CRITICAL APPRAISAL OF PILLAR DESIGN AS REQUIRED BY COAL MINES REGULATIONS OF INDIAN VIS-À-VIS LATEST ROCKMECHANICS FORMULAE

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ABSTRACT

The present study attempts to critically review the pillar design as required by Coal Mines Regulations of India vis-a-vis latest rock mechanics formulae. Equivalent material modelling was the approach adopted for testing the safety and stability of the pillar sizes predicted by various formulae.

Two parameters considered here for calculating pillar sizes were the stresses acting over the pillars and the strength of the pillars.

Stresses acting on the pillars were calculated by the tributary area method. Based on the studies of Coates and Australian, the stress obtained was reduced by 50 percent.

For calculating the strength of the pillars, three formulae, namely Holland and Gaddy, Salomon and Munro and Central Mining Research Station India, were used.

The pillar widths were then determined by equating the product of recommended factor of safety and pillar stress with the pillar strength.

INTRODUCTION

Underground mining of coal is essential when surface mining loses its economic viability. The prevalent methods of underground coal mining in India are Bord and Pillar mining and longwall mining. Of the total planned production of 200 million tons in 1990-91, around 27 percent would come from the underground mining (Anon, 1991). More than 93 percent of the total underground coal production would come from the Bord and Pillar method. Indian experience with longwall mining is not very encouraging. Hence, here a case is made for the adoption of partial planned extraction.

The partial extraction of coal is rendered essential when the strata above and the ground surface is to be protected from subsidence. This is needed when surface has important structures or water bodies, immediate seam is wet. or has fire or the working seam is prone to spontaneous combustion. Here, caving being detrimental is prevented through partial extraction, which eliminates the most hazardous and complicated job in the Bord and Pillar mining— the depillaring.

The adoption of planned partial extraction needs innovative design of newers boards and pillars. Hence, pillar designing requires immediate relaxations from rigid legislative guidelines. Even today, the mine owners have to design the pillars on the basis of coal mines regulations of India (CMR, 1957). CMR prescribes the minimum width of the pillars at a particular depth and gallery size. The maximum height of the roof and minimum span of the galleries are also specified. The
statutory pillar sizes are highly oversized.

Recommended pillar sizes must be reduced without sacrificing the safety and stability of the working. Many formulas are now available for calculating the optimum pillar sizes. But, these formulas are empirical in derivation. Thus, before using in a new area, its suitability must be tested.

In the present study, the suitability of the following three formulas were tested for Indian underground conditions:
1. Holland and Goodly (Holland, 1964),
2. Salamon and Munro (Salamon, 1967), and
3. Central Mining Research Station, India

Pillar sizes were calculated by equating the stresses acting over the pillars, with the strength predicted by formulæ. Recommended factor of safety was then incorporated in the equation obtained, for solving the resulting polynomial equations, a computer programme was developed. The calculated pillar sizes were tested for safety and stability.

The pillar sizes obtained were tested through equivalent material modelling (EMM) technique, for this, an equivalent material model, one of the major coal mining blocks of Indian coal field was made. Excavations were made in the seam II/III (3 m thick seam) at the depth of 119 m. The pillar sizes were kept as predicted by different formulæ.

FACTORS AFFECTING PILLAR DESIGN

Factors affecting pillar-design can be enumerated as below:
1. Stresses acting on the pillar,
2. Strength of the pillars,
3. Relative strength of the roof, pillar and floor,
4. Deformation and failure of coal pillar, and
5. Width of the gallery.

Stresses Acting on the Pillar

During extraction has two components - firstly the stress existing in the undisturbed seam and secondly, the stress induced during progressive extraction of the coal. The stresses existing in the undisturbed seam consists of geological stresses (gravitational stresses and tectonic stresses), tectonic stresses, stresses in coal material and hydrodynamic stresses.

The stresses induced during progressive coal extraction comprises of abutment stresses and stresses due to dynamic loading. The average value of the stresses acting on the pillar increases more rapidly than the maximum value of stress, on immediate extraction. When 25 percent of coal is extracted, the two values of stress are approximately equal. Practically, due to stress adjustment around openings in underground, this condition occurs even with 50 to 65 percent of coal left as support. Hence, except for some unusual circumstances, designs are based on average value of stresses in mine pillars rather than the maximum value of stress (Brady and Brown, 1985).

