2013

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Publication Details

M. Colwell, and R. Frith, Analysis and design of faceroad roof support (ADFRS), 13th Coal Operators' Conference, University of Wollongong, The Australasian Institute of Mining and Metallurgy & Mine Managers Association of Australia, 2013, 74-85.

ANALYSIS AND DESIGN OF FACEROAD ROOF SUPPORT (ADFRS)

Mark Colwell[1] and Russell Frith[2]

ABSTRACT: This paper summarises the results of a research project whose goal was to provide the Australian coal industry with a longwall installation roadway design methodology that could be utilised by suitably qualified colliery staff. This goal has been achieved and the design methodology (and software package) is referred to as *Analysis and Design of Faceroad Roof Support (ADFRS)*. The intended benefits to underground operations, in the provision of this information and resource, are a safer and more productive workplace. ADFRS now fills the gaping void that existed in the Australian underground coal industry with respect to the geotechnical design and management of longwall installation roadways. In addition to the standard two-pass widening, ADFRS deals with all other aspects of installation roadway design, including faceroad intersections, stables and adjacent maingate and tailgate intersections. ADFRS is based on a sound mechanistic understanding of the roadway development and widening process and the design equations (with strong to very strong correlations) are fully consistent with measured roof behaviour. To the best of the authors' knowledge ADFRS is the first systematic faceroad design technique to be developed for any country's underground coal industry.

INTRODUCTION

The original intent of the project was to develop a roof support design methodology for wide roadways, where a wide roadway is generally considered to be greater than 5.5 m wide and in many cases is the result of widening an existing underground roadway (e.g. a longwall installation roadway). The widening of an existing underground roadway is prescribed as a high risk activity by the NSW Coal Mine Health and Safety Regulation 2006 requiring an approval under the NSW Coal Mine Health and Safety Act 2002 (refer Clause 49, Part 2 - Page 57). It is apparent that our industry fully appreciates that increasing roadway width results in a disproportionate decrease in stability and therefore a significant increase in safety and business risk.

However, during the data collection phase (initial year) of the project it was found that other than for longwall installation roadways, colliery records in relation to other types of wide roadways (e.g. drive head excavations) were generally incomplete (i.e. accurate roof support plans and/or monitoring information was not readily available). Fortunately this was not the case for most longwall installation roadways, particularly those widened in recent years, where quite detailed/accurate records were generally available.

Therefore it was decided to focus the research effort on longwall installation roadways (i.e. faceroads) so that the design methodology would (as best as possible) encompass all aspects of installation roadway design, including faceroad intersections, stables and adjacent maingate and tailgate intersections. Therefore the aim of this project became the development of a roof support design methodology for longwall installation roadways encompassing all aspects of their formation.

BACKGROUND

In relation to other strata control issues, such as coal mine pillar and roof support design (for standard roadway widths), there has been comparatively very little research undertaken in relation to the geotechnical design and management of longwall installation roadways. As a result, in terms of a satisfactory outcome, faceroads within Australia have been quite problematic and by way of example of the 207 cases associated with the two-pass dataset, 40 resulted in an unsatisfactory outcome involving the use of standing support, Polyurethane Resin (PUR) injection and/or high levels of remedial tendon support with two faceroads "lost" and having to be re-driven due to major roof falls. Another 33 of the 207 cases were considered manageable.

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The authors were also aware of several other faceroads that were abandoned in recent years due to major roof falls however due to a lack of site specific information they could not be included in the database. Nonetheless *a failure rate* of approximately 20% is judged to be unacceptable. The authors' contend the principal reason for such a failure rate is the clear absence of suitable design equations that relate the required levels/type of roof support as a function of the competency (or some valid measure of the competency) of the roof and the horizontal stress acting across the roadway.

Due to the lack of reference material on the topic and to assist in achieving the goal of developing a roof support design methodology for installation roadways that can be effectively utilised at all Australian collieries, a comprehensive review of current practices associated with the design and management of longwall installation roadways was undertaken as a part of the study.

LONGWALL INSTALLATION ROADWAYS - CURRENT PRACTICE AND OUTCOMES

The vast majority of longwall installation roadways in the Australian underground coal industry are developed in two or more "passes" in order to form the final excavation width. For the majority of an installation roadway's length, it would be usual to form up an initial or 1st pass at the standard roadway width used at the mine (typically between 4.8 m and 5.5 m) and then strip out on one side (which can be either side of the roadway) to form the final roadway width of approximately 7.5 m to 12 m depending upon the size and length of the longwall face equipment.

