DESIGN OF RIB PILLARS IN LONGWALL MINING BASED ON THEORETICAL AND PRACTICAL APPROACHES

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ABSTRACT

The paper outlines the purpose of continuous pillars in longwall mining and presents a methodology of pillar design based on analytical and practical approaches. A brief review of various pillar design methods is presented together with the design validation technique utilising "Boundary Element Strain-Stress Analyses and Stability Database" This design technique is illustrated with a case example.

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1. INTRODUCTION

Design of rib pillars is one of the most important parameters of longwall layout planning which has a great influence on the stability of gate roadways. Until recently, the width of rib pillars between two longwall faces was determined empirically, based on past experience and by analytical methods. In order to maintain the stability of access roadways in longwall advance mining, a coal pillar of adequate dimension should be left between two longwall faces. But for the sake of economy, the aim of pillar design should be to maximise percentage extraction. It is, therefore, necessary to optimise the rib pillar width in order to maximise coal recovery, consistent with obtaining stable gate roadway conditions. The paper briefly outlines the purpose of leaving rib pillars in longwall mining and describes a method of pillar design.

The effects of the rib pillar width on gate roadway stability for different methods of gate roadway formation are presented. A computer simulation study to validate rib pillar design has been carried out by using the Boundary Element Method incorporating both stress as well as stress-strain analyses. The predicted gate roadway closures from the numerical analyses can then be compared with that obtained from the roadway deformation database.

2. PURPOSE OF PILLARS IN LONGWALL MINING

The purpose of pillars in longwall mining are as follows:

- **Strata Control:**
  In longwall mining transverse and rib pillars are left to protect main and gate roadways against closure due to abutment strata pressures and due to caving and subsidence of overlying strata above the current extractions.

- **Regional Support:**
  Careful design of longwall extraction spans and size of rib pillars can be used to control surface subsidence. Thus, coal reserves below important surface features can be safely extracted by causing minimum damage to the surface structure.

- **Barrier Pillar:**
  Barrier pillars are left in between two mines or two mining districts to contain their local problems such as fire and other environmental problems within the panel. Barrier pillars between two mines are also left to protect the mine at the lower side against water danger.
• Safeguard of Mine Workings Below Water Hazards:
Mine workings below major surface water hazards of major aquifers are controlled by designing partial extraction mining systems. The design of such workings are based on the following principles:

i. Designing the maximum span of caved workings based on strata properties,
ii. Adequate size of pillar to control surface strains, thus, limiting the water danger.

• Protection Against Geological Hazards:
Geological disturbances, such as faults, highly stressed areas because of strata movement and weak zones may change the stability condition adversely. Such conditions can best be overcome by leaving an adequately sized rib pillar to shield the gate roadway against high induced stresses.

• Pillars in Multiple Seam Situations:
Increases in vertical stresses due to existence of rib pillars may create some unfavourable working conditions above and especially below rib pillar levels. Hence, planing of the layout of longwall panels for multi-seam mining should be carried out as a whole to avoid possible interaction problems.

3. LONGWALL PILLAR DESIGN METHODOLOGY

Determination of optimum width of rib pillars is of importance from stability, conservation of reserves and safety viewpoints. A rational design is, therefore, an iterative process, as shown in Figure 1. A planning engineer in consultation with the production team prepares a mining layout and generates various alternative schemes. The most acceptable layout is examined in view of the existing development programme and the production strategy. The preliminary design of a pillar is carried out based on its designed function. Either an empirical design method or an analytical technique is used to produce a preliminary pillar design. Boundary Element Analysis is carried out to compute pillar stresses. For the purpose of stability evaluation of the design layout, a number of input strength parameters such as E, v, c, O and UCS are used and stress-strain analyses using boundary element method is carried out. Both the displacement of the pillars and that of the country rock are calculated and the closure of gate roadways assessed. The final pillar design is checked for the stability of gate roadways using a gate roadway deformation survey database.
Figure 1 — Pillar design in longwall mining
4. REVIEW OF THE RIB PILLAR DESIGN METHODS

The literature on underground mining stability can be divided into three categories describing theoretical, practical and experimental approaches. Until recently, none of these three methods had been proved adequate on their own for the designing of underground roadways and pillars. Inadequacy of the theoretical approaches for the rib pillar design has prompted mining engineers to base their designing on the past experience and empirical methods.

