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 desing based on analytical and practical approaches. A brief review of various pillar desing methods is presented together with the desing validation technique utilising "Boundary Element Strain-Stress Analyses and Stability Database" This desing technique is *illustrated with a case example*

ÖZET

Bu bildiride uzunayak panoları arasında, tali yolları korumak amacı ile bırakılan topuk genişliği tasarımı teorik, pratik ve nümerik yaklaşımlarla incelenmiştir. Bu amaç doğrultusunda topuk tasarımını konu alan öteki genel yaklaşımlar, karşılaştırılarak, daha gerçekçi bir yaklaşımda bulunulmuştur. Değişik yöntemler sonucunda bulunan topuk genişlikleri pratik ve nümerik sonuçlarla karşılaştırılmıştır. Bu topuk genişliği ve konumu tasarım yönteminin elde edilebilecek en iyi sonucu verdiği düşünülmektedir

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t. INTRODUCTION

Desmg 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 desing 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 desing.

The effects of the rib pillar width on gate roadway stability for different methods of gate roadway formation are presented (4). A computer simulation study to validate rib pillar desing has been carried out by using the Boundary Element Method incorporating both stress as well as stress-scrain analyses. The predicted gate roadway closures from the numerical analyses can then be compared with that obtained from the roadway deformation database (4).

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 desing 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 desing 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 con 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 existance 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 DESING METHODOLOGY

Determination of optimum width of rib pillars is of importance from stability, conservation of reserves and safety viewpoints. A rational desing 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 desing method or an analytical technique is used to produce a preliminary pillar desing. Boundary Element Analysis is carried out to compute pillar stresses. For the purpose of stability evaluation of the design layout, a number of input strenght 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.

