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Stability Analysis of Underground Developed Pillars of Opencast Mine using Three-Dimensional Finite Element Method Authored

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Abstract

The major coal producing companies of the India are running most of the opencast mines to excavate the underground developed pillars as the underground mines possess various strata control issues, subsidence, ensures low production and makes losses. During extraction of such developed pillars, the men and machineries may trap in the developed galleries. Hence, the conditions of the pillars and galleries need to be assessed before approaching the developed pillars. In this study, a case study of Jharia Coal field is chosen for detailed stability analysis of the workings. For this, 3D numerical modelling technique is applied to assess the condition of the underground pillars and galleries. From the study, it is observed that the pillars and galleries of the workings for a maximum of 15 m from the slope surface fails severely. It is therefore, these area requires special precautions while approaching the developed coal seam/workings.

Keywords: *Developed Pillars, Finite Element Model, Displacement, Stress, Safety Factor*

1. Introduction

Jharia Coalfieldis located in the east part of India and has the major source of coking coal in India, which is being mined mainly by Bharat Coking Coal Limited (BCCL) of Coal India Limited (CIL). This company has been experiencing the various problems, mainly fire, subsidence, land acquisition and others for commencing the new projects. The mining activities in Jharia coalfield was started way back in 1894 and was intensified in 1925, as a result,most of the mines/collieries are having old workings and few mines are currently working in virgin seams.

The pillars of these old workings are standing for more than 20–30 years. Since the technology has changed, there has been a gradual shift from underground labor-intensive mining to Opencast machinery intensive mining. This shift has made it feasible to mine some oldest underground mines which were earlier not considered feasible for opencast mine and this has resulted to win the standing pillars with Opencast mine technology. At present, most of the opencast mines in India are being

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operated to excavate the developed/standing pillars by old underground mine.

During the mining of these pillars specially while approaching the parting of 6 to 10 meters between top of underground workings/coal seam and overburden, the accurate plans of the old workings need to be seen and the corners of the pillars need to be blasted to fill the developed gallery of the workings. Then proper levelling should be done to perform the production blast and deployment of other machineries to excavate the coal. This work should be carried accurately with care and also the condition of the standing pillars and galleries need to be assessed before commencing the mining of these old workings, otherwise it may result sometime the trapping of men, machinery and others in the old gallery/yielded pillars.

Hence, the assessment of condition of old workings/ developed pillars and galleries is paramount for mining of the underground developed pillars with safety and productivity. In this study, 3D finite element modelling technique is used to estimate the stability of the pillars, galleries and barriers of the old workings.

There is very few study has carried out for stability analysis of the workings (Laybourne and Watts, 1990). However, most scientists have conducted study for the stability analysis of opencast highwall and dumps (Dhawan *et al.*, 2015; Chandarana *et al.*, 2016; Satyanarayana et al, 2021), occurrence of spontaneous heating and its effects (Panigrahi *et al.*, 2013), problems and challenges need to be taken while extraction of these pillars (Ngwenyama and de Graaf, 2021), design of maximum charge per delay for blasting operations (Roy *et al.*, 2020). Hence, this study is essential to determine the behavior of the standing pillars and galleries to excavate the pillars by open pit method.

2. Description of the Study Mine

The study area is located in the western part of Jharia coalfield in Dhanbad district of Jharkhand State, under the jurisdiction of BCCL. The mining activities were started in 1960. The project is having a leasehold area of 731.35 Ha with latitude23°46'00" N to 23°48'24" N and longitude 86°12'45'E to 86°15'24" E. Total nine numbers of coal seam exist in leasehold area namely I, II, III, IV, V/VI/VII (combined), VIIIA, VIIIB and VIIIC seam and these seams are lying in the ascending. The present working depth of the mine is around 80 mts and working is progressing in the seam V/VI/VII (combined) commonly known as combined seam. The thickness of the seam varying from 22 m to 28 m. The average thickness of this seam is 24.5 m and is already developed with bottom and top sections considering 9.65 m parting. Top section lies at 5.5 m below the roof of the seam and bottom section lies at 4 m from the floor of the seam. Height of top and bottom sections are 2.91 m and 2.44 m respectively as shown in Figure 1.

