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ALTS 2009 - A Ten Year Journey

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ABSTRACT: This paper summarises the development and application of the ALTS (Analysis of Longwall Tailgate Serviceability) design methodology for longwall gateroad design associated with Australian collieries. The original ALTS design methodology was presented to the industry via workshops in early 1999 and since that time continued research, updating of the database and direct support from most Australian longwall operations has resulted in the ALTS 2009 software package, which also incorporates ADRS (Analysis and Design of Rib Support). In addition to the chain pillar design component, ALTS 2009 now provides design recommendations for primary and secondary roof and rib support for both the belt road and travel road/tailgate. ALTS and ADRS are empirical techniques which recognise that several geotechnical and design factors affect gateroad performance and in addition that operational and safety issues essentially dictate the level of performance required. These techniques are based on a sound mechanistic understanding of roadway behaviour, are transparent in their content and application and geotechnical engineers can be readily trained in their use.

As part of the review of ACARP's geomechanics-related research in 2991, 52 underground geomechanics-related projects were highly rated in terms of their research quality and industry application. ALTS was one of 11 projects that received the highest rating and yet it took several years for it to gain the widespread acceptance it now enjoys. It is suggested that the principal causes of this delay were; a misguided point of view when relating the science of rock mechanics to engineering and, some ill-informed commentary concerning empirical modelling in general and specifically with respect to ALTS. The myths and some of the mis-information surrounding ALTS are addressed.

INTRODUCTION

In many cases prior to 1998, chain pillars in Australia had been designed utilising a process similar to that used for pillars within bord-and-pillar operations, which applies a Factor of Safety in relation to pillar collapse. As discussed by Colwell et al (1999) this approach was inadequate and there was a clear need for a design method uniquely developed for Australian longwall chain pillars. In 1997 with ACARP (Australian Coal Association Research Program) and colliery support a research program (ACARP Project C6036, Chain Pillar Design – Calibration of ALPS) commenced to develop such a method.

The starting point or basis of that research program was ALPS, i.e. Analysis of Longwall Pillar Stability. The ALPS methodology (Mark, 1990 and Mark et al, 1994) was chosen because of its operational focus, as it uses tailgate performance as the determining chain pillar design criteria rather than simply *inner core* pillar stability which is the sole focus of factor of safety design methods. Furthermore ALPS recognises that several geotechnical and design factors, including (but not limited to) chain pillar stability, affect tailgate performance.

Based on this initial research the original ALTS design methodology was developed (Colwell, 1998 and Colwell, 1999). During the initial ALTS research, it was identified that a compromise between pillar size, primary roof support and secondary roof support is possible and necessary to efficiently achieve satisfactory tailgate conditions.

The original database (1997/8) was of sufficient size to confidently make recommendations for chain pillar size and to provide guidelines in relation to the installed level of primary roof support. However it was only possible to make a subjective assessment in relation to secondary roof support requirements. Funding from individual collieries and mining companies allowed for the expansion of the database in 2000, from which the ALTS II design methodology was developed (Colwell et al, 2003).

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As part of his review of ACARP's geomechanics-related research, Brown (2001) considered 52 underground geomechanics-related projects and individually rated the projects in terms of their research quality and industry application. ALTS was one of only 11 projects that received the highest rating and yet it took several years for it to gain the widespread acceptance it now enjoys. It is suggested that the principal causes of this delay were due to a misguided point of view when relating the science of rock mechanics to engineering and some ill-informed commentary concerning empirical modelling in general and specifically with respect to ALTS.

The development of ALTS II marked a significant leap forward for the Australian coal industry, in that the interaction between roof quality, primary and secondary roof support and chain pillar size had been quantified in terms of satisfactory tailgate performance. With ALTS II the roof support levels could (and should) be assessed in combination with rather than independently of the chain pillar dimensions.

In subsequent years the ALTS database was continually updated and significantly expanded such that it now includes detailed information in relation to both the tailgate (148 cases) and maingate belt road (58 cases). Further funding from individual collieries and mining companies resulted in the 3-year ALTS 2006 Project. A major component of the ALTS 2006 project was to conduct research so as to develop a roof support design capability for the maingate belt road which would then be included as a design module within the ALTS 2009 software package. This paper details those and associated analyses and their impact on ALTS.

LONGWALL LAYOUT AND TERMINOLOGY

To assist with subsequent discussion contained in this paper and terminology used, reference is made to Figure 1, which is a plan schematic of a typical Australian longwall mining layout utilising a two heading gateroad system. Figure 1 depicts a fully extracted longwall panel, one currently being extracted and a third where the gateroads (MG 3 – 'A' and 'B' Headings) are still to be completed to fully delineate the longwall panel and chain pillars. 'A' Heading is generally referred to as the travel road along which men, materials and machinery will travel, while 'B' Heading is called the belt road where the conveyor belt is installed to transport coal from the longwall extraction face.

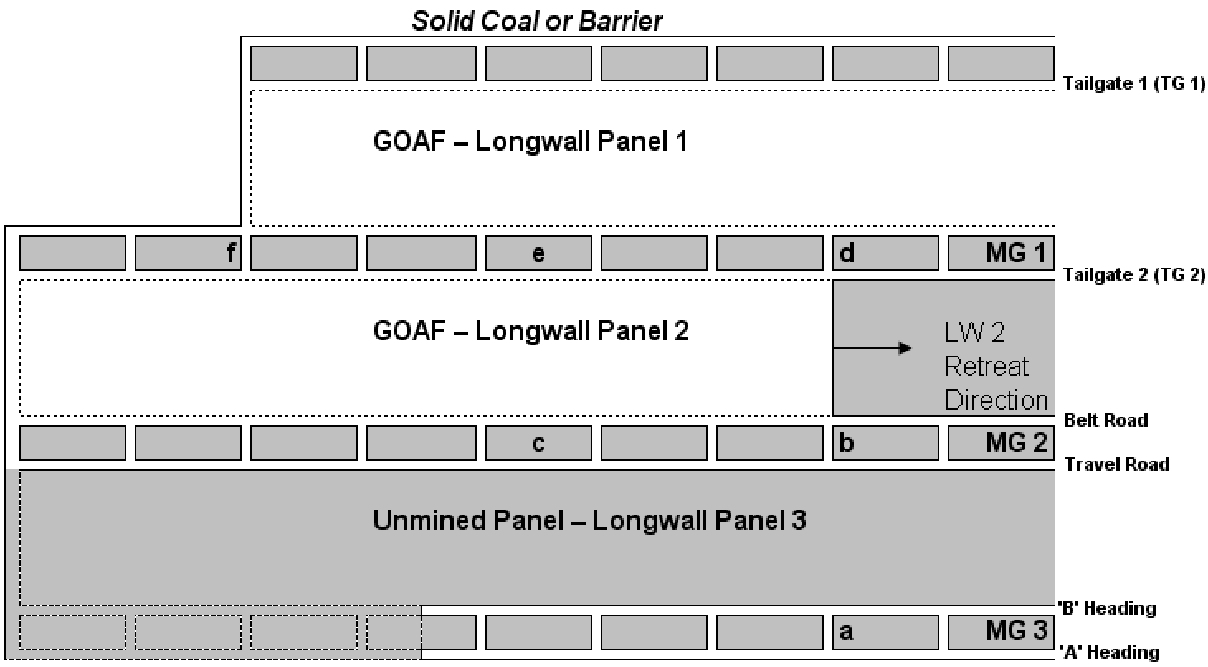

Figure 1 - Typical Australian longwall layout

In a series of longwall panels, 'A' Heading typically serves two roles, firstly as the travel road of the current longwall panel and secondly as the tailgate of the next. For example, the travel road of Longwall Panel 2 (LW 2, refer Figure 1) will become the tailgate of LW 3. Therefore this travel road/tailgate is subject to a series of changing geotechnical environments, moving from development

(Position a) to the passage of the 1st adjacent longwall face (Positions b and c respectively) and finally being subject to the approach of the second adjacent longwall face up to the tailgate intersection (Position d) with the travelling longwall face.

