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ORIGINAL PAPER

Design of rhombus coal pillars and support for Roadway Stability and mechanizing loading of face coal using SDLs in a steeply inclined thin coal seam—a technical feasibility study

Mohammad Jawed[1] · **Rabindra Kumar Sinha**[1]

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Abstract

Coal seams that dip more than 15° are classified as steeply inclined in Indian mining context. Mining of steeply inclined seams poses variety of problems starting from strata control to problems related to efficient mechanisation. Sawang-C seam of Govindpur Underground Project of Central Coalfields Limited is one such seam. Presently, the seam is being developed on bord and pillar method of mining, and the blasted coal is loaded manually into tubs using hand shovel and basket. In order to mechanise the loading operation, technical feasibility of formation of rhombus pillars and deployment of side discharge loader (SDL) are investigated along with design of supports from the point of view of roadway stability. This paper thus seeks to address the technical feasibility of deployment of Side Discharge Loader in a 1.7–2.2-m thin seam inclined at 16° if developed with rhombus pillars and to suggest suitable and adequate support system for such workings.

Keywords Bord and pillar mining · Steeply inclined seams · Rhombus pillars · Thin seams · Numerical modelling

Introduction

Development of inclined/steeply inclined seams with formation of square or rectangular pillars pose difficulties in movement of loading and hauling machinery on account of seam gradient. Development of rectangular pillars is prescribed by Regulation 111(3) of The Coal Mines Regulations, 2017 for improved stability of pillars. Rhombus pillars and pillars with diagonally opposite obtuse angle are considered suitable for easy manoeuvrability of loading and transport machinery such as SDLs. Inclined seams invariably face strata control problems. The component of strata weight in dip direction increases whereas the component normal to bedding plane reduces which makes the roof unstable leading to shear failure.

Mechanising either of cutting or loading and transport operation with tyre mounted or crawler mounted machinery is not feasible in bord and pillar mining if the seam gradient is steeper than 1 in 4. Mechanising loading operation using SDL in bord and pillar mining with rhombus pillars can be one option, provided favourable gradient and working height are there.

Govindpur underground project

Govindpur underground project lies between the latitude 23°46′23″N to 23°48′23″N and longitude 85°51′41 E to 85°53′39″ E in the East Bokaro Coalfields situated in Giridih District of Jharkhand State, India. Govindpur Project is surrounded by Sawang Colliery on the West and Kathara Colliery on the South. Konar River, of which Bokaro River is a tributary, makes its boundary on the South-west side.

Eighteen seams have been reported to be outcropping in Govindpur, the average thickness being more than 1.2 m. Of these 18 seams, only 9 seams are workable. Total leasehold area of Govindpur is 1284.49 acre (Jarangdih North Block). The strata has general strike in East-west direction with southerly dip direction. The two major faults namely Gobindpur Pichri Fault and Borea Fault form eastern and western boundary of the property.

Sawang-C seam is 1.7–2.0 m thick including 0.68 m dirt distributed in 1 to 5 bands. The entire section of the seam is workable. The net geological reserve is 5.79 million tonnes

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✉ Rabindra Kumar Sinha
rabindrakumar.sinha@gmail.com

[1] Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand, India

and the net mineable/extractable reserve is 3.76 million tonnes. Coal of this seam is medium coking grade with an average ash content of 24%. Gradient of the seam is 1 in 3.5 near the outcrop region and 1 in 5 towards dip side boundary.

Sawang-C seam working is situated at an average depth of 100 m and overlain by major workable seams namely Jarangdih seam of thickness 3.8–5.5 m, Jarangdih New seam 1.8 to 3.0 m thick and Jarangdih-A seam 0.6–1.9 m thick.

Surface features and status of underground workings

Bokaro Thermal Power Station and its Colony, and Eastern Railway Barkakana loop line are located on southern end of the property. Konar River flows on the western side. Ground level slopes gently towards Konar River and rises steeply towards east in the form of hillock beyond the eastern boundary of the property. A 132-kV power transmission line runs across the property in N-S direction.

Govindpur underground project is currently making production through bord and pillar development in Sawang-C seam only. All three overlying seams have been developed on bord and pillar scheme of mining.

Two panels in Jarangdih seam have already been depillared in conjunction with stowing. The depillaring operation in third district (TS-3) is suspended since March 2013. Jarangdih New seam and Jarangdih-A seam overlying Sawang-C seam are standing on pillars. At present, about 240 ton production is being made per day through development workings in Sawang-C seam.

Access to the seam is through a pair of inclines dipping at 1 in 3.0. The seam is being developed on bord and pillar scheme since 1.12.2014 by driving two sets of orthogonal galleries of 4.2 m wide and 1.8 m high to form rectangular pillars measuring 20 m × 18 m. Till date, about 400 m × 220 m area has been developed. The galleries are being supported with wooden props. Occasionally, roof bolts are also used to reinforce supports for patches of weak roof. The workings have encountered 0.4-m-thick dyke and a local fault having 1.5–2.0 m down throw. In areas close to these dykes and faults, slightly higher support density has been maintained through cement grouted 22 mm diameter ribbed bolt of 1.5 m length at 1 m × 1 m grid.

Design criteria of pillars for long-term stability

Stability consideration of coal pillars essentially consists of estimating the pillar strength and load on pillars and linking the two through a proper factor of safety (F.O.S).

The load or rock pressure on pillar comprises the vertical virgin stress, in level or near level coal seams, and the stress induced by the galleries around the pillar. In inclined seams, the virgin horizontal stress must also be considered.

On a regular array, consisting pillars of a more or less uniform shape and size, the vertical virgin stress is taken equal to the cover weight of the strata in normal coal measures. However, in geologically disturbed areas, in situ stress measurement results should be used. Figure 1 shows the block of overlying rock each pillar has to support. The average rock pressure P over the pillar is simply the weight of this block divided by the pillar area.

$$P = \gamma H \left(\frac{W + B}{W} \right)^2 \tag{1}$$

$$P = \gamma H \frac{(W + B)(L + B)}{W.L} \tag{2}$$

where H is the depth of seam, W is the width of pillar, L is the length of pillar and B is the width of bord/gallery.

The average pressure on infinitely wide uniform pillar array is given by Eq. (1) and Eq. (2) mentioned above. These equations work very well in practice for regular array of pillars, provided the extent of array, i.e. width of a panel of pillars, is at least equal to the depth of cover. If it is less, the pillar load may be less.

