Design of underground structures and support systems for extraction of inclined coal seam

Arka Jyoti Das
CSIR-Central Institute of Mining and Fuel Research, Barwa Road, Dhanbad, India

Prabhat Kumar Mandal
CSIR-Central Institute of Mining and Fuel Research, Barwa Road, Dhanbad, India

Ranjan Kumar
CSIR-Central Institute of Mining and Fuel Research, Barwa Road, Dhanbad, India

ABSTRACT: Strata control problems are observed more in dipping coal seams than flat coal seams due to shearing effects, asymmetric failure and stress distribution in inclined rock strata. As most of the pillar strength formulae are derived for the conditions of flat coal pillars, their embracing in the stability analysis of inclined pillars may jeopardize the workings. In this study, inclined pillars are designed by using the strength formulae derived for the inclined pillars. The strength of pillars decreases with the increase in the dip of the coal seams and with the decrease in the acute-angle of the corners of the rhombus-shaped pillars. A parametric study is carried out to quantify the effect of inclination on the failure characteristics of inclined pillars and surrounding rock mass. Based on the study, an adequate size of pillars and an effective support system have been designed for a case study mine.

Keywords: Inclined coal pillar strength, Dip angle, Yield zone, Asymmetric stress distribution, Support system.

1 INTRODUCTION

The mining of dipping and level coal seams is different in terms of mining method, strata behaviour, support system, ground control, etc. Extensive shearing in the inclined rock mass causes (a) a large amount of overlying strata movement, (b) a reduction of the pillar strength, and (c) an increase in the requirement for roof support. The stability of underground structures is affected more in the case of dipping coal seams in comparison to flat coal seams (He 2011; Ching et al. 2013). With the increase in the dip of the coal seam, underground structures become more prone to shear failure along the contact surface i.e., bedding planes (Alejano et al. 1999; Li et al. 2017). The inclined coal pillars and inclined rock strata behave differently in the case of flat coal seam due to the asymmetrical stress distribution and high anisotropy in strength of the inclined laminated rock strata. Moreover, the failure of the roof strata is not similar along the dip-rise and strike directions. Therefore, the stability of underground structures vis-à-vis ground control decreases with the increase in the dip angle of the coal seams. As most of the pillar strength formulae and support design methodologies are derived for the conditions of flat coal seams, their adoption in evaluating stability may endanger the workings of inclined coal seams (Das et al. 2019a, 2019b). If these steeply dipping coal seams are mined in similar methods as a flat seam, there may be chances of serious ground control issues besides numerous operational difficulties. Therefore, the shearing characteristics of the strata should be considered for designing the underground structures in the dipping coal seams.

This paper expounds on the effects of different parameters on the failure characteristics of the inclined rock strata. It also elucidates suitable procedures for stability analysis of underground structures and support systems during the mining of inclined coal seams. One case study is described to get practical experience in ensuring the safety of underground working places in dipping coal seams.

2 STRENGTH FORMULAE FOR INCLINED COAL PILLARS

The evaluation of the strength of the inclined coal pillars is indispensable for the safe mining of the inclined coal seam. Most of the pillar strength formulae used globally were derived for flat coal pillars. Das et al. (2019a) derived mathematical expressions of the strength formulae by considering the 3-D asymmetric stress distribution, asymmetric failure and the confined core concept. Eq. (1) shows the analytical formula for the estimation of the strength of inclined pillars.

$$
\begin{aligned}
s = &\left(\sigma_{1T}-\sigma_{cbm}\right)-\frac{2}{w\xi_D\xi_S}\left[\xi_S\left(\sigma_{1T}-k_1k_2\right)\ln\left(\frac{\sigma_{1T}}{k_1}-k_2\right)+\xi_D\sigma_{1T}\ln\frac{\sigma_{1T}}{\sigma_{cbm}}-\left(\sigma_{1T}-\sigma_{cbm}\right)\left(\xi_D+\xi_S\right)\right] \\
&+\frac{4}{w^2\xi_D\xi_S}\left[\begin{aligned}&\sigma_{1T}\left(\ln\frac{\sigma_{1T}}{\sigma_{cbm}}-1\right)\ln\left(\frac{\sigma_{1T}}{k_1}-k_2\right)+k_1k_2\ln\left(\frac{\sigma_{1T}-k_1k_2}{\sigma_{cbm}-k_1k_2}\right)-k_1k_2\left\{Li_2\left(\frac{\sigma_{1T}}{k_1k_2}\right)-Li_2\left(\frac{\sigma_{cbm}}{k_1k_2}\right)\right\}\\&-k_1k_2\ln\frac{\sigma_{1T}}{\sigma_{cbm}}\left\{\ln\left(\frac{\sigma_{1T}}{k_1k_2}-1\right)-1\right\}+2\left(\sigma_{1T}-\sigma_{cbm}\right)\end{aligned}\right]
\end{aligned}
\quad (1)
$$

