Analysis and Design of Rib Support (ADRS) A Rib Support Design Methodology for Australian Collieries

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ABSTRACT

This paper summarises the results of a research project whose goal was to provide the Australian coal industry with a rib support design methodology and software tool that could be utilised by suitably qualified colliery staff. The project was primarily funded by Australian Coal Association Research Program (ACARP) and further supported by several Australian longwall operations.

The outcome of the project is a design methodology and software tool called, Analysis and Design of Rib Support (ADRS). ADRS is an empirical technique, which recognises that several geotechnical and design factors affect ribline performance and in addition that operational and safety issues essentially dictate the level of performance required. Therefore, the design recommendations associated with ADRS are specific to the Australian coal industry; however the procedure(s) for data collection and analysis could be applied to other countries' 'underground coal industries.

Case history data were compiled from 34 longwall and two bord and pillar operations resulting in 204 case histories with each case history data set being defined by approximately 130 individual data fields. In addition monitoring (incorporating stress cells and extensometers) was undertaken at 10 collieries to assess and quantify the effectiveness of different rib support patterns and hardware on rib performance. The monitoring sites allowed for an improved understanding of the mechanisms of rib failure and degradation in terms of its interaction with the installed support and at the various stages of the mining cycle.

The design methodology deals with both mains development and gateroad development specific to Australian longwall mines. This paper focuses on longwall gateroads subjected to abutment loading and in particular the travel road which becomes the tailgate of the subsequent panel. The statistical analyses associated with these cases suggested that the level of rib support should be based primarily on the development height and the pillar stress level. The ADRS software guides users through the design process, allowing them to develop rib support plans based on sound science and a broad base of in-mine experience.

To the best of the authors' knowledge ADRS is the first systematic rib support design technique to be developed for any country's underground coal industry. The development and use of empirical models in mining have substantially contributed to improving safety and productivity. ADRS further demonstrates that empirical techniques are particularly relevant and beneficial in dealing with the complexities of geotechnical design associated with underground coal mining.

INTRODUCTION

Over the last decade many aspects of strata management have evolved, such that risk management has become the *"core"* of the strata management process at most Australian collieries. This is borne out with the advent of Strata Management Plans (SMP), roadway and longwall hazard plans and the categorisation of various roof zones as a part of the Mine Manager's Support Rules.

This evolution has had a significant impact on pillar design, longwall face design/management, roof control and the use and implementation of instrumentation to monitor the strata behaviour. The one area that has severely lagged behind is rib control. It is assessed that the primary reasons for this disparity have been a lack of understanding of rib failure mechanisms and the significant factors that affect rib behaviour.

Coal mine rib instability is a significant safety and productivity issue facing the Australian underground coal industry. There are currently no formalised or widely accepted engineering techniques in relation to rock mass classification of a coal mine rib and for rib support design. In many cases rib support is installed in a reactive manner and changes to rib support patterns/hardware often occur following unsatisfactory conditions that are highlighted by personnel injury and/or extensive rib failure.

Information supplied by the Queensland (Qld) Department of Natural Resources and Mines and New South Wales (NSW) Coal Services Pty Ltd shows that for years 1997 to 2003 (inclusive) there were 175 Lost Time Injuries (LTIs) as a result of roadway rib spall. During this period there were unfortunately three fatalities, one in NSW and two in Qld. Figure 1 shows that approximately 41% of the rib related LTIs occurred during the installation of ground (roof or rib) support off the continuous miner (CM), 22% took place in the vicinity of the CM, while the remainder occurred away from the CM.

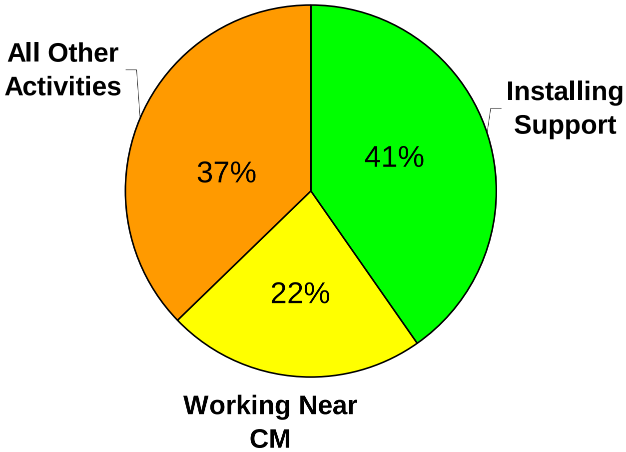

Figure 1. Rib injury experience in Australian underground coal mines, 1997-2003.

In addition to safety, rib instability can negatively impact on productivity or development rates in a number of other direct and/or indirect ways such as:

- Unplanned (i.e., reactive) installation of primary and/or secondary rib support.
- Longer transit times for men and machinery and/or roadway "clean-up" due to excessive rib spall.
- Increased roof span requiring secondary roof support and/or resulting in roof instability.
- Unnecessarily over-supporting the ribs.

The aim of this project was to provide the Australian coal industry with a rib support design methodology and computer-based design tool. The safety of personnel was the "key driver" for this research project and a safer workplace should result in a more productive workplace.

BACKGROUND

In comparison to other strata control issues, such as pillar and roof support design, there has been comparatively little research undertaken in relation to rib support design. However, four significant research projects have been completed in Australia during the past two decades (O'Beirne, et al., 1987; Fabjanczyk, et al., 1992; Frith and Ditton, 1993; Hebblewhite, et al., 1998).

While there is some minor difference of opinion between the four studies in relation to the driving force behind rib degradation, all would appear to agree that buckling is a common failure mechanism. Figure 2 is an excellent example of ribline buckling. The studies also agree that efficient strapping, mesh and plate systems assist in maintaining the integrity of the immediate rib in most conditions, with the face plate being a vital component.

Cuttable (fibreglass and plastic) rib bolts are widely used in Australian mines for support in the longwall blockside riblines. The studies of O'Beirne, et al (1987), Fabjanczyk, et al (1992) and Frith and Ditton (1993) all highlighted significant limitations in relation to cuttable bolts. Roof and rib bolts, both steel and cuttable, are strong in *"pure"* tension, but when acting as rib support are also subjected to large bending moments. When cuttable bolts are called upon to resist bending, their poor elongation properties make them susceptible to rupture.

Figure 2. Photograph illustrating rib failure by buckling.

The results from this project would appear to confirm many of the findings of these four prior Australian studies. While these prior studies advanced our knowledge they ultimately did not provide the Australian coal industry with a rib support design technique.

MONITORING STUDIES

As part of the project, 11 monitoring sites were established at ten different collieries, with seven of those collieries providing sufficient information for which an individual report was prepared. Those seven sites covered a wide variety of geological conditions and a total of 30 different support patterns. Of the seven sites, four were located in Bowen Basin coalfield of Central Queensland with one each in the Newcastle, Southern and Western coalfields of NSW.