With reference to Figure 1 it can be seen that the chain pillars are also subject to a series of changing loading environments with the following terminology being used to describe each stage of the chain pillar loading cycle:

- Position a – Development loading
- Position b – Maingate belt road or front abutment loading
- Position c – Maingate (MG) loading
- Position d – Tailgate (TG) loading
- Position e – Double goaf (DG) loading

MAINGATE BELT ROAD ROOF SUPPORT ANALYSES

The maingate belt road database comprises 58 cases representing 33 longwall operations where the Coal Mine Roof Rating (CMRR) ranges from 25 to approximately 80 and the cover depth ranges from 100m to 510m. The analyses clearly indicated that the principal geotechnical drivers which, in combination, essentially dictate the level of roof support required to maintain a satisfactory level of roof performance during longwall extraction include:

1. The structural integrity of the immediate roof (as measured by the CMRR) and,
2. The magnitude of (or at least a reliable estimate or indicator of) the horizontal stress acting across the roadway roof adjacent to the 'travelling' intersection with the longwall face (refer Position b – Figure 1).

Calculating the Resultant Horizontal Stress (σ_R-Dev & σ_R-MGB)

The following information is required to calculate/estimate the horizontal stress acting perpendicular to the direction of drivage (i.e. σ_R-Dev, MPa) and subsequently that stress acting across the roof of the belt road adjacent to the intersection with the longwall face during retreat extraction (i.e. σ_R-MGB, MPa):

- Longwall retreat direction (LW(θ), degrees from true north)
- Major horizontal stress direction (σ_H orientation – degrees from true north)
- Magnitude of the major horizontal stress (σ_H, MPa)
- Magnitude of the minor horizontal stress (σ_h, MPa)

The angle between the longwall retreat direction and the major horizontal stress direction is designated as "β - Beta" (refer Figure 2). Note: the minor horizontal stress direction is taken to be at 90° to the major horizontal stress direction.

The resultant horizontal stress acting perpendicular to the direction of driveage (i.e. σ_R-Dev) is calculated using equation 1 (refer Page 92, Hoek & Brown, 1980) which is derived from Mohr's Circles:

$$\sigma_R\text{-Dev} = [0.5 * (\sigma_H + \sigma_h) - 0.5 * (\sigma_H - \sigma_h) * \cos(2\beta)] \quad \text{MPa} \qquad (1)$$

The change and increase in horizontal stress in the roof that occurs about the belt road intersection with the longwall face during retreat extraction (i.e. refer Position B – Figure 1) is often referred to as *Maingate Stress Notching*. The magnitude of the resultant stress (in MPa) is denoted as σ_R-MGB, and was estimated based on the research findings of Gale and Matthews (1992), Mark et al (1998) and Su and Hasenfus (1995) to estimate σ_R-MGB.

Gale and Matthews (1992) linked a Stress Concentration Factor (SCF) to the angle between the longwall retreat direction and the stress direction (i.e. the angle "β" - refer Figure 2). This relationship is detailed in Figure 3 such that the SCF is used as a multiple of the magnitude of the *in situ* horizontal stress to estimate the resultant stress acting across the roof about the belt road intersection with the longwall face. When the angle (β) between the direction of longwall retreat and the major horizontal stress (σ_H) is between 0° and 90° then the belt road is subject to a concentration of the major horizontal stress such that σ_R-MGB = SCF * σ_H.

The maingate is technically within a zone of major horizontal stress relief when 90° < β < 180°, however in this situation the SCF would need to be applied to the minor horizontal stress (σ_h) to assist in calculating a resultant horizontal stress magnitude (σ_R-MGB) for design purposes. Therefore it is necessary to have reliable/realistic estimates for the magnitude and direction of both the major and minor horizontal stresses. Where possible the estimates used for σ_H and σ_h should be that which best represent the immediate roof strata. The database was formulated and analysed in this manner

A similar relationship to that displayed in Figure 3 was found by Su and Hasenfus (1995) using three-dimensional finite element modelling. The research findings of Su and Hasenfus (1995) were also utilised by Mark et al (1998) and incorporated by NIOSH in their software program, Analysis of Horizontal Stress in Mining (AHSM). In this instance the angle (β) between the direction of longwall retreat and σ_H (from 0° to 180°) is plotted against a percentage (%) of the maximum possible stress concentration.

It was found that the maximum (or 100% of the maximum) stress concentration occurred when $\beta \approx 70°$ (similar to that by found Gale and Matthews, 1992 – refer Figure 3) and when $\beta \approx 160°$ the stress concentration is a minimum, which is expressed or plotted as 0% (Mark et al, 1998). In terms of the horizontal stress magnitude acting across the roof this is not possible i.e. 0 MPa. While there may be 100% relief of the major horizontal stress there will still be a concentration of the minor horizontal stress as previously explained.