The average value of pillar stress can be calculated by tributary method. This method is generally applied for a flat seam, but with correction for seam-inclination it can be used for pitching deposits also. This method is based on the analysis of single pillar.

Salamon (1964, 1967) studied multipillar situation and adopted more sophisticated analytical method for calculation of average stress on the pillars.

Sheorey and Singh (1974) estimated pillar stress by a complex approach in terms of differential equations. These equations provide for overburden deflection by treating the rock strata as a thick seam composed of of layers having different elastic properties.

Coates (1966) through his elastic theory...
approach found that tributary area method yields 40 percent higher value of the average pillar stress.

Hastrulid (1981) found in the field measurements that the tributary area estimations were 40 percent higher than the actual average stress on the pillar. It is significant, that both obtained same value of 40 percent, through different approaches.

Here, stress was calculated by tributary-area method. A correction of 40 percent was made, based on the findings of Coates (1966) and Hastrulid (1981). This had twin advantages of simplistic calculation and realistic average pillar stress values.

In tributary area method, stress is calculated by assuming that the pillars uniformly support the entire load overlying above the pillar and the mined out area (fig.1) in the method, \( \sigma' \) is calculated by

\[
\sigma' = 0.6 \sigma \left( \frac{1}{1 - Re} \right)
\]

Where,
- \( \sigma' \) = vertical stress,
- \( \gamma' \) = unit weight of overburden strata,
- \( h \) = height of the overburden,
- \( Re \) = extraction ratio, and
- 0.6 = Coates-Hastrulid correction factor.

But, the evaluation of stress by tributary area method does not take into account abutment stress distributions and deformations of the pillar. Also, if there is displacement interaction between the surrounding strata and the pillar itself, stress may be redistributed within the system. This results in a stress state considerably different to the theoretical state.

**Strength of Live Pillars**

Pillar strength is influenced by the size-effect, shape-effect, ground-pressure, strength of the coal material and dynamic loading.

**Fig. 1. The tributary area analysis—basic premises (Bieniawski, 1964)**

**Size-effect**

The strength of the pillar reduces to a minimum value with the increase in size. The size at which the strength is minimum is called critical size. Beyond this size, the strength is almost constant. This phenomenon is called as size-effect. According to Bieniawski (1969), critical size is reached for a critical span of side 1.5 m. However, Peng (1989) disagrees with the value of the critical size. The concept of critical size is not yet refuted. Presence of discontinuity is probably the main reason behind the strength reduction due to size-effect. When the discontinuities develop across the pillars, strength reduction is proportional to \( \frac{1}{V^{1/6}} \), where \( V \) is the volume of the test specimen (Choi, 1989).

**Shape-effect**

The strength of a pillar goes on increasing with the increase in width/height ratio. This increase in strength is called the shape-effect. This is valid from laboratory size
specimens to full size pillars. Pillars become almost indestructible for width/height ratio higher than ten.

**Ground-pressure**

The increase in depth increases the load of the superincumbent strata. This further increases the confinement of the pillar. This increased confinement results into higher strength of the pillar.

**Strength of the material**

The strength of the pillar also depends on the rank of the coal, presence of cleats and laminations. High rank coal is stronger than lower rank coal. The presence of cleats and laminations weaken the coal material and the pillar.

**Dynamic loading**

Pillar weakens because of dynamic loading due to blasting. The rocks loosen, crush or planes of weaknesses are induced in intact rocks because of dynamic loading.

**Relative Strength of the Roof, Floor and Pillar**

During designing a pillar, the relative strength of the three—roof, floor and pillar becomes important. The weakest element of the three is the critical element. This study considers pillar as the critical element.

**Deformation and Failure of Coal Pillar**

Pillar loading is a continuous process during which progressive pillar fracturing may result in transition of pillar strength from one of excessive strength to that of zero strength. Therefore, the strength of the pillar is corrected for long term strength. On loading, cracks are initiated in the pillar then compaction occurs. Finally the failure takes place with total viscous flow. The velocity of this flow depends on the coal viscosity.