The major advantage of forming up a wide roadway in two or more passes is that it allows the full range of roof conditions along the roadway to be exposed at a standard roadway width prior to stripping. Therefore the actual condition of the roof and the need for secondary tendon support (i.e. longer cables) prior to stripping can be reviewed on an informed basis and secondary support prior to stripping can usually be installed whilst the continuous miner is driving the adjacent bleeder roadway.

In terms of reviewing current practice, formulating/analysing the database and subsequently developing a credible design methodology some measure or statement of acceptable or unacceptable outcomes needs to be available. Furthermore in addressing the issue of success for an installation roadway, it is necessary to consider the operational context in which the safety of mine workers is taken as a mandatory requirement.

In overall risk terms it is clear that as per most other geotechnical design in underground coal mining, the general design requirement is for a suitably conservative level of roof support in the installation roadway while no more than is prudent from a risk-based perspective. Both optimistic under-support and highly cautious over-support carry significant business risks in the context of minimising the production outages between successive longwall panels.

In technical terms success or failure with respect to roof support design will be related to a roof stability outcome, accepting that this will have a consequent effect on mining operations as discussed above. As a roof support design study, the focus is on roof stability outcomes and the necessary operational responses in defining success and failure for longwall installation roadways.

In terms of a satisfactory outcome, ostensibly there really is only one definition, namely that the roof of the installation roadway behaved in such a way that there was no requirement to either trigger the Trigger Action Response Plans (TARP) or undertake remedial roof support measures in order to maintain its serviceability up to the time of longwall shield installation. This does not mean that the roof does not move or that time dependent creep effects do not occur following widening. Simply that the measured outcomes were tolerable in the context of the requirements of the installation roadway. Furthermore with respect to roof movement there are many instances where only the first level of the TARP is triggered and this generally simply requires greater observation/more frequent monitoring rather than the immediate introduction of remedial support.

In addition, from a practical point of view, there are instances where a low (or even moderate level of remedial support in isolated areas along a roadway) is tolerable dependent on the type of roadway and its use. For example a low or moderate level of remedial support in isolated areas along a tailgate (while of course never desirable) may be tolerable and/or have minimal/negligible effect on safety or productivity, as opposed to a belt road where the installation of remedial support about the belt is difficult, will inevitably cause production stoppages and is essentially unacceptable.

With respect to a longwall installation roadway, in this regard it is far more akin to a tailgate than a belt road. The critical issue is that remedial support, if required, is installed to further reinforce and control a roof that is still largely self-supporting and that the roof has not softened to an extent where a roof fall is imminent. Therefore the use of standing support in an installation roadway or remedial cables to "suspend" a softened installation roadway roof would be an unacceptable outcome in terms of a proactive design methodology.

Another important aspect of an installation roadway is the "stand-time" between widening and the setting of the longwall shields. For a very short "stand-time" following widening, significant time dependent creep effects in the roof may be an acceptable outcome if it allows the construction period to be reduced by the use of less roof support. Conversely for a roadway with a stand-time of say six months, any significant long-term creep effects would probably be unacceptable from an operational perspective. Such stand-time considerations will clearly have an impact upon the degree of conservatism used in the overall roof support design.

In terms of an unsatisfactory outcome relating to roof stability, these are varied and carry a significant range in terms of operational consequences:

(i) The need to install unplanned/remedial roof support to arrest unacceptable rates/levels of roof movement following widening, in the context of whether they may lead to unacceptable roof deterioration at some point in the future if left unabated.

(ii) The need to erect standing support in the roadway to arrest what has been predicted to be an imminent roof fall based on either physical roof conditions in the roadway or high measured rates of movement. Usually this cannot be initially achieved with long tendon type roof support due to the time period required to install such support and the capacities needed to control "dead weight roof loads" in a wide roadway. Once set in place though, such standing support will need to be removed, hence significant other remedial support measures (e.g. cable slings, extra long tendons or strata consolidation via resins or grouts i.e. PUR) will be required before this can occur.

(iii) The occurrence of a roof fall is obviously the worst case operational outcome. It will require that either (a) the fall is recovered or (b) a replacement installation roadway is driven. This brings into question issues such as how to recover a major roof fall safely and the need to then back-fill the roof cavity so as to allow longwall shields to be set to the roof, against the time and cost of driving a replacement roadway. The business consequences of a major roof collapse in a longwall installation roadway are always severe.

Clearly the operational consequences involved can vary from relatively minor in the case of (i) if the installation of the extra support does not delay the start-up of the longwall, to major in the case of (iii).

Remembering then that many installation roadways are formed up on the critical path for the start-up of the next longwall and that in itself, an overly conservative roof support system may be an unacceptable mining outcome, risk-based considerations may allow some likelihood that point (i) occurs in a portion of the installation roadway, this being a trade-off between minimising the time required to form the roadway and the downside risks should it not be fully stable following widening. However neither points (ii) or (iii) can be tolerated from either a safety or business consequence perspective, hence the roof support design must be highly reliable in terms of their prevention.