Figure 1 shows the lithology of mine site and is used for developing the 3D finite element model in ANSYS software. Figure 2 shows the typical old workings exist in the highwall/ slope of the bench and the local failure has also occurred in the same working bench during September 2020.

3. Material Properties

Rock mass rating of the coal seam, sandstone and shale are 59, 65 and 62.5 respectively. The intact rock properties of the mine site are collected from the mine site and are converted to rock mass properties using Hoek-Brown rock media (Islavath and Deb, 2018). Rock mass properties such as modulus of elasticity (E), density (ρ) and Poisson's ratio are used in the finite element modelling and are listed in Table 1 and Hoek – Brown rock mass parameters m_i for coal is considered as 10 and other parameters such as m_b, s and a are estimated to be 5.48, 0.003 and 0.5 respectively.

4. Development of 3D Finite Element Model of Openpit Mine

The plan of the mine is studied in detail and 05 sections were sorted, out of which one section BB' is selected (Figure 3). The section along BB' is created as shown in Figure 4. The final model is created with the borehole section, plan and other information obtained from the mine. The length and width of the model are 827 m in strike direction and 507 m in dip direction with a height of 428 m. The study area/section consists of 05 benches. Bench 1 consists of two thin seams of coal having 3.18 m and 2.57 thickness with 8.25 m parting of shale. Benches 2, 3, 4 consist of sandstone with few traces of shale and having average of 12 m height. The lower bench of the pit is Bench no. 5 commonly known as the combined seam has average thickness of 24.5 m . The average angle of

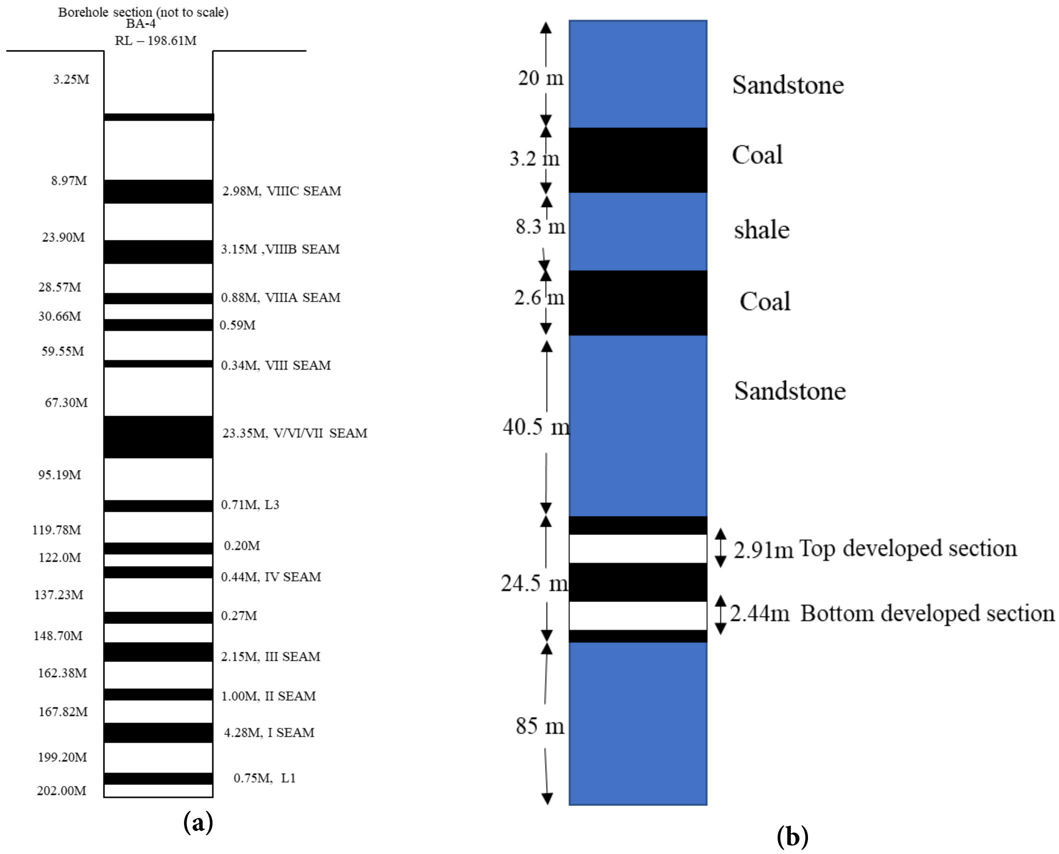

Figure 1. Key borehole data and lithology of mine site used for numerical modelling. **(a)** Borehole no. BA-4 **(b)** Lithology for study.

bench is 40 degrees and overall slope angle of the mine is 26 degrees.