Where s is the inclined coal pillar strength, σ_{1T} is the peak value of stress over pillars, k_1 is equal to $\frac{(2\mu-\tan\alpha)\sigma_{cbm}-h\gamma\sin\alpha}{(2\mu-\tan\alpha)}$ and k_2 is equal to $\frac{h\gamma\sin\alpha}{(2\mu-\tan\alpha)k_1}$, μ is the coefficient of friction of the contact surface, h is the height of pillars, γ is the bulk weight of coal, α is the dip angle of coal seams.

Das et al. (2019b) also derived simplified formula to evaluate the inclined coal pillar strength by numerical simulation and multivariate non-linear regression. Inclined coal pillars are simulated under the conditions of uniaxial compressive strength (UCS) to obtain the strength of inclined coal pillars. Different constitutive models for numerical simulations are shown in Figure 1.

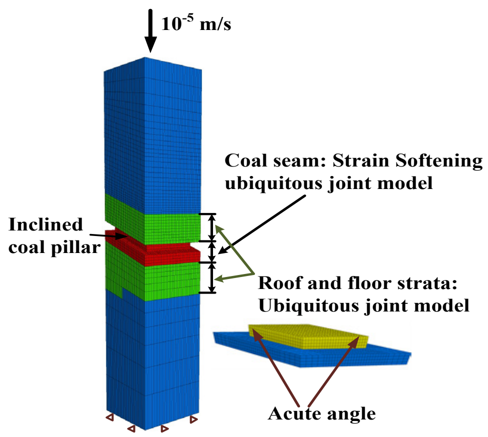

Figure 1. Grid with the constitutive models used in the numerical simulation (Das et al. 2019b).

The inclined coal pillar strength ($S_{inclined}$) found from the regression model is as follows (Das et al. 2019b):

$$S_{inclined} = \left[1 - \left[1 - (\cos\theta)^{2.4} (\sin\varphi)^{0.8} \right] \times \left(\frac{H}{w/h} \right)^{0.04} \right] \times S_{flat} \quad (2)$$

Where θ is the dip angle of the coal seam (degree), φ is the acute angles of the coal pillar corners (degree), H is the cover depth (m), w and h are the width and height of the pillar respectively (m), $S_{flat} = 0.27\sigma_c h^{-0.36} + \left(\frac{H}{250}+1\right)\left(\frac{w}{h}-1\right)$, S_{flat} is the flat coal pillar strength (MPa), σ_c is the intact strength of the coal (MPa).

3 FAILURE CHARACTERISTICS OF INCLINED ROCK MASS BY PARAMETRIC STUDY THROUGH NUMERICAL SIMULATION

Field investigation reveals that the junctions and the acute corners of the inclined coal pillars are more prone to fail during working in dipping coal seams. To ensure safety, the failure characteristics of the junctions and the acute corners of the pillars have been studied by changing the parameters through elasto-plastic numerical modelling. The shearing characteristics of dipping rock strata are simulated by the ubiquitous joint model. Figure 2a shows the grid for numerical modelling by Flac3D (Itasca 2017).

In the parametric study, the dip angle of the coal seam is changed from 0^0 to 40^0 with an interval of 10^0 and the acute angle of the corners is varied from 30^0 to 90^0 with an interval of 10^0. As the failure of the rock strata depends upon the in-situ stress conditions, the in-situ stress ratio is varied from 0.5 to 2 at an interval of 0.5. Figure 2b quantifies the failure characteristics of the acute corners. It is found from Figure 3 that the failure zones in corners increase with the increase in the coal seam dip angle owing to the high shearing among the inclined strata, whereas it increases with the decrease in the acute angle value of corners. It happens because of the increase in the area of exposure at the junctions resulting in high-stress concentration. From the parametric study, it is obtained that the failure of the corners is more prominent when the dip angle and in-situ stress ratio are more than 20^0 and 1.5 respectively, and the acute angle of the corners is less than 40^0.