The principle objectives of the monitoring program within the project were:

1. To assess and quantify the effectiveness of different rib support patterns and hardware on rib performance and,
2. To develop a better understanding of the mechanisms of rib failure and degradation in terms of its interaction with the installed support and at the various stages of the longwall extraction cycle.

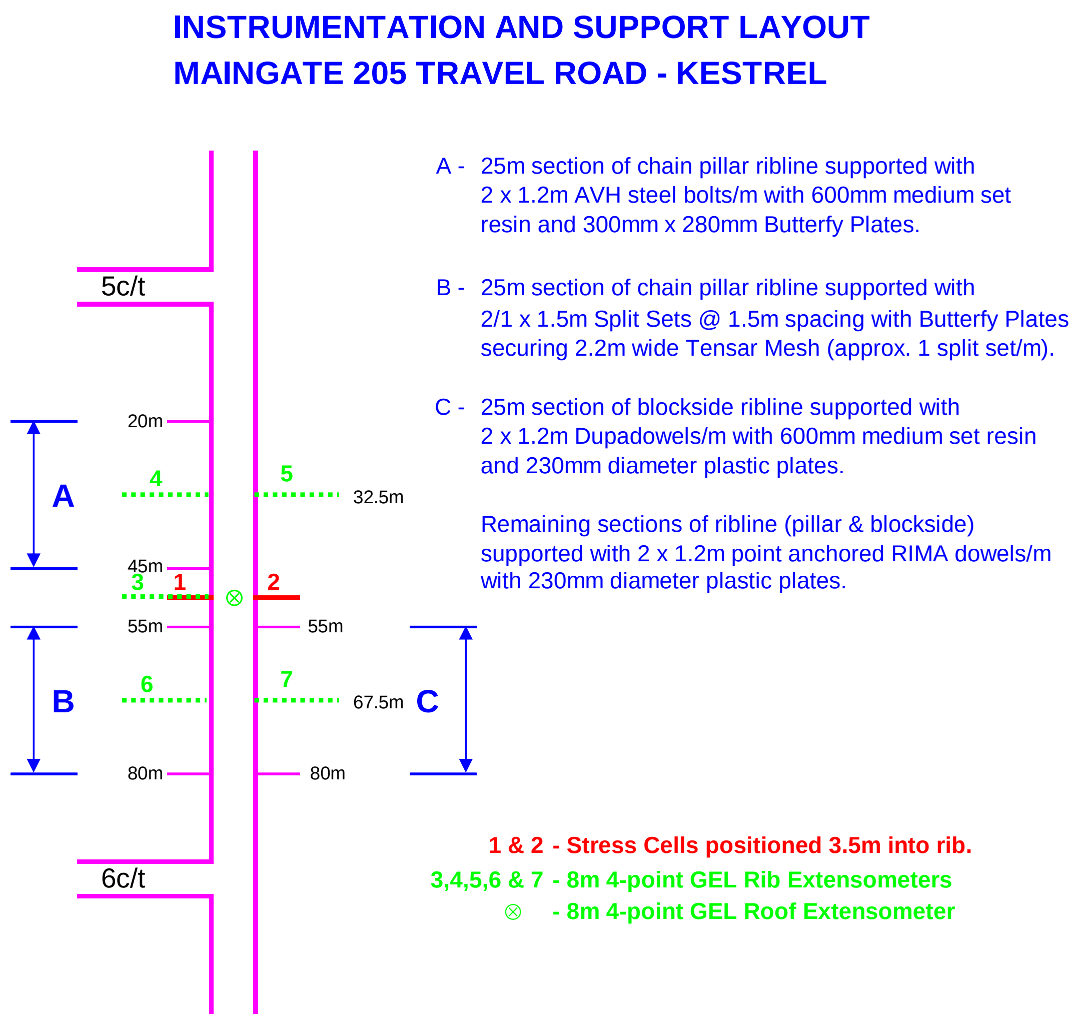

Figure 3. Typical instrumentation plan for a monitoring field site.

The monitoring sites at each colliery were located within the travel road of the maingate development (with one additional site located in a belt road). In each instance the instrumentation was installed some months after development but generally well before the site was subject to abutment loading. Each monitoring site incorporated the use of hydraulic stress cells, rib extensometers and at least one roof extensometer. Figure 3 depicts the rib support and instrumentation layout at Kestrel Colliery and is reasonably typical of the instrumentation layout.

The extensometers were used to compare rib behaviour, primarily in terms of Total Rib Displacement (TRD) and Depth of Softening (DOS) for the various support patterns employed. TRD was simply defined as the horizontal displacement of the ribline surface. Assessing the DOS was more subjective particularly when using a 4 or 5 point extensometer. In general the overall shape of the plots was more useful in assessing the DOS than attempting to define specific values.

The DOS in this study is deemed as the practical, rather than absolute, extent of horizontal displacement or fracturing within the coal rib. In terms of the pillar behaviour model proposed by Hebblewhite, et al (1998), the absolute extent of softening would actually extend into the elastic core of the pillar, where horizontal displacement is a result of Poisson's Effect. In terms of rib extensometry this would equate to using zero horizontal displacement to define the DOS. It is assessed that using the absolute extent of movement to define the DOS is impractical and this is best illustrated with the response of the pillar side stress cell and adjacent rib extensometer associated with the RIMA dowel pattern at Kestrel Colliery (refer Figure 3).

In this instance the stress cell is positioned 3.5 m into the rib, while the rib extensometer has anchors located at 1, 2, 4 and 8 m into the rib. The output in relation to said extensometer is detailed in Figure 4 while the pillar side stress cell response is illustrated in Figure 5.

If the absolute extent of horizontal displacement were used to define the DOS, then in relation to the extensometry information presented in Figure 4 (and in terms of the final set of readings – Tailgate Loading) the DOS would be somewhere between 4 to 8 m. However, the pillar side stress cell response (refer Figure 5) clearly indicates that at the stress cell's depth of 3.5 m, this section of the