**Width of the Gallery**

An increase in gallery width increases the load on the pillar. So, gallery width restricts the minimum size of the pillar.

**THE PILLAR STRENGTH FORMULAE**

**HOLLAND and GADDY Formula**

\[
Sp = K \sqrt{\frac{W}{h}}
\]

where,

- \(Sp\) = Strength of the pillar in kPa,
- \(W\) = least lateral dimension of pillars in inches,
- \(h\) = thickness of seam in inches,
- \(K = \frac{S_1}{\sqrt[3]{D}}\)
- \(S_1\) = strength obtained by testing a cubical specimen of the bed under consideration,
- \(D\) = edge dimension of specimen tested, and
- \(K\) = a coefficient depending on the material making up the mineral, obtained by testing representative cubes of constituent material.

Recommended factor of safety is 1.2-2.2. The formula according to Holland and Gaddy should be valid for width/height ratio of two to eight. For higher width/height ratio the results underestimate the in situ pillar strength due to significant confinement effect. This formula did not consider this effect.

**SALOMON and MARIO (C.M.R.S.>modified) Formula**

\[
Sp = 0.70 \text{ MPG}^{0.46} \text{ A}_{0.66}
\]

where,

- \(Sp\) = strength of the pillar in kPa,
- \(R\) = long term strength factor,
- \(K\) = in situ strength of coal in kPa,
- \(W\) = pillar-width in m, and
- \(h\) = thickness of seam in m.

**C.M.R.S. Equation**

\[
Sp = 0.27 S_c \left( \frac{h}{150} + \frac{H}{150} \right) + 1
\]

where,

- \(S_c\) = strength of the pillar in kPa,
- \(H\) = depth of the seam in m,
- \(h\) = height of the seam in m, and
- \(S_p\) = strength of the pillar in kPa.

**Calculations**

A generalized polynomial equation as given below, was obtained for the width of
the pillar,

\[ F_1(W) = F_2(W) \cdot f_a \]  \hspace{1cm} (5)

where,  

\[ F_1(W) = \text{strength of the pillar expressed as a function of width of the pillar,} \]
\[ F_2(W) = \text{stress acting on the pillar described as function of width of the pillar,} \]
\[ f_a = \text{factor of safety, and} \]
\[ W = \text{width of the pillar.} \]

Problems of the Pillar Designing

The problems of the pillar designing can be summed up as overestimating the stress acting over the pillar, underestimating the strength of the pillar and dealing of the laboratory results to yield results. These causes over sizing of the designed pillars.

One of the reasons behind this conservative designing is the ignorance of rock behaviour. Various pillar design approaches attempt to strike the balance between the ability to predict design parameters and the factor of ignorance. The CMR given in the appendix is open to many serious objections.

CMR considers only two parameters of the width of the gallery and the depth of the working. Probably CMR advises the pillar sizes for the development which is reduced further in depillaring. This needs alteration when planned partial extraction would be adopted. Moreover, it does not consider stress field, relative strength of rock, pillar and floor; strength of the material of the pillar; the variation in local geology and the post-failure rock behaviour as design parameters. Therefore, instead of designing an optimum pillar size it opts for an oversized pillar. The regulatory authorities apprehend that the available rock mechanics formulae do not predict the real strength of the pillar. Therefore, the main problem of this study was to predict and check the safety and stability of the calculated pillar sizes. It further wanted to stress upon the suitability of these formulae for designing coal mine pillars in India. It further suggests planned partial extraction.

Modeling

Two modelling techniques namely numerical and physical modelling technique were available for checking the pillar stability.

Now a days, numerical modelling technique is widely used and accepted. But this technique suffers a serious disadvantage. While the computer simulation of structural behaviour of excavations provide a reasonably reliable quantitative picture, qualitative evaluation of the excavation stability is still very limited (McClain, 1983). Moreover, for an identical problem being solved by a number of computer simulations featuring different nodes, widely varying results are possible. Hence, numerical modelling was not preferred.