The value of the unit rock pressure is generally taken as 0.025 MPa/m^2. In an irregular pillar array or for panels whose width is less than the depth of cover H, the load is over estimated for small pillars by tributary area theory and underestimated for large pillars. Under hard sandstone cover, the overestimation and underestimation of cover load in irregular arrays will be further magnified (Poulsen 2010) and over a narrow pillar panel, the pillar load will be further reduced. In inclined seams, the load distribution over the pillars is non-

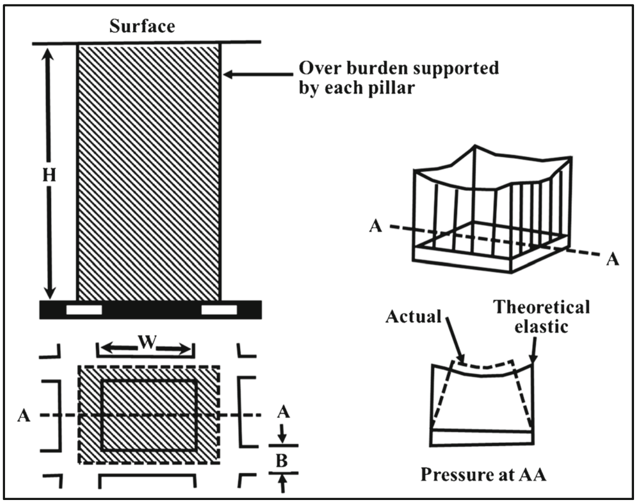

Fig. 1 Pillar supporting overlying block of rock

symmetric (Lianjin 2000; Wen 2013), and the fracture zone within the pillar is also inconsistent (De Qi et al. 2014).

Pillar arrays in inclined seam

The rock pressure normal to inclined seam pillar arrays is given by Trumbachev and Melnikov (1964) as follows.

$$P = \gamma H \left(\frac{W+B}{W} \right)^2 \left(\cos^2\alpha + K\sin^2\alpha \right) \tag{3}$$

where α is the angle of inclination of seam with the horizontal and K is the ratio of horizontal to vertical in situ stresses.

Strength of pillar

The strength of pillar is influenced inter-alia by numerous factors (Jawed et al. 2013) such as uniaxial and triaxial coal strength, width-to-height (w/h) ratio of pillar, pillar size, pillar shape in plan, pre-excavation horizontal stresses, end conditions or conditions at the roof-pillar or floor-pillar contact, presence of bands in the seam, water and weathering underground, method of road drivage, viz. roadheader or with blasting etc.

Water and weathering underground is usually accounted for in the factor of safety. Wagner and Madden (1984) have found that blasting cracks can occur up to 0.3 m inside the pillars, and therefore the effective dimension of a machine-formed pillar is 0.6 m greater than a drill-blasted pillar. In other words, effective dimension of drilled-blasted pillars is 0.6 m less than the machine cut pillars.

Some authors of pillar strength equations have included laboratory-determined compressive strength of coal (Bunting 1911; Greenwald et al. 1939; Gaddy 1956; Holland and Gaddy 1957; Obert and Duvall 1967; Bieniawski 1968; Hustrulid 1976; Logie and Matheson 1982; Sheorey et al. 1987b; Madden 1991; Sheorey 1992), some others the in-situ large scale strength (Bieniawski and Van Heerden 1975; Wilson 1982; Mark and Barton 1997; Mark and Chase 1997), while some a constant strength or no strength (Salamon and Munro 1967; Cook et al. 1971; Wilson 1972; Agapito and Hardy 1982; Maleki 1992; Gale 1999; Murali Mohan et al. 2001). Since the strength at pillar corners are uniaxial, at the sides biaxial and deeper inside triaxial (Wei 2014), it is reasonable to assume that both uniaxial and triaxial coal strengths will influence pillar strength at least to some extent.

The influence of w/h ratio of a pillar on its strength is, in general, very significant. A linear rise in strength is generally assumed for slender pillars ($w/h < 4$–6) but squat pillars still fall into a grey area.

Larger pillars are usually weaker due to presence of geological discontinuities. This effect according to Bieniawski (1968) may be negligible if a sufficiently large coal cube is tested, the recommended size being 1.52 m. Size effect is generally described by

$$S = KW^{-\alpha} \tag{4}$$

where K = unit cube strength and $\alpha = 0.2$–0.5.

The shape of a pillar in plan is usually considered by substituting an equivalent pillar width W_e for the square pillar of width W in any strength equation.

The relation proposed by Wagner (1974) based on servo-controlled in situ tests is

$$W_e = 4A/C_p \tag{5}$$

where A = plan area and C_p = perimeter of pillar.

Galvin (1999) has considered alternative to equation (5) as $W_e = \sqrt{W \times W_1}$ or taking simply minimum width and ignoring the greater width of a rectangular pillar.

Strength equations

Pillar strength equations, which are being used all over the world, have been derived using one of the five methods viz. laboratory compression tests, large-scale in situ tests, closed form methods, case study of collapsed and stable pillars and mixed methods.

A strength equation should be examined in the light of the following desirable features. It should fit as many cases of collapsed and stable pillars as possible, especially the former ones. It should preferably be applicable to both slender and squat pillars, and it should incorporate as many of the factors, which influence strength, as possible.

An extensive research in India ultimately led to equation (6) (Sheorey 1992), which has been in regular use in Indian coal mines since then.

$$S = 0.27\sigma_c h^{-0.36} + \left(\frac{H}{250} + 1 \right) \left(\frac{w}{h} - 1 \right); \text{MPa} \tag{6}$$

The basis of derivation of this equation is theoretical, empirical as well as case study. The equation was designed to include both slender and squat pillars. The equation includes a term for the effect of size on strength and another term for the width to height ratio. Substituting $w = h = 1$ *inch*, in equation (6), results into strength of one cubic inch of coal specimen. The performance of this equation was tested by Sheorey for its practical use and was found to be fit with actual cases of failed and stable cases in Indian context (Sheorey et al. 1987a).

Salamon and Munro (1967) formula (equation 7) in its modified form has been used for standing pillars in Indian condition.

$$S = 7.2 \left\{ \frac{w^{0.46}}{h^{0.66}} \right\}; \text{MPa} \tag{7}$$

Factor of safety vis-à-vis long-term stability

The life of pillars is an important aspect of pillar design. Directorate General of Mines Safety (DGMS) requires factor of safety of the pillars to be 2.0 or more for long-term stability while using equation (6) as above. For stowed pillar, it has to be 1.0 or more.

Physico-mechanical properties of coal measure rocks of Govindpur underground project

Physico-mechanical properties of coal measure rocks, namely, uniaxial compressive strength (UCS), tensile strength, modulus of elasticity and poisson's ratio, are essential input parameters for designing pillars and support system and their corroborations through numerical modelling. Determination of physico-mechanical properties of coal is a cumbersome job as it is very difficult to prepare the requisite samples (Mark and Barton 1997). Even if samples are prepared, a lot of problems are faced during testing.

Blocks of coal and roof rock were obtained from mine for determination of physico-mechanical properties. With lot of difficulties, only a few core specimens could be recovered from these blocks. Tests were conducted on these limited number of specimens only. The cores recovered were of 54 mm in diameter and 125 mm in length for determination of uniaxial compressive strength and elastic properties. Smaller sized cores of the same diameter and lengths varying between 27 and 30 mm were utilised to determining the tensile strength. All the tests were conducted in accordance with ISRM suggested methods. Figures 2, 3 and 4, showing the coal specimen, speak of the difficulty faced in retrieving core specimens.

Table 1 provides the results of the tests conducted on shaly sandstone and coal specimens of Govindpur underground project. The results of test have been used for analysis in this paper.

