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Calibration of the Analysis of Longwall Pillar Stability (ALPS) Chain Pillar Design Methodology For Australian Conditions

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ABSTRACT

This paper summarizes the results of a research project whose goal was to provide the Australian coal industry with a chain pillar design methodology readily usable by colliery staff. The project was primarily funded by the Australian Coal Association Research Program and further supported by several Australian longwall operations.

The starting point or basis of the project was the Analysis of Longwall Pillar Stability (ALPS) methodology. ALPS was chosen because of its operational focus; it uses tailgate performance as the determining chain pillar design criterion rather than simply pillar stability. Furthermore, ALPS recognizes that several geotechnical and design factors, including (but not limited to) chain pillar stability, affect that performance.

There are some geotechnical and mine layout differences between United States and Australian coalfields that required investigation and, therefore, calibration before the full benefits offered by the ALPS methodology could be realized in Australia.

Ultimately, case history data were collected from 19 longwall mines representing approximately 60% of all Australian longwall operations. In addition, six monitoring sites incorporated an array of hydraulic stress cells to measure the change in vertical stress throughout the various phases of the longwall extraction cycle. The sites also incorporated extensometers to monitor roof and rib performance in response to the retreating longwall face.

The study found strong relationships between the tailgate stability factor, the Coal Mine Roof Rating, and the installed level of primary support. The final outcome of the project is a chain pillar design methodology called Analysis of Longwall Tailgate Serviceability (ALTS). Guidelines for using ALTS are provided.

INTRODUCTION

In many cases, chain pillars in Australia have been designed solely with regard to pillar stability using a process similar to that used for pillars within bord-and-pillar operations. The bord-and-pillar approach is based on analysis of collapsed pillar cases from Australia and the Republic of South Africa (*1*) and applies a factor of safety in relation to pillar collapse. This approach is inappropriate for a number of reasons when designing chain pillars.

Australian chain pillars typically have minimum width-to-height (w/h) ratios >8, which is approximately 4.5 standard deviations away from the mean of the pillar collapse case histories. In addition, the chain pillar loading cycle and active life are significantly different from those experienced by pillars within a bord-and-pillar operation. Finally, the goal of maintaining gate road stability is very different from that of avoiding a pillar collapse.

The need for a design method uniquely developed for Australian longwall chain pillars was clear. The original submission for funding by the Australian Coal Association Research Program (ACARP) stated that the calibration (to Australian conditions) of a proven chain pillar design methodology offered the least risk for a successful and timely outcome. It was assessed that the most comprehensive chain pillar design tool then available was the Analysis of Longwall Pillar Stability (ALPS) (*2, 3*). The primary consideration in selecting ALPS is that it uses gate road (i.e., tailgate) performance as the determining chain pillar design criterion. Secondly, ALPS is an empirical design tool based on a U.S. coal mine database; thus, it provided a ready framework for calibration to Australian conditions.

The aim of the project was to provide the Australian coal industry with a chain pillar design methodology and computer-based design tool readily usable by colliery staff. A further objective was to ensure that the methodology developed by the project had the widest possible application to all Australian coalfields by identifying where local adjustments and limitations may apply.

In formulating the design methodology, the primary goal was to optimize pillar size (specifically pillar width) so as to—

- Maintain serviceable gate roads such that both safety and longwall productivity are unaffected;

- Minimize roadway drivage requirements so as to have a positive impact on continuity between successive longwall panel extraction; and

- Maximize coal recovery.

In designing chain pillars, specifically with regard to satisfactory gate road performance, the following design criteria were proposed:

- The chain pillar must provide adequate separation between the main gate travel road and belt road, such that the travel road (tailgate of the subsequent longwall panel) will be satisfactorily protected from the reorientation and intensification of the stress field caused by the extraction of the first longwall panel.

- The tailgate (with a focus on the tailgate intersection with the longwall face) will be sufficiently serviceable for ventilation and any other requirements (setting of secondary support, second egress, etc).

BACKGROUND

ALPS was originally developed by Mark and Bieniawski (*4*) at The Pennsylvania State University. It was further refined (*2, 3, 5*) under the auspices of the former U.S. Bureau of Mines (USBM)[1].