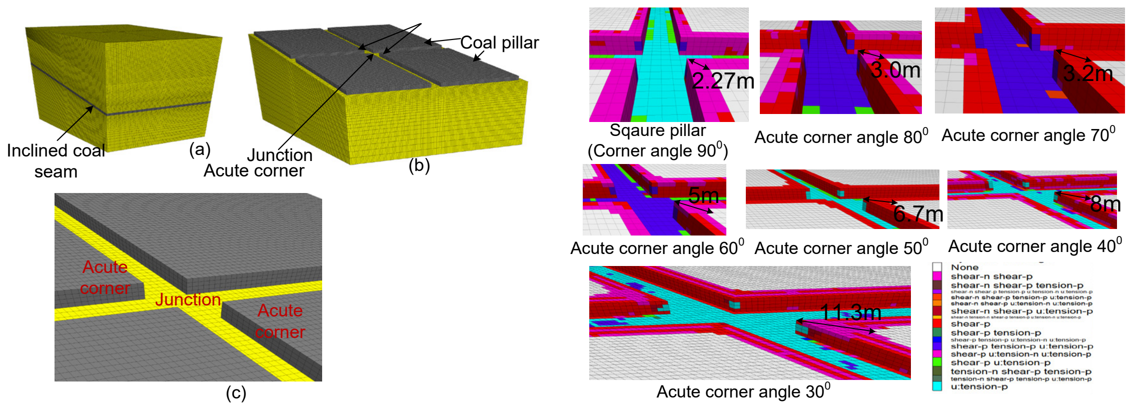

Figure 2. (a) Grid used for numerical modelling and (b) Failure zone in the pillar for varying acute angle of the corners.

The failure behaviour of the roof rock and the junctions is described in Figure 4 and Figure 5. It is found that the failure height increases with the increase in the coal seam dip angle and the decrease in the acute angle of corners. The area of the exposure at the junction increases with the decrease in the acute angle of the pillar corners. When the in-situ stress ratio is high, horizontal stress is more prominent. It results in differential movement of the rock strata and high shear stress among them.

As the rock mass frequently fails under shear, the roof rock at the junction fails and it causes the bed separation and falling of rock at the junction.

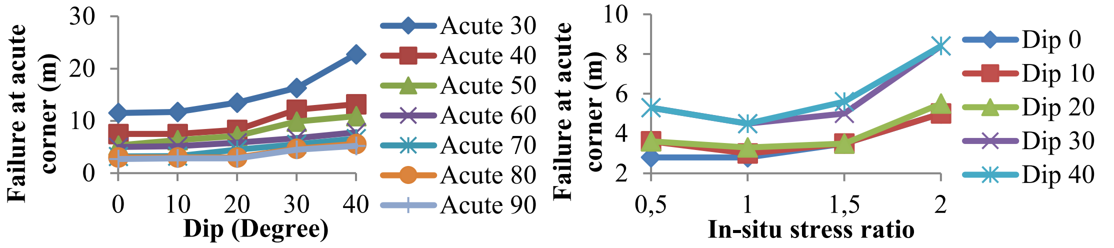

Figure 3. Effects of the coal seam dip angle, acute-angle of corners and in-situ stress ratios on the failure characteristics of the corners of pillars.

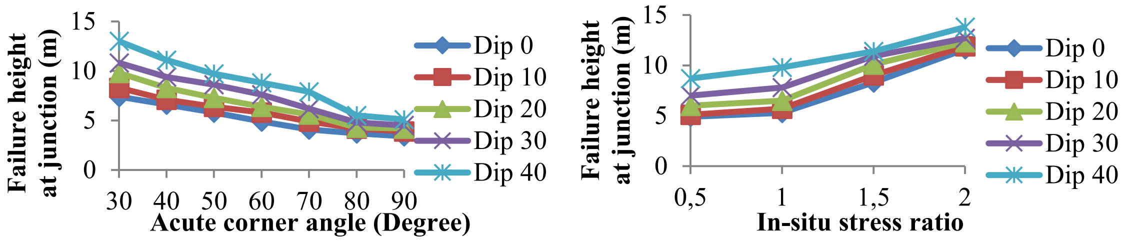

Figure 4. Failure characteristics of the junctions for different coal seam dip angles, acute-angles of corners and in-situ stress ratios.

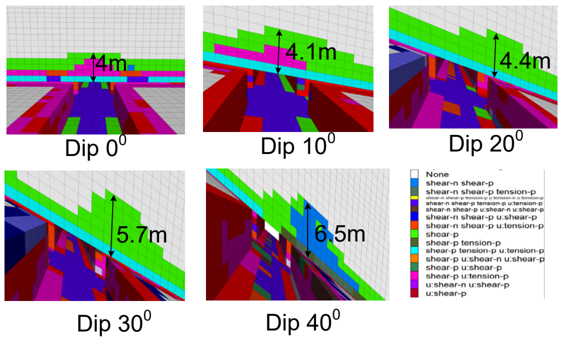

Figure 5. Height of yield zone in the roof rock at the junction for different dips of coal seams.