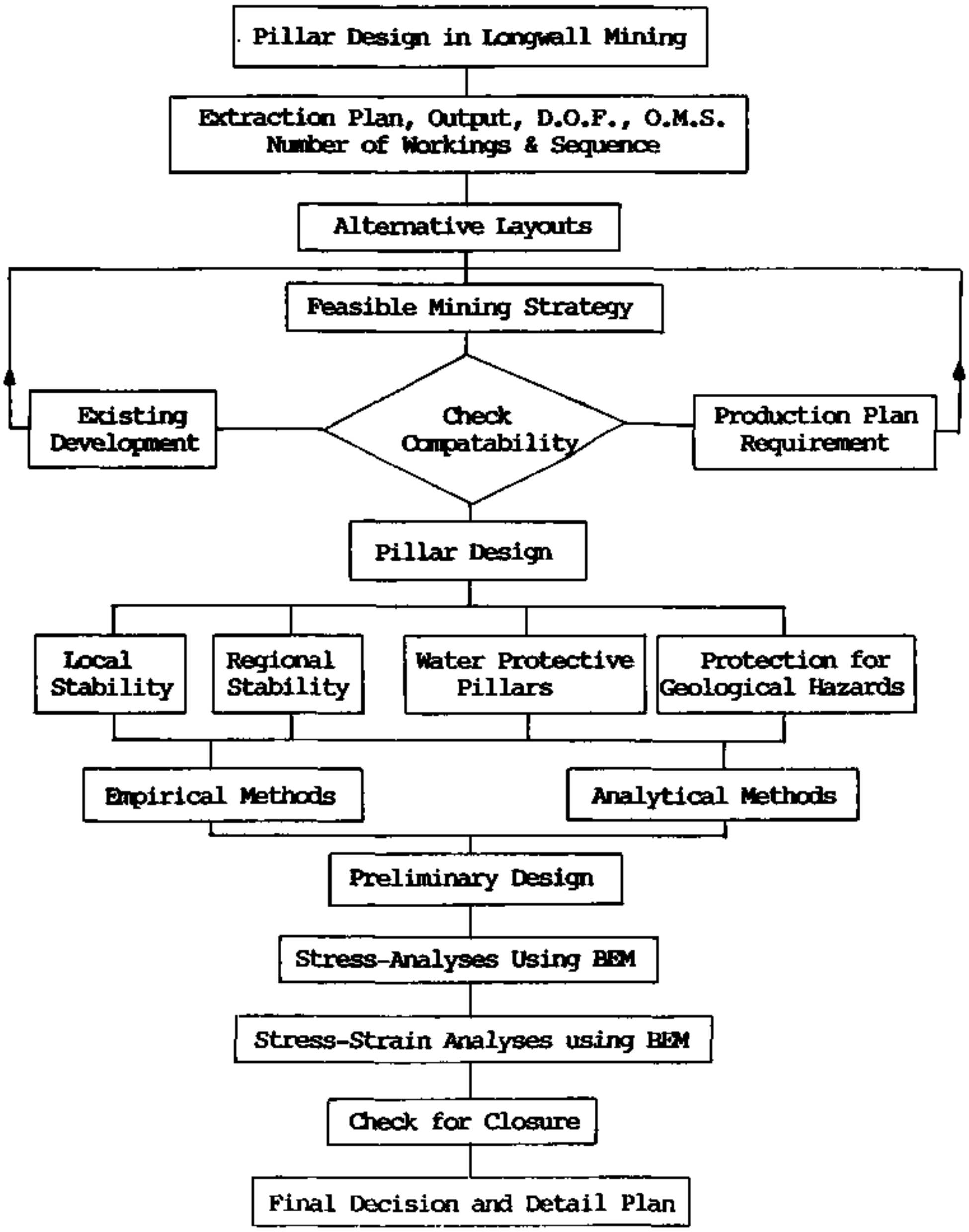

Figure 1 — Pillar desing in longwall mining

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 desing of underground roadways and pillars. Inadequacy of the theoretical approaches for the rib pillar design has prompted mining engineers to base their desing 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;

$$P = 0.1\ h + 15 \qquad (1)$$

Where,
P = Pillar width, (m)
h = 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 ICO - 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. (2) 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;

$$\text{Pillar Strength} = 2\ 76 + 1379\ (w/h) \qquad (2)$$

Where,

w — Width of the pillar, (m)
h = Height of the pillar, (m)
and pillar strength is given in MPa

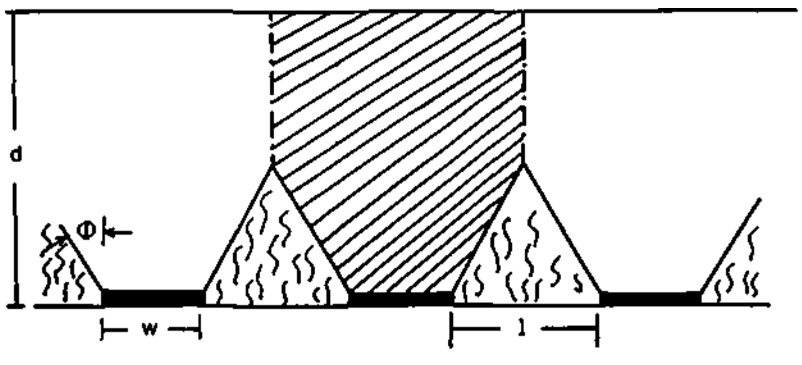

Figure 2 - Rib pillar loading considerations
(after King and Whittaker, 1971) (2).

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 — $(7.34 \times 10^{-4})\ (ld - (2\ l\ \mathrm{Cot}\ \phi/4))$ (3)

Where,

1 = Face length (m),

d = Depth below surface (m),

Ø = 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 strenght and increased load over o 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 lonwgall pillars.