Based on the preceding discussion and in terms of the database, the roadway condition (or section thereof) was assessed both subsequent to 1st pass drivage and after the faceroad was fully widened utilising the following three criteria based categories:

1. Satisfactory - is where the faceroad development went according to plan and while there may be a low level or infrequent triggering of the TARP, essentially no remedial support was required.
2. Manageable - is where the TARP is being triggered on a more frequent basis and/or there is a need for low to isolated moderate levels of remedial tendon roof support.
3. Unsatisfactory - is where a roof fall or faceroad abandonment has occurred, where PUR or standing support is required and/or where significant levels of remedial tendon roof support is required.

THE INDUSTRY REVIEW

The aim of the industry review is to:

1. Construct both a contemporary and historical database of longwall installation roadway (i.e. faceroad) performance and,
2. Utilise this information to determine the significant predictors of faceroad performance.

The data collection phase of the project predominantly took place during 2010 with faceroad information collected from 26 longwall operations involving all the major coalfields. Information associated with 162 faceroads was reviewed in terms of completeness and accuracy for inclusion in the final database. Unfortunately on many occasions it was not possible to fully verify support patterns, levels of roof movement and/or remedial support measures where required. Based on the quality and completeness of the information provided, this resulted in 123 case studies suitable for inclusion in the project database. These 123 case studies have generated:

- 169 standard widening cases ranging in width from 7.5 m to 9.5 m;
- 160 stables (i.e. shearer, maingate and tailgate stables) ranging in width from 7.7 m to 12 m;
- 30 faceroad intersections;
- 64 maingate/tailgate intersections adjacent to the faceroad.

A standard widening case is where after development of the initial roadway (i.e. the 1st pass of the faceroad) there is only one further drivage sequence referred to as the 2nd pass. The standard widening will account for the vast portion of the faceroad; however there are instances associated with a number of the case studies where the roof properties change resulting in variable behaviour and/or requiring variable levels of support along the length of the faceroad generating two or more standard widening cases for the one case study.

With respect to the stables, it was not uncommon that the formation of this section of the faceroad involved three and even up to four passes. In terms of the shearer stables, where a shearer stable was removed from or away from the influence of the maingate/tailgate intersections (i.e. it is not a maingate or tailgate stable) 38 of these 54 faceroad cases were formed by a 1st and 2nd pass sequence. Therefore these 38 shearer stable cases can be readily combined with the 169 standard widening cases in terms of the statistical analyses as they are formed on simply a two pass basis (i.e. 207 two pass cases).

During the site inspections information was collected on factors affecting faceroad performance including geometric details, *in situ* and mining induced stresses, roof and floor properties, as well as the ground support patterns which includes the type, placement, timing and quantity of roof and rib support installed (including remedial support where required). All available monitoring information as well as TARP related information was also collected. Where stress relief roadways were utilised this was noted and the effect on faceroad performance was assessed.

In addition, discussions were held with colliery personnel to ascertain how current faceroad performance compared to past experience. On many occasions this resulted in a detailed description of the gradual development of the faceroad ground support/monitoring/TARP systems currently employed, which allowed for a greater appreciation of some of the difficulties faced by the collieries satisfactorily managing faceroad behaviour. The collection of this information also allowed for a thorough understanding of the current faceroad design techniques employed in the Australian underground coal industry.

Construction of the database

Based on a literature review, the authors' own experience and discussions with colliery personnel, the following are assessed to be dominant factors influencing faceroad behaviour for which data was collected:

1. Structural integrity of the roof and floor;
2. Geometry (i.e. roadway width, height and drivage direction for each pass, cover depth and pillar size where a bleeder or stress relief roadway is driven);

3. The ground support systems employed (roof and rib);
4. *In situ* and mining induced stress;
5. TARP;
6. Stand Time (time in days between final widening and installation of longwall supports).

In addition to collecting information concerning the factors affecting faceroad behaviour, all available monitoring information (i.e. extensometry data) was also collected to assist in assessing faceroad performance (i.e. The Outcome). The database includes the following broad input and/or output categories:

- General
- Roof and floor details (i.e. identification of geotechnical units, rock mass ratings and material properties)
- Geometry
- Roof and rib support hardware and patterns
- Roof support ratings
- *In situ* stress parameters
- Where applicable the additional abutment stress from the previous longwall panel
- Analytical Model for Coal Mine Roof Reinforcement Factor of Safety (AMCMRR FOS) Values in relation to 1st pass drivage - refer Colwell and Frith (2010)
- Measured roof displacements
- 1st pass roadway condition
- Fully widened roadway condition

Rock mass classification systems

In developing a roof support design methodology for longwall installation roadways it was decided to assess/calculate, record and "test" all the readily available Rock Mass Ratings/Classification Systems utilised in the Australian underground coal industry for roof support design as a part of the database analyses. By far the most commonly used index is the Coal Mine Roof Rating (CMRR) which is specific to the primary bolted interval. Via the various ALTS research projects (Colwell, 1998; Colwell, *et al.*, 2003; Colwell and Frith, 2009; Colwell, 2010) it has been clearly demonstrated that the CMRR can be successfully used for roof support design purposes at all Australian collieries.