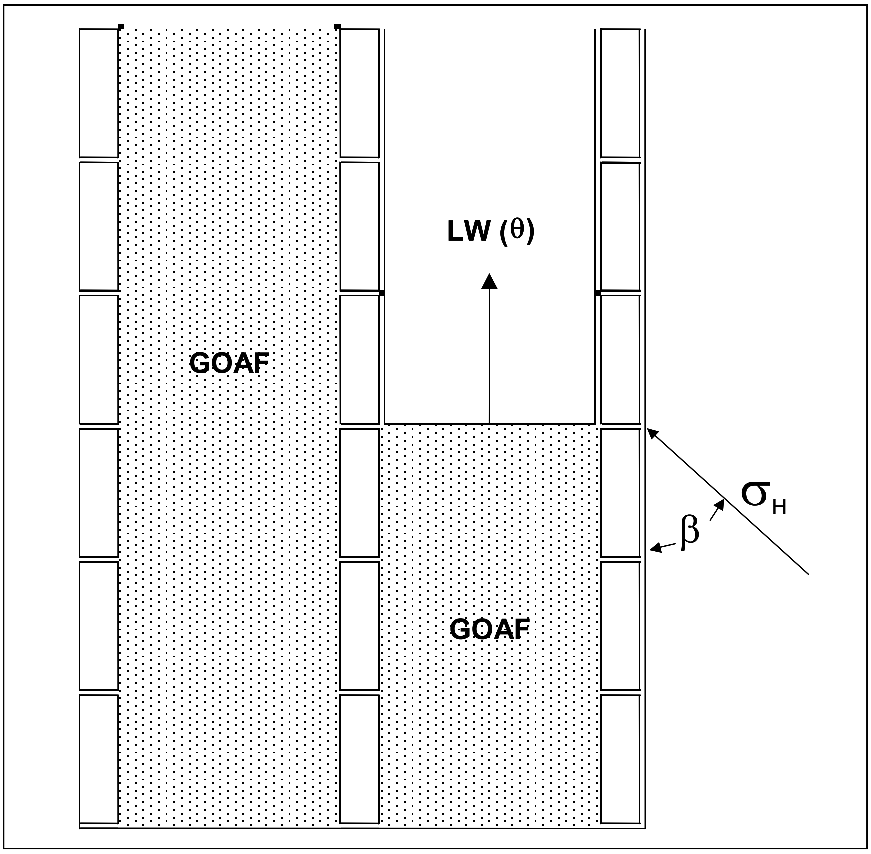

Figure 2 - The angle β used to determine the values of σ_R-Dev and σ_R-MGB

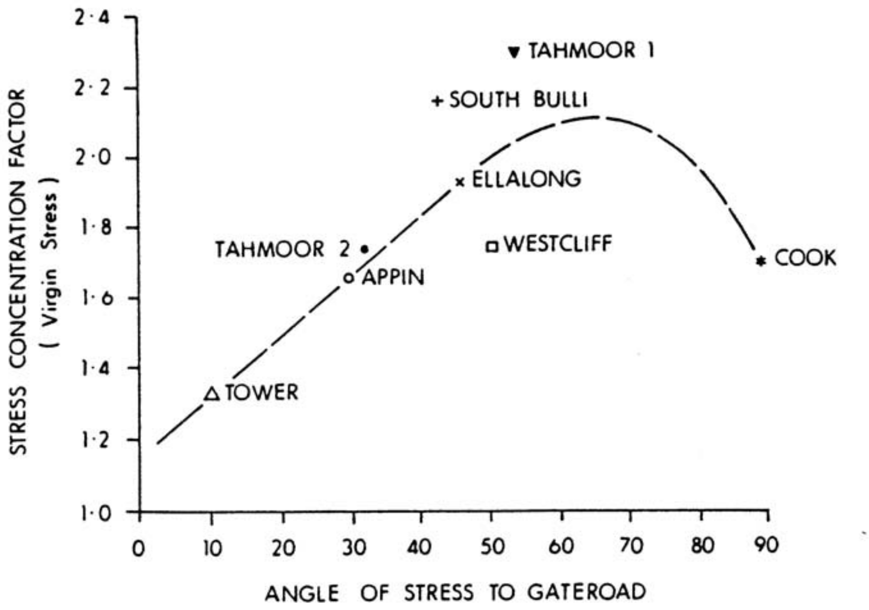

Figure 3 - Relationship between stress concentration factor and angle of gateroad to stress direction (after Gale and Matthews 1992)

Utilising the research findings of Gale and Matthews (1992), Mark et al (1998) and Su and Hasenfus (1995), Figure 4 was developed in terms of the SCF associated with the major horizontal stress (σ_H), which is now denoted as SCF_H, to estimate the maximum stress in terms of σ_H. When $90° < \beta < 180°$ then a concentration of the minor horizontal stress (σ_h) occurs. The SCF associated with the minor horizontal stress is denoted as SCF_h. Figure 4 can be used to interpret SCF_h; for example if $\beta = 150°$ then the angle between the direction of longwall retreat and the minor horizontal stress would be 30° and therefore $SCF_h \approx 1.7$, while $SCF_H \approx 1.05$.

Based on Figure 4 and the above discussion the following logic is utilised in calculating σ_R-MGB.

1. When $0° < \beta < 90°$ then $\sigma_R\text{-MGB} = SCF_H * \sigma_H$ (2)
2. When $90° < \beta < 180°$ then $\sigma_R\text{-MGB} = \text{Max}\,[(SCF_H * \sigma_H)\ \&\ (SCF_h * \sigma_h)]$ (3)

Roof Support Analyses

The initial series of analyses associated with the maingate belt road database plotted the total roof support level measured by the Ground Support (GRSUP) rating - see Appendix A) against the CMRR for both headings and intersections. It should be noted that "Headings" initially refers to the sections of the belt road, either travel road or tailgate (refer Figure 1) between cut-through intersections, while "Intersections" refers to the sections of the gateroad that intersect with the cut-throughs. It was found during the course of the research that most collieries (as a part of their Support Rules) increase roof support levels within the intersections and for certain distances either side of the cut-through edge along the heading (i.e. inbye and outbye of the intersections). This practice is consistent with both the geotechnical environment and operational factors.

For example with respect to the belt road Thomas & Wagner (2006) state that *"during longwall retreat the magnitude of horizontal stress notching in a maingate belt road will increase on the inbye side of a cut-through and reduce on the outbye side of a cut-through. This phenomenon is related to the tendency for the horizontal stress to concentrate between the longwall goaf and the cut-through (termed "stress pinching") and the subsequent ability of the cut-through to relieve the horizontal stress about the gate road when the face retreats outbye of the cut-through".*

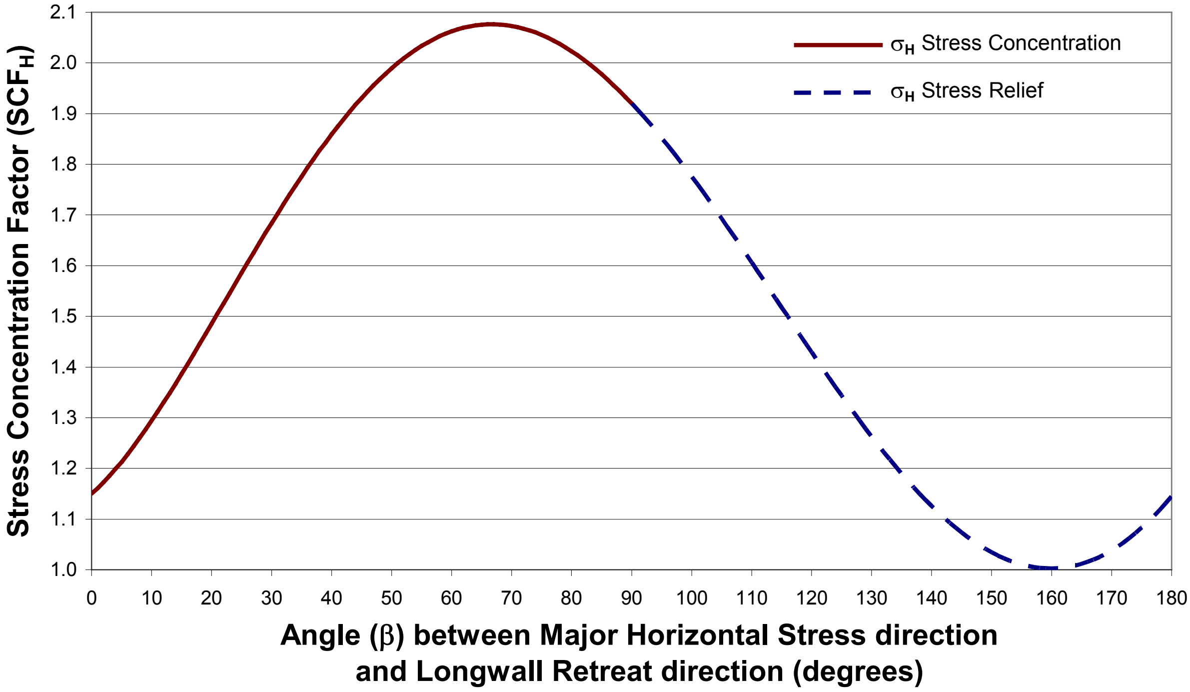

Figure 4 - SCF_H versus β

Furthermore the size or "effective area" of an intersection can be due to operational issues (i.e. how the intersections are formed), what level of standing support (if any) is installed at the mouth of the cut-through during longwall retreat and whether pillar corners are lost post development or as a result of increased vertical load associated with longwall retreat. These issues would also impact on support densities within and about intersections (for both the maingate and tailgate). Due to space constraints associated with a conference paper it is only the "Headings" analyses that are presented.

Based on linear regression analyses; a strong exponential relationship was found between the installed level of roof support (GRSUP refer Appendix A) and the structural integrity of the bolted mine roof interval (CMRR). Figure 5 displays the database for headings as well as the exponential trendline relationship and upper and lower boundaries that encompass the vast bulk (approximately 95%) of the data.

However further analyses, utilising the statistical technique of multiple regression revealed that in addition to the structural integrity of the roof (as measured by the CMRR), σ_R-MGB also had a major impact on the resultant GRSUP utilised by the collieries. Based on the multiple regression analyses the following relationship was found with respect to headings:

$$LN\ (GRSUP_{Headings}) = 5.3604 - 0.0415\ CMRR + 0.0201\ \sigma_R\text{-MGB} \qquad (4)$$

or

$$GRSUP_{Headings} = 212.81 \times e^{-0.0415\ CMRR} \times e^{0.0201\ \sigma R\text{-MGB}} \qquad (5)$$

With the inclusion of σ_R-MGB the correlation (in terms of GRSUP v's CMRR & σ_R-MGB) increases significantly and is an exceptionally high 0.89. Based on the relationships associated with equations 4 & 5; a roof support monogram can be produced to "visually" demonstrate the combined impact of the CMRR <u>and</u> σ_R-MGB on GRSUP. Figure 6 clearly illustrates that the GRSUP v's CMRR relationships for varying stress levels acting across the roof (i.e. σ_R-MGB) fit seamlessly within the upper and lower boundaries of the database. The maximum σ_R-MGB associated with the maingate belt road database is approximately 45 MPa.