It is important to consider pillars ultimate strength since they are used for ground support, based on their resistance to large scale failure as a consequence of stress concentrations.

4.1. Empirical Method

The traditional rule of thumb approach for determining rib pillar width is given by the following equation;

\[ P = 0.1 \, h + 15 \]  
Where, 
\[ P = \text{Pillar width, (m)} \]
\[ h = \text{Depth below surface, (m)} \]

This approach can be considered to give good results when the design parameters and conditions of the longwall face are close to mean values. For instance, it gives fairly good results when the face length is between 100 - 200 metres. Since the rule of thumb approach depends only on past experiences, the use of this method to extrapolate results for greater depth is considered to be inappropriate.

4.2. Subsidence Engineering Method

Designing of barrier pillars or panel pillars are based on the premise that these pillars are virtually indestructable and sustain overburden stresses as shown in Figure 2. (3) has used Bieniawski’s (1) pillar strength formula for strength prediction of coal pillars based on large scale in-situ tests on square pillars. The strength of the pillar can be extrapolated by using the following equation;

\[ \text{Pillar Strength} = 27.6 + 1379 \, (w/h) \]  
Where, 
\[ w \rightarrow \text{Width of the pillar, (m)} \]
\[ h \rightarrow \text{Height of the pillar, (m)} \]
and pillar strength is given in MPa
Figure 2 - Rib pillar loading considerations
(after King and Whittaker, 1971)

King's approach is based on the assumption that, pillars have to sustain an average load, above its own depth pressure equal to the load bridging across the pillars. The waste carries only the weight of strata which is enclosed by the inward angles of draw, average value taken as 31°. The increased pillar load is given by the following equation;

Increased Pillar Load = (7.348x10^-6) \( (\text{ld} - \left(21 \cot \phi / 4\right)) \) \( \text{Pa} \) \( 1 \) \( \text{(3)} \)

Where,
- \( l \) = Face length (m),
- \( d \) = Depth below surface (m),
- \( \phi \) = the limiting angle as shown in Figure 2.

and increase in pillar load is given in MPa.

This method mainly depends on the comparison between the strength and increased load over a rib pillar. Applicability of this approach is restricted because of the assumptions that the increased pressure is uniformly distributed across the pillar, whereas, the most important feature of a rib pillar design is the actual stress distribution on the pillar.

A similar approach by Whittaker and Singh (5) used Salamon’s (3) pillar strength formula to design longwall pillars.
For w/h ratio $< 2\tan \Phi$ (narrow extraction), the pillar size is given by the following equation:

$$h (p + w) - \left( \frac{w \cdot \cot \Phi}{4} \right) - \left( \frac{7.32 \times 10^8 p^\phi}{h F m^\omega} \right) = 0 \quad (4)$$

And for $w/h > 2\tan \Phi$,

$$h^2 \tan \Phi + ph - \left( \frac{7.32 \times 10^8 p^\phi}{h F m^\omega} \right) = 0 \quad (5)$$

Where,

- $h$ = Depth below surface, (m)
- $\mu$ = Average density of overburden, (kg/m$^3$)
- $p$ = Width of rib pillar, (m)
- $w$ = Width of longwall face, (m)
- $\Phi$ = Average angle of shear of strata having over goaf, ($^\circ$)
- $m$ = Factor of safety, (1.3 — 19)

Equations 4 and 5 can be solved iteratively to find the rib pillar width.

This method of design slightly overdesigns the width of rib pillars and can only be justified for designing protective pillars for a group of longwall faces.