For w/h ratio $< 2\tan\Phi$ (narrow exraction), the pillar size is given by the following equation;

$$h(p + w) - (w^2\cot\Phi/4) - (7.32\times10^5\ p^{1.46}/\gamma F m^{0.66}) = 0 \quad (4)$$

And for w/h $\geq 2\tan\Phi$;

$$h^2 \tan\Phi + ph - (7.32\times10^5\ p^{1.46}/\gamma F m^{0.66}) = 0 \quad (5)$$

Where,

h = Depth below surface, (m)

o = Average density of overburden, (kg/m^3)

p = Width of rib pillar, (m)

w = Width of longwall face, (m)

Φ = Average angle of shear of strata hading over goaf, (°)

= Mactor of safety, (1.3 — 19)

m = Pillar height, (m)

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 Desing Approach

Wilson's (7) method of pillar desing 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;

$\sigma_1 = \sigma_0 + kq$

Where,

σ_1 = Pe*k abutment pressure, (MPa)

σ_0 = 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 os 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 (1) = A, + (2)

or A„ f xi, q = A, t Ai.

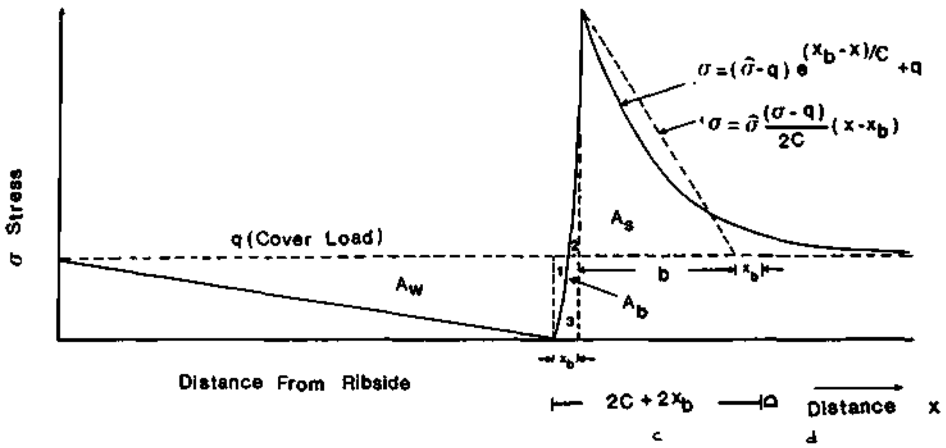

Figure 3 - Concentration of stress on the pillar as a conseuuence of de-stressing within the goaf,
(after Wilson, 1983) (7)

The minimum width of the rib pillar can be calculated by the following relationship as shown in figure 3;

Rib Pillar Width $\geqslant 2(C + x_b)$ (5)

Where,

$C = (A_u + q.x_b - A_b) / (\sigma - q)$ (6)

The values of xb, q and Ab can be calculated as follows;

a) Rib-side with yield roof, seam and floor;

Vertical S t $\sigma = k(p+p')\ (2x/M+1)^{(k-1)}$ 7)

Peak Abutment S $\sigma = kq + \sigma_0$ 8)

Width o f Yield Z $x_b = M/2.\ [\{q/(p+p')\}^{(/(k-1)} - 1]$)

Load Taken By Xb $A_b = M/2\ (p+p').\ [\{q/(p+p')\}^{(k/(k-1)} - 1]$ (10

b) Rib-side with yield in seam only (rigid roof and floor);

Vertical S t $\sigma = k(p+p').\ \exp(zF/M)$ 1)

Peak Abutment S $\sigma = kq + \sigma_0$ 1 2)

Width of Yield Zone $z_b = M/F \log_n [q/(p+p')]$ (13)

Load Taken By x_b $A_b = M/F.k.\ [q - (p+p')]$ (14)

Where,

F = $(k-1)/\sqrt{k} + (k-1)^2/k.\tan^{-1}\sqrt{k}$ ($\tan^{-1}$ in radians)

k = Triaxial stress factor,

M = Height of opening, (m)

p = Support resistance, (MPa)

p = Apperent 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)

oo = Unconfined compressive strenght 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 o 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, o 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 desing 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 dicsussed in a susequent section.