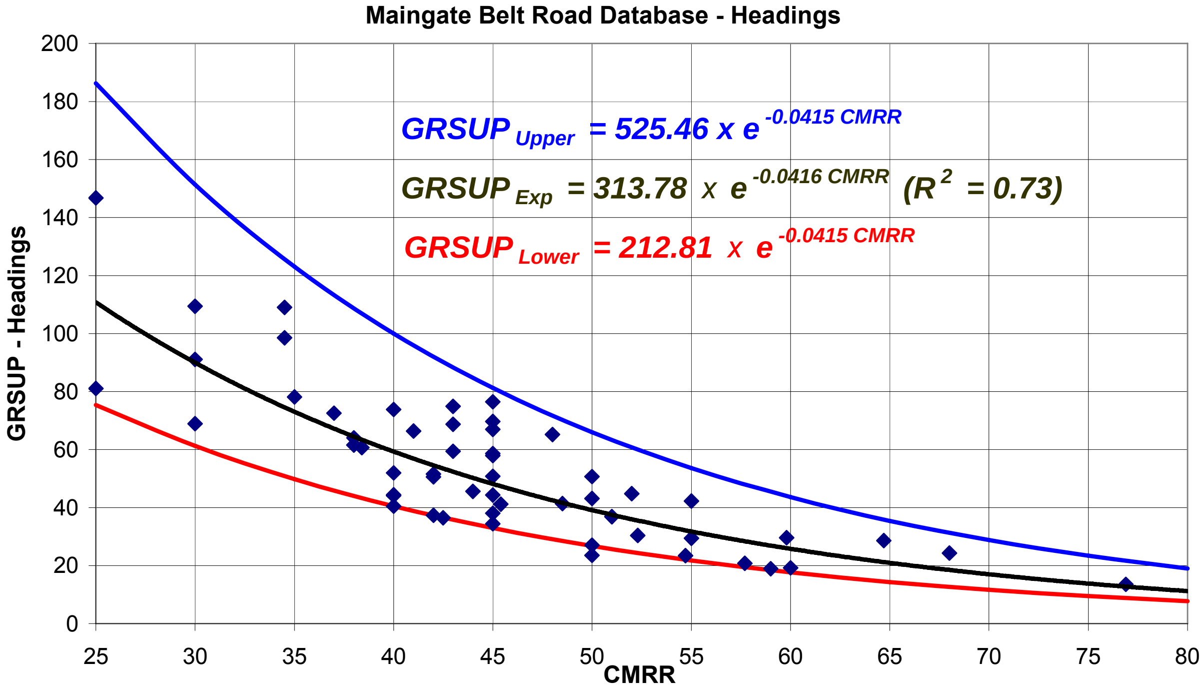

Figure 5 - GRSUP v's CMRR maingate belt road headings

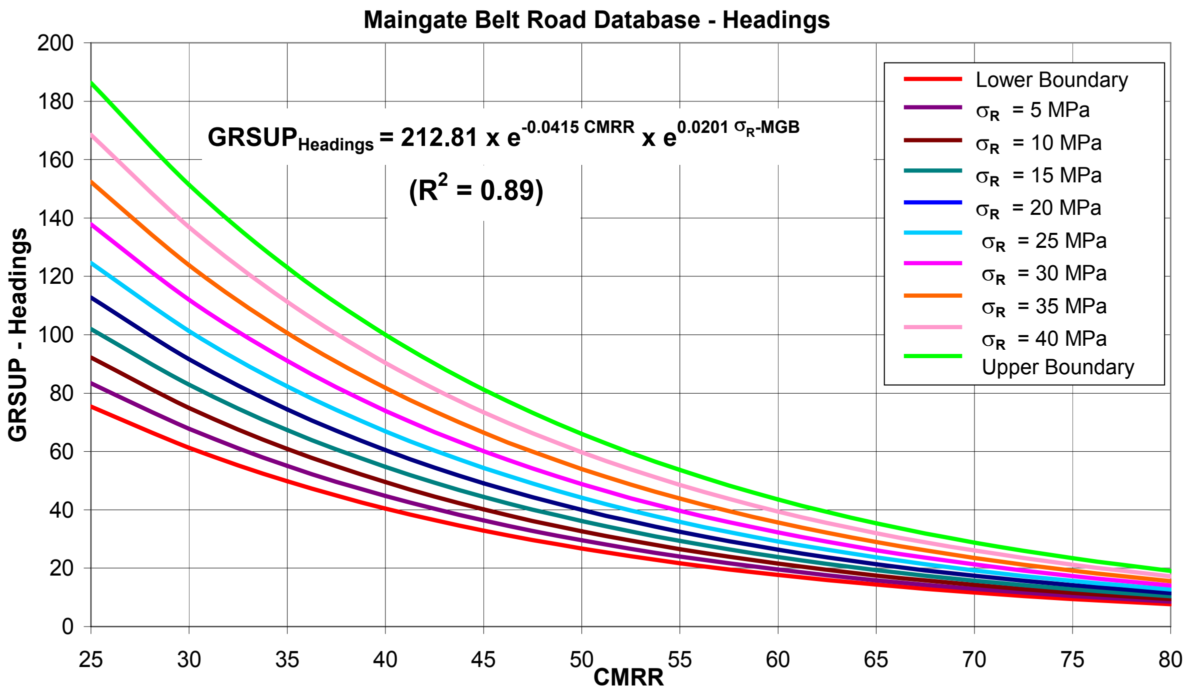

Figure 6 - GRSUP v's (CMRR and σ_R-MGB) – maingate belt road headings

Supplementary roof support analyses

When utilising empirical models for geotechnical design, the size (i.e. number of cases) and extent (i.e. number of different coalfields/collieries) of the database is an important factor to consider with respect to the confident application of the statistical relationships.

For example Salamon et al (1996) describe the Australian pillar database of 19 collapsed and 16 unfailed cases as a *"relatively small database"*, however the resultant UNSW pillar strength equation (Galvin et al, 1999) derived from the Australian database can be confidently used for design as

Salamon et al (1996) combined the Australian database with the much larger South African database (142 cases) and clearly demonstrated, *"that the strength estimates derived from the combined database approximate well both the Australian and South African strengths computed from the individual estimators"*. In practical terms what this means is that the large South African database essentially *underpins* our confident use of the *UNSW rectangular pillar strength formula* for the design of pillars which fall within the *limits of the geotechnical parameters* associated with the combined database.

With respect to the above analyses, pillar failure was defined as *collapse* of the pillar not simply *pillar yield*. An outcome of this type (i.e. pillar collapse) when a pillar is designed to be stable would not be acceptable within any country's underground coal industry and therefore is a *black & white* outcome.

Unfortunately with respect to roof support design it not generally practical to combine another coal industry's roof support database with an Australian roof support database as the tolerable level of risk, in terms of roof instability, will vary from country to country.

For example the roof support design methodology developed by NIOSH for the United States underground coal industry, ARBS (Analysis of Roof Bolt Systems – Mark et al, 2001) defines *Failure* as, *"more than 1.5 reportable roof falls per* 3048 m (10,000 ft) *of drivage"*. These are roof falls as a result of roadway development and therefore do not include gateroad roof falls associated with longwall retreat. This definition of roof failure (or level of roof falls) would be totally unacceptable in the Australian underground coal industry and this discussion highlights that a country's tolerable level of risk is a critical factor in the level (and type of support) utilised and in developing a roof support design methodology.