The initial ALPS research involved field measurements of longwall abutment loads at 16 longwall panels at 5 mines. These measurements were used to calibrate a simple conceptualization of the side abutment, similar to models proposed by Wilson (*6*) and Whittaker and Frith (*7*). The side abutment (A) equates to the wedge of overburden defined by the *abutment angle* (β) (figure 1). The tailgate loading condition is considered to be some percentage of the side abutment, called the *tailgate abutment factor* (F_t). The U.S. field measurements found a range of abutment angles, from $\beta = 10.7°$ to $\beta = 25.2°$. A value of $\beta = 21°$ and $F_t = 1.7$ was selected for use in design.

Because of the encouraging results obtained from the initial study, the USBM commissioned further research directed toward quantifying the relative importance of roof and floor quality and artificial support on gate road performance. The approach was to analyze actual longwall mining experience. Case histories from 44 U.S. longwall mines were characterized using 5 descriptive parameters. Pillar design was described by the ALPS stability factor (ALPS SF); roof quality was described by the Coal Mine Roof Rating (CMRR) (*8, 9*). Other rating scales were developed for primary support, secondary support, and entry width.

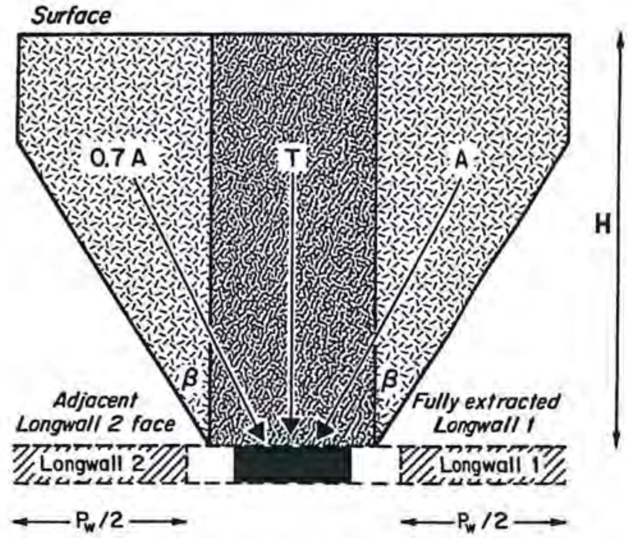

Figure 1. Conceptual model of the side abutment load.

Mark et al. (*3*) reported that statistical analyses indicated that in 84% of the case histories the tailgate performance (satisfactory or unsatisfactory) could be predicted correctly using only the ALPS SF and the CMRR. It was further stated that most of the misclassified cases fell within a very narrow borderline region. The analyses also confirmed that primary roof support and gate entry width are essential elements in successful gate entry design. The relative importance of the floor and of secondary support installed during extraction could not be determined from the data.

The following equation (relating the ALPS SF and CMRR) was presented to assist in chain pillar and gate entry design:

$$\text{ALPS SF}_R = 1.76 - 0.014\,\text{CMRR}, \qquad (1)$$

where the ALPS SF_R is the ALPS SF suggested for design.

The Primary Support Rating (PSUP) used in ALPS was developed as an estimate of roof bolt density and is calculated as follows:

$$\text{PSUP} = \frac{L_b * N_b * D_b}{S_b * w_e * 84}, \qquad (2)$$

[1]The safety and health research functions of the former U.S. Bureau of Mines were transferred to the National Institute for Occupational Safety and Health in October 1996.

where L_b = length of bolt, m,
N_b = number of bolts per row,
D_b = diameter of the bolts, mm,
S_b = spacing between rows of bolts, m,
and w_e = entry (or roadway) width, m.

PSUP treats all bolts equally and does not account for load transfer properties, pretensioning effects, etc.

NEED FOR CALIBRATION

Conventional longwall mines in the United States generally use a three-heading gate road system; Australian longwall panel design typically employs a two-heading gate road system with rectangular chain pillars separating these gate roads. A typical Australian longwall panel layout is presented in figure 2. Figure 2 also details the stages of the chain pillar loading cycle:

1. Development loading (calculated using tributary area concepts);
2. Front abutment loading, which occurs when the first longwall face is parallel with the pillar;
3. Main gate (side) abutment loading, when the load has stabilized after the passage of the first face;
4. Tailgate loading, when the second face is parallel with the pillar; and
5. Double goafing, when the pillar is isolated between two gobs.