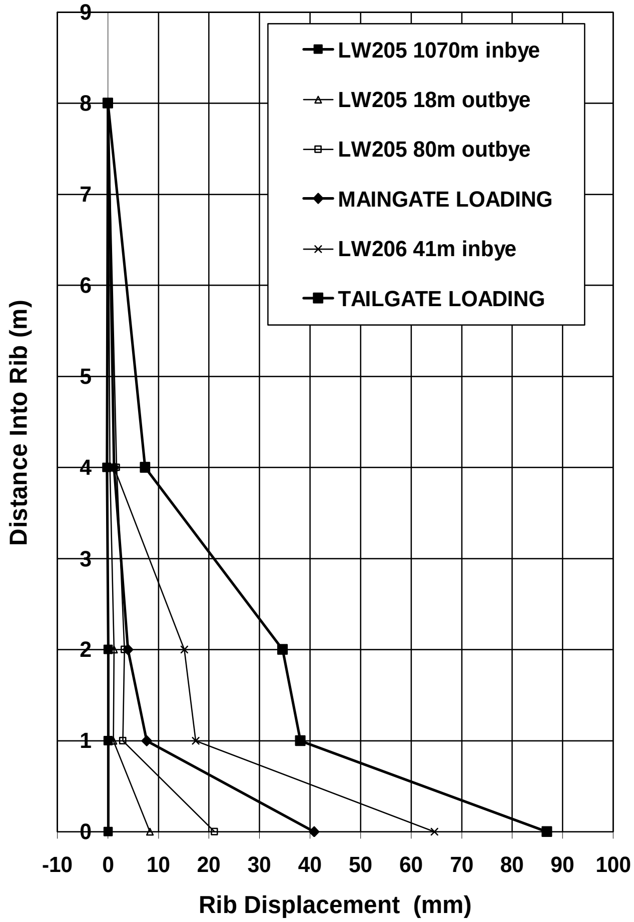

Figure 4. Chain Pillar Rib Extensometer – RIMA

pillar is still well and truly capable of supporting a significant change in load, as evidenced during the approach of LW 206 or the Tailgate Loading phase of the extraction cycle. Therefore, in practical terms the DOS is certainly no more than 4m.

All seven sites provided sufficient information to assess the effect on travel road ribline performance at the Maingate (MG) Loading stage of the longwall extraction cycle. In addition three of the collieries were also able to provide data to fully assess the Tailgate (TG) Loading ribline performance. Figure 6 details five specific stages of the chain pillar loading cycle utilising a typical Australian longwall mining layout. Those stages are described below:

1. Development Loading: The vertical loading condition of the chain pillars subsequent to development while prior to any adjacent longwall extraction.
2. Front Abutment (MGB) Loading, occurs when a chain pillar is first subjected to longwall retreat and the longwall face is parallel with the chain pillar. This is a transient loading phase and its impact (for the purposes of this study) is specific to the belt road riblines about the maingate intersection with the longwall face.
3. Maingate (MG) Loading, is when the side abutment load has stabilised after the passage of the first adjacent longwall face. This is essentially a static loading phase and is specific to the travel road riblines.
4. Tailgate (TG) Loading, is when the face of the second adjacent panel is parallel with the chain pillar. Once again this is a transient loading phase and its impact is specific to the riblines about the tailgate intersection with the longwall face. In this instance the current tailgate would have acted as the travel road of the previous longwall panel.
5. Double Goaf Loading, is when the pillar is isolated between two goafs. For rib support design purposes this loading phase is not required to be considered.

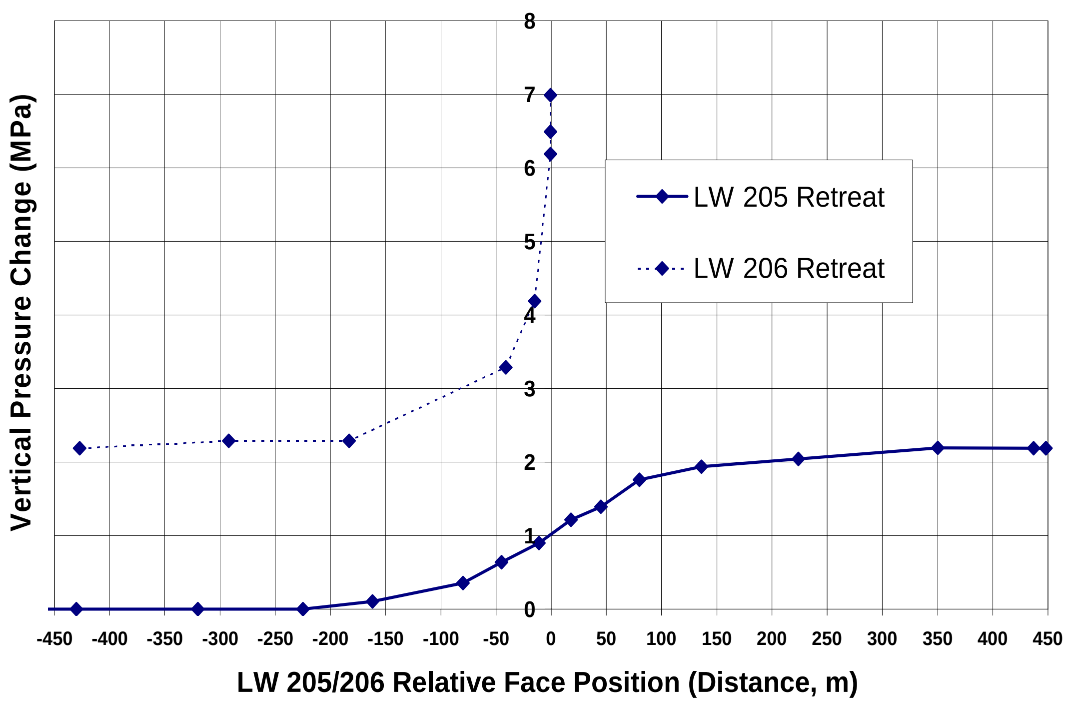

Figure 5. Stress Cell Vertical Pressure Change versus LW's 205/206 Face Position, Kestrel Colliery.