Physical modelling can provide useful information particularly when examining the modes of failure. The use of physical models as tools in rock mechanics is now quite popular. Its validity is already established for mine prototypes and was used successful by several workers for different mining cases (Singh, 1988; Singh et al., 1987; Singh, 1990).

Statement of the Problem

Equivalent material model was constructed to study the optimum pillar design of 14200 m high accret. An underground openings were created in lowermost coal seam (3.6 m thick). The 5 galleries and 4 pillars were developed. The galleries were 4 cm long and 3 cm high. The 20 cm barriers were left on both ends. Later on the galleries were widened and pillar width were reduced according to the selected rock mechanics formulae. After that, they were further widened till optimum size was obtained in the model.

Construction of EM Model

The model was constructed in a steel
frame (2m x 2m x .2m) pivoted at one end. The frame was tilted to 8° for simulation of average amount of dip observed in the field. Another joint set (60°) was simulated in each layer with the help of a joint simulator and knife.

RESULTS AND DISCUSSION

The complete model with instrumentation (LVDTs and Dial gauges) is shown in Fig. 2. In all 10 LVDTs and 10 Dial gauges in X and Y directions were connected. Excavations were initiated at coal seam II/III, 3 cm (3m in prototype) thick at an average depth of 116 cm. Dial gauges were fixed, above the working seam, which were able to record the smaller deformations up to 0.003 mm. But during the initial development of pillar (4 cm x 3 cm) no deformations were recorded.

Fig. 2. The EM model with LVDTs and dial gauges.

The pillars left were further reduced. The excavation proceeded from dipmain side. At the pillar width advised by CMR no displacement was recorded (Fig. 3). Expecting that the pillars can be reduced safely, excavation was continued. The observation points had no deformations at the stage predicted by the CMRS (Fig 4).

Fig. 3. Workings with the pillar width as suggested by CMR (1957)

The model condition when the excavation had reached the pillar width advised by Salamon and Munro is depicted in Fig. 5. No deformations were recorded. The strata movement above the seam no. II/III were not noticed.

The pillar sizes were kept as recommended by Holland and Godby (Fig. 6). This did not show any deformation or movement in the superincumbent strata. It was probably because the load on the pillars were still safe. This confirmed that Holland and Godby can predict safe and stable pillar sizes. On further reduction of the pillars, as observed in Fig. 7 no deformation took place till 4 cm pillar.
size (4m in the prototype). This is recommended as the safe and stable pillar size for the planned partial extraction through present study.

Fig. 5. Workings with the pillar predicted by Balamurugan and Murugesan (1987)

Fig. 6. Workings with pillar as predicted by Hockland and Gaddie (1964)

The pillar sizes were further reduced up to 4cm (4m in prototype) and no roof fall took place. The rib crushed on further reduction of the pillar and subsidence reached up to the surface (Fig. 8). A major crack developed from the dip side, followed by a similar major crack on the rise side. The development of the cracks on the dip side was due to the existing joints and resulting excavations. The pillars and ribs were further loaded due to excavation and presence of joints against the bedding plane. This initiated the propagation of cracks above the excavated area. Similar observations were made through computational approach by Singh (1990).

The crack propagated along the angle of fracture. Angle of fracture was measured to be 60° from the horizontal for the dip side and 90° for the rise side. This angle of fracture is the outcome of the 'Edge-effect' of the excavations (Bieniawski, 1986). The cracks in the dip side propagated along the joints. This created an open space because of which the strata moved along the joints. The immediate roof collapsed on complete withdrawal of the rib. The separation of the strata reduced
gradually form the excavated seam to the top strata.

On complete excavation, maximum subsidence of 65 percent was recorded. This result is comparable with the actual percentage of maximum subsidence recorded for India coal seams (Saxena and Singh, 1986). The following figures take a comparative look into the pillar sizes predicted by the selected formulae, at various depths and for varying gallery widths.