The maingate belt road database of 58 cases (reported here) were all considered successful by the respective colliery in the sense that the colliery reported that there had been no production delays or safety concerns and certainly no roof falls or remedial roof support measures required. In terms of size, the maingate belt road database would be considered medium size with respect to worldwide databases utilised for geotechnical design in relation to underground coal mining. Therefore the question is, *"can the maingate belt road database be supplemented or tested to increase our confidence in the application of equation 5 for the geotechnical design of roof support associated with the maingate belt road?"*

The primary roof support database developed via the various ALTS research projects comprises 109 cases (representing 38 collieries; being 36 longwall and 2 bord & pillar). The analyses associated with the primary roof support database found that the principal geotechnical drivers which, in combination, essentially dictate the level of roof support required to maintain a stable roof during and as a result of roadway development are the structural integrity of the immediate roof (as measured by the CMRR) and the horizontal stress acting perpendicular to the drivage direction (i.e. σ_R-Dev)

The maingate belt road and primary roof support databases cannot be directly combined due to an operational factor. With respect to the primary roof support database it is known that in addition to the geotechnical/risk related issues, operational factors directly influence the level of primary support utilised within the gateroads of Australian collieries. For example many collieries elect to install a level of primary roof support off the continuous miner greater than what would be required to simply maintain satisfactory roadway conditions on development as it is operationally more convenient or effective to do so off the miner rather than installing secondary support at a later stage to maintain satisfactory roadway conditions during longwall retreat.

The maingate belt road roof support database is not subject to a similar operational issue as only that roof support deemed necessary to satisfy the geotechnical (e.g. subject to σ_R-MGB) and risk related issues is installed, i.e. a colliery would not plan to install "tertiary" support in the belt road during longwall retreat as all planned roof support is installed prior to longwall retreat.

To overcome this operational issue and in an attempt to *test* the maingate belt road database it was decided to combine the maingate belt road roof support database with those cases from the primary roof support database where the colliery proactively installed secondary tendon support within the travel road prior to longwall retreat. Of the 109 primary roof support database cases, 32 cases satisfy that criteria.

If a colliery is proactively installing secondary tendon support within their travel road prior to longwall retreat then it is reasonable to conclude that the level of primary roof support (measured by the PRSUP Rating - see Appendix A) would be sufficient to maintain satisfactory roadway conditions subsequent to development and prior to longwall retreat, however it would be deemed as insufficient by the colliery to deal with the horizontal stress increases associated with longwall retreat. Furthermore, in terms of remedial roof support, it is also reasonable to conclude that the level of roadway roof stability required by the colliery as a result of development is approximately the same as that expected in the belt road during longwall retreat.

A colliery would not typically plan to install secondary roof support to simply maintain satisfactory roadway conditions solely as a result of development in basically the same way as a colliery would not plan to install "tertiary" support in the belt road during longwall retreat. Therefore via this combined database the operational issue related to installing a level of roof support greater than that required to effectively deal with the resultant horizontal stress acting across the roof (i.e. σ_R-Dev or σ_R-MGB as the case may be) is substantially eliminated from the analyses. This combined and relatively large database of 90 cases essentially represents a level of *reinforced* roof stability in terms of:

1. a tolerable level of risk specific to Australian collieries and;
2. the two principal geotechnical drivers being the structural integrity of the immediate roof (as measured by the CMRR) and the resultant stress (σ_R).

Furthermore, if the above logic holds true then the resultant level of correlation (R^2) and the regression equation should be similar to that found in relation to the maingate belt road database on its own. Figure 7 presents the relationships for GRSUP along headings plotted against the CMRR for varying stress levels acting across the roof (i.e. σ_R). The multiple regression relationships relating GRSUP to the CMRR and σ_R are also displayed. It can be seen that the overall shape of the relationships plotted on Figure 7 are comparable with those associated with Figure 6 as well as the correlation associated with the respective regression relationships.

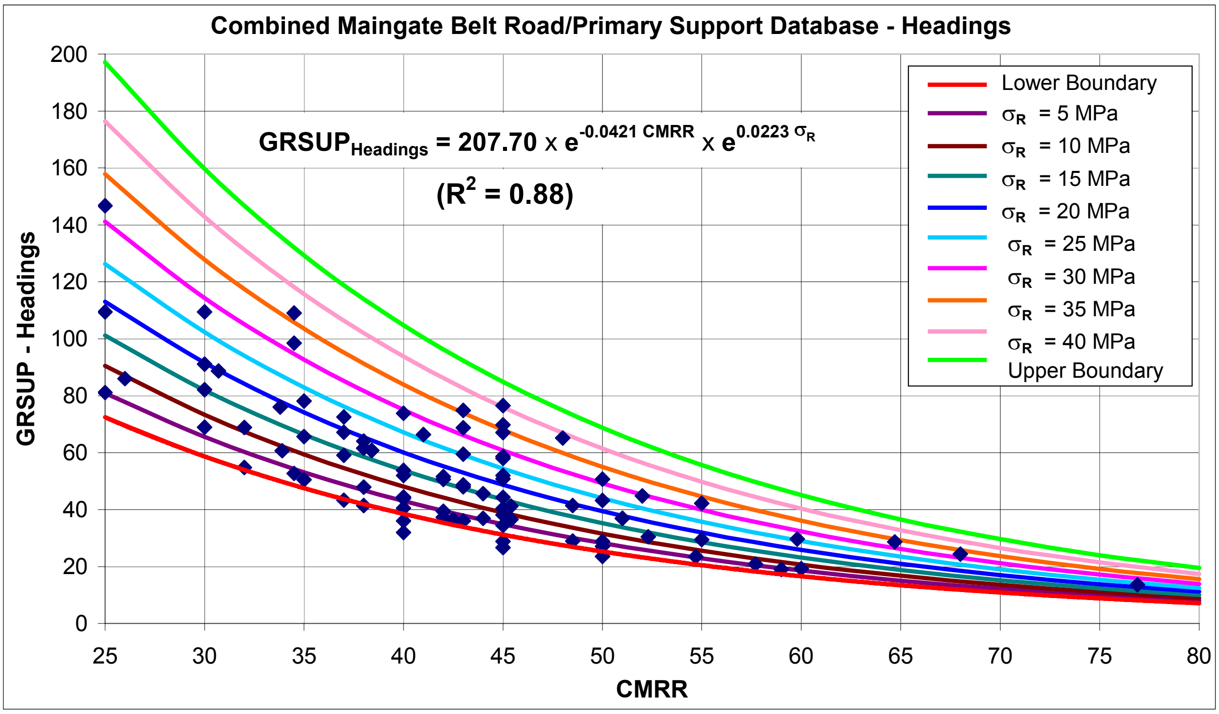

Figure 7 - GRSUP v's (CMRR & σ_R) – combined database – headings

IMPACT ON ALTS

In terms of tailgate roof support design, ALTS had been specific to the typical case where a tailgate had acted as the travel road of the previous longwall panel and therefore the roadway is subject to double (or 2nd) pass longwall extraction (e.g. refer TG 2 – Figure 1). While some level of horizontal stress increase will occur in the travel road due to the approaching longwall face it will generally be significantly less than that experienced in the belt road.

Furthermore under this travel road/tailgate scenario, once an adjacent goaf is established a substantial amount of the *in situ* horizontal stress increase (if any) is relieved and any further increase in horizontal stress acting across the roof (for example during tailgate loading refer Position d – Figure 1) is not related to the *in situ* horizontal stress and can only be as a result of Poisson's Effect associated with an increase in the vertical load acting above the riblines adjacent to the roadway.