Pillar design of Sawang-C seam

The estimation of pillar stress is made using Tributary Theory as discussed above through equation (2). The pillar strength has been calculated using Sheorey's formula (equation 6). The equation requires the input of compressive strength of one cubic inch coal specimen. However, owing to the difficulties posed during sample preparation and testing of coal specimens, the compressive strength of core specimens of NX-size was determined according to ISRM suggested method. It has been found through testing and experience on various coal samples that the compressive strength of one cubic inch specimen is more or less in the range of ± 5% of the compressive strength of core specimens of NX-size. This is due to the fact that preparation of one cubic inch specimen in laboratory is a cumbersome process which induces micro-fracture in the specimens leading to reduction in its strength. At a depth of 100 m, the normal stress over the inclined pillar turns out to be 4.127 MPa. The strength of using equation (6) turns out to be 13.22 MPa. The factor of safety of pillar consequently comes to 3.23 for a uniaxial compressive strength of coal sample as 14.49 MPa.

The pillars under study are squat pillars, i.e. having w/h ratio of more than 4–6, and therefore equation (6) has been used for calculation of strength and factor of safety of pillars. This equation, Sheorey (1992), has been regularly used for estimating strength of squat pillars in Indian condition. The necessary correction in stress on pillar due to inclination of the seam has also been incorporated as shown in equation (3).

Design of support system for stability of roof in development workings of Sawang-C seam

Design of support system for development workings of Sawang-C seam in order to ensure roadway stability is based on rock mass rating (RMR) value of the immediate 2-m-thick roof rock overlying the seam, as suggested by Paul Committee (Paul et al. 1990) and accepted by DGMS. The RMR value of the roof rock of Sawang-C seam, as determined by the Mining

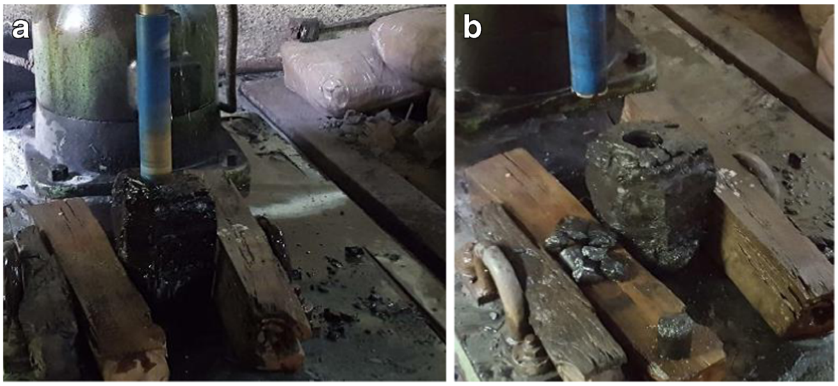

Fig. 2 **a** Coal block placed for retrieval of core specimens and **b** details of core retrieved from the coal block

Fig. 3 Core samples from coal block obtained in third phase

Laboratory, Central Mine planning and Design Institute (CMPDI) Ranchi, was provided by the mine management of Govindpur Project and the same has been used in this paper for the purpose of support design.

The immediate 2-m roof rock consists of 0.8-m-thick sandy shale, 0.2-m-thick shale and 1.0-m-thick medium grained sandstone. There are two sets of joints/cleats with spacing less than 0.30 m. The values of the parameters considered for calculation of RMR is given in Table 2.

Combined RMR is the weighted average of the RMR of each bed which comes out to be 58.8 falling under Class III, Fair Category. For the aforesaid RMR value, likely rock load in $tonnes/m^2$ (Raju et al. 1987) is $Span\ of\ gallery\ in\ metre \times mean\ rock\ density \times (1.7 - 0.037 RMR + 0.0002\ RMR^2)$ and calculated to be 2.257 te/m^2. Roof bolts as support have been widely accepted for bord and pillar development workings in India. This is installed early to support the green roof and as an active support, has a distinctive edge over the passive support currently in use. Full column grouted bolts using quick-setting cement capsules appear ideal for most of the geo-mining conditions prevailing in Indian coalmines. Quick setting implies the development of an anchorage capacity of at least 10 kN in 30 min and about 50 kN in 2 h.

Considering 4 full column cement-grouted roof bolt of 1.5 m long, 22 mm diameter ribbed bar in a row, each having the bearing load of as 6 te/m^2 , with a spacing between the rows being 1.2 m, the resistance offered by each bolt will be 4.76 te/m^2. This results into a factor of safety of 2.1 and bolt density of 0.793 $bolt/m^2$ which is good enough. The recommended bolting density for fair category of roof of RMR values ranging from 40 to 60 and good category of roof of RMR values ranging from 60 to 80 are 1.0 $bolt/m^2$ and 0.7 $bolt/m^2$, respectively. Thus, the roof bolt will be grouted on a grid of 0.84 $m \times 1.2\ m$. That is, the spacing between the bolts in a row shall be 0.84 m and the spacing between the rows will be 1.2 m (Fig. 5). Bolt density shall be increased by 25% at the junctions.

Corroboration of pillar and support design with numerical modelling

The factor of safety of the pillars and the rock load height above the development galleries have been determined using numerical modelling also. Adequacy of suggested support system as mentioned in section “Design of support system for stability of roof in development workings of Sawang-C seam” has been corroborated through numerical modelling and found to be in order. The various inputs for numerical modelling are discussed in the following sub sections.

Numerical analysis of the stability of development galleries

Numerical modelling for designing of roadway support in developed galleries of Sawang-C seam has been carried out. The objectives of the numerical modelling study were to get quantitative answers for the following queries.

i. Under the present status of development in Sawang-C seam, what is the likely rock load height at a factor of safety of 2.0 in the galleries and at junctions of the galleries?
ii. What is the factor of safety of the pillars and the thickness of plastic zone around the pillars?
iii. In view of the proposed development by forming rhombus pillars, what could be the likely rock load height at a factor of safety of 2.0 in the galleries and at junctions?

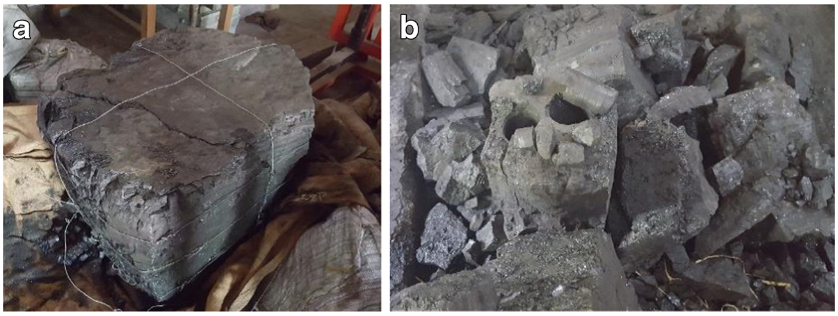

Fig. 4 **a** Coal block received from Govindpur underground mine in fourth phase. **b** Attempts to retrieve cores from the specimen

Table 1 Physico-mechanical properties of coal measure rocks collected from Govindpur underground mine

	Density (kg/m^3)	UCS (MPa)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Poisson's ratio
Shaly sandstone	2530.35	64.21	4.41	11,308.3	0.19
Shaly sandstone	2493.23	51.33	5.72	9619.2	0.23
Shaly sandstone	2519.24	57.89	6.15	10,014.7	0.21
Coal	1365.87	12.32	1.72	1924.2	0.37
Coal	1587.08	19.57	1.24	3688.6	0.33
Coal	1343.84	10.87	1.43	1789.4	0.39
Coal	1433.84	14.99	1.14	2353.9	0.36
Coal	1393.52	14.72	1.73	2198.8	0.34

iv. What is the factor of safety of the rhombus pillars and the thickness of plastic zone around the pillars?
v. Is there any possibility of crushing of corners of the rhombus pillars?