4 DESCRIPTION OF STUDY SITE

The Salarjung seam of Shanthikhani Mine, The Singareni Collieries Company Limited (SCCL) is being mined by deploying the continuous miner (CM). The seam thickness has a variation from 5.0 m to 8.7 m. The roof of the coal seam mainly consists of sandstone. The average depth cover of the seam is 380 m. The adjusted RMR of the immediate roof is 41. The maximum portion of the immediate roof rock strata above the seam is having an RQD of less than 60%.

As the inclination of the coal seam is 1 in 4.5 (~12^0), it creates a problem for the manoeuvring of men and machinery. Thus, to negotiate the true dip, rhombus-shaped pillars of 60 m x 60 m (centre to centre) with an acute angle of 60^0 are formed along an apparent dip of 1 in 7.5 (~8^0). The development is carried out along the roof by leaving the coal in the floor. The gallery width is 5.5 m. The section of level galleries is formed in the shape of a trapezium to avoid skidding towards the sidewall on the dip. Therefore, the height on the rise side and dip side of the level galleries is kept at 4.0 m and 2.7 m respectively. The height at the middle of the level galleries is 3.4 m. The dip rise galleries are driven with a height of ~3.4 m.

5 STABILITY ANALYSIS AND SUPPORT DESIGN

Numerical modelling is carried out to study the stress distribution, failure analysis and support design. The average major-induced principal stress within the pillar obtained by the numerical modelling is 11.5 MPa as shown in Figure 6a. The strength of the inclined coal pillars of size 53.6 m x 53.6 m (corner to corner) with an acute angle of 60^0 and of 3.4 m height is calculated as 33.24 MPa by Eq. (2). Therefore, the safety factor of the pillar is 2.9. Figure 6b shows the asymmetric failure in coal pillars.

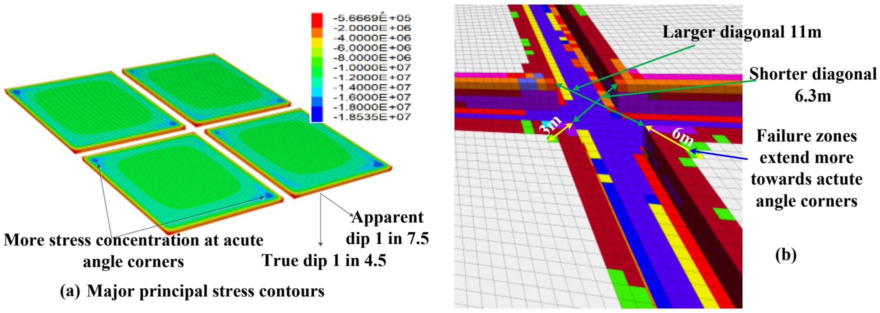

Figure 6. (a) Major principal stress distribution and (b) failure zone in coal pillars.

The height of the failure zones at the level gallery and junction reaches 5 m and 8.3 m respectively as shown in Figure 7. Due to the tendency of the sliding down of the roof strata along the contact surface, the failure zones are more at the dip side in the roof. The galleries are supported by the combination of 5.0 m long flexi-bolts and 2.4 m long rock bolts. In each row, four rock bolts are installed by placing two bolts on each side of the central line. At the central line of the row, the rock bolt and flexi-bolt are installed alternatively as shown in Figure 8. The junction is supported by the 2.4 m long full-column grouted rock bolts and 6.0m long bulbed-cable bolts as shown in Figure 8. The rock bolts are 22.0 mm in diameter and made of TMT/MS cold-rolled M22 threaded ribbed bar. The anchorage capacity of rock bolts and bulbed-cable bolts is considered as 25.0 t and 50.0 t respectively. The support safety factors are shown in Table 1.