6. RIB PILLAR DESING 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 longwall gate roadway stability using observation method. Gate roadway deformation surveys have been caried 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 desing 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.

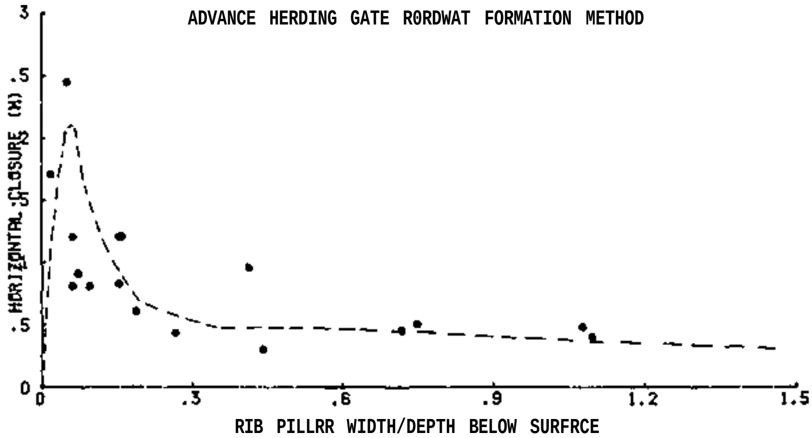

Figure 4 - Relationship between horizontal closure and rib pillar width expressed in terms of depth below surface of the gate roadways formed by advance heading

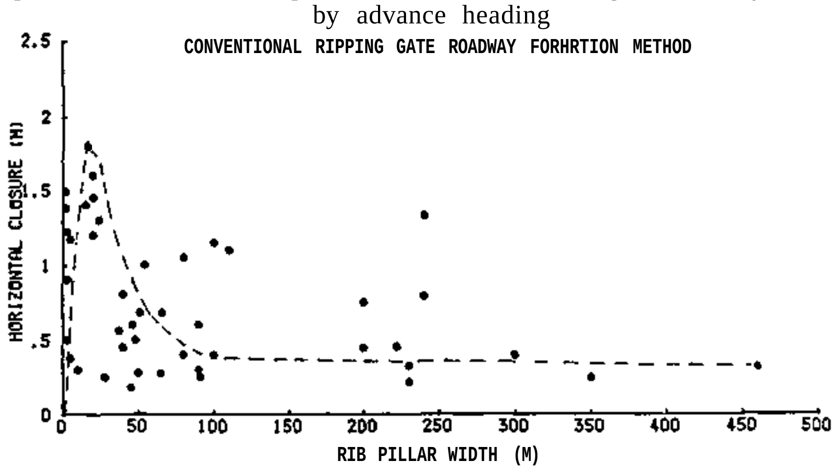

Figure 5 - Relationship between horizontal closure and rib pillar width for the gate roadways formed conventional ripping

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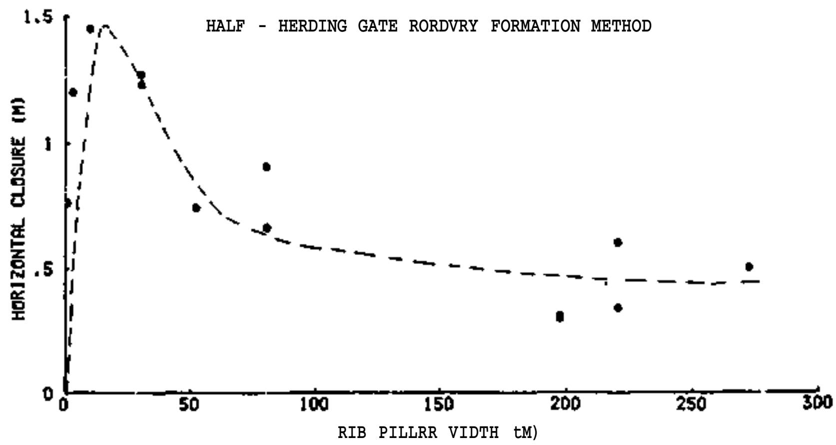