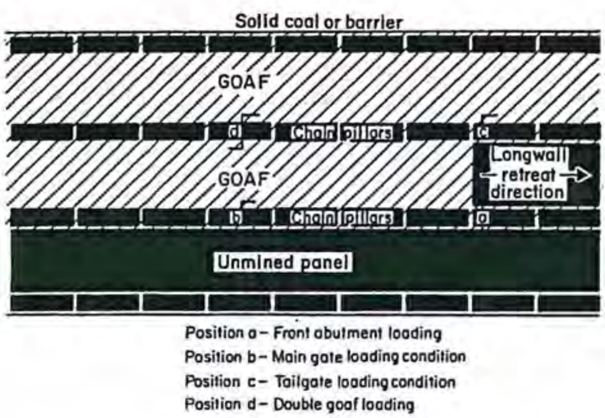

Figure 2. Stages in the dynamic loading cycle of longwall chain pillars.

It is during tailgate loading that the chain pillar (or cross section thereof adjacent to the tailgate intersection) experiences the greatest vertical loading during its "active life," i.e., the period where the chain pillar is playing its role in helping to maintain satisfactory gate road conditions. This project focused on tailgate performance (at the T-junction) as the design condition. The pillar stability factor in relation to the tailgate loading condition is designated as the "tailgate stability factor" (TG SF).

The project found that Australian chain pillars have an average length-to-width ratio of 3.2; crosscut centers on average are spaced at 100 m. The pronounced rectangular shape of Australian chain pillars may add strength to the pillar compared to a square pillar of the same minimum width. Mark et al. (*10*) reanalyzed the U.S. database using the Mark-Bieniawski rectangular pillar strength formula and found a slightly better correlation (in relation to the predictive success rate) than using the Bieniawski equation. In addition to the Bieniawski equation, this project assessed both the Mark-Bieniawski rectangular pillar formula (*11*) and the squat pillar formula (*12*) in relation to the correlation between the pillar stability factor and the CMRR.

In Australia, the significant impact of horizontal stress on coal mine roof stability is well documented (*13, 14*). The in situ horizontal stresses should not have a significant direct influence on tailgate roof stability due to the presence of an adjacent goaf. However, there is an indirect influence in terms of the degree of damage done to the roof during the initial roadway development and then to the main gate travel road and cut-throughs during longwall retreat. The effect of the in situ horizontal stress field on gate road serviceability (particularly on roof stability) is not taken into account directly by the ALPS methodology and was considered in more detail by the ACARP project. Finally, the project aimed to verify the applicability of the ALPS loading parameters β and F_t to Australian conditions.

MEASUREMENTS OF AUSTRALIAN ABUTMENT LOADS

The project measured changes in vertical stress across (and within) chain pillars at six collieries to determine whether the ALPS approximations should be refined. Three sites were located in the Bowen Basin Coalfield in Queensland (Central, Crinum, and Kenmare Collieries), two were in the Newcastle Coalfield (Newstan and West Wallsend Collieries), and one was at West Cliff Colliery in the Southern Coalfield (figure 3). Each monitoring site included an array of hydraulic stress cells (HSCs) generally located at midseam height to measure the changes in vertical stress. Most sites also included extensometers to monitor roof and rib performance. A general instrumentation layout is shown in figure 4.

Figure 3. Location of the field instrumentation sites.

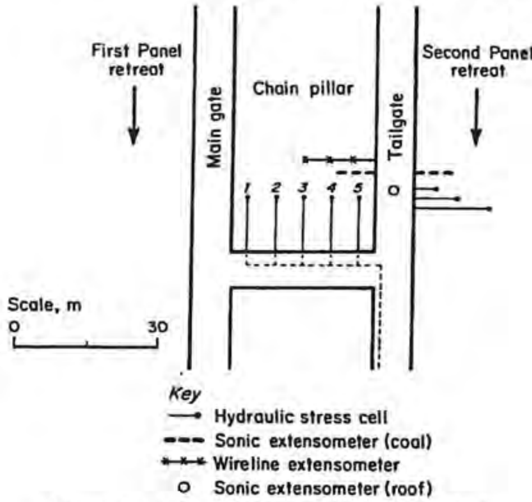

Figure 4. Instrumentation layout at a typical stress measurement site.

The six sites add considerably to the ALPS abutment load database. They include a much wider range of cover depths and width-to-depth ratios than the original U.S. data. There is also much more variety in the geologic environments. In addition, because the stress readings could be made remotely, monitoring was possible subsequent to the passing of the second longwall face. Of the 16 original U.S. panels, there were sufficient data to characterize the side abutment load in only 6, and only one panel provided data on the tailgate abutment factor. In contrast, data on both the side and tailgate loads were obtained from all six Australian monitoring sites. Details on the sites have been published elsewhere (*15, 16*).