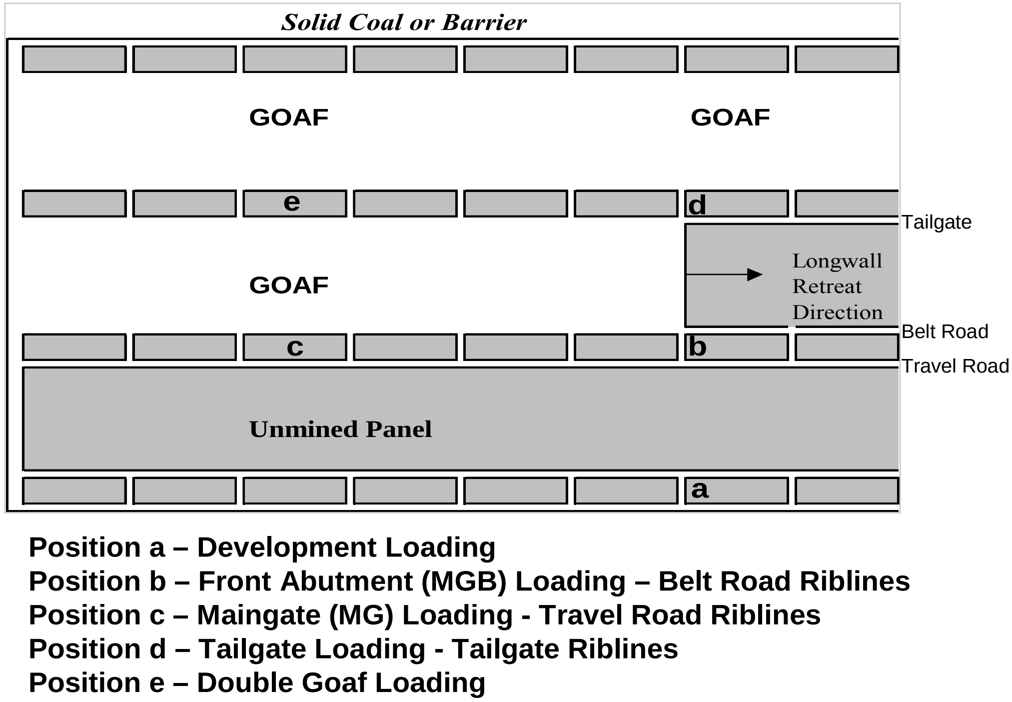

Figure 6. Chain pillar loading cycle, showing location of Development, MG/TG, and MGB loading conditions.

While full details on the monitoring studies are available elsewhere (Colwell, 2005), the most significant conclusions are summarised below:

- The nature of the rib movement appears to be consistent with the buckling of thin coal plates or slabs. While a precursor to buckling may be tensile failure in the form of vertical splitting along cleat or Mining Induced Fractures (MIF) or the formation of new cracks, it is clear from the extensometry that the nature and magnitude of the lateral displacement is a result of buckling.
- Total Rib Displacement would appear to be primarily driven by the change in vertical load applied to the pillar (or more accurately the pillar rib) due to longwall abutment loading and appears to be largely independent of the variation to the ground support installed. This finding is supported by the research of Fabjanczyk, et al. (1992), who indicate, *"that long tendons (50 tonne units) placed at a density of 1 tendon/m length of rib can assist in maintaining the integrity of the rib, but do not significantly reduce the total rib deformation under extreme vertical stresses"*.
- The use of mesh (particularly steel mesh) offers confinement to the ribline, which reduces the depth of softening and in some instances appears to delay the onset of initial rib displacement; however, mesh does not have a significant impact on the TRD. In addition, mesh greatly assists in the effective maintenance of gateroad serviceability throughout the longwall extraction cycle.
- When not utilising mesh it would appear that the bolting density of a support pattern is directly related to the level of spall. Based on observation, it is assessed that the likely or primary reason is the greater areal plate coverage which simply offers greater restraint to the *skin* of the ribline. This strongly suggests that the face plate should be as large as possible, while considering handling, installation and stiffness issues, which will limit its size.
- Most (if not all) steel rib support systems offer greater collar integrity (which is critical to rib maintenance) than any cuttable system.
- Stone bands within a seam appear to have several roles. Where present they tend to act as the 'hinge' or apex in relation to bulging in the riblines and/or the end point of the buckling slab. When acting as the end point, these stone bands typically modify the end condition allowing lateral movement. This increases the *effective length* of the coal *plates* or slabs dramatically lowering the critical load or stress for which buckling can occur. In addition, stone bands often delineate the extent of rib deterioration.
- The orientation of the face (or dominant) cleat in relation to the driveage direction also appeared to be an important factor in terms of ribline behaviour. It seems that when the face cleat is sub-parallel to the driveage direction then the greater the depth of softening. Cleat orientation was considered in more detail when analysing the database and formulating the design methodology.

THE INDUSTRY REVIEW

The aim(s) of the industry review were to:

1. Construct both a contemporary and historical database of rib performance.
2. Conduct statistical analysis of the data to determine the significant predictors of rib performance and,
3. In combination with the monitoring exercises, to assist in developing a rating classification system for coal ribs in relation to their structural competence and a rib support rating in terms of the amount and type of rib support installed.

During the course of the project, 25 longwall mines and two bord and pillar operations were visited. Several of these collieries were visited on more than one occasion and in total 44 underground inspections were conducted. The underground inspections were carried out to evaluate rib performance at specific localities within an operation (i.e., mains, belt and travel roads and tailgate) and for the various stages of the longwall extraction cycle (refer Figure 6). In addition, information collected during previous underground investigations undertaken as a part of the ALTS (Analysis of Longwall Tailgate Serviceability) research (Colwell, et al., 2003 and Colwell, 1998), was included within the database.

During the site inspections information was collected on factors affecting rib performance including coal seam properties (i.e., quality, strength and structure), roof/floor contacts, geometric details (i.e., development height, pillar dimensions, cover depth, etc.), in situ and mining induced stresses, as well as the type, timing and quantity of rib and roof support installed. Subsequent to an underground inspection, a site inspection report was prepared which was then forwarded to the respective colliery for review and confirmation. This process was undertaken to ensure the integrity of the information contained in the database.

In addition, discussions were held with colliery personnel to ascertain how current rib performance compared to past experience. On many occasions this resulted in a detailed description of the gradual development of the rib support system currently employed, which allowed for a greater appreciation of some of the difficulties faced by the collieries satisfactorily managing rib behaviour.

The Database

The final database consisted of 204 case histories obtained from 26 collieries. Of the 204 case histories, 13 are related to main headings, two are in relation to bord & pillar panels while the remaining cases are related to longwall gateroads. Of the 189 gateroad cases, 42 are associated with the belt road, 69 with the travel road, and 75 were observations from the tailgate. Only three cases are related to longwall gateroad cut-through ribline performance and this was where the reorientation of the face cleat to the driveage direction clearly had a significant effect on ribline behaviour at the development stage.

On a number of occasions, subsequent to longwall retreat, cut-through ribline performance was worse than that associated with the travel road. However, these cases were not included in the database as there is a distinct difference in ribline abutment loading between the two conditions. Away from the intersections ribline loading should be reasonably constant along the heading whereas it would vary significantly within the cut-through moving from the goaf to the travel road.

Of the 189 gateroad cases, 62 are associated solely with the blockside ribline, 82 directly with the chain pillar and 45 cases with both. In terms of those 45 cases where both riblines are designated, this only applied if the level of spall between the opposing blockside and chain pillar riblines is essentially the same and in addition the same level and type of rib support had been installed.

In terms of assessing risk there was significant difficulty in comparing the rib performance about the CM as opposed to those work-related activities associated about the maingate belt road intersection with the longwall face (refer Position b – Figure 6) and those associated with the travel road/tailgate when subject to maingate or tailgate loading (refer Positions c and d – Figure 6).

For example, in relation to operational activities within the gateroads about the longwall face, it was generally found that rib spall posed a greater safety risk in relation to those activities conducted about the belt road intersection with the face. The stage loader and conveyor belt structure firstly places men in close proximity to the riblines when entering or leaving the longwall face, or when working adjacent to the blockside ribline during a belt retraction, and secondly can restrict an underground worker's ability to take evasive action in the event of a rib fall.