4.3. Wilson’s Continuous Pillar Design Approach

Wilson’s (7) method of pillar design is applicable to soft rock at great depth and is based on the following main assumptions;

i. According to stress balance theory, de-stressing caused by mining in the caved zone must be redistributed on the pillars. This results in stress concentration on the strata abutment zones on the pillars.

ii. The maximum concentration of stress on the abutment zone is given by the following equation;

$$\sigma_i = \sigma_o + \text{kg}$$

Where,

- $\sigma_i$ = Peak abutment pressure, (MPa)
- $\sigma_o$ = Uniaxial compressive strength in situ, (MPa)
- $q$ = Cover load, (MPa)

iii. When the abutment stress exceeds an excavation breaks and the strata abutment pressure is transferred inbye on the solid pillar, thus, forming a yield zone surrounding the excavation. Friction of the broken rock within the yield zone partially supports the excavation.

Figure 3 shows the concentration of stress on the pillar as a consequence of de-stressing within the goaf. It can be shown that the stress deficiency in the goaf can be equated to the stress concentration on the pillar. Thus,

$$A_i = \frac{1}{1} = A_i \quad \text{or} \quad A_i \cdot f \cdot x_i = A_i \cdot t \cdot A_i$$
The minimum width of the rib pillar can be calculated by the following relationship as shown in figure 3:

\[
\text{Rib Pillar Width} \geq 2(C + x_b) \quad (5)
\]

Where,

\[
C = \frac{(A_w + q_xb - A_b)}{(\sigma - q)} \quad (6)
\]

The values of \(x, q\) and \(A_b\) can be calculated as follows;

a) Rib-side with yield roof, seam and floor:
- Vertical Stress \(\sigma = k(p+p') \cdot (2x/M+1) \quad (7)\)
- Peak Abutment Stress \(\sigma = kq + \sigma_0 \quad (8)\)
- Width of Yield Zone \(x_0 = M/2 \cdot \{q/(p+p') \cdot \exp(zF/M) \} \quad (9)\)
- Load Taken By Xb \(A_b = \frac{M}{2} (p+p') \cdot \{q/(p+p') \cdot \exp(zF/M) \} \quad (10)\)

b) Rib-side with yield in seam only (rigid roof and floor):
- Vertical Stress \(\sigma = k(p+p') \cdot \exp(zF/M) \quad (11)\)
- Peak Abutment Stress \(\sigma = kq + \sigma_0 \quad (12)\)
- Width of Yield Zone \(x_0 = M/F \log_{10} \{q/(p+p') \} \quad (13)\)
- Load Taken By Xb \(A_b = M/F \cdot \{q - (p+p') \} \quad (14)\)

Where,

\[
F = \frac{(k-1)}{\sqrt{k}} + \frac{(k-1)^2/\sqrt{k}}{\tan^{-1} \sqrt{k}} \quad (15) \quad (\text{in radians})
\]

- \(k\) = Triaxial stress factor,
- \(M\) = Height of opening, (m)
- \(p\) = Support resistance, (MPa)
- \(p'\) = Apparent cohesion factor = approximately 0.1 MPa
- \(q'\) = Cover load, (MPa)
- \(x\) = Distance into rib-side, (m)
- \(z\) = Distance into rib-side (yield in seam only), (m)
- \(\sigma_0\) = Unconfined compressive strength in-situ, (MPa)
In the case of retreat mining the roadways are predriven, therefore, the condition of the roadway must be suitable for the next face to operate. To achieve this the finger pillar width should not be less than \(2(C + Xb)\). As different than other approaches Wilson (7) suggests that the calculated pillar width should be referred as "roadway stability limit" rather than a "pillar stability limit".

5. BOUNDARY ELEMENT ANALYSIS FOR VALIDATING RIB PILLAR DESIGN

The Boundary Element Method (BEM) has been applied to a wide variety of problems in stress analysis including plasticity, fracture mechanics and viscoelasticity. Stress analysis problems in geomechanics are suited to boundary elements as this usually requires a very small number of nodes in comparison to finite elements. As only the surface of continuum needs to be discretized, problems extending to infinity can be described by a very small number of elements on the rock mass surface or around the excavation. In addition, the boundary conditions of the infinite domain are properly defined by using boundary elements, as the technique is based on fundamental solution valid for unbounded domains.