As discussed above, the combined seam was developed around 25 years back with bord and pillar method in top and bottom sections with a parting 19.15 m. In this study, a total of 80 pillars are considered, out of which 10 pillars in strike and 8 pillars in dip directions. The model consists of 11 galleries along strike and 9 galleries along dip directions respectively and also barrier pillar of 20 m size surrounding the workings/pillars (Figures 5 and 6). Similarly, the pillars and galleries are developed in the bottom sections. The top sections pillars are lying exactly vertical on the bottom section pillars. Figure 5 shows the three-dimension finite element model of open pit mine. Figure 6 shows the pillars developed in the coal seam.

Table 1. Rockmass properties

Rock type	Stiffness, E (GPa)	Poisson's ratio	Density, ρ (Kg/m^3)
Coal	1.2	0.32	1500
Sandstone	5.4	0.27	1900
Shale	2.4	0.30	1700

The rock mass properties of the coal bearing strata as mentioned in Table 1 are applied to the finite element models for analyzing the conditions of the underground developed workings.

The FEM model is discretized with element type SOLID 185 and developed 18,93,992 elements and 79,89,249 nodes. Figure 7 shows the discretization of opencast 3D model. The bottom of the model is constrained in Z or vertical direction, along strike and dip directions are applied horizontal stress of 1.17 and 1.0 times of vertical stress respectively. The ratio of horizontal to vertical stress is obtained from hydraulic fracturing test. The gravitational force is applied along the vertical or Z-axis direction.

Figure 8 shows the various paths considered along the dip and strike sections. A total of 20 paths considered on galleries and 18 paths on the pillars along strike and dip sections. Here, G10 meaning that path on 10th gallery and

(a)

(b)

Figure 2. **(a)** Old developed galleries being seen in the opencast bench. **(b)** Local Failure observed around old developed galleries.

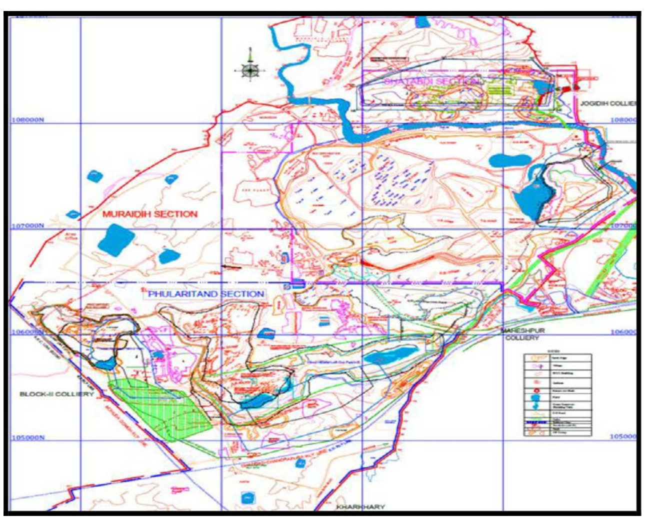

Figure 3. Plan view of the study area.

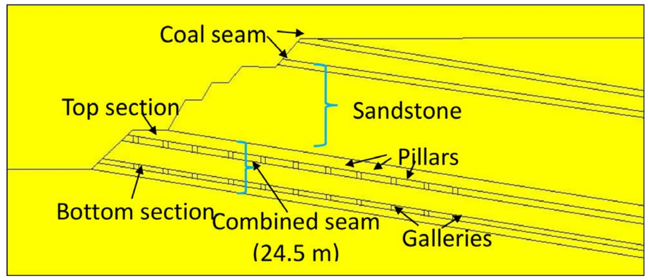

Figure 4. Sectional view along BB' of the study area.