Figure fi - Relationship between Horizontal closure and rib pillar width for the gate roadways formed by hall heading method

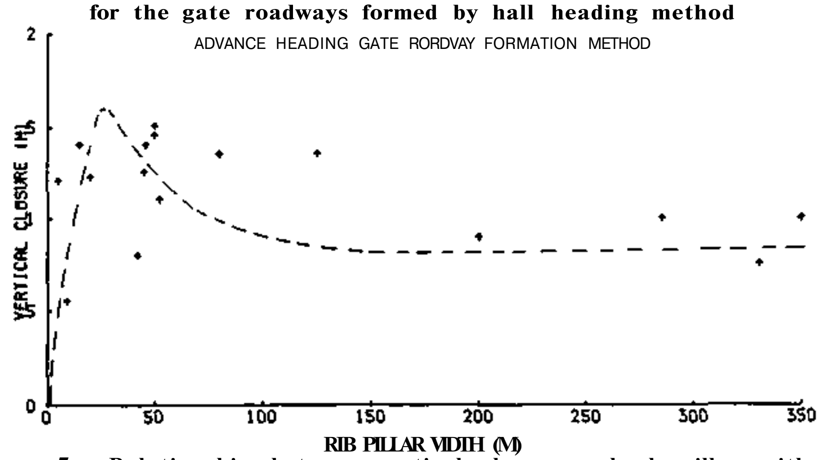

Figure 7 - Relationship between vertical closure and ub pillar with for the gate roadwajs formed bj advame heading

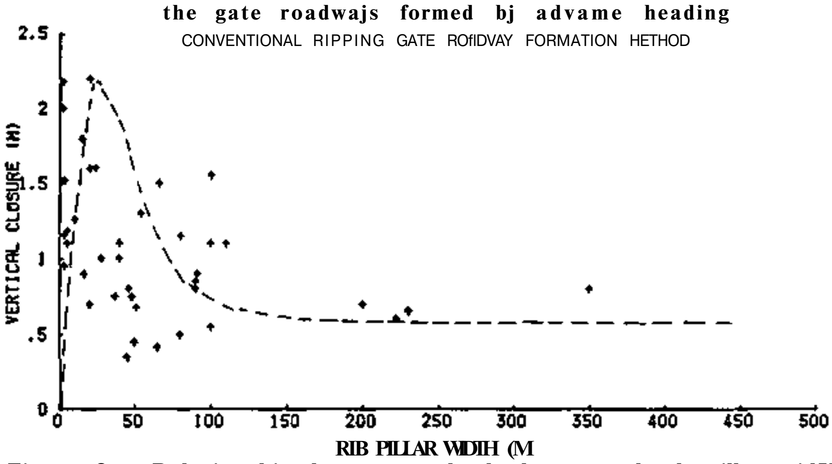

Figure 8 - Relationship between wrlual closure and rıh pill.tr «idIlı loi the gate roadway formed by conventional ripping

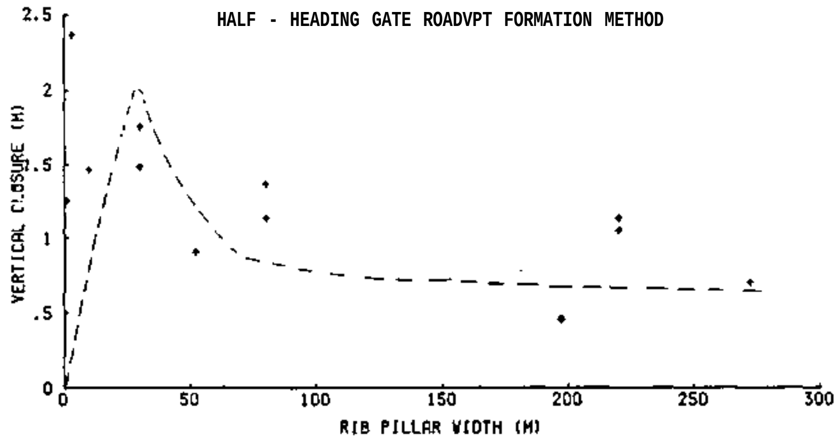

Figure 9 - Relationship between vertical closure and rio pillar width for the gate roadways formed by half heading method