Measurements of the main gate side abutment loading are used to calculate the abutment angle; measurements of the tailgate abutment (when longwall 2 is parallel with the instruments) are used to calculate the tailgate abutment factors. Figure 5 shows that the abutment angles at the three Queensland sites and from Newstan Colliery clearly fall within the range of the U.S. data.

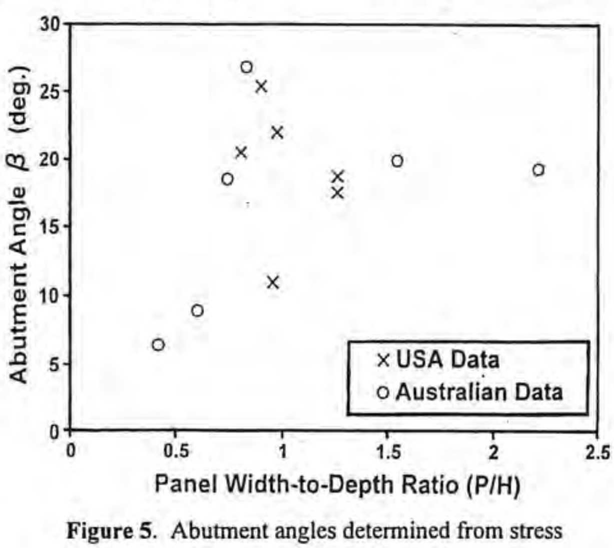

Figure 5. Abutment angles determined from stress measurement.

However, the abutment angles calculated for the two deepest mines, West Wallsend and West Cliff, are the smallest of any in the database. The overburden at these two mines (and at Newstan Colliery) also contains the massive sandstone and sandstone/ conglomerate strata commonly associated with the Newcastle and Southern Coalfields. The low width-to-depth ratio, along with the strong overburden, may be affecting the caving characteristics of the gob.

The Australian measurements of the tailgate abutment factor also show a high variability, with the mean at 1.3 in relation to an ALPS-style analysis. Figure 6 plots the development of the change in load during tailgate loading (as a multiple of the side abutment) against face position. It clearly indicates that the nature of the loading behavior at Central, Crinum, and Kenmare Collieries closely approximates that proposed by ALPS. However, the tailgate loading behavior at Newstan Colliery and particularly at West Wallsend Colliery reveals that the *double goaf load* is significantly greater than twice the measured main gate side abutment load. These data clearly suggest that a *much* greater portion of the main gatabutment load is distributed onto the adjacent unmined longwall panel than calculated on on theoretical grounds (figure 2).

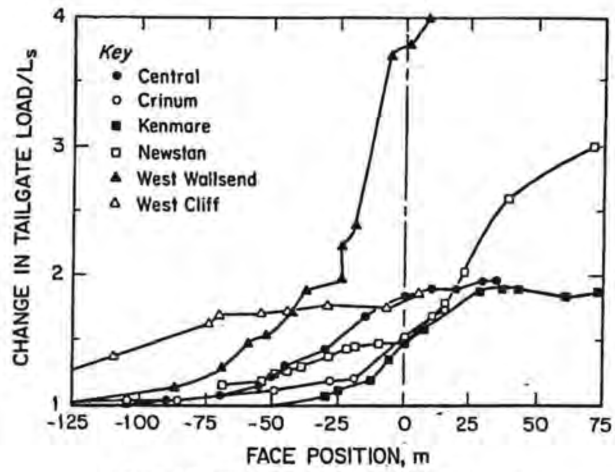

Figure 6. Development of abutment load at six monitoring sites.

The stress measurements collected by the project were supplemented by data from similar investigations previously conducted by other collieries, which were gratefully made available to the project (*16*). In general, the supplementary field data support the observations made from the project data. In Bowen Basin collieries, the loading behavior closely approximates that proposed within ALPS. For New South Wales collieries with strong, spanning overburden and a low width-to-depth ratio, the measured side abutment angles were significantly less than 21°.