The details of the numerical modelling carried out to answer the above-mentioned queries are discussed below.

Geometrical configuration of numerical model of the existing pillars in Sawang-C seam

Numerical modelling of existing pillars of dimension 20 m × 18 m (centre to centre) developed for bord and pillar method of working having 4.2 m wide and 1.8 m high galleries has been considered in the present study. Seam thickness of 1.8 m having a gradient of 1 in 3.5 is considered in the model. The existing pillars at a depth of 100 m are considered for analysis. A panel size of 5 × 5 pillars in the numerical analysis is sufficient to answer the queries posed in section "Numerical analysis of the stability of development galleries". The central pillar in the panel and its surrounding galleries have been selected for thorough analysis. The roof boundary in the model up to the free surface at a height of 100 m has been considered, and in a similar manner, the floor surface up to a depth of 100 m has been incorporated in the model. A portion of the mesh generated for numerical analysis as shown in Fig. 6 depicts the panel of 5 × 5 pillars with development galleries all around and the side and bottom boundary of the model showing artificial boundaries. The mesh above the coal seam has been removed in this picture to show the pillars and development galleries.

Rockmass failure criterion

The limiting state of stress that includes all sorts of stresses which cause failure is defined by a failure surface in principal stress co-ordinates(σ_1, σ_2, σ_3) by $f(\sigma_1, \sigma_2, \sigma_3) = 0$. Sheorey's (1997) failure criterion is found suitable for effective application in Indian coal measures. The Sheorey's criterion was developed by adopting Balmer's (1952) criterion for intact rocks including coal after applying it to over 200 triaxial data sets. The Sheorey's criterion is defined as:

$$\sigma_1 = \sigma_c \left(1 + \frac{\sigma_3}{\sigma_t}\right)^b \tag{8}$$

This equation is changed for rock mass as:

$$\sigma_1 = \sigma_{cm} \left(1 + \frac{\sigma_3}{\sigma_{tm}}\right)^{b_m} \tag{9}$$

Table 2 RMR of immediate 2-m roof rock of Sawang C Seam, 1-3L/2E-2W Dip District, Govindpur project (U/G), CCL

Parameters	Sandy shale 0.8 m		Shale 0.2 m		Medium grained sandstone 1.0 m	
	Immediate roof		Overlying 0.8-m sandy shale roof		Overlying 0.2-m shale roof	
	Value	Rating	Value	Rating	Value	Rating
Layer thickness (cm)	5.1	9.1	3.3	7.0	11.3	15.1
Structural indices	10.0	12.3	10.0	12.3	10.0	12.3
Slake durability (%)	98.6	16.4	97.4	14.6	98.7	16.6
Rock strength (kg/cm^2)	620.2	11.1	615.6	11.1	347.3	7.5
Ground water seepage (ml/min)	Moist	9.0	Moist	9.0	Moist	9.0
Total rating		57.9		54		60.5

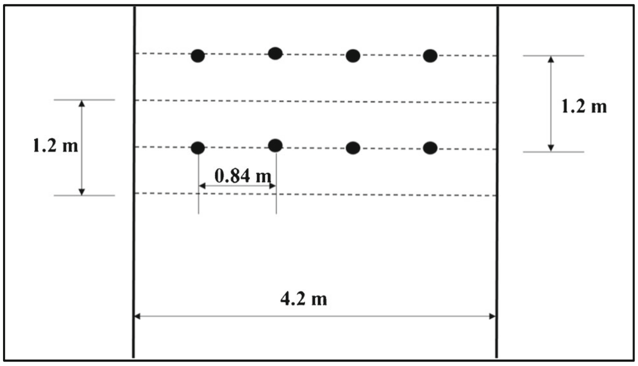

Fig. 5 Recommended bolting pattern in development galleries for Govindpur (U/G) Colliery

where σ_c is the compressive strength of intact rock, MPa; σ_t is the tensile strength of intact rock, MPa; σ_{cm} is the compressive strength of rock mass, MPa; σ_{tm} is the tensile strength of rock mass, MPa; *b* and b_m are the exponent in criterion for intact rock and rock mass, respectively.

These quantities and constants are related to *RMR* as

$$\sigma_{cm} = \sigma_c\, exp\left(\frac{RMR-100}{20}\right) \tag{10}$$

$$\sigma_{tm} = \sigma_t\, exp\left(\frac{RMR-100}{27}\right) \tag{11}$$

$$b_m = b^{\frac{RMP}{100}}, b_m < 0.95 \tag{12}$$

In all models, the basic CMRS-RMR value is used directly instead of Bieniawski's *RMR*, since this procedure has been found to be acceptable after application in many coalmines (Kushwaha and Banerjee 2005; Kushwaha et al. 2010; Sinha et al. 2013, 2015a, b; Singh et al. 2016). RMR value of 58.8 is used in the numerical models. The value of constant "*b*" in Sheorey's failure criterion was taken as 0.5. Strain softening models are required especially for the determination of stress strain characteristics of the pillar. The rock mass shear strength τ_{sm}; the coefficient and the angle of internal friction μ_{0m} and φ_{0m} are obtained as using the Sheorey's Mohr Coulomb equivalent as follows. While using equations 13 and 14, prescribed correction factors are also incorporated in models.

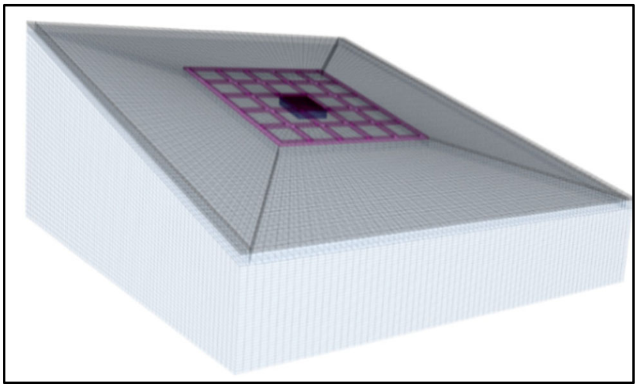

Fig. 6 A portion of the mesh generated for numerical modelling of existing rectangular pillars

$$\tau_{sm} = \left[\sigma_{cm}\sigma_{tm}\frac{{b_m}^{b_m}}{(1+b_m)^{1+b_m}}\right]^{1/2} \tag{13}$$

$$\mu_{0m} = \frac{\tau_{sm}^2(1+b_m)^2-\sigma_{tm}^2}{2\tau_{sm}\sigma_{tm}(1+b_m)} \tag{14}$$

$$\varphi_{0m} = \tan^{-1}(\mu_{0m}) \tag{15}$$

Based on the laboratory test results, the following data as shown in Table 3 were used for defining the failure criterion of coal and coal measure rocks.