Tailgates subject to *single or super stress notch* conditions

The maingate belt road analyses have a significant impact on ALTS in two ways. Firstly, in terms of tailgate roof support design ALTS can now clearly deal with those tailgates subject to a *single or super stress notch* conditions. Figure 1 reveals that Tailgate 1 (i.e. TG 1) would only be subject to single pass longwall extraction such that the roof about the tailgate intersection with the face is subject to a *Single Stress Notch*, similar to that experienced in a belt road. While similar, it is manifestly different in the sense that for a series of panels a notching or increase of the major horizontal stress for TG 1 (with respect to Figure 1) would mean that the maingate is technically within a zone of major horizontal stress relief, such that a notching of the minor horizontal stress would occur (or vice-versa).

Position f (refer Figure 1) relates to a specific (but not uncommon) situation which can result in a large increase in horizontal stress acting across a tailgate roof and is commonly referred to as a *super stress notch*. To occur, the longwall commences inbye of the start-line of the previous LW panel, in this case LW 2 in relation to LW 1. In this instance a larger (than typically encountered by the colliery) horizontal stress increase occurs as the faceline of LW 2 approaches and passes the start-line (or installation face) of LW 1.

While there is no database (per se) that specifically relates to either of the *Single or Super Stress Notch* tailgate scenarios, nonetheless the findings and recommendations associated with the primary roof support, maingate belt road and ALTS tailgate databases allow for a design process to be developed and high level of confidence in the roof support recommendations provided.

Under these two tailgate scenarios, the tailgate roof is subject to *in situ* horizontal stress increases as a result of longwall retreat in a similar manner as the belt road roof and will react accordingly dependent on the structural integrity of the roof (as measured by the CMRR), the level of horizontal stress acting across the roof and installed level of roof support. In this instance the stress acting across the tailgate roof as a result of longwall retreat is referred to as σ_R-TG (MPa). However being a tailgate (as opposed to a belt road) the design process needs to consider the possible use of or option of including secondary standing support as a part of the overall roof support strategy. The ALTS research provides the ability whereby a *trade-off* between tendon and standing support (within limits) can be assessed in terms of a serviceable tailgate.

Tailgates subject to double (or 2nd) pass longwall extraction

Previous ALTS research (Colwell, 1998 and Colwell et al, 2003) clearly revealed that chain pillars should not be designed without a detailed consideration of the level and type of ground support installed along the tailgate as well as a colliery's operational requirements. Furthermore said research established that for the same CMRR there is a *trade-off* between the total level of tailgate roof support (bolts/tendons plus standing support) and chain pillar width while maintaining the same level of tailgate serviceability.

In this instance ALTS focuses on tailgate performance (at the T-junction, refer Position d - Figure 1) as the design condition. The pillar stability factor in relation to the Tailgate (TG) loading condition is designated as the Tailgate Stability Factor (TGSF). The level of standing support is measured by the Standing Support (SSUP) Rating and therefore the total level of tailgate roof support equates to

GRSUP plus SSUP. The calculation of the TG SF and SSUP ratings remains unchanged from that previously published and the interested reader is referred to Colwell (1998) and Colwell et al (2003).

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However it is recognised that this *trade-off* is within various limits. For example a base level of primary roof support is required, independent of the chain pillar size, to maintain satisfactory roadway conditions during and subsequent to development (while prior to longwall extraction). This base level of primary roof support (designated as $PRSUP_{Dev}$) cannot be a part of the trade-off between GRSUP + SSUP and TG SF and should to be determined (along with SSUP & TG SF) prior to calculating the recommended, upper and lower GRSUP values.

The additional roof support required to satisfy Travel Road/Tailgate serviceability is referred to as $ROOFSUP_{TG}$, where $ROOFSUP_{TG}$ equals GRSUP plus SSUP minus $PRSUP_{Dev}$. $ROOFSUP_{TG}$ is the measure of the level of roof support which, for a specific CMRR, can be involved in a *trade-off* with the TG SF while maintaining the same satisfactory level of tailgate serviceability.

Utilising multiple regression, it was found that when the base level of primary support was subtracted from the total installed roof support only two parameters were significant predictors of the resultant level of roof support (i.e. $ROOFSUP_{TG}$) being the CMRR and TG SF. It is noted that σ_R-Dev ceased to be a significant predictor of (or have an impact on) $ROOFSUP_{TG}$ even though the logistic regression analyses found σ_R-Dev to be a significant predictor of eventual tailgate serviceability.

As discussed by Colwell (2006) it is critical when utilising empirical modelling for geotechnical design that a clear understanding of the geotechnical environment and rock mass failure/behavioural mechanisms is required. σ_R-Dev is clearly critical to primary support levels and therefore it is more than reasonable that it has a significant impact on the eventual outcome i.e. tailgate serviceability. However in terms of σ_R-Dev's impact on $ROOFSUP_{TG}$ these analyses are totally consistent with the nature of the geotechnical environment associated with a travel road/tailgate subject to 2nd (or double) pass longwall extraction.

As previously discussed once an adjacent goaf is established any increase in horizontal stress acting across the roof is not related to the *in situ* horizontal stress and can only be as a result of Poisson's Effect associated with an increase in the vertical load acting above the riblines adjacent to the roadway. This will vary dependent on several factors including (but not limited to) the distribution of the abutment load, the nature of the coal, the rib height (i.e. the development height) & pillar width and the installed level/type of rib support. The TG SF successfully *"captures"* a large proportion of the combined effect.

COMMENTS ON EMPIRICAL MODELLING AND ALTS

The authors contend all geotechnical models utilised for design associated with underground coal mining are in fact empirical in nature as calibration may be required and engineering judgement will always need to be used when applying any design outcomes. It does not matter whether the *engine room* of the model is analytical or numerical as either will require significant calibration prior to the model being effectively or confidently utilised for design purposes, whereas the calibration process is intrinsically a part of an empirical model whose *engine room* is an industry database.

The authors assess (based on industry research/experience) that for small vertical roof displacements (up to around 50mm and possibly to 100mm), slender beam behaviour or buckling is the dominant behavioural mechanism occurring within the immediate coal mine roof measures which, if not controlled, leads to large scale roof displacement and eventually a major collapse. One of the primary reasons that numerical models (as they are being used with respect to the underground coal industry) require a high level of calibration via parameter manipulation is that the modelling process does not include the mechanistic principles of this dominant behavioural/failure mechanism.

With the advent of more powerful computers, some researchers have tended to move away from empirical and physical models to numerical modelling. While the modelling of rock behaviour using numerical methods has improved and mathematical routines have been developed in an attempt to account for both elastic and plastic behaviour (e.g. FLAC – Gadde & Peng, 2005 and Gale & Tarrant, 1997; 3STRESS – Medhurst, 1996 and MAP3D – Palmer & Morrison, 2005), the various models do not incorporate mathematical routines associated with buckling.

In addition these researchers have been considering geometries (or setting up their models) which contain structural elements that, by their very nature, cannot buckle and must fail in either direct compression (as one would observe in a laboratory based strength test) or shear. This is in complete contrast to the slender beams associated with coal mine strata, which either form the immediate roof or quickly develop within the immediate roof due to roadway formation or as a result of a horizontal stress increase. Therefore it is not surprising that the issue of buckling as a failure mechanism about mine openings/roadways has been largely ignored by researchers that rely heavily on numerical modelling in an attempt to replicate and understand roadway behaviour.

It is also realistic to suggest that there is a *point of view* held by a significant segment of the rock mechanics fraternity that numerical modelling provides a researcher/consultant with a tool to undertake *real engineering* whereas empirical-statistical techniques offer only *"simplistic formulae"* (Tarrant, 2005). It would be naïve for any researcher whose objective is to provide an underground coal mining industry with a widely accepted empirical geomechanics model, to be unaware of this *point of view*.