In these instances minor levels of spall or the unpredictable manifestation of that spall (observed on a number of occasions particularly in relation to the blockside ribline) present a clear and additional risk to personnel as compared to most work related activities conducted in the travel road or tailgate.

Essentially, one is not comparing *apples and apples* in terms of risk when comparing the belt road ribline performance to that associated with the travel road and tailgate. It was decided to separate the maingate belt road (MGB) loading cases from the MG/TG cases when analysing the effects of longwall abutment loading and required support levels. The database was refined as necessary to assess ribline performance at the various stages of and locations related to the mining/chain pillar loading cycle (refer Figure 6).

Statistical Analysis

Logistic regression was the primary statistical technique used in the analyses. Logistic regression allows for the classification of the case histories into two (or more) populations based on a particular *outcome.* Logistic regression was used to determine which *predictive variables* were most significant in determining the outcome being essentially the ribline condition's impact on safety and productivity.

The result of a logistic regression analysis is an equation (in terms of the predictive variables) that acts as a *boundary of separation* between the two populations in terms of the outcome. We refer to the equation that separates the two groups as the *Discriminant Equation.* The Discriminant Equation can be used to formulate quantitative guidelines for the design of rib support systems in order to achieve the desired outcome. The statistical software package SPSS was used for the logistic regression analyses.

Statistical analyses were conducted to assess ribline behaviour for the following:

1. Development Ribline Condition (1), which is defined as the ribline condition just prior to and/or during the installation of roof and/or rib support or essentially the condition of the exposed ribline about the CM that the miners encounter while preparing (i.e., drilling) and then installing roof and rib support.
2. Development Ribline Condition (2) which is defined as the ribline condition subject to Development Loading (refer Position a – Figure 6). These analyses were conducted to assist in determining the required levels of primary support to maintain satisfactory ribline conditions prior to abutment loading effects.
3. MGB Loading Condition, which is defined as the ribline condition about the maingate belt road intersection with the longwall face. These analyses were conducted to assist in

assessing appropriate total (primary and secondary) rib support levels for belt road riblines.
4. MG/TG Loading Condition (travel road/tailgate riblines subject to longwall abutment loading). These analyses were conducted to assist in assessing appropriate total rib support levels for travel road (and subsequently tailgate) riblines.

In this study the ribline performance was assessed in three ways:

1. Satisfactory or Unsatisfactory (criteria based).
2. Safety/Productivity Risk (five categories ranging from low through moderate-low, moderate, moderate-high to high). The initial risk categorisation was based on the author's own experience in consultation with colliery personnel.
3. The volume of spall per lineal metre of ribline (m^3/m).

To be classified as unsatisfactory, a case had to meet one of six criteria:

- Management changed the rib support design (hardware or pattern density) in response to poor rib conditions.
- Unplanned use of secondary rib support.
- Unpredictable/Unsafe rib failure in terms of when and/or where it will happen (but it does happen).
- Excessive rib spall.
- Excessive remedial clean-up of roadway or ribline.
- Resultant rib spall presents a clear risk to personnel (typically associated with a Hazardous Zone).

Where the resultant rib condition is unsatisfactory then generally more than one of the above criteria is met. A Hazardous Zone typically refers to a location/work practice that by its nature places men in close proximity to the riblines and where an underground worker's ability to take evasive action in the event of a rib fall is restricted.

The Rib Support Rating (RIBSUP)

For logistic regression to be successful, the number of case histories must be significantly larger than the number of predictive variables. Therefore, it is often necessary to combine groups of related variables into rating scales. In this study, the most important rating scale was the Rib Support Rating (RIBSUP). There are four components to RIBSUP, being:

1. A measure of the bolting capacity per square metre of ribline – RBOLT
2. A measure of the relative effectiveness/confinement offered by the face plate – FPLATE
3. A measure of the confinement offered by a liner – Confinement Factor (CF)
4. A methodology to combine these values, for both primary and secondary rib support, into one rating (RIBSUP).

RBOLT incorporates the shear strength, rather than the tensile strength, as the most appropriate indicator of a bolt or dowel's performance in terms of modifying rib behaviour. However given the sometimes wide discrepancy in shear strength values between dowels and bolts (e.g. the shear strength of a glass reinforced nylon Dupadowel is 25 kN or approximately one-ninth that of an X grade 24 mm steel bolt) it was judged that the square root of the shear strength resulted in a more appropriate comparison.

RBOLT is defined as:

$$\text{RBOLT} = \frac{\text{L x N x Sh}^{1/2}}{\text{S x h}} \qquad (1)$$

where L = Length of the rib bolt/dowel (m)
N = Average number of bolts/dowels per vertical row
Sh = Typical shear strength of the rib bolt/dowel (kN)
S = Spacing between vertical rows of bolt/dowels (m)
h = Development Height (m)

The primary rib bolt length varied from 0.9 to 1.8 m within the database, with 1.2 m being by far the predominant value. There was a wide variation in the grade or type of bolt used, however the average steel bolt UTS and Shear Strength was 240 and 160 kN, respectively. On average two bolts are installed every 1.2 m, however, once again there is a wide variation in bolting density.

FPLATE starts with the Standard Butterfly Plate (with an approximate area = 300 x 280 mm = 0.084 m^2) that is the predominant face plate used at Australian collieries in terms of chain pillar riblines and mains development. FPLATE has a value of 1.0 for the Standard Butterfly Plate, and is adjusted for other plates in proportion to their area relative to the standard, such that:

$$\text{FPLATE} = [(\text{Area of Face Plate})/(\text{Area of Standard Butterfly Plate})]^{1/2} \qquad (2)$$

In terms of the database the area of the face plates ranged from a minimum of 0.01 m^2 to a maximum of 0.123m^2 resulting in an average FPLATE of 0.84 with a standard deviation of 0.19.

CF starts with the premise that the confinement factor owing to a liner operates as a multiple within the RIBSUP calculation. Therefore, the CF=1 where the rib support does not include some type of liner. The CF increases in proportion to the surface area covered by the liner up to a maximum value of 4.0.

The use of straps as a liner typically results in a $1< \text{CF} < 2$. In terms of the analyses and design methodology, straps are defined as being less than or equal to 400mm wide and can be made of polymer or steel as well as being solid (i.e., W Strap) or mesh type construction. Where mesh sheets/rolls were used the resultant $\text{CF} \geq 2$, essentially meaning that at least one-third of the ribline surface area was covered. Mesh sheets/rolls can be of polymer or steel construction.

In relation to face plates and liners, the methodology only distinguishes between the different products in terms of their areal size, not their strength. It is the colliery's decision as to whether the face plate or liner chosen satisfies the operational purpose for which it is required. If the face plate or liner chosen does not satisfy operational requirements then it simply needs to be replaced by a product that does.