Factor of safety

Once the failure criterion is selected, the stresses around the excavation (σ_{1i} ,σ_{3i}) are calculated. The stability of excavation can be assessed by estimating factor of safety of different points and drawing the safety factor contours. The safety factor is estimated as:

$$SF = \frac{\sigma_1-\sigma_{3i}}{\sigma_{1i}-\sigma_{3i}}\ except, when-\sigma_{3i} > \sigma_{tm}\ SF = -\frac{\sigma_t}{\sigma_{3i}} \tag{13}$$

where $\sigma_{1\mathrm{i}}$ and σ_{3i} are the induced major and minor principal stresses obtained from the numerical models. The plotting of factor of safety of roof rock helps derive the rock load height (Loui et al. 2007; Yajun et al. 2014).

Deformational properties of coal measure rocks used for numerical modelling

As Sheorey's failure criterion is selected, the models are run elastically. The induced stresses are calculated by solving the model. The induced stresses of this elastic model are utilised for drawing the factor of safety contours. Elastic properties of

Table 3 Laboratory determined properties used for defining the failure criterion in numerical models

Rock type	Compressive strength (MPa)	Tensile strength (MPa)
Coal	14.49	1.45
Non-coal (coal measure rocks)	57.81	5.43

the rock mass are used in numerical models either as bulk and Shear modulus or as Young's modulus and Poisson's ratio.

The bulk and shear modulus (K and G) are related to Young's modulus (E) and Poisson's ratio (ν) by the following relations:

$$\mathrm{K} = \frac{E}{3(1-2\nu)} \tag{14}$$

$$\mathrm{G} = \frac{E}{2(1+\nu)} \tag{15}$$

An empirical relation given by Mitri et al. (1995) for relating the rock mass deformation modulus E_m and intact rock deformation modulus E_r is given as follows:

$$\frac{E_m}{E_r} = \frac{1-\cos\left(\pi \times \frac{RMR}{100}\right)}{2} \tag{16}$$

where E_m is the deformation modulus of rock mass, E_r is the deformation modulus of intact rock, RMR is the rock mass rating, and $\pi \times \frac{RMR}{100}$ is expressed in radians.

Using the relationship given in equation (16), the rock mass deformation modulus was calculated as given in Table 4.

Table 5 summarises the values of elastic properties of rock mass used for numerical modelling.

In situ stress

In situ stress is a boundary condition required as an input parameter for numerical models. Global estimate for in situ stress has been given by Hoek and Brown, 1980. However, there exists a wide variation in the value of K, a ratio of average horizontal stress to the vertical in situ stress, ranging from 1.3 to 15.5 at a depth of 100 m. Another estimate for horizontal stress is based on geothermal gradient (Sheorey 1994) given by equation (17).

$$\sigma_{horizontal} = \frac{\nu}{1-\nu}\sigma_v + \frac{\beta_r E G_t}{1-\nu}(z+1000) \tag{17}$$

where $\sigma_{horizontal}$ is the horizontal stress (MPa), σ_v is the vertical stress (MPa), ν is the Poisson's ratio (0.25), β_r is the coefficient of thermal expansion ($30 \times 10^{-6}/^{\circ}C$ for coal, $8 \times 10^{-6}/^{\circ}C$ for other types of coal measures), E is the Young's modulus of rock (MPa), G_t is the average value of geothermic gradient for Indian coal measures = $0.03^{\circ}C/m$, z is the depth of cover (m).

Table 4 Calculation of rock mass deformation modulus based on laboratory determined elastic modulus of coal and roof rock specimens

Rock type	$+E_r$ (GPa)	E_m (GPa)
Coal	2.42	1.47
Non-coal	10.3	6.27

Table 5 Elastic properties of rock mass used in numerical models

Rock type	E_m (GPa)	Poisson's ratio	Calculated bulk modulus (GPa)	Calculated shear modulus (GPa)
Coal	1.47	0.36	2.84	0.89
Non-coal	6.27	0.21	3.61	2.59

Calculation of the ratio K at a depth of 100 m using the laboratory determined values of Young's modulus of 10.3 GPa turns out to be 1.73. However, the measured in situ stress in Indian coal measure rocks varies from a minimum of 1.2 to a maximum of 2.12 (Table 6). Hence, a reasonable estimate of K was taken as 1.75 for use in the numerical models.

Results of numerical modelling for the existing rectangular pillars in Sawang-C seam of Govindpur underground mine

Factor of safety contours over the roof rock and pillars was drawn for the case of existing pillars in Sawang-C seam of Govindpur underground workings. A cut view of the pillar is shown in Fig. 7.

From Fig. 7, it is evident that the roof rock up to 1.75 m is stable with a factor of safety of 2.0. This further corroborates the visual observation of roof that was stable with spot bolting at only few places. However, when the workings go beyond 150–200 m depth, the support design must again be reviewed to take care of the effect of depth. The skin of the pillar exposed to air is in a plastic state up to a depth of 0.5 to 0.75 m as the factor of safety is less than 1.0 in the plastic zone (Fig. 8a). The stress-strain curve of inclined rectangular pillar, through numerical modelling (Fig. 8b), shows a failure load of 8.8 MPa resulting into a FoS of 2.13.

Geometrical configuration of numerical modelling of proposed rhombus pillars in Sawang-C seam

Rhombus pillar at a depth of 100 m is considered for analysis. Using the relationship of true dip and apparent dip (Fig. 9), the parameters of rhombus pillars were calculated. In order to maintain an apparent dip of 1 in 5, the acute angle of rhombus pillar turns out to be 44° for seam of true dip of 1 in 3.5. Seam thickness of 1.8 m is taken in the model. Here also, the central pillar in the panel and its surrounding galleries have been selected for thorough analysis. The panel size, roof and floor boundaries have similar dimensions as discussed in section "Numerical analysis of the stability of development galleries". A portion of the mesh generated for numerical analysis is shown in Fig. 10.

Table 6 Summary of measured in situ stress in Indian coal fields

Sl. No.	Location	Depth of cover (m)	σ_V (MPa)	σ_H (MPa)	σ_h (MPa)	K	Direction of σ_H	Reference
1	Parascole colliery (ECL)	135	3.24	5.21	4.46	1.60	N43.47°	Sinha et al. (2002)
2	Chinakuri Mine No. 3 (ECL)	255	6.12	8.94	7.15	1.40	N83.8°	
3	Jhanjhra mine (ECL)	110	2.64	5.84	4.68	2.12	N68.80°	
4	Tandsi mine (WCL)	230	5.06	9.0	4.5	1.77	N120°	Sinha et al. (2004)
5	Thesgora mine (WCL)	212	4.66	6.04	4.03	1.29	N50°	
6	KTK-5 Incline mine (SCCL)	246	5.3	9.52	3.81	1.79	N50°	Venkateswarlu et al. (2007)

Results of numerical modelling for the proposed rhombus pillars of Govindpur underground mine

Factor of safety contours over the roof rock and pillars were drawn for the case of rhombus pillars in Sawang-C seam of Govindpur underground mine. A view of the pillar and roof rock above the pillar is shown in Fig. 11.