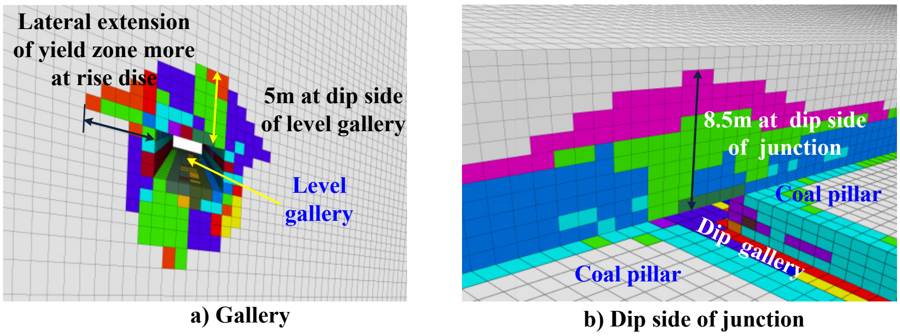

Figure 7. Height of yield zones at (a) gallery and (b) junction.

Table 1. Adequacy of support system by the support safety factor.

Location	Height of yield zone	Rock Load	Support resistance	Support safety factor
Junction	8.5 m	17.43 ton/m^2	36.0 ton/m^2	2.02
Gallery	5.0 m	10.5 ton/m^2	21.0 ton/m^2	2.0

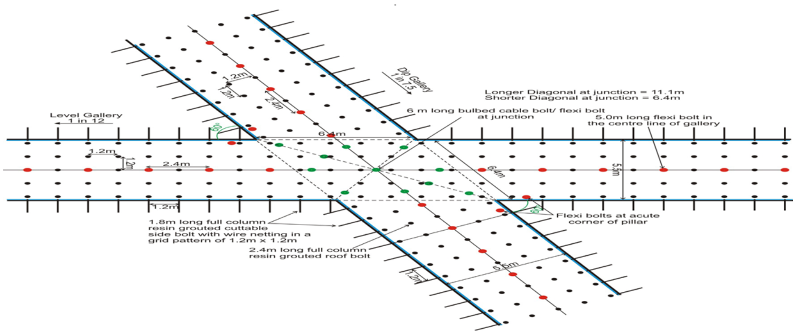

Figure 8. Support pattern of the gallery and junction.

6 CONCLUSIONS

Working in underground inclined coal mines is associated with several strata control problems. As the characteristics of inclined rock strata is different from the flat strata, explicit consideration of dip effects is necessary to ensure safety during the mining of dipping coal seams. The study shows that the inclined pillar strength decreases with the increase in the dip angles of the coal seam. Thus, the strength formula derived for the inclined coal pillars should be used to design the coal pillars in inclined coal mines. As found from the study, the failure is more prominent when the coal seam dip angle and in-situ stress ratio are more than 20^0 and 1.5 respectively, and the acute corners are less than 40^0. The proper support system is designed with an adequate safety factor to make the underground working place. This study helps the practising mining engineers to ensure human safety by properly designing the coal pillars and support system for underground working in dipping coal seams.

ACKNOWLEDGEMENT

The authors are indebted to the Director, CSIR-CIMFR, Dhanbad, India for his approbation to publish this paper. The part of this study is funded by CSIR under project No.: MLP-144/2020-21. The views communicated in this paper are that of the authors and not necessarily of their organisation.

REFERENCES

Alejano, L.R., Ramírez-Oyanguren, P. & Taboada, J. 1999. FDM predictive methodology for subsidence due to flat and inclined coal seam mining. *International Journal of Rock Mechanics and Mining Scienc*es 36, pp. 475-491.

Ching, J., Yang, Z.Y., Shiau, J.Q. & Chen, C.J. 2013. Estimation of rock pressure during an excavation/cut in sedimentary rocks with inclined bedding planes. *Structural Safety* 41, pp. 11-19.

Das, A.J., Mandal, P.K., Paul, P.S. & Sinha, R.K. 2019a. Generalised analytical models for the strength of the inclined as well as the flat coal pillars using rock mass failure criterion. *Rock Mechanics and Rock Engineering* 52 (10), pp. 3921-3946.

Das, A.J., Mandal, P.K., Paul, P.S., Sinha, R.K. & Tewari, S. 2019b. Assessment of the strength of inclined coal pillars through numerical modelling based on the ubiquitous joint model. *Rock Mechanics and Rock Engineering* 52 (10), pp. 3691-3717.

He, M. 2011. Physical modeling of an underground roadway excavation in geologically 45^0 incline rock using infrared thermography. *Engineering Geolo*gy, 121, pp. 165-176.

Itasca. 2017. Itasca Consulting Group, Inc., FLAC3D (Fast Lagrangian Analysis of Continua in 3 dimensions). Version 5.0. Minneapolis, MN.

Li, X., Wang, Z. & Zhang, J. 2017. Stability of roof structure and its control in steeply inclined coal seams. *International Journal of Mining Science and Technology* 27, pp. 359-364.