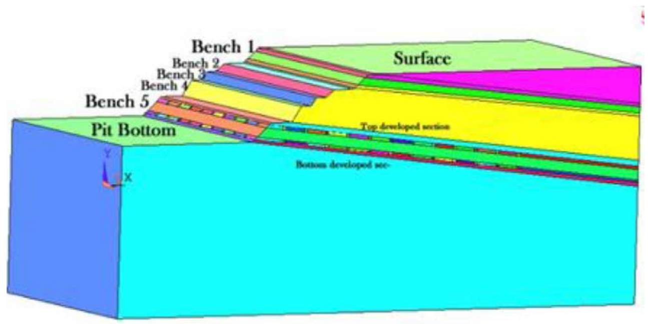

Figure 5. 3D model of the of opencast mine.

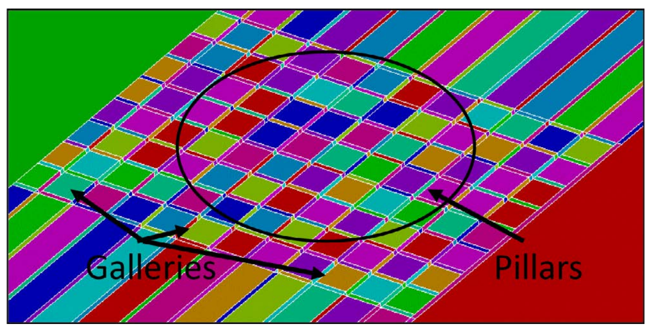

Figure 6. Coal seam developed using bord and pillar method.

Figure 7. Mesh of the model with opencast mine.

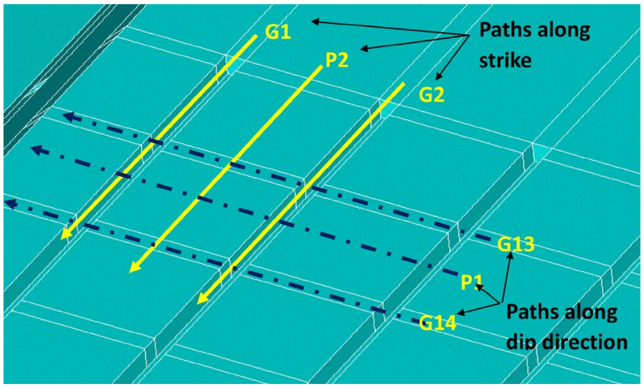

Figure 8. Path developed along galleries and pillars.

P20 meaning that path on 20th pillar. Similarly, all other paths are numbered as shown in Figure 8.

5. Results and Discussions

Results in terms of vertical displacement, major and minor principal stresses and vertical stress developed on the underground developed pillars are extracted along the various critical paths (Figure 8). The safety factor of the developed pillars are estimated using Hoek-Brown rock mass failure criterion. In this section, vertical displacement, principal stress, vertical stress and safety factor distributions of the underground developed workings are presented.

5.1 Vertical Displacement Distribution

Vertical displacement profiles along the paths from G1 to G20 have been extracted from the excavation model and this displacement is subtracted from the displacement of insitu model considering the same path. Figure 9 shows the displacement profile along the strike direction. In this figure, path G1 is situated near to the slope surface of opencast mine and G11 located at the boundary of the workings.

It is observed that minimum vertical displacement of 14.1 cm has occurred along path G1. Due to opencast workings, the stresses have been released. As a result, the less vertical displacement has developed. The maximum vertical displacement of 16.6 cm has occurred in the G11 path as the gallery is situated at deeper depth in the underground.

Figure 10 shows the displacement profile along the dip direction. In the figure, all the paths from G12 to G20 moves from the rise to dip directions. It is observed that minimum vertical displacement of 14.1 cm has occurred near to the surface and maximum displacement of 17.1 cm has occurred in the dip most working. This phenomenon has occurred in all the paths.

5.2 Principal Stress Distribution

Figures 11 and12 show the major and minor principal stress distribution pillars in the strike and dip direction respectively. Figure 11show the major principal stress from P1 to P10 . From the Figure 11, it is observed that major principal stress varies from 1.2 MPa to 1.8 MPa. As mentioned earlier, the minimum value is observed in the path P1 (lower depth) and maximum in the P10 (deeper depth).