It is evident from Fig. 11 that the roof rock is stable with a factor of safety of 2.0 and above. The skin of pillars will be in a plastic state up to a depth of 1.5 m. The corners of the pillars up to a depth of 5–6 m have a factor of safety less than 1.0 indicating crushing of the corners in short term (Fig. 12a). The stress-strain curve of inclined rhombus pillar, through numerical modelling (Fig. 12b), shows a failure load of 8.3 MPa resulting into a FoS of 1.96.

Existing and proposed scheme of loading of blasted coal at face

At present, loading of coal at face is manual in Sawang-C seam. Coal is hand shovelled into basket, carried on shoulder up to a distance where train of tubs is standing and unloaded into it. Nowadays, manual loading has become almost extinct, particularly in mines where geo-mining conditions are favourable for mechanising the loading operation. Geo-mining parameters such as working height, inclination of seam and floor condition, in general, are the main arbiters in deciding suitable schemes of mechanised loading at face. In past, Gathering Arm Loaders, Duck Bill Loaders, Scraper Loaders were popular for loading of coal at face. In present days, Bucket Loaders, namely Load Haul Dumpers (LHDs) and Side Discharge Loaders (SDLs), are popularly used for loading of face coal in Bord and Pillar mines. Use of SDLs, however, is more popular in coal mines. Both machines have their operational limitations in terms of inclination of seam and working height/thickness of seam. However, these days, low height crawler mounted SDLs are also available to work in seams as low as 1.2 m thick. But the major constraint posing operational limitation of these machines is inclination of the seam.

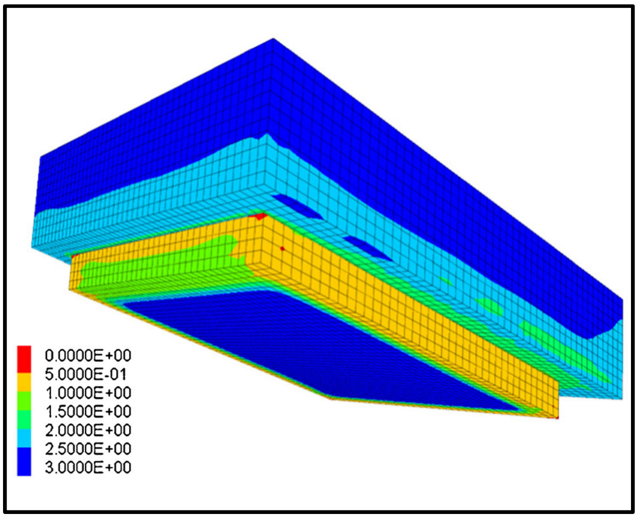

Fig. 7 Cut view of rectangular pillar and the roof rock showing factor of safety contours

An exhaustive literature search was made to ascertain meaningful deployment of SDL in inclined seams (IS 14480: 2006; Singh 2007; Mathur 2012; SCCL 2013). Almost every information documented speaks of a limiting inclination of 1 in 4 (inline). Para 9.4 of The Indian Standard (IS 14480: 2006) recommends limiting gradient of 1 in 6. The standard states that SDL shall not be allowed to ply on a gradient exceeding 1 in 6 unless otherwise permitted in writing by the Directorate General of Mines Safety, Dhanbad.

Tender Specification for low height SDL floated by The Singareni Collieries Company Limited is also available wherein SDL suitable for cross gradient of 1 in 6 has been asked for.

A written consultation through email was made with EIMCO ELECON about operational limitations of company's low height versions of SDL. Neither the planners in CMPDIL nor the manufacturers is positive about successful operation of SDL in seam having inclination of 1 in 3.5. EIMCO ELECON has categorically mentioned in writing that its SDL will not be suitable for such seam.

According to EIMCO ELECON, though its low height SDL is suitable for loading in 1 m high tub but its operation is restricted in seams having inclination less than 1 in 6.

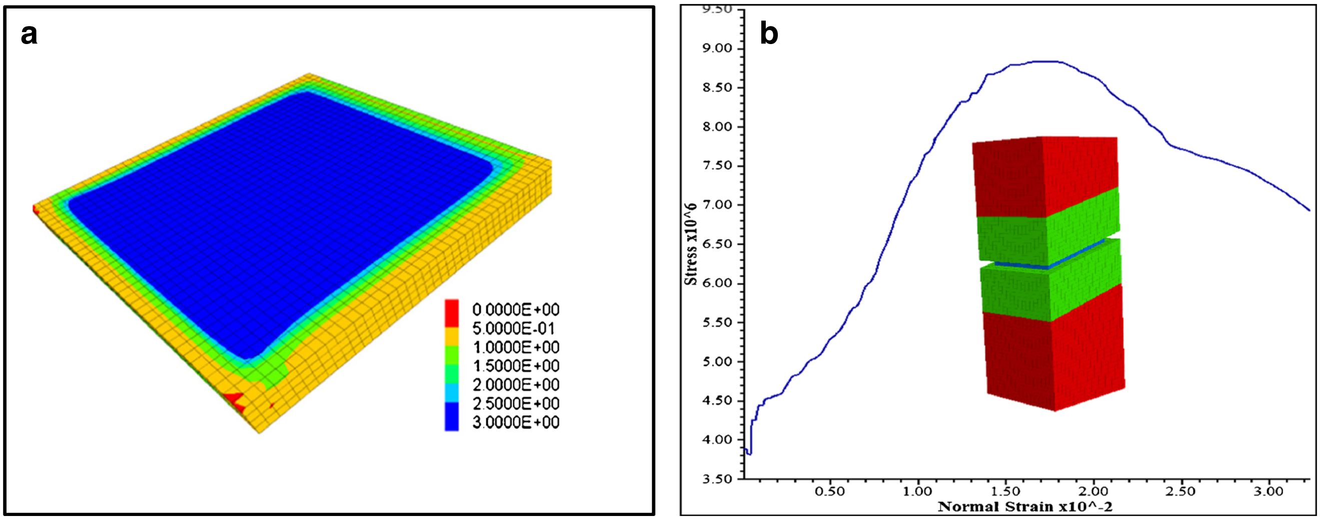

Fig. 8 **a** View of rectangular pillar showing factor of safety contours at a depth of 100 m. **b** Stress-strain curve of inclined rectangular pillar

According to it, the maximum gradient for successful deployment of SDL is 1 in 4 (inline) and 1 in 6 (cross). Figure 13 explains the possibility of deployment of SDL in galleries along strike, true dip and apparent dip of the seam. The inline gradient i.e. gradient in direction of movement of SDL in Gallery G1, G2 and G3 are, respectively, 0°, 1 in 3.5 and 1 in 5. The cross gradient of these galleries are 1 in 3.5, 0° and 1 in 3.5. Cross gradient is the inclination across the direction of movement of machine and the machine will slide along this direction while moving in inclined seam either in a galleries driven along strike or a galleries driven along apparent dip. The cross gradient in galleries, other than those driven along the true dip direction, is always equal to true dip of the seam. While moving in level galleries driven along the strike direction or in galleries driven along apparent dip direction, the machine will always slide on floor in true dip direction i.e. direction “A”.