With the increased power of computers and possibly due to the time and considerable effort involved in collecting, verifying and analysing the large volume of information involved in formulating an industry-wide database, a number of researchers utilise numerical modelling, as Tarrant (2005) suggests, to develop a *"better understanding"* of roadway behaviour. Tarrant (2005) points out that, *"Use of such tools is limited by the simplifications required however when used in conjunction with field measurement and observation, the model findings can be tested and a level of confidence in the results defined."*

The use of numerical modelling in the manner described by Tarrant (2005) is reasonable but unfortunately generally only provides a calibrated (via measurement) model to then be used for site specific prediction or design. Calibrating a numerical model to a limited number of sites does not provide an underground coal industry with a widely applicable and therefore accepted design tool for roadway ground support design. This is particularly the case when the numerical model being calibrated to said roadway behaviour does not incorporate mathematical code associated with buckling. Invariably one finds that in these instances the researcher does not produce a model or design technique that can be readily utilised by others in the industry, but typically it remains within the domain of the researcher or consultant for its application.

As part of his review of ACARP's geomechanics-related research, Brown (2001) considered 52 underground geomechanics-related projects and individually rated the projects in terms of their research quality and industry application. ALTS was one of only 11 projects that received the highest rating and yet it took several years for it to gain the widespread acceptance it now enjoys. It is suggested that the principal causes of this delay are a) the misguided *point of view* previously suggested and b) some ill-informed commentary concerning empirical modelling in general and specifically that with respect to ALTS.

For example, Tarrant (2004) suggests that ALPS (Analysis of Longwall Pillar Stability, refer Mark et al 1994) and ALTS provide a *"line in the sand"* in terms of chain pillar width with respect to tailgate serviceability. Neither method ever suggested there was a *line in the sand* in terms of chain pillar design and related tailgate serviceability. In fact Colwell et al (2003) detail a wide range in chain pillar width that can be employed while maintaining serviceable tailgate conditions and that the pillar width selected is contingent on the installation of recommended (i.e. engineered) levels of roof support (primary & secondary, tendon & standing). In spite of this information, Tarrant (2004) provides a diagram relating tailgate serviceability to pillar width which makes the erroneous suggestion that at a certain pillar width (derived by ALTS or ALPS) *no engineering is required* in terms of roof support.

Gale and Hebblewhite (2005) go further and state that ALPS and ALTS, *"have been developed largely on simple statistical correlations of tailgate conditions and support requirements, relative to pillar dimensions".* However the formulation of a geotechnical database, the minesite investigations, the identification & understanding of the failure mechanisms and the statistical (Data Mining) techniques employed in the development of ALTS, ALPS and ADRS is anything but a *simple* process.

Quality empirical modelling is in fact a scientific process of significant challenge and complexity. With respect to the underground coal geotechnical environment; empirical modelling allows for the development of practical and fully engineered design methodologies and techniques/tools that can provide the minesite strata control engineer with timely solutions to complex geotechnical design issues. These techniques are also consistent with the thoughts of Professor Hustrulid (2006) where he indicates that marked progress in the field of mining rock mechanics requires, *"the careful collection, analysis and presentation of field/mine experience."*

The idea portrayed by some that ALTS, ADRS, empirical modelling per se and the resultant statistical relationships are simplistic and are limited in their application is at best misguided and at worst, misleading. Both methods (and the associated relationships) are founded on almost the entire range of geotechnical environments as well as roof and rib control practices in the Australian underground coal industry. The resulting statistical "cause and effect" relationships, which are then utilised for design, are exceptionally strong and are fully consistent with the changing nature of the geotechnical environment and failure mechanisms.

The geotechnical environment and the way in which roof and rib support interacts with the rock mass are complex issues. However it is generally recognised that without prudent simplification, the complexity of the problem will overwhelm all current geotechnical methods of modelling. While the problem should not be oversimplified (i.e. the dominant failure mechanisms or critical data input parameters should not be ignored), without question judicious simplification is at the heart of all engineering design. Therefore the findings of ALTS and ADRS should give the industry heart that the problems faced can be reasonably understood by all and ultimately designed for at a mine site level.

The principal geotechnical drivers identified for both general roof and rib stability make good engineering sense and are fully consistent with what an engineer would expect to find according to the proven principles of slender beam behaviour and buckling. For anyone to now dismiss, *pigeon hole* or use unjustified *throw away lines* in relation to ALTS or the CMRR (i.e. Tarrant, 2004 & 2005, Gale and Hebblewhite, 2005 and Calleja, 2008) would simply display a significant level of engineering ignorance as well as conveniently ignoring the scientific evidence supporting the practical benefits of this design technique and rock mass classification index.

CONCLUSIONS

The analyses reported in this paper are totally consistent with and accurately reflect the changing geotechnical environment encountered by both the belt and travel roads from development through to respectively *Maingate Stress Notching* and *Tailgate loading*. The strength of the various relationships developed for roof support design are exceptionally high and are also fully consistent with what an engineer would expect to find according to the behavioural/failure mechanisms occurring within the roof.

In relation to empirical modelling Salamon (1989) states, *"The main advantage of this approach is its firm links to actual experience. Thus, if it is judiciously applied, it can hardly result in a totally wrong answer. Also, in our legalistic world, it has the added advantage of defensibility in a court of law. After all, it is based on actual happenings and is not just a figment of imagination".* ALTS and ADRS go even further, as the statistical relationships and the way they are utilised as a part of the design methodologies intrinsically represent a tolerable level of risk specific to Australian collieries. Therefore while the recommendations emanating from ALTS need to be applied judiciously (as for all design techniques) they can be confidently applied to all Australian longwall operations.

The ALTS 2009 Software Package assists and offers the user the ability to undertake roof and rib support design (primary & secondary, tendon & standing and also in terms of ADRS the appropriate use of rib mesh) for both the maingate belt road and travel road/tailgate and of course chain pillar design (where ALTS all started). When the original ALTS Project was completed in October 1998 the lead author had the "picture" in mind of developing an integrated approach to longwall gateroad design that could be utilised by the minesite geotechnical engineer at all Australian longwall operations. After 10 years and with the Australian coal industry's support the picture has become a reality.

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REFERENCES

Brown, E.T. 2001. Review of ACARP's Underground Coal Geomechanics Research. Final Report - ACARP Project C11001, 44p.

Calleja, J. 2008. CMRR – Practical Limitations and Solutions. Proceedings of the 8th Underground Coal Operator's Conference, Wollongong NSW, pp. 92-103

Colwell, M.G. 1998. Chain Pillar Design - Calibration of ALPS. Final Report - ACARP Project C6036, 67p.

Colwell, M.G. 1999. User's Guide – ALTS Design Methodology, ACARP Project C6036. ACARP Technical Seminars Qld and NSW, March 1999.

Colwell, M.G. 2006. A Study of the Mechanics of Coal Mine Rib Deformation and Rib Support as a basis for Engineering Design. PhD Thesis, School of Engineering – Mining Engineering Program, The University of Queensland, 374p.

Colwell, M.G., Hill, D.J., & Frith, R.C. 2003. ALTS II – A Longwall Gateroad Design Methodology for Australian Collieries. Proceedings of the 1st Australasian Ground Control in Mining Conference: Ground Control in Mining: Technology & Practice: Sydney 10 – 13 November 2003, pp 123-135

Colwell, M.G., Frith, R.F. & Mark, C. 1999. Analysis of Longwall Tailgate Serviceability (ALTS): A Chain Pillar Design Methodology for Australian Conditions. Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design. NIOSH Information Circular 9448, pp 33-48.

Gadde, M.M. & Peng, S.S. 2005. Recent advances in numerical simulation of cutter roof failure in underground coal mines. Proceedings of the 24th Conference on Ground Control in Mining. Morgantown West Virginia University, pp 162 – 168.

Gale, W.J. & Hebblewhite, B.K. 2005. Systems Approach to Pillar Design; Module 1 – pillar design Procedures. Final Report, Volume 1 (of 3) – ACARP Project C9108, 68p.

Gale, W.G and Matthews, S.M. 1992. Stress Control Methods for Optimised Development and Extraction Operations. Final Project Report, NERDDC Project C1301.