In summary, it seems that an tailgate abutment factor $F_t = 1.5$, in conjunction with an abutment angle of $\beta = 21°$, is a reasonable and generally conservative approximation of the actual tailgate load for most Australian mines. The exceptions are two collieries and one locality (containing three collieries) within the Australian database, where there is sufficient evidence to suggest that site-specific loading parameters are more applicable. These are the Central and West Wallsend Collieries, and the deepest collieries within the Southern Coalfield (South Bulli, Tower, and West Cliff Collieries). For Central Colliery, the appropriate loading parameters seem to be β = 26° and F_t = 1.6. With regard to the three Southern Coalfield collieries, the recommended loading parameters are β = 10° and F_t = 1.5, which also apply to areas associated with West Wallsend Colliery that are unaffected by the *near-seam* sandstone/conglomerate channels. In areas where thickening of the channel occurs, it is assessed that the abutment angle of β = 10° should be maintained, while F_t should be increased to 3.5.

Two other variables can influence the calculation of pillar stability factors: *in situ coal strength* (S_1) and the *overburden density* (γ). A comprehensive study in the United States recently concluded that uniaxial compressive strength tests on small coal samples do not correlate with in situ pillar strength (*17*). That study and others in Australia and the Republic of South Africa (*1*) found that using a constant seam strength works well for empirical pillar design methods. Accordingly, the in situ coal strength is taken to be 6.2 MPa, as used in ALPS.

In some Australian mines, there is so much coal in the overburden that the overburden density is significantly reduced below the γ = 0.25 MN/m^3 that is typical for sedimentary rock. Dartbrook and Kenmare Collieries have undertaken satisfactory analyses of their overburden and have determined that γ = 0.22 MN/m^3 and 0.23 MN/m^3, respectively.

INDUSTRY REVIEW

The aim of the industry review was to construct a historical database of gate road and chain pillar performance. During the course of the project, 19 longwall mines (a cross section from the 5 major Australian coalfields) were visited. Underground inspections were conducted at each that incorporated a subjective assessment of gate road performance while documenting the relevant details in relation to panel and pillar geometry, roof and floor geology, artificial support, and in situ stress regime. Brief summary reports were then forwarded to each mine to confirm the accuracy of the recorded data. The complete data set has been summarized elsewhere (*16*).

The U.S. database included the Secondary Support Rating (SSUP), which is described as a rough measure of the volume of wood installed per unit length of the tailgate (*3*). It should be noted that 59 of the 62 cases (i.e., 95%) within the U.S. database used standing secondary support (predominantly in the form of timber cribbing) along the tailgate. In the Australian database, less than 50% (9 out of 19) mines routinely installed standing secondary support along the tailgate. In the context of this study, standing secondary support refers to timber cribbing, the Tin Can system, Big Bags, etc., and does not include tendon support (cable bolts or Flexibolts) installed within the roof. Because of the variety of secondary supports used, a yes/no variable was used instead of a quantitative rating. Figure 7 illustrates the relationship between SSUP, CMRR and depth within the Australian database. The presence of adverse horizontal stress conditions was also described by the yes/no variable HORST.

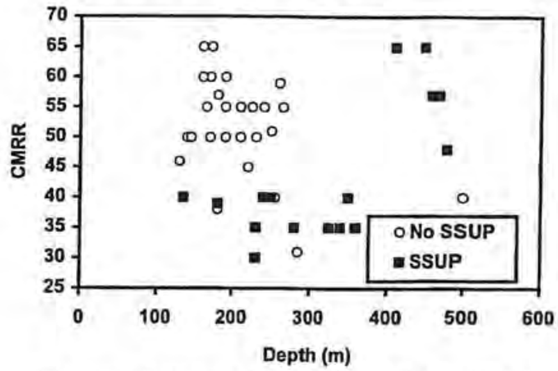

Figure 7. Relationship between SSUP, CMRR and depth of cover within the Australian data base.

STATISTICAL ANALYSES

The same statistical technique used with the U.S. ALPS database, that of discriminant analysis, was used with the Australian data. Discriminant analysis is a regression technique that classifies observations into two (or more) populations. In the case of the ALPS data, the classified populations are tailgates with satisfactory and unsatisfactory tailgate conditions.

An initial change that was made with the Australian data was to include "borderline" tailgates with the unsatisfactory cases. This modification is consistent with the Australian underground coal industry's desire to have in place strata management plans that design against both borderline and unsatisfactory gate road conditions. It also adds to the otherwise small pool of unsatisfactory cases available for analysis.