The maximum cross gradient recommended by Bureau of Indian Standard and also as prescribed by the manufacturers for successful deployment of SDL (with no sideway sliding) is 1 in 6. This clearly indicates that SDLs are not suitable for deployment in seams having true dip more than 1 in 6 (about 9.5°). In seams having dip less than 1 in 4, SDLs can be deployed in dip galleries for loading operation. But deployment of SDL for loading in level galleries or galleries driven along any apparent dip direction in seams having true dip more than 1 in 6 will not be operationally successful. Therefore, under the backdrop of the aforesaid explanation, successful deployment of SDL for loading of coal at face in Sawang-C seam, having inclination of 1 in 3.5 is ruled out.

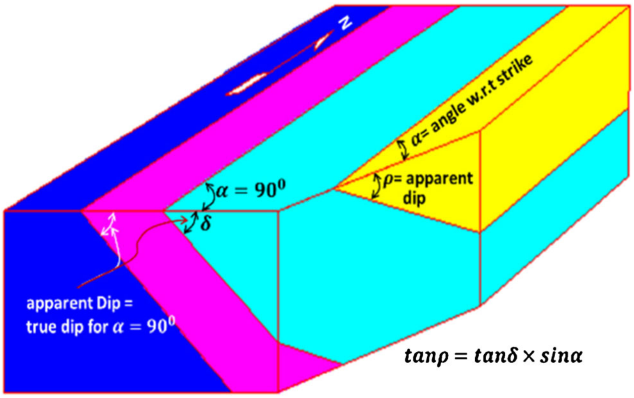

Fig. 9 Relationship between true dip and apparent dip

Possible mechanised loading scheme at face

Successful deployment of SDL in Sawang-C seam cannot be thought of unless some amount of dinting is done along the floor on rise side of galleries driven along strike direction to bring the gradient down to at least 1 in 6. This means across the gallery, 0.7-m floor will require to be chipped off which is neither making any practical sense nor it will be economically

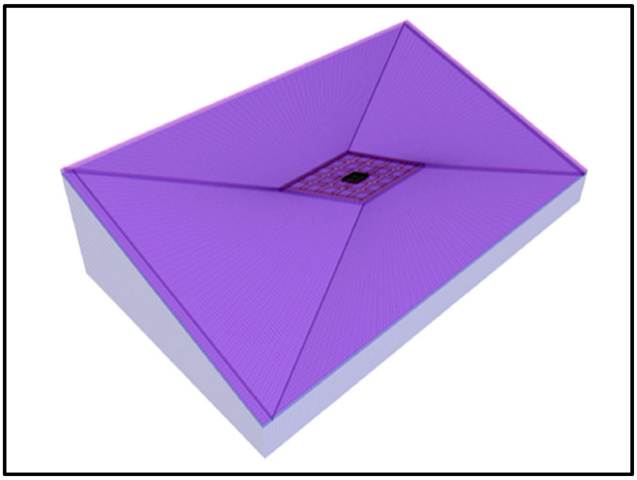

Fig. 10 A portion of the mesh generated for numerical modelling of rhombus pillars

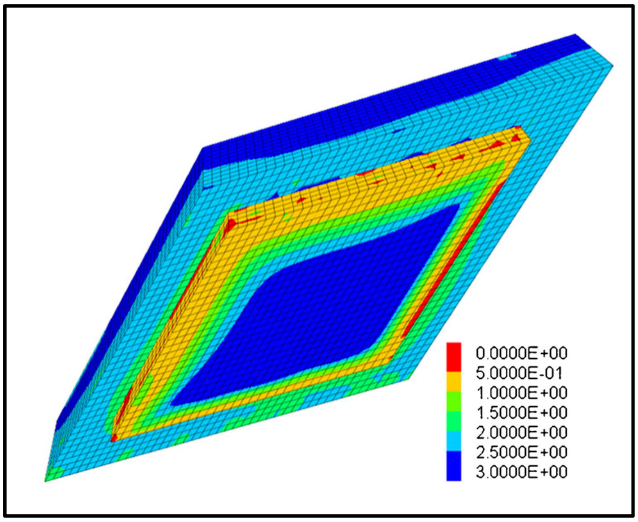

Fig. 11 Cut view of rhombus pillar and roof rock showing factor of safety contours

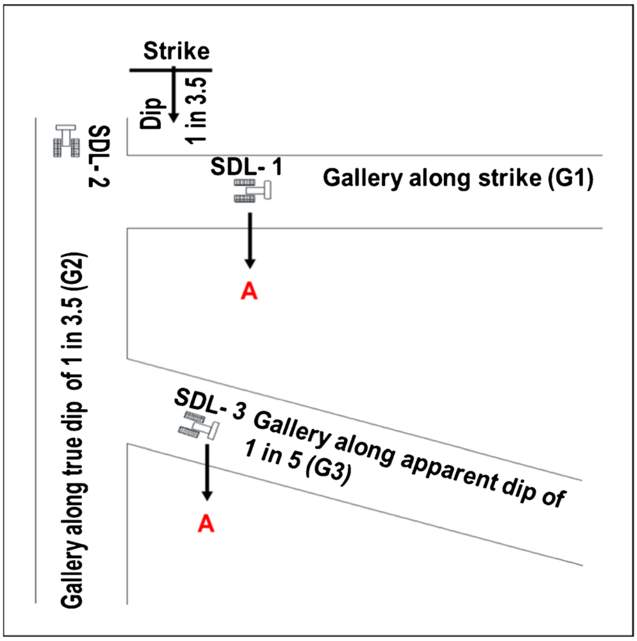

Fig. 13 SDL deployment in inclined coal seams

feasible. Alternatively, the floor can be made to have inclination of 1 in 6 by leaving 0.7 m coal along the floor on dip side of these galleries, thereby making the effective height of these galleries to 1.1 m by loosing roughly 20% coal. Though leaving coal looks easier than dinting of floor but this make effective height of galleries unsuitable for deployment of low height SDLs. Moreover, nothing can be done in dip galleries to make them have required threshold inline gradient of 1 in 4. This means even if the deployment and working of SDL can be made possible by dinting of floor in galleries driven along strike direction of seam, irrespective of hardship involved and its economic viability, the same cannot be done in the dip galleries.

Further, as the workings will extend beyond certain depth to encounter true dip of 1 in 5, the loss of coal for maintaining floor gradient of 1 in 6 will be much less of the order of 0.315 m^3 per running meter of the gallery requiring to leave only 0.15-m coal on the dip side of the galleries driven along strike. In this zone of property, the inline gradient in dip galleries will also be favourable being less than threshold inline gradient of 1 in 4 for deployment of SDLs. Therefore, deployment of SDL may be thought of, if at all it is a compulsion to do so, at a later stage when the property encounters a true dip of 1 in 5.