From the Figure 12, it is observed that the minor principal stress near the surface is tensile in nature (P1) and this changes to compressive, as the working moves towards the dip direction or depth. The maximum value of minor principal stress which is found to be 1.33 MPa (in P10) at the dip most part of the underground working.

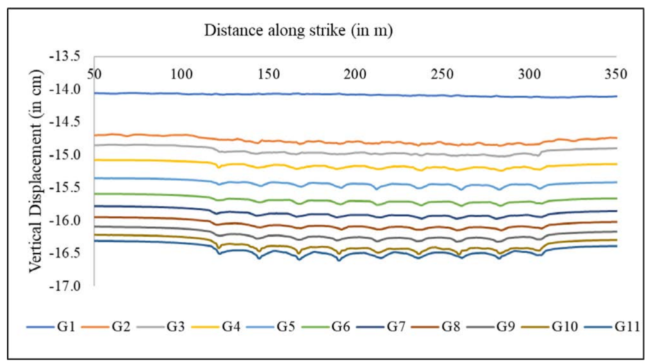

Figure 9. Vertical displacement profile of the roof of the galleries along strike direction.

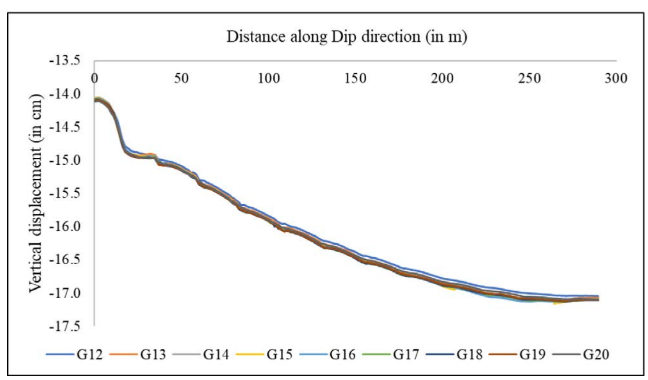

Figure 10. Vertical displacement profile of the roof of the galleries along dip direction.

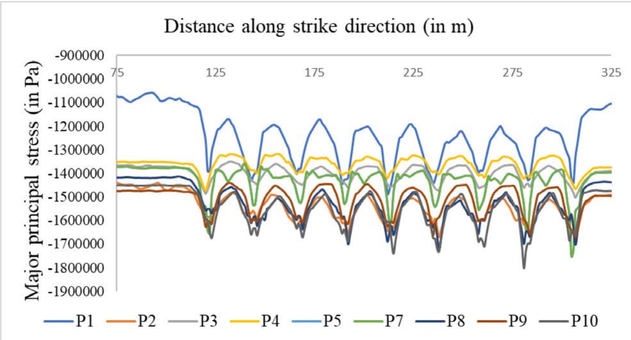

Figure 11. Major Principal stress on the developed pillar along strike direction.

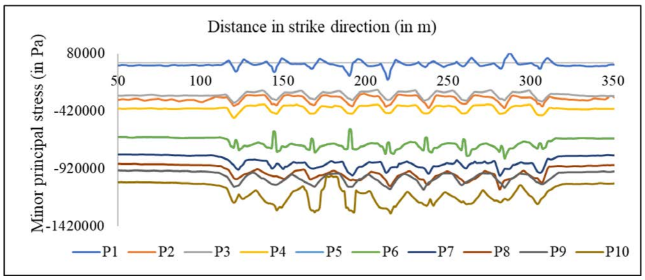

Figure 12. Minor Principal stress on the developed pillar along strike direction.

5.3 Vertical Stress Distribution

Figures 13 and 14 show the development of vertical stress distribution on the pillars of the strike and dip direction respectively. The development of vertical stress is found to be more in P10 (deeper depth) and less in P1 (low depth). As shown in the Figure, the occurrence of stress concentration is higher in the corner of the pillar and lesser in middle of the pillar. The vertical stress varies from 0.35 MPa to 1.33 MPa.