For the purpose of this analysis, a Boundary Element Package Program developed by "PAFEC" was used. This program enables the successful modelling of caved mine workings by taking mine boundaries at appropriate locations.

Vertical stresses, and consequent vertical and horizontal displacement values can be calculated by changing design and geological parameters of mining excavations. The distribution of stresses on coal pillars and goaf were computed for the depths of 300, 500 and 700 metres. The change of pillar stress distribution with rib pillar width was calculated for the depth of 500 metres and the rib pillar widths of 50, 75, 100 metres. Some of these results are discussed in a subsequent section.

6. RIB PILLAR DESIGN AND ASSESSMENT OF GATE ROADWAY STABILITY BASED ON PAST EXPERIENCE

For the past 15 years, a research group at the Department of Mining, Nottingham University, has been engaged in the study of long-wall gate roadway stability using observation method. Gate roadway deformation surveys have been carried out at 230 gate roadways in 41 different collieries of Midland Coalfields over this period, and a database in a computer file has been formulated. A detailed statistical analysis of this database has been carried out to evaluate important variables affecting the gate roadway closure (4). Rib pillar width has
been found to be one of the most important design parameters which has great influence on the stability and economics of the gate roadway.

Figure 4 shows the relationship between horizontal closure and rib pillar width expressed in terms of depth below surface for the gate roadways formed by advance heading. Figure 5 and 6 show the relationships between horizontal closure and rib pillar width for the gate roadways formed by conventional ripping and half heading formation methods. Similarly, Figures 7 to 9 show the influence of rib pillar width on gate roadway vertical closure for various methods of gate roadway formation methods. The relationships can be used to predict the gate roadway closure for given designed width of pillar under variety of geological and mining conditions.

**Figure 4** - Relationship between horizontal closure and rib pillar width expressed in terms of depth below surface of the gate roadways formed by advance heading.

**Figure 5** - Relationship between horizontal closure and rib pillar width for the gate roadways formed conventional ripping.
HALF - HERDING GATE ROADWAY FORMATION METHOD

Figure 6 - Relationship between Horizontal closure and rib pillar width for the gate roadways formed by hall heading method

ADVANCE HEADING GATE ROADWAY FORMATION METHOD

Figure 7 - Relationship between vertical closure and rib pillar width for the gate roadways formed by advance heading

CONVENTIONAL RIPPING GATE ROADWAY FORMATION METHOD

Figure 8 - Relationship between vertical closure and rib pillar width for the gate roadway formed by conventional ripping
7. CASE EXAMPLE OF RIB PILLAR DESIGN AND GATE ROADWAY STABILITY ASSESSMENT

For the design parameters, geological conditions and strata properties given in table 1, rib pillars were designed using various empirical and theoretical approaches and the results were validated by using the boundary element method.

Table 1. Design Parameters for the Case Example.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth below surface</td>
<td>500 m</td>
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<tr>
<td>Face Length</td>
<td>200 m</td>
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<tr>
<td>Seam Height</td>
<td>2.0 m</td>
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<tr>
<td>Horizontal Stress</td>
<td>0.5 x Vertical Stress</td>
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<td>Triaxial stress factor</td>
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<td>Roof Strata</td>
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<td>Young's Modulus</td>
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<td>Poisson's Ratio</td>
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<td>Q System Classification</td>
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<tr>
<td>Coal</td>
<td></td>
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<tr>
<td>Uniaxial Comp. Strength</td>
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<td>Young's Modulus</td>
<td>25 GPa</td>
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<td>Poisson's Ratio</td>
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<tr>
<td>Q System Classification</td>
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<tr>
<td>Floor Strata</td>
<td>Seatearth</td>
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<tr>
<td>Uniaxial Comp. Strength</td>
<td>25 MPa</td>
</tr>
<tr>
<td>Young's Modulus</td>
<td>15 GPa</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>&gt; 0.30</td>
</tr>
<tr>
<td>Q System Classification</td>
<td>Very weak rock</td>
</tr>
</tbody>
</table>