7. CASE EXAMPLE OF RIB PILLAR DESING AND GATE ROADWAY STABILITY ASSESSMENT

For the desing 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. Desing Parameters for the Case Example.

Depth below surface	=	500 m.
Face Length	=	200 m.
Seam Height	=	2.0 m.
Horizantal Stress	=	0.5 x Vertical Stress
Triaxial stress factor	=	4
Roof Etrata	=	Siltstone,
Uniaxial Comp. Stregth	=	50 MPa.
Young's Modulus	=	40 GPa.
Poisson's Ratio	=	0.25
Q System Classification	=	Fair rock.
Coal		
Uniaxial Comp. Strength	=	28 MPa
Young's Modulus	=	25 GPa
Poisson's Ratio	=	0 30
Q System Classification	=	Weak rock
Floor Strata	=	Seatearth,
Uniaxial Comp Strength	=	25 MPa.
Young's Modulus	=	15 GPa
Poisson's Ratio	=	> 0 30
Q System Classification	=	Very weak rock

Above strata conditions are the average conditions for Midland Coalfields as stated by Whittaker and Smgh (6)

7 1 Rule of Thumb Approach

Rib pillar width = 01 h + 15
= 65 m

1 King s Approach —
Rib pillar width = 61 67 m
Peak pillar stress = 49 MPa

11 Whittaker and Singh Appoach
Rib pillar width = 105 m (with a safety factor of 1 "s)

1 3 Wilson'« Approach

Rib pillar width = 56 m
Peak Pillar Stress = 55 MPa
C = 24 m
Xb = 4 m
A„ = 1020 MPa m
Ai = 91 MPa m
q = 1 2 25 MPd
o — 5 MPa (in s tu)

7 4 Boundan Flemenl Analv sis

The boundary element analysis was carried out to compute vei tıcal stı esses on the pillar situated between two gate roadwavs and caved zone on the othei side The width of the pillar was take 1 as 60 m as estimated by the preliminary desmg The width of the gate roal ways taken as 5 m Fıguıe 10 (a) shows the stress distribution con touis on the pillai roof and floor strata Figure 10(b) shows th'^ sttoss distribution alone; \ \ These results indicate the quantitatne and qualitative stress distnbutions in the pillars the peak stiess being 28 MPa Based on this stress distribution the pillar displacement were calculated using the boundary element progtam Fıguıe ilta' shows the vertical displacement contours on the rib pillai and ad joining roof and flooi strata Figure 11(b) shows vertical displacement acıoss the pillai gateroadwavs and goof Figure 11(c) shows the rela tıve veıtıcal closure in roof floor and coal at the edge of <he gate road w a v It indicates that the vertical displacements in coal and flooi are much hıgheı than that in roof strata as would be expected from the strength values F*-om these results the expected gate roadway closuie will be in order of 1 6 m Figure 12(a) and (b) show the hon

zontal displacement contours across the pillar, and roof and floor strata. The results show that the maximum horizontal movement is at the f>H frp nf t.hp ni 11 n r ı c a hnı 11 (1 (İS m