5.4 Factor of Safety of the Workings

The factor of safety of the developed pillars and galleries has been estimated along the various paths such as P1 to P18 for pillars and G1 to G20 for galleries. The Hoek and Brown criteria as mentioned in equation 1 (Islavath and Deb, 2018) is applied to determine the safety factors along the chosen paths. The safety factor distribution of the developed pillars and galleries are shown in Figures 15, 16, 17 and 18.

The factor of safety *(FS)* is defined as the ratio of strength *(R)* of the pillar/roof of gallery over stress *(S)* acting on pillar/gallery. It is expressed as:

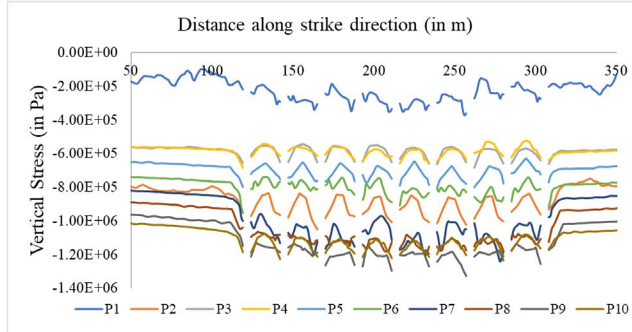

Figure 13. Vertical stress on the developed pillar along strike direction.

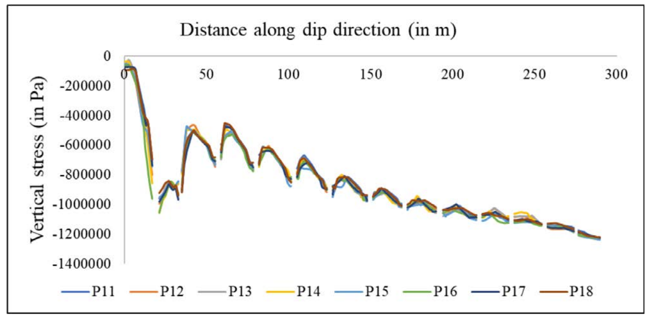

Figure 14. Vertical stress on the developed pillar along dip direction.

$$FS = \frac{R}{S} \tag{1}$$

A pillar/ roof of gallery is considered to be safe if SF>1.0. From the Hoek – Brown Yield criterion.

$$Fs = \frac{\left(\sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a\right)}{\sigma_1}$$

$$m_{b=} m_i \exp\left(\frac{GSI-100}{28}\right), s = \exp\left(\frac{GSI-100}{9}\right),$$

where,

$$a = \frac{1}{2} + \frac{1}{6}\left[\exp\left(\frac{-GSI}{15}\right) - \exp\left(\frac{-20}{3}\right)\right]$$

$\sigma_{ci \text{ and }} m_{b,}$ *s, a* are uni axial compressive strength and Hoek-Brown rockmass parameters

5.4.1 Factor of Safety of Developed Pillars

Figures 15 and 16 show the safety factor distribution of the developed pillars along the strike and dip directions respectively. Figure 15 shows that factor of safety of pillars near the surface is observed to be lesser than 01 in path P1.

This implies that the pillars near to the opencast benches are more susceptible for failure as compared to the pillars away from the open pit slope. The same phenomenon is also observed in Figure 16. In this figure, the factor of safety varies from 0.68 to 1 up to a distance of 13.78 m from the surface and then increases as it moves towards depth from the surface due to the more confinement stress. It shows that special care need to be taken while exploiting the coal from the pillars for a minimum distance of 14 m from the slope surface.

5.4.2 Safety Factor of Galleries

Figures 17 and 18 show the safety factor distribution on the roof of galleries along the strike and dip directions respectively. In general, the low safety factor is observed in the junction and more in other places as it moves towards/near the pillar. The safety factor increases with increment of the depth of the workings or move to the deeper galleries which is away from the open pit slope surface. In dip galleries, factor of safety varies from 0.36 to 1 till 15.2 m from the surface and further increases to 2.56 at a distance of 300 m. This also shows that galleries/pillars sides are required to be blasted and fill the galleries and specially at the junction area. Otherwise, the deployed HEMMs, men and other supporting equipment on those pillars and galleries may be trapped in those galleries.