Figure 9 - Relationship between vertical closure and rib pillar width for the gate roadways formed by half heading method
Above strata conditions are the average conditions for Midland Coalfields as stated by Whittaker and Singh (6)

7.1 Rule of Thumb Approach

Rib pillar width = 0.1 h + 15
= 65 m

1 King’s Approach

Rib pillar width = 61.67 m
Peak pillar stress = 49 MPa

1 Whittaker and Singh Approach

Rib pillar width = 105 m (with a safety factor of 1.5)

3 Wilson’s Approach

Rib pillar width = 56 m
Peak Pillar Stress = 55 MPa
C = 24 m
x₀ = 4 m
A₀ = 1020 MPa m
A₁ = 91 MPa m
q = 12.25 MPa
o = 5 MPa (in s tu)

7.4 Boundary Element Analysis

The boundary element analysis was carried out to compute vertical stresses on the pillar situated between two gate roadways and caved zone on the other side. The width of the pillar was taken as 60 m as estimated by the preliminary design. The width of the gate roadways taken as 5 m. Figure 10(a) shows the stress distribution contours on the pillar roof and floor strata. Figure 10(b) shows the stress distribution alone; \( \backslash \backslash \) These results indicate the quantitative and qualitative stress distributions in the pillars, the peak stress being 28 MPa. Based on this stress distribution, the pillar displacement was calculated using the boundary element program. Figure 11(a) shows the vertical displacement contours on the rib pillar and adjoining roof and floor strata. Figure 11(b) shows vertical displacement across the pillar gate roadways and goaf. Figure 11(c) shows the relative vertical closure in roof, floor, and coal at the edge of the gate roadways. It indicates that the vertical displacements in coal and floor are much higher than that in roof strata as would be expected from the strength values. From these results, the expected gate roadway closure will be in order of 1.6 m. Figure 12(a) and (b) show the...
horizontal displacement contours across the pillar, and roof and floor strata. The results show that the maximum horizontal movement is at the \( \text{frp} \) at the pillar, roof, and floor strata.

Figure 10 - Mrees distribution on the pillar, roof and floor strata

Figure 11 - Vertical displacement on the pillar, roof and floor strata

Figure 12 - Horizontal displacement on the pillar, roof and floor strata

8. PREDICTION OF GATE ROADWAY CLOSURES

Gate roadway closures were predicted by using longwall deformation database. The details of this method are given in a previous paper (4). The vertical closure for a gate roadway formed by conventional ripping method is given by the following regression equation (4);
\[ V = 0.711 E + 0.0008 D < 0.0145 \ln R - 0.0418 RI + 0.516 FI - 0.836 \]  \hspace{1cm} (15)

Similarly the closure equation for a gate roadway formed by the half heading system is given by the following regression equation (4):

\[ V - 0.354 E ^ {0.0022} D - 0.0017 R + 0.24 RI + 0.355 FI + 4.35 \]  \hspace{1cm} (16)

Where,
- \( V \) = Vertical closure, (m)
- \( E \) = Extracted seam height, (m)
- \( D \) = Depth below surface, (m)
- \( R \) = Rib pillar width, (m)
- \( RI \) = Roof strength index (4-8, Strong-Weak)
- \( FI \) = Floor strength index (4-8, Strong-Weak)

The calculations show that the predicted closure for the conventional ripping method was 1.59 m and that for roadway formed by the half heading system was 1.64 m.

9. DISCUSSION AND CONCLUSIONS

The results indicate that the rib pillar width computed by empirical approaches, subsidence theory method and by Wilson's method give comparable results. However, for deep situations, the subsidence theory approach and empirical method slightly overdesign the pillar width. The subsidence theory method should be used to design longwall barrier pillars. Boundary element method was found to be an adequate tool to compare pillar displacements as well as gate roadway closures. The results are comparable with those obtained by the predictive equations derived from the roadway stability database. Thus, the method of design of longwall pillars used in this study inspires confidence.

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