In their analysis, Mark et al. (*3*) were not able to quantify the effect of standing secondary support on tailgate conditions. However, because nearly every U.S. case used some standing support, SSUP is basically *intrinsic* to the design equation (equation 1). Because less than 50% of Australian mines use secondary support, it seems reasonable to assume that tailgates that presently incorporate standing secondary support would become unsatisfactory if it were removed. A major modification was to include all collieries utilizing standing secondary support in the modified-unsatisfactory category of tailgate conditions. The final database includes 50 case histories with 29 modified satisfactory and 21 modified-unsatisfactory cases.

Numerous analyses were conducted to determine the best design equation. Ultimately, the most successful design equation relates the required TG SF to the CMRR, as shown in figure 8:

$$TG\ SF = 2.67 - 0.029\ CMRR \qquad (3)$$

Equation 3 correctly predicted the outcome of all except seven case histories, for a success rate of 86%. Comparing equation 3 to the U.S. design equation (equation 1), it may be seen that the TG SF is generally more conservative than the ALPS SF for weaker roof, but the TG SF decreases more rapidly than the ALPS SF as the roof becomes stronger.

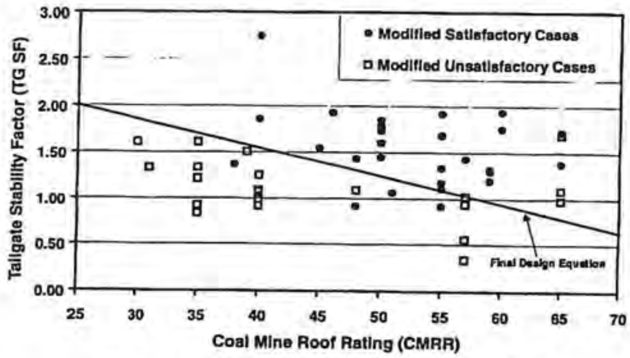

Figure 8. The final design equation relating the CMRR to the TG SF.

Another strong relationship that was evident in the case histories was between the primary support and the roof quality. Figure 9 plots the PSUP against the CMRR, and the best-fit regression is of the following form:

$$PSUP = 1.35 - 0.0175\ CMRR \qquad (4a)$$

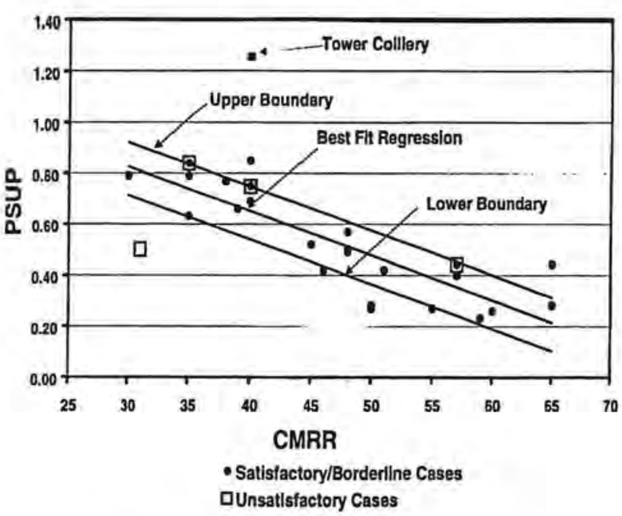

Figure 9. Design equations for primary support based on the CMRR.

It seems that Australian mine operators have intrinsically adapted their primary support patterns to the roof conditions and operational requirements. Mark et al. (*3*) reached a similar conclusion for the United States.

Upper- and lower-boundary equations (4b and 4c, respectively) relating CMRR to PSUP have also been proposed and are illustrated in figure 7:

$$PSUP_U = 1.45 - 0.0175\ CMRR \qquad (4b)$$

$$PSUP_L = 1.24 - 0.0175\ CMRR \qquad (4c)$$

Equation 4c may be applicable, for example, when the mining layout is not subject to adverse horizontal stress conditions and/or standing secondary support is planned as part of the colliery's strata management plan.

Mark et al. (*3*) also found a strong correlation between the CMRR and the entry width. No such correlation was seen here.

It is interesting to note some similarities and differences between the U.S. and Australian databases. For example, overall roof quality seems to be reasonably similar in the two countries. The mean CMRR in the United States is 53.7 with a standard deviation (SD) of 13.9; this compares with an Australian mean of 49.5 and SD = 10.0. However, the mean Australian PSUP is 0.49 (SD = 0.23), which is approximately twice that of the U.S. database.

