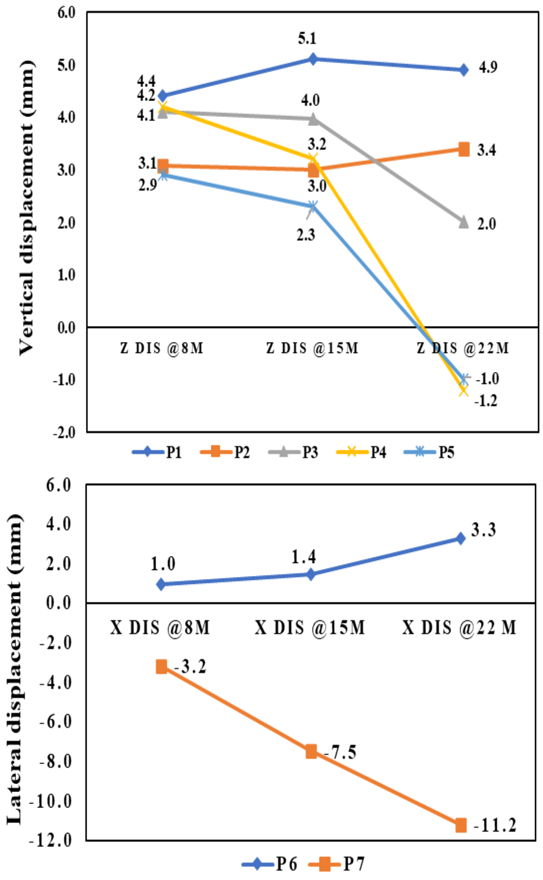

Figure 12. Vertical and Lateral displacements at monitoring points

The factor of safety (FoS) is also determined for both the conditions and the FoS for rock under fair category is 3.04 and for rock under good category is 3.56 which clearly indicates that pillar is more stable in case of good category condition.

V. CONCLUSIONS

This study on parameters influencing the Crown Pillar's stability gives the findings mentioned below.

- With increase in the span of the pillar, the pillar seems to be under high stress condition which is not quite good. This shows that the pillar with larger spans is to be additionally supported with bolt systems during underground mining operations.
- The increase in the pillar's thickness results in lower displacements and stresses. But as the crown pillar zone is comprised of ore, it's necessary to find the optimum thickness during the design of pillar.
- The pillar has to be supported adequately in case of higher ore dip as the pillar is greatly affecting at higher dip with high amount of stresses. However, at the slope angle of 38° the pillar, the pillar is found to be more stable and so it's necessary to determine the safest slope angle to be maintained at site during the process of transitioning.
- The depth of open pit has larger scale influence on pillar, and the pillar experiences high magnitude of stress with increase in depth of open pit and this is due to increase in amount of vertical stresses and the influence of open pit geometry. So adequate support system should be provided at greater depths.
- As the pillar's stability is also based on rockmass condition at site, it's necessary to have a detail information regarding the rockmass at site while transitioning from open pit to underground mining.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Ritesh D. Lokhande and Supriya NVL. Pathapati done the numerical modelling work and wrote the paper. Chandrani P. Verma helped in providing the field data required and to analyze the results obtained through numerical modelling. Pankaj Dewangan contributed the work by reviewing and framing the paper.

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