For example, steel mesh is clearly superior to cuttable polymer mesh types in terms of tensile strength and resisting tear, as well steel mesh/face plates are generally stiffer than polymer products offering greater potential confinement and collar integrity. If a cuttable face plate or liner does not satisfy the operational requirements (i.e., because the product is not stiff enough or of sufficient size to resist movement or maintain a satisfactory level of surface contact) then steel products may have to be considered and used.

In terms of face plates and liners the requirement within the methodology is that, **"the face plate or liner maintains effective surface contact with the ribline."** It may be that the face plate/liner is not the only or primary cause of losing effective contact with the ribline and that the nut/thread tensile strength (or head load bearing capacity in relation to Thrust Dowels) is also a factor. The size of the face plate, its material properties and the nut/thread tensile strength can essentially be grouped together in terms of the collar integrity of the rib support system when assessing the issue of the face plate or liner maintaining effective surface contact with the ribline.

RIBSUP combines the other three ratings as follows, for two different situations:

(1) Where a liner is utilised and securely fitted to the rib by the bolts/dowels and face plates then:

$$RIBSUP = CF \times RBOLT \qquad (3)$$

(2) If there is no liner but simply the face plates then:

$$RIBSUP = FPLATE \times RBOLT \qquad (4)$$

In relation to the above equations, essentially where there is a liner and as long as it is securely fitted then the size of the face plate has far less impact on the overall rib performance and is, therefore, ignored. In certain instances when combining primary and secondary rib support, some modifications to the above equations are necessary.

MG/TG Loading Condition

The following discussion presents those findings associated MG/TG Loading Condition. Full details of the analyses associated with the other loading conditions have been reported elsewhere (Colwell, 2005).

A total of 116 MG/TG gateroad cases were available, in which the entries had been subjected to significant longwall abutment loads. Of these, 78 were related to the Maingate Loading (MG) condition within either the travel road or tailgate, and the other 38 cases were specifically related to ribline performance in the immediate vicinity of the tailgate intersection with the longwall face (i.e., Tailgate or TG Loading condition).

This sub-set of the database included 25 longwall mines with only one of those collieries not currently operating. Developments heights range from 2.4 m up to 4.1 m, while depth of cover ranges from 105 to 510 m.

As previously stated risk management has become the *"core"* of the strata management process at most Australian collieries. Therefore a risk based outcome was considered necessary so as to emphasise that if a colliery intends to utilise ADRS, it needs to do so in the context of risk management. It is recognised that the risk based outcome utilised in this study of low through to high (with five categories) would be different to a colliery based assessment (where *risk = probability x consequence*), however the criteria can be adapted to suit a colliery's risk assessment process and operational requirements.

Assessing risk is not an exact science (neither is underground coal mining) and while guidelines and some set criteria are necessary, utilising engineering judgment is just as important. In terms of the MG/TG cases the risk based outcome, which was utilised, incorporated all three ribline performance assessment criteria, such that:

1. If the rib performance was assessed as unsatisfactory then risk must be classified moderate or higher.
2. If the change in the volume of spall (subsequent to development) was greater than 0.88 m^3/m (average) then risk must be classified moderate or higher.
3. If the rib performance was assessed as unsatisfactory and the change in the volume of spall was greater than 0.88 m^3/m then risk must be classified moderate-high or high.
4. If the rib performance was assessed as satisfactory and the change in volume of spall was less than 0.55 m^3/m (average minus 1 sd) then risk would typically be classified low or moderate-low.

The above set of criteria rightly allows for a certain amount of engineering judgment to be incorporated in the process of deciding which of the actual five categories best assesses the risk. Using the above criteria the 116 case histories were grouped as follows:

- 9 cases were assessed as low risk.
- 27 cases were assessed as moderate-low risk.
- 26 cases were assessed as moderate risk.
- 35 cases were assessed as moderate-high risk.
- 19 cases were assessed as high-risk.

For the logistic regression analyses, the case histories were divided into two outcome groups. The first group consisted of those cases with low & moderate-low risk (36 cases). The other group included those cases with moderate-high & high risk (54 cases). The moderate risk cases were initially excluded to have a clear distinction in the outcome (being beneficial to the analyses). Therefore the resultant discriminant equation would potentially represent a design equation for approximately moderate risk.

Three separate measures of the vertical load were initially employed in the analysis, the cover depth (H), average pillar stress (σ_P), and the Pillar Factor (PF = Pillar Strength/Average Pillar Stress). Since these three measures are strongly correlated with each other, only one could be retained for the final equation. It was found that the average pillar stress (calculated using tributary area and abutment angle concepts) resulted in the greatest predictive success rate. The average pillar stress has the additional advantage that it, unlike PF, is totally independent of the development height (h).

At a significance level of "alpha" = 0.05, it was found that four variables were significant predictors of rib performance, being:

1. Average Pillar Stress (σ_P, ranging from 4.8 to 42.5 MPa)
2. Development Height (h, ranging from 2.4 to 4.1 m)
3. RIBSUP (ranging from zero to 80.8)
4. Hardgrove Grindability Index (HGI, ranging from 30 to 88).

In terms of the individual impact or weighting on the outcome of the four significant predictor variables, σ_P has a 35.2% impact on the outcome, followed by RIBSUP with 29.3%, h with 25.2% and HGI with 10.3%. The discriminant equation was calculated as:

$$RIBSUP = 41.0\,h + 2.58\,\sigma_P + 0.47\,HGI - 175 \qquad (5)$$

Equation 5 successfully classified 47 of the 54 moderate-high/high risk cases (87% correct) and 27 of the 36 moderate-low/low risk cases (75% correct) for an overall classification success rate of

82.2%. Equation 5 essentially represents a design equation for rib support in terms of operating with a moderate level of risk.

It was found that if the constant in equation 5 was adjusted by +6 (refer equation 6) then all 54 of the moderate-high/high risk cases were successfully classified. This equation resulted in a drop in the successfully classified moderate-low/low risk cases from 27 to 22 of the 36 cases (i.e., 61% correct). However, the overall classification success rate increased from 82.2% to 84.5%. In addition when assessing the moderate cases with equation 6, 22 of the 26 cases are successfully classified. Equation 6, which is illustrated in Figure 7, essentially represents a design equation for rib support in terms of operating with a moderate-low level of risk.

$$\text{RIBSUP} = 41.0\ h + 2.58\ \sigma_P + 0.47\ \text{HGI} - 169 \qquad (6)$$

During the MG/TG analyses several other variables were found to have a secondary to minor impact on rib performance, including the dominant/face cleat orientation to driveage direction (Φ). While Φ is not a significant predictor of ribline performance for the MG/TG Loading Condition, it is important to note that for Development Condition (1), Φ <u>is</u> a significant predictor of ribline performance.