Studies by Mark (*18*) and Mark et al. (*19*) suggest that the horizontal stress levels in the two countries are comparable. It seems that philosophical differences are more likely responsible for the different levels of primary support. Most Australian coal mines have an unwritten (sometimes written) policy of no roof falls; U.S. multientry mining systems seem more tolerant of roof falls. Also, most Australian coal mines have an antipathy toward standing secondary support for reasons associated with a two-entry gate road system. It seems that the main way in which Australian operations prevent poor tailgate conditions is to install substantial primary support on development. Therefore, in Australia one would expect a strong relationship between the level of primary support and a reliable roof rating system. This is exactly what transpires, which adds to the credibility of the CMRR.

Additional statistical analyses tested whether the accuracy of ALPS could be improved by replacing the original Bieniawski formula with another pillar strength formula. It was found that the Mark-Bieniawski formula had virtually no impact on the classification success rate, while the squat pillar formula significantly reduced classification success rate. The conclusion was to remain with the original Bieniawski formula used in the "classic" ALPS.

ANALYSIS OF TAILGATE SERVICEABILITY (ALTS)

The chain pillar design methodology proposed by the project is referred to as "Analysis of Longwall Tailgate Serviceability" (ALTS). The design methodology recognizes the impact of ground support on tailgate serviceability and incorporates guidelines in relation to the installed level of primary support and the influence of standing secondary support on the design process.

A design flowchart (figure 10), Microsoft® Excel Workbook, and user manual have been developed. The spreadsheet workbook (*ALTS Protected.xls*) was formulated to facilitate the computational components of the design methodology.

The ALTS design process should only be employed in designing chain pillars that are subject to second-pass longwall extraction. If the chain pillars under consideration are not to be subject to second-pass longwall extraction, then an alternative pillar design method should be employed based on pillar stability and outer gate road serviceability requirements. The monitored chain pillar loading behavior (conducted as a part of the project) will assist in estimating the main gate load for design purposes.

The recommended chain pillar width (rib to rib) is contingent upon an appropriate level of primary support. That level of primary support (i.e., $PSUP_L$ to $PSUP_U$) is dependent on (1) the orientation of longwall retreat in relation to the magnitude and direction of the major horizontal stress and (2) the use of standing secondary support along the length of the gate road.

The database is able to identify situations where it is likely that standing secondary support may be required. However, there are insufficient data at this stage to make numerical recommendations for the SSUP similar to those made for the TG SF and PSUP. Appropriately qualified personnel should assess the type, level, and timing of SSUP installation.

CONCLUSIONS

The following main goals of the project were achieved:

- To establish a chain pillar design methodology that has widespread application to Australian longwall operations; and

- To quantify the probable variance in the chain pillar loading environment between collieries and mining localities and to incorporate this variance within the design methodology.

In addition, the study has been able to propose definitive guidelines with regard to the installed level of primary support and to conduct a subjective analysis regarding the impact of standing secondary support on the design process. This provides the Australian coal industry with a truly integrated design methodology with regard to tailgate serviceability that has been able to address the main factors controlled by the mine operator.

The initial benefit from this project is that mine managers and strata control engineers will be able to identify where chain pillars can be reduced in size and where increases may be necessary. They can make these decisions with the confidence that a credible Australian database is the foundation for the design methodology.

This project has identified that there is an opportunity for some mines that do not currently incorporate the routine installation of secondary support along their tailgate to make significant reductions in chain pillar width. It is an operational decision whether a reduction in pillar width is more or less beneficial to production output and costs than the introduction of secondary support along the length of the tailgate. This project simply highlighted that the opportunity exists.

The chain pillar monitoring exercises conducted at collieries under deep cover or with strong roof have found that the abutment load may be overestimated by using a generic abutment angle of $\beta = 21^{\circ}$. However, the aggressive tailgate loading behavior monitored at West Wallsend Colliery (figure 5) provided a warning, which emphasized the need to use great caution before making any sweeping changes to a proven chain pillar design tool. Although the way in which the load manifested itself at West Wallsend was significantly different from that proposed by ALPS, the resultant tailgate load was quite similar.