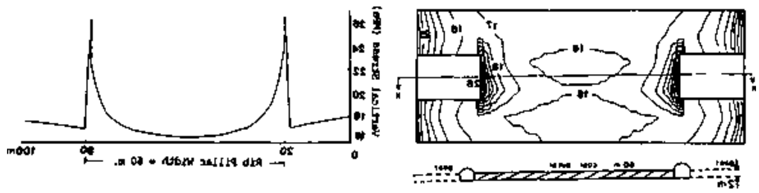

Figure 10 - Mrees distribution on the pillar, roofand floor strata

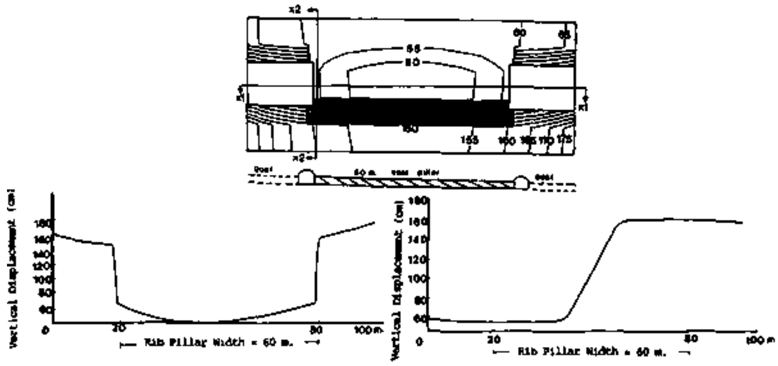

Figure 11 - Vertical displacement on the pillar, roof and floor strata

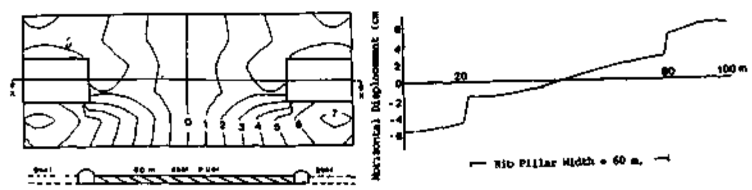

Figure 12 - Horizontal displacement on the pillar, roof and floor strata

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);

$$V = 0.711\ E + 0.0008\ D < 0.0145\ \ln R - 0.0418\ RI + 0.516\ FI - 0.836 \quad (15)$$

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

$$V - 0.354\ E \wedge 0.0022\ D - 0.0017\ R + 0\ 24\ RI\ 0.355\ FI + 4\ 35 \quad (16)$$

Where,

V = Vertical closure, (m)

E = Extracted seam heigth, (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 situtations, the subsidence theory approach and empirical method slightly overdesign the pillar width. The subsidence theory method should be used to desmg longwall barrier pillars. Boundary element method was found to be adequate tool to compare pillar displacements as well as gate roadway closures. The results are compatable 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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REFERENCES

1 BIENIAWSKI, Z T, "Note on In-situ Testing of the Strength of Coa! Pillars", J S Afr Inst Mm Metall 68, May 1968, pp 455-465

2 KING, H J and WHITTAKER. BN, 'A Review of Cunent Knowledge on Roadway Behaviour", Proc Symp on Roadway Strata Control IMmE, Paper No 6, 1971 pp 73-87

3 SALAMON. M D G , "A Method of Desingning Bord and Pillar Workings ' J S Afr Inst Min Metall, 68 1967, pp 68-78

4 SINGH RN and UNVER B "Prediction of Gate Roadway Closure m Longwall Advance Mining", The AusIMM Illawana Bianch Ground Movement and Control Related to Coal Mining Symposium August 1986. pp 159-167

5 WHITTAKER, BN and SINGH, RN "Desing and Stability of Pillars in Longwall Mining", The Mining Engineer 214 July 1979 pp 59-73

6 WHITTAKER, BN and SINGH, RN 'Stabıltıy of Longwall Mining Gate Roadways in Relation to Rib Pillai Size Technical Note, Int J Rock Mech Mm Sei and Geomech Abstr Vol 18, 1981, pp 331-334

7 WILSON AH, "The Stability of Underground Workings in the Soft Rocks of the Coal Measures", Int Journal of Mining Engineering. No 1. 1982, pp 91-187