There are sound technical reasons that help to explain why cleat orientation was not found to be a significant predictor of the outcome at the MG/TG stage. Firstly in contrast to the development stage where the principal vertical stress trajectories would *"surround"* the development face; during and after longwall extraction the principal vertical stress trajectories associated with the blockside and chain pillar riblines (away from the chain pillar corners) must run parallel with the travel road orientation. Therefore vertical cracking as a result of stress increase will preferentially develop parallel to the roadway orientation.

In addition to the above, existing cracking within the ribline (whether natural or mining induced) will act as stress raisers and it takes significantly less energy to extend an existing crack than to develop a new crack. For example, even if the butt/minor cleat is only moderately or poorly developed and were sub-parallel to the heading then it would preferentially act as a stress raiser and under abutment stress may readily be extended.

In the above situation the dominant or face cleat would be near perpendicular to the ribline which would appear to be favourable until one realises that the butt cleat (or MIF for that matter) can also act to "split" the coal. In addition each said cleat direction actually represents the statistical mean of a spread of cleat directions. Fundamentally coal is a relatively highly fractured rock type that can more readily split in several directions (as compared to other rock types), while preferentially splitting parallel with the stress trajectories.

ANALYSIS AND DESIGN OF RIB SUPPORT (ADRS)

The results of the statistical analyses have been incorporated in the rib support design methodology *Analysis and Design of Rib Support (ADRS)*. The following discussion relates to the design

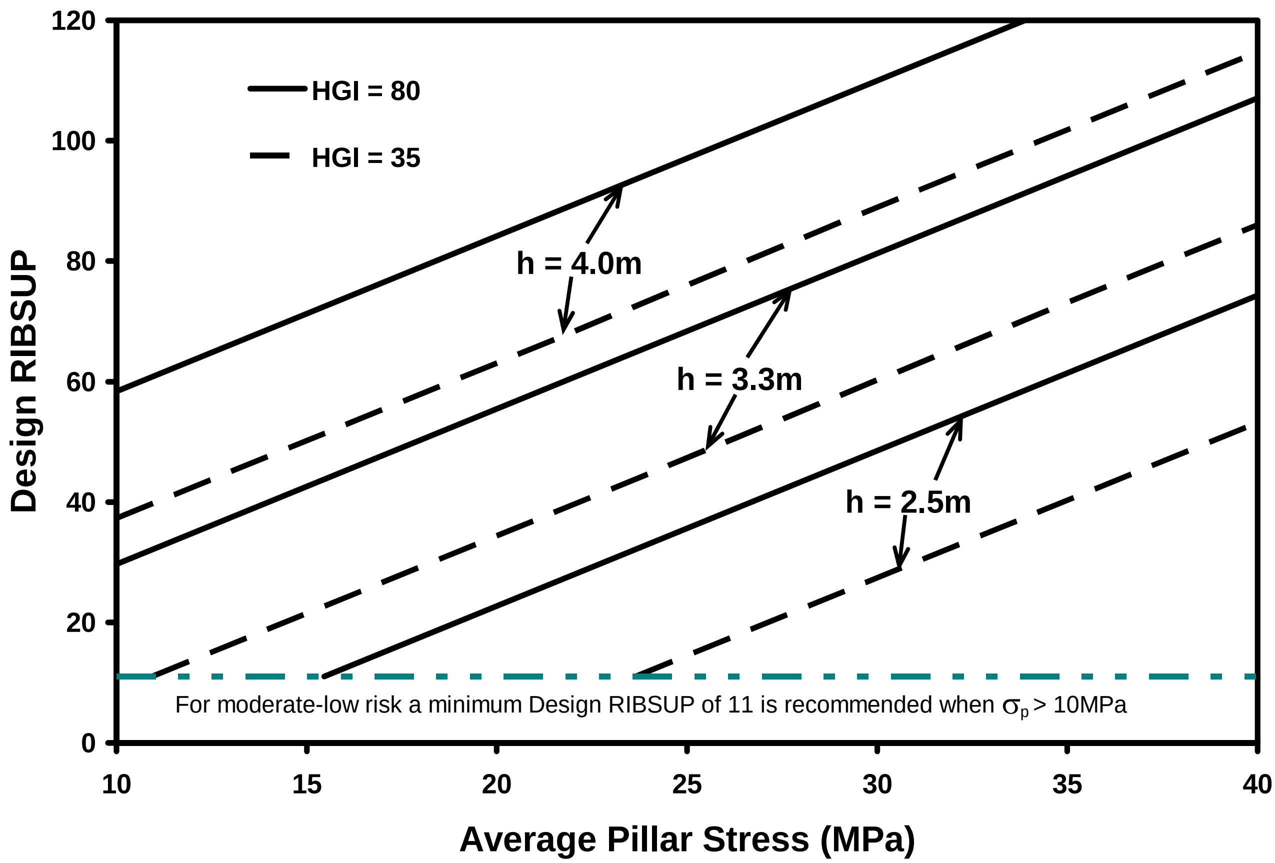

Figure 7. Design equation for the MG/TG Rib Condition, for Moderate-Low Risk Level.

issues associated with the more challenging matter of controlling the travel road/tailgate riblines subjected to the MG and TG Loading Conditions. The impact of future longwall abutment loading can and often does place a severe demand on the rib support requiring a significant increase in RIBSUP over and above that necessary for development.

The design methodology does not differentiate between the blockside and chain pillar side riblines in relation to what type of support hardware is utilised. In general, Australian collieries would clearly prefer to use either no rib support or cuttable support without mesh in relation to the blockside ribline so as to reduce the risk of certain issues associated with the longwall face extraction/cutting process. For example (but not limited to):

- Coal contamination
- Belt damage.
- Blockages due to mesh.
- Sparks associated with cutting steel bolts.
- Mesh getting caught around the shearer.

It is the colliery's decision on how to *"balance"* the safety/productivity risks associated with the longwall extraction process and those safety/productivity risks associated with gateroad ribline performance. ADRS should provide sufficient information so that a colliery can more rationally assess the risk in relation to rib performance and therefore make a more informed decision.

In terms of the travel road riblines, once the colliery has decided what abutment loading condition (MG or TG) and what level of risk (moderate or moderate-low) is appropriate for design purposes then the next step is to calculate the suggested RIBSUP utilising equations 5 or 6. However, the design methodology also needs to provide guidelines in relation to the use of liners and cuttable/steel support to provide the end user with a workable technique. In addition, minimum limits need to be imposed in some circumstances.

The relationships between the type of liner (i.e., none, straps or mesh) and rib bolt (i.e., none, cuttable or steel) versus the four significant predictor variables (RIBSUP, h, σ_P and HGI) were assessed in a unique and simple manner to provide realistic limits in terms of hardware selection and minimum levels of rib support. It was found that the RIBSUP (suggested for design purposes) and σ_P had the most influence on what hardware should be selected to satisfy the recommended levels of rib support.