Gale, W.J. & Tarrant, G.C. 1997. Let the Rocks Tell Us. Symposium on Safety in Mines: The Role of Geology, 24-25 November 1997, Newcastle, NSW, pp 153-160.

Galvin, J.M., Hebblewhite, B.K. & Salamon, M.D.G. 1999. University of New South Wales Coal Pillar Strength Determinations for Australian and South African Mining Conditions. Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design. NIOSH Information Circular 9448, pp 63-71.

Hoek, E. and Brown, E.T. 1980. Underground Excavations in Rock. The Institution of Mining and Metallurgy, London, 527p.

Hustrulid, W. 2006. Some Thoughts regarding Mining and Rock Mechanics. Keynote Address – Colorado School of Mines, "50 Years of Rock Mechanics – Landmarks and Future Challenges" Symposium. Colorado, USA, July 2006.

Mark, C. 1990. Pillar Design Methods for Longwall Mining. United States Bureau of Mines Information Circular 9247, 53p.

Mark, C., Chase, F.E. & Molinda, G.M. 1994. Design of longwall gate entry systems using roof classification. Proceedings: United States Bureau of Mines Technology Transfer Seminar - New Technology for Longwall Ground Control. USBM Special Publication 01-94, pp 5-17.

Mark, C., Molinda, G.M. & Dolinar, D.R. 2001. Analysis of roof bolt systems. Proceedings of the 20th International Conference on Ground Control in Mining. Morgantown, West Virginia, pp 218 - 225.

Mark, C., Mucho, T.P., & Dolinar, D.R. 1998. Horizontal stress and longwall headgate ground control. Mining Engineering, Jan. 1998 pp 61 - 68.

Medhurst, T.P. 1996. Estimation of the in-situ strength and deformability of coal for engineering design. PhD Thesis, Department of Mining, Minerals and Materials Engineering, The University of Queensland, 325p.

Palmer, P. & Morrison, D. 2005. Numerical Modelling as a Tool to Predict Pillar Condition and Assist in Mining Sequencing. Proceedings of the 24th Conference on Ground Control in Mining. Morgantown West Virginia University, pp 232 – 237.

Su, D. and Hasenfus, G. 1995. Regional horizontal stress and its effect on longwall mining in the Northern Appalachian Coal Field. Proceedings of the 14th International Conference on Ground Control in Mining, Morgantown, W. V. pp 39 - 45.

Salamon, M.D.G. 1989. Significance of strata control to the safety and efficiency in mining. In: Proceedings of the 8th International Strata Control Conference, Düsseldorf, Germany.

Salamon, M.D.G., Galvin, J.M., Hocking, G. & Anderson, I. (1996). Coal pillar strength from back-calculation. University of New South Wales, School of Mining Engineering, Research Report 1/96, 60p.

Tarrant, G.C. 2004. Tailgate field investigations metropolitan colliery. Appendix to Final Report - ACARP Project C12006.

Tarrant, G.C. 2005. Standing Support – It's Time for an Engineered Solution. Final Report - ACARP Project C12006, 52p.

Thomas R. and Wagner, C. 2006. Main Gate Roof Support Design and Management during Longwall Retreat in the Australian Coal Industry. Proceedings of the 25th International Conference on Ground Control in Mining. Morgantown, West Virginia, pp 191 - 197.

APPENDIX A. PRSUP & GRSUP RATING CALCULATIONS

Primary Roof Support (PRSUP) Rating

The Primary Roof Support (PRSUP) Rating is a measure of the bolting capacity (kN) per square metre of roof and includes all bolt/tendon support that is installed off the continuous miner or mobile bolter as part of development. The equation to calculate PRSUP is:

$$PRSUP = \frac{L_b \,.\, N_b \,.\, C_b}{14.5 \,.\, S_b \,.\, w_e} + \frac{L_b \,.\, N_t \,.\, C_t}{14.5 \,.\, S_t \,.\, w_e}$$

where L_b = Length of bolted horizon defined by the primary bolt type (m)
N_b = Average number of bolts per row
N_t = Average number of longer tendons per row
C_b = Ultimate tensile strength of the primary bolt (kN)
C_t = Ultimate tensile strength of the longer tendon (kN)
S_b = Spacing between rows of the same bolt type (m)
S_t = Spacing between rows of the same longer tendon type (m)
w_e = Roadway width (m)

This rating considers all support installed at the face from the continuous miner (or mobile bolter where place changing is used) whether in the same row as the primary bolt type or not. It also considers each type of support separately and adds the values for each into a single value. The capacity for each support element is taken as the typical Ultimate Tensile Strength (UTS, kN) given in the product catalogues of the various suppliers.

Where some support elements may be longer than the primary bolt type, only the length of the primary bolt type is considered; for example where 2.1m bolts are being installed and longer tendons are also being used, a simulated value of 2.1m is assigned as the length of the longer tendons (i.e. L_b remains constant). The longer tendons were found to unfairly influence the rating if their entire length was included in the calculation.

GRSUP Calculation

The GRSUP rating incorporates all bolt and longer tendon roof support installed within the roof of a roadway into a single rating, regardless of when the roof support is installed. This includes all roof bolts, longer tendons, cables and trusses. The GRSUP is calculated in a similar manner to that of the PRSUP; in fact if no additional support is installed within the roof subsequent to that installed off the continuous miner or mobile bolter then GRSUP will equal PRSUP. The rating value for each type of roof bolt, tendon or cable is calculated and the values summed as a single number representing the total installed tendon roof support capacity.

Once again only the length of the primary roof bolt (i.e. referred to as the bolted horizon, L_b) is considered when calculating the influence of longer tendons or cables. The GRSUP is calculated as follows:

$$GRSUP = \frac{L_b}{14.5 \,.\, w_e} \sum N_m \,.\, C_m$$

where m = number of different support types
N = number of support elements per metre
C = Ultimate tensile strength of each support element (kN)
w_e = Roadway width (m)

To clarify the PRSUP and GRSUP Ratings, consider the following example.

Example Calculation

A mine installs 6 x 2.1m X-grade bolts (UTS 340kN) at 1.2m spacing on development with 2 x 6m high strength tendons (UTS 580kN) also installed from the continuous miner between every second row of bolts (i.e. 2.4m spacing). Before the 2nd adjacent longwall begins extraction, a further 2 x 8m long single strand cable bolts (UTS 265kN) are installed every 2m. The roadway width is 5.2m.

For PRSUP, only the support installed off the miner is included, i.e. the 2.1m X-grade bolts and 6m tendons.

$$PRSUP = \frac{L_b \,.\, N_b \,.\, C_b}{14.5 \,.\, S_b \,.\, w_e} + \frac{L_b \,.\, N_t \,.\, C_t}{14.5 \,.\, S_t \,.\, w_e}$$

$$PRSUP = \frac{2.1 \times 6 \times 340}{14.5 \times 1.2 \times 5.2} + \frac{2.1 \times 2 \times 580}{14.5 \times 2.4 \times 5.2}$$

$$PRSUP = 47.3 + 13.5$$

$$PRSUP = 60.8$$

To calculate GRSUP all support elements are included (i.e. 2.1m bolts, 6m tendons and 8m cables) such that:

$$GRSUP = \frac{L_b}{14.5 \,.\, w_e} \sum_{1}^{m} N_m \,.\, C_m$$

In this case there are three support types, so m=3 and therefore:

$$GRSUP = \frac{L_b}{14.5 \,.\, w_e} \left(N_1 \,.\, C_1 + N_2 \,.\, C_2 + N_3 \,.\, C_3 \right)$$

$$GRSUP = \frac{2.1}{14.5 \times 5.2} \times \left(\frac{6}{1.2} \times 340 + \frac{2}{2.4} \times 580 + \frac{2}{2} \times 265 \right)$$

$$GRSUP = 68.2$$