Scrapper/slusher loading: Loading of face coal on chain conveyor using scraper/slusher could be another alternative (Fig. 14). Though this scheme is a bit cumbersome in the sense that with every blast a pair of converging drill holes have to be made into the newly created coal face for fixing

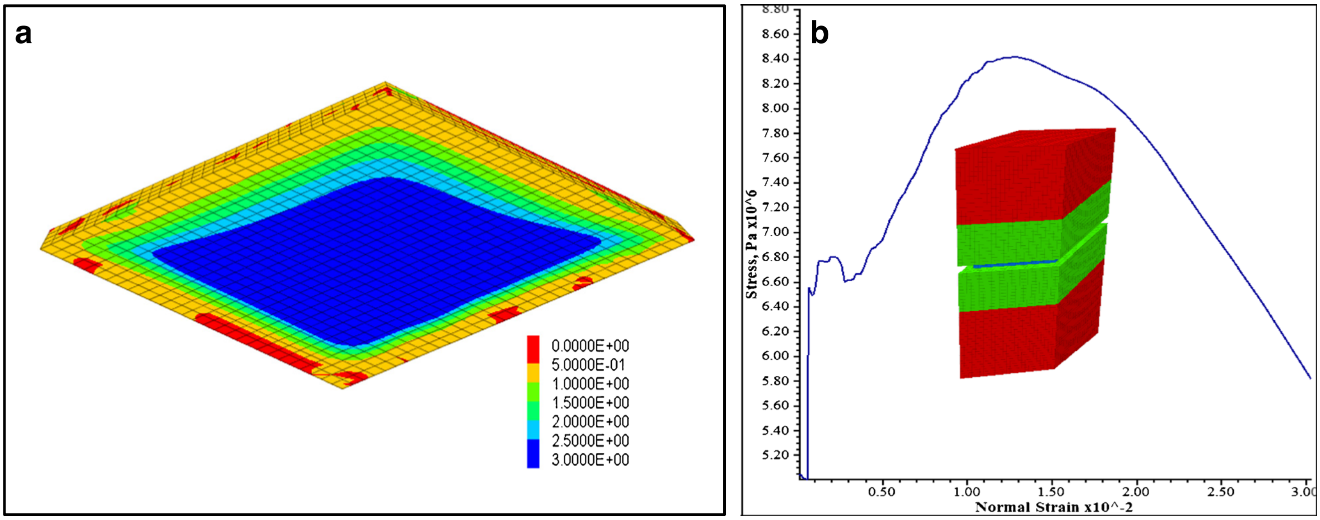

Fig. 12 **a** View of rhombus pillar showing factor of safety contours. **b** Stress-strain curve of inclined rhombus pillar

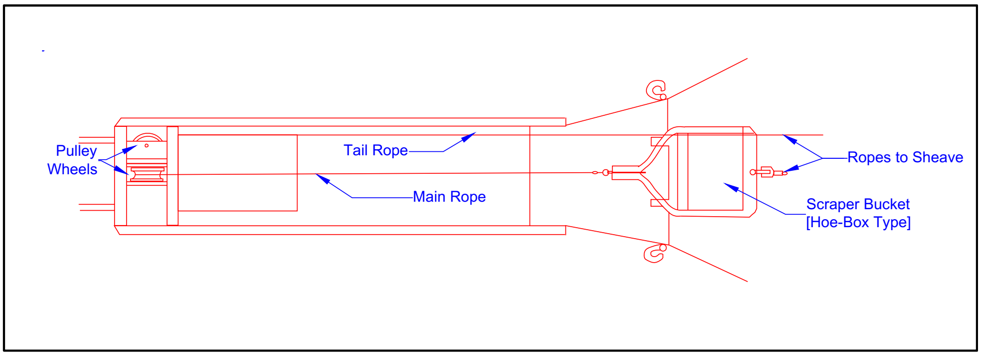

Fig. 14 Scheme for loading of face coal on chain conveyor

pulley through which tail rope of the scraper basket will return to the rope drum. Though this scheme is mechanised, some amount of spilled coal will have to be shovelled manually onto the chain conveyor. Also, for initial few metres of advance in cross galleries, loading will have to be made manually.

Conclusion

Development working with bord and pillar layout is being carried out in Sawang-C seam of Govindpur underground project at a depth of 100 m. The seam thickness is 1.8–2.0 m. The dip of the seam is 1 in 3.5 at the existing depth of working. According to Sheorey's Empirical Formula (equation 6), strength of coal pillars comes out to be 13.22 MPa. Accordingly, for the stress value of 4.127 MPa (equation 3) existing at the depth of 100 m, the factor of safety of pillars works out to be 3.20. Factor of safety thus obtained indicates that the size of the existing rectangular pillars of coal (20 m × 18 m) is adequate for long-term stability. This is to be mentioned, however, that the empirical relation is incapable of showing inherent weakness, in terms of induced stress in pillars. This necessitates use of numerical modelling. Accordingly, numerical modelling was carried out that shows a factor of safety of 2.99. This amply corroborates the factor of safety of pillars obtained empirically.

Calculations indicate that in order to achieve an apparent dip of 1 in 5 of the cross galleries for the proposed rhombus pillars, if at all made, the acute angle of the rhombus pillar should be 44°. The average factor of safety of the rhombus shaped coal pillars through numerical modelling works out to be 2.07 as compared to 2.99 for the rectangular pillars of the same size. The numerical modelling results indicate that the skin of rhombus shaped coal pillars will be in plastic state up to a depth of 1.5 m in comparison to 0.5–0.75 m in case of rectangular pillars. The corners of the rhombus pillars up to a depth of 5–6 m have a factor of safety of less than 1, indicating crushing of corners in short term, if not adequately reinforced. Hence, the formation of rhombus pillars for deployment of SDL deployment is ruled out.

For designing support system to ensure stability of roof in the existing development workings, the likely rock load comes out to be 2.257 te/m^2. Considering the bearing load of each bolt as 6 te/m^2, the resistance offered by the bolts will be 4.76 te/m^2 and the resulting factor of safety of the support system will be 2.1. Numerical analysis carried out for the existing workings to see the factor of safety contours over the coal pillars in the roof rock reveals that roof rock up to a height of 1.75 m is stable with a factor of safety of 2.0.

The proposition of deploying low height SDLs in order to replace manual basket loading was examined thoroughly. A thorough literature search and discussion with different levels of planning, managerial and manufacturing experts led to the conclusion that a trouble free deployment of SDL is not possible in seam like Sawang-C having gradient of 1 in 3.5. Driving of cross galleries along apparent dip of any value will not change the inclination (true dip) of the floor on which SDL will move and therefore SDL will continue to slide.

Limiting inclination of 1 in 4 (inline) and 1 in 6 (cross) is required for successful deployment of SDLs. The deployment of SDLs on the face of existing state of inclination (i.e. 1 in 3.5) is, therefore, ruled out. Dinting of floor in level galleries may ease out the problem of cross sliding in these galleries but the minimum required gradient of 1 in 4 (inline) still remains to pose problem for movement of SDLs in cross galleries. This problem, however, will automatically ease out in the dip side of the property encountering true dip of 1 in 5. Quantum of dinting of floor in level galleries in this part of property will also be less. Therefore, deployment of SDLs may be thought of at a later stage when the property encounters a true dip of 1 in 5.

In the present condition, scrapper/slusher loading looks to be the only feasible option for mechanising loading operation at face with limited success.

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