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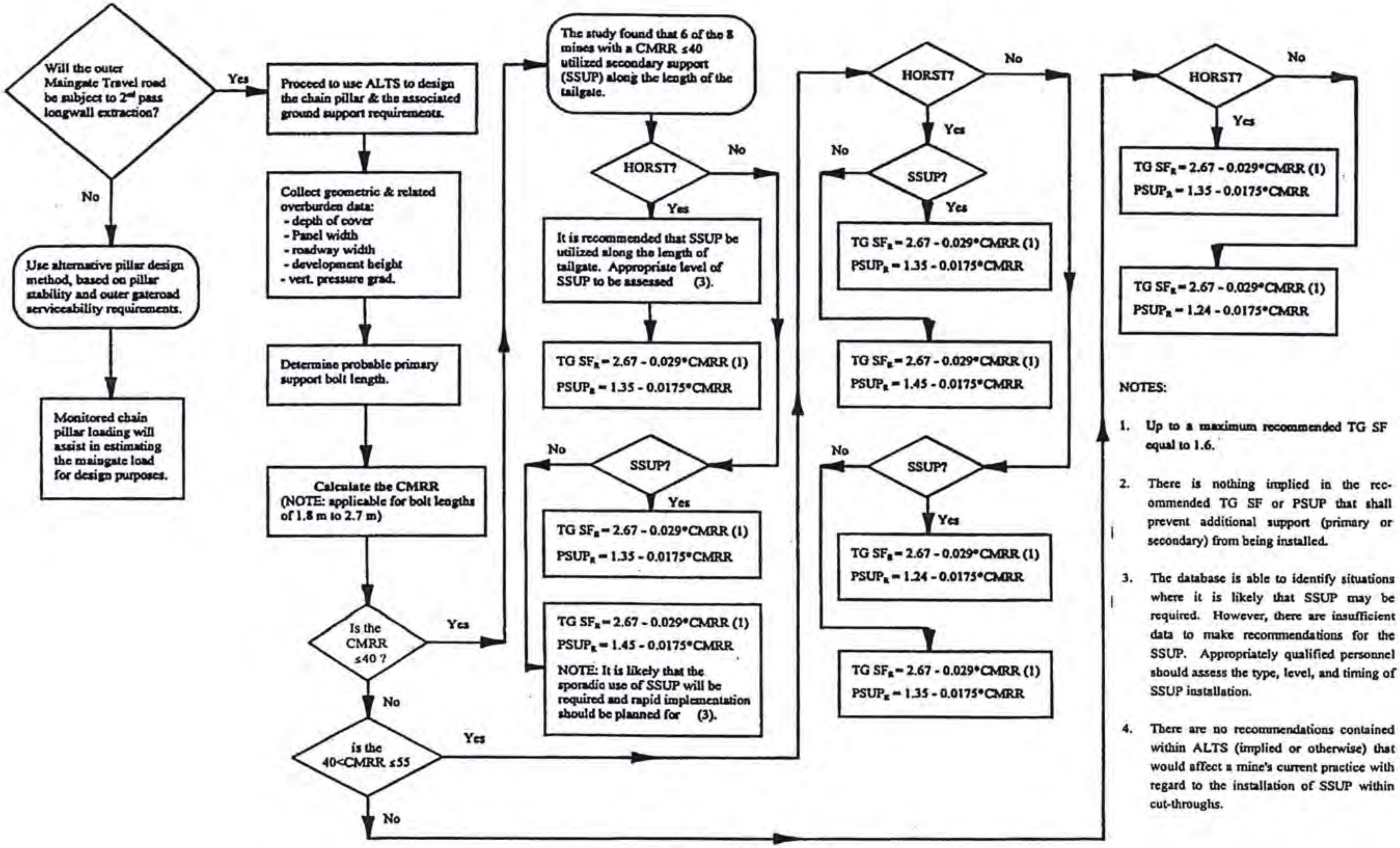

NOTES:

1. Up to a maximum recommended TG SF equal to 1.6.
2. There is nothing implied in the recommended TG SF or PSUP that shall prevent additional support (primary or secondary) from being installed.
3. The database is able to identify situations where it is likely that SSUP may be required. However, there are insufficient data to make recommendations for the SSUP. Appropriately qualified personnel should assess the type, level, and timing of SSUP installation.
4. There are no recommendations contained within ALTS (implied or otherwise) that would affect a mine's current practice with regard to the installation of SSUP within cut-throughs.

Figure 10. Design flowchart for the Analysis of Longwall Tailgate Serviceability (ALTS).