The results of these analyses in relation to RIBSUP and σ_P (the two predictors having the greatest impact on the outcome) are summarised in Table 1. Further recommendations apply in relation to h and HGI and the interested reader is referred to Colwell (2005) for that additional information and a more detailed explanation of said analyses. To assist the reader in the interpretation of Table 1 the following example is provided.

Example

A colliery is operating at a cover depth of 325 m with a development height of 2.9 m, roadway width of 5 m, chain pillar width of 35 m (rib to rib) and longwall panel width of 250 m. The representative HGI of the coal seam is 42. Following a review, the colliery has selected the MG Loading condition for rib support design purposes. Utilising tributary area concepts, the abutment angle model (for a 2D "slice") and incorporating a vertical pressure gradient of 0.025 MPa/m and an abutment angle of 21°, it is calculated that the average pillar stress (σ_P) is 21.1 MPa.

If a Moderate risk level is used for design purposes then ADRS would utilise equation 5 resulting in a Design RIBSUP of 18 and provide the following *Design Statement* (based on Table 1) to guide the user in the selection of the hardware:

> ***"Consideration should be given to including some form of liner as a part of the rib support system utilising steel in preference to cuttable support."***

However, if a Moderate-low level of risk is used for design purposes then ADRS would utilise equation 6 resulting in a Design RIBSUP of 24 and provide the following *Design Statement* (based on Table 1) to guide the user in the selection of the hardware:

> ***"The rib support system should incorporate mesh (preferably steel with a CF ≥ 2.5) that is firmly secured to the ribline with steel bolts and plates."***

Table 1. ADRS Recommended Hardware and Support Levels

Risk Level				Suggested Rib Support Hardware/Level
Moderate		Moderate-low		
RIBSUP	σ_P (MPa)	RIBSUP	σ_P (MPa)[1]	
-	> 11	-	> 8	Rib support should be installed [2, 3]
> 6	> 13	> 0	> 10	Steel bolts & plates are preferred to cuttable support [4]
> 40	> 23	> 6	> 13	Steel bolts & plates should be utilised
>10	>15	> 6	>10	Some form of liner (i.e., straps or mesh) is preferred [5]
> 20	-	-	> 13	Some form of liner (preferably mesh with a CF ≥ 2.5) should be utilised
> 50	> 23	> 20	> 20	Mesh (preferably steel with a CF ≥ 2.5) should be utilised

[1]If σ_P > 22MPa then even with the use of mesh and steel bolts the colliery should adapt their SMP to accommodate operating with a moderate (or possibly greater) level of risk in relation to rib performance based on current industry support levels and hardware.
[2]For Moderate risk a minimum Design RIBSUP of 2.5 is recommended when σ_P > 11 MPa.
[3]For Moderate-low risk a minimum Design RIBSUP of 5 is recommended when σ_P > 8 MPa.
[4]For Moderate-low risk a minimum Design RIBSUP of 11 is recommended when σ_P > 10 MPa
[5]For Moderate risk a minimum Design RIBSUP of 11 is recommended when σ_P > 15 MPa

The increase of 6 in the Design RIBSUP moving from Moderate to Moderate-low is straight-forward, however the two *Design Statements* are radically different in their intent when utilising ADRS as part of the risk assessment process.

Risk and Abutment Loading Selection for Design

It is for the colliery to decide what abutment loading condition (MG or TG) and what level of risk (moderate or moderate-low) is appropriate for design purposes. A preliminary risk assessment or at least discussions involving several colliery personnel should be undertaken in evaluating both these aspects. If there is uncertainty at this initial design stage, then possibly all four scenarios need to be assessed. The following discussion and examples are provided to assist with that process.

It was found during the underground inspections that at a number of collieries the vast bulk of the overall rib deterioration associated with the travel road/tailgate occurred as a result of Maingate Loading and in relation to Tailgate Loading the additional deterioration was comparatively minor (if any) and confined to the immediate tailgate intersection. In this situation or with this general experience (at an individual mine) it would be reasonable for a colliery to utilise MG Loading for design purposes.

Conversely, there were also many instances where Tailgate Loading had a significant impact on ribline performance with the resultant ribline deterioration extending 20 to 50m outbye of the longwall face (sometimes further). In these instances it may be more appropriate to use TG Loading for design and would be essential if an increase in the roadway span could lead to roof instability.

In terms of risk, two examples or scenarios are provided. Firstly, a colliery may wish to use the future tailgate for longwall equipment relocation purposes, if this were the case then a moderate-low/low level of risk may be required along the roadway during the relocation process due to the man traffic and productivity issues (i.e., minimising the risk of delaying the longwall relocation). Therefore in this instance the design condition may be MG Loading for moderate-low risk.

The second example relates to a colliery where there are discernable Tailgate Loading effects in relation to ribline performance, however, the roof is quite “strong” (i.e., CMRR > 55) and largely unaffected by moderate levels of rib spall increasing roadway width. In this situation utilising the TG Loading condition with a moderate level of risk may be the most appropriate for design purposes.

The preceding discussion is only meant to highlight a few factors that may affect a colliery’s decision in relation to assessing the appropriate risk level and abutment loading condition for design purposes. There are numerous other factors to consider particularly in relation to the subsequent longwall extraction process, 2nd egress issues, safety of men when working in the tailgate (i.e., installing secondary support) and productivity factors that can only satisfactorily be assessed within the forum of a properly facilitated mine site risk assessment.

CONCLUSIONS

The aim of this project was to provide the Australian coal industry with a rib support design methodology and computer based design tool that can be utilised by colliery engineers and geologists who have sufficient experience and training in relation to underground coal mine strata mechanics. These aims have been achieved and the design methodology and software package is referred to as ***Analysis and Design of Rib Support (ADRS)***. The intended benefits to underground operations, in the provision of this information and resource, are a safer and more productive workplace.

ADRS provides a Design Rib Support Rating (Design RIBSUP) and guidelines in relation to the use of liners and cuttable/steel support to provide the end user with a workable technique. The rib support *hardware* component of the software assists the strata control engineer with the selection of suitable products and rib support patterns to satisfy the Design RIBSUP. Also within the software package a database search can be conducted to assist in the design process.

Assessing risk is not an exact science (neither is underground coal mining) and while guidelines and some set criteria are necessary (which are clearly defined), utilising engineering judgement is just as important. <u>Therefore, ADRS is not a prescriptive technique</u>, but a tool to assist collieries in assessing their rib support requirements in the context of the risk assessment process associated with the development of a colliery’s Strata Management Plan.

Therefore, if a colliery intends to use ADRS it is critical that the recommended levels of rib support <u>and</u> how that support would be implemented is assessed within the framework of a properly facilitated risk assessment being a team exercise that draws on the experience of the colliery staff and employees.

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