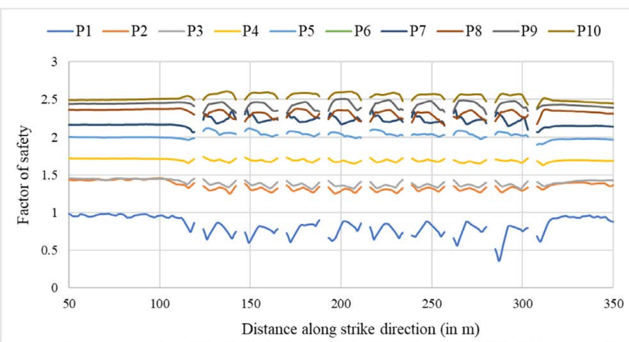

Figure 15. Safety factor of the developed pillar along strike direction.

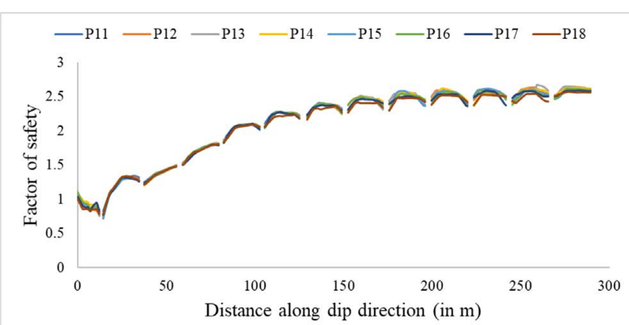

Figure 16. Safety factor of the developed pillar along dip direction.

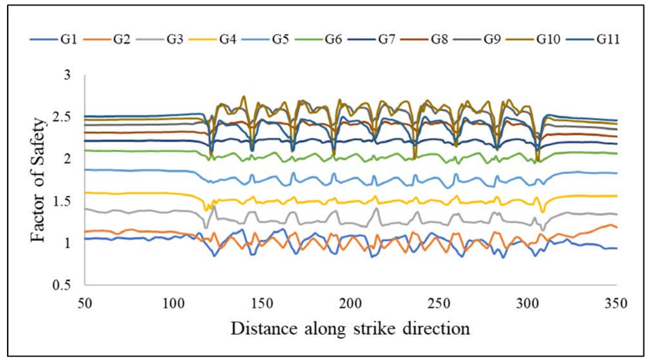

Figure 17. Factor of safety of galleries along strike direction.

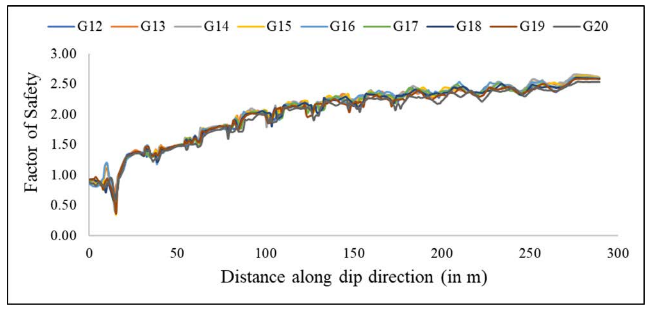

Figure 18. Factor of safety of galleries along dip direction.

6. Conclusions

A 3D numerical analysis has been carried out to determine the conditions of the developed/standing pillars for extracting them with safety using open pit mining. From this study, it is observed that minimum vertical displacement of 14.1 cm occurred near the surface and maximum vertical displacement of 17.1 cm is occurred at dip most part of the underground working.

The principal stress at all the places is compressive in nature however, it is observed in tension near the surface. The major and minor principal stress varies from 0.02 (tension)~1.33 MPa and 1.2~1.8 MPa respectively.

The minimum safety factor of the pillars is observed as 0.68 at a distance of 13.78 m from the slope surface and increases to a maximum of 2.56 at a distance of 300m. In galleries, minimum factor of safety of 0.36 is observed at a distance of 15.2 m. These safety factor values suggest that the junctions near the surface can yield severely due to tension. Also, the pillars of the first row of the workings near the slope surface may yields severely.

These safety factor values show that the requirement for accurate surveying to identify junction, galleries and pillars before commencing the mining operation and special precautions need to be taken for at least 15 m distance from the slope surface for deployment of HEMMs, drill machine and other supported machineries to improve production and safety.

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