For all the formulae, variation of pillar sizes with depth is shown in Fig.9. The pillar sizes increase with the increase in depth. Up to 30m depth Holland and Gadday and Salamon and Munro (1967) give the same value. CMS gives higher value for this range. But the widest pillar size is recommended by CMS. After this range Holland and Gadday predicts smaller sizes than Salamon and Munro. The gap between values predicted by Holland and Gadday and Salamon and Munro is less at lower depth which increases at greater depths. At 150m depth CMS gives start recommending smaller pillar sizes than that predicted by Salamon and Munro. But it is still more conservative than Holland and Gadday. At 190m, it predicts lesser values than Holland and Gadday.

Two differences between CMS stipulations:

1. Many times objections are raised on the observation of the standing of the pillars to a size of 4cm (4m in the prototype) in the EBM. Previous studies made by Singh (1986), Singh (1990) have reported similar observation even in this study, the roofs did not collapse when rib was of 40cm. The pillars have an open face on all four sides and are thus uniaxially loaded. But, the core of the pillar is triaxially loaded because of lateral confinement. These induced confining stresses acting on the pillars cause an increase in strength of the pillar. In field, at lancoonpur colliery (India) at comparable depth, the stock designed for 8.1 MPa could sustain upto 16 MPa. This indicated inherent characteristics of the confined coal strucks to quench excess load during failure (Singh and

Fig. 9. Trends of pillar width variation with gallery width (D = 46 m)
Sinha, 1969). The stresses sustained by the stock is yet another study at Govinda colliery (India), was coincidentally equal to the laboratory strength of 41mm core samples and nearly double the in-situ strength of 30 cm cube. This could be justified by the fact that core of the pillar acted under triaxially confined state. Even though the stock side was crushed and had less rebound strength, it increased the strength of the core to nearly double the in-situ strength (CMS Report, 1969). Hence, the observation of this study is justified.

CONCLUSIONS

This study enables to reach the following conclusions:

1. The pillar size predicted by three different rock mechanics formulae are safe and stable but are oversized.
2. The pillar size was stable even the width of the pillar was 4m (30m prototype in BM model) but they can stand only few days not for a longer period.
3. There is still further scope for optimization of the pillar size for planned partial extraction.
4. CR should adopt a more rational approach in pillar design.
5. Holland and Caddy gives the most economic, safe and stable pillar size at the studied depth. However, for greater depths CMS RECOMMENDS smaller sizes of the pillars.

REFERENCES

Arnold, 1969. Optimization of design of mine pillar parameters and feasibility of extraction of locked up coal below built-up structures, water logged areas and hard cover, CMS Report: 16-96.


Biamikazi, 27th, 1968. Towards a creative design program in mining, Mining Engineer, 1040:194.


APPENDIX - 1
Comparison of predicted pillar sizes at gallery width, 3 m.

<table>
<thead>
<tr>
<th>Depth of the seam from the surface (m)</th>
<th>Distance between centres of adjacent pillars should not be less than</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CHM</td>
</tr>
<tr>
<td>Less than 60</td>
<td>12.0</td>
</tr>
<tr>
<td>90</td>
<td>13.5</td>
</tr>
<tr>
<td>150</td>
<td>16.5</td>
</tr>
<tr>
<td>240</td>
<td>22.5</td>
</tr>
<tr>
<td>360</td>
<td>28.5</td>
</tr>
<tr>
<td>450</td>
<td>39.0</td>
</tr>
<tr>
<td>115.5 (case study)</td>
<td>16.5</td>
</tr>
</tbody>
</table>

APPENDIX - 2
PILLAR Width suggested by CHM

<table>
<thead>
<tr>
<th>Depth of the seam from the surface (m)</th>
<th>CHM Width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M100 (m)</td>
</tr>
<tr>
<td>not exceeding 60</td>
<td>12.0</td>
</tr>
<tr>
<td>exceeding 60 but not 90</td>
<td>13.5</td>
</tr>
<tr>
<td>exceeding 90 but not 150</td>
<td>16.5</td>
</tr>
<tr>
<td>exceeding 150 but not 240</td>
<td>22.5</td>
</tr>
<tr>
<td>exceeding 240 but not 360</td>
<td>38.5</td>
</tr>
<tr>
<td>exceeding 360</td>
<td>39.0</td>
</tr>
</tbody>
</table>

CHM = Maximum Gallery Width permitted.