In addition to the CMRR, at many collieries the average Uniaxial Compressive Strength (UCS) of the roof (over various distances above the roof line) is contoured and at some collieries (e.g. Crinum - Payne, 2008) the average UCS is utilised on a site specific basis to specify levels of roof support. On most occasions the UCS is derived from sonic velocity logs where sonic velocity has been correlated with laboratory UCS values.

Another rock mass classification index which is sometimes utilised is the Roof Strength Index (RSI, refer Stam, *et al.*, 2012). The RSI is once again calculated over various distances above the roof line and is the average UCS divided by the vertical stress (i.e. RSI = Average UCS/σ_V). As yet no industry wide based roof design tool/methodology has been successfully demonstrated in using Average UCS or RSI.

In recent years another rock mass classification index has been proposed namely the Geophysical Strata Rating (GSR) having been developed with the funding support of ACARP. Hatherly, *et al.,* (2009) suggest that the GSR delivers results that are commensurate with CMRR values (or more to the point the Unit Rating values where the Unit Ratings, for the individual rock units, are essentially the "basic building blocks" of the CMRR). It should be noted that a GSR value is actually calculated every 5 cm to 10 cm (dependent on the geophysical logs) along the section of the borehole under review, therefore once the rock unit has been identified an average GSR for the unit is calculated.

Via ACARP Project C17009 (Medhurst, *et al.*, 2010) the GSR was extended to allow for the assessment of coal roof. This is extremely important as in the Australian underground coal industry there is currently and historically an abundance of coal roofs or mine roofs with a significant percentage of coal i.e. Angus Place, Austar, Broadmeadow, Dartbrook, Dendrobium, Elouera, Moranbah North, Newlands, North Goonyella, Springvale, Ulan, United and West Wallsend collieries. All these collieries are contained within the ALTS database and all except Elouera and Dartbrook (which have closed) are contained in the database associated with this project. In terms of coal as a rock unit, it comprises approximately 40% of all the rock types within the ALTS and Analysis and Design of Faceroad Roof Support *(*ADFRS) databases (i.e. as compared to sandstones, mudstones and shales).

Therefore including the GSR within the analyses associated with this project was considered to be most worthwhile. Also the real test of any rock mass classification index when used for ground support design is the strength of the correlations with respect to ground support levels. This can only be truly ascertained if the index is tested within an industry wide database and the GSR was yet to be tested in this manner. If the GSR can find the same widespread application and acceptance as for example the CMRR has (in terms of roof support design), then our industry could take full advantage of available borehole information (i.e. geotechnical/geophysical logging and geomechanical testing of the core) for geotechnical design and evaluation purposes.

STATISTICAL ANALYSES

The statistical techniques of linear and logistic regression were utilised in examining the database. Linear (or in this instance multiple) regression is routinely used where the dependent variable (i.e. outcome) is continuous rather than categorical. Multiple regression was successfully utilised throughout the various ALTS research projects when assessing the required level of roof support (i.e. PRSUP and GRSUP) in terms of the CMRR and resultant horizontal stress acting across the roof.

The Primary Roof Support (PRSUP) Rating is a measure of the bolting capacity (kN) per square metre of roof normalised to the primary bolted interval and includes all bolt/tendon support that is installed off the continuous miner or mobile bolter as part of development. 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. For further information in calculating PRSUP and GRSUP the interested reader is referred to Colwell and Frith (2009) and Colwell and Frith (2012).

In relation to similar multiple regression analyses associated with the various ALTS projects all unsatisfactory cases are removed from the dataset, such that the resultant outcome (PRSUP and GRSUP) is based solely on satisfactory cases (e.g. belt road design) or in other instances where remedial action is more tolerable (i.e. productivity risk is lower) a combined satisfactory/manageable dataset is utilised. Similar analyses where conducted in relation to the various faceroad datasets combining the satisfactory and manageable cases.

A limitation of ordinary linear regression models is the requirement that the outcome is continuous rather than categorical. But many interesting dependent variables/outcomes are categorical - patients may live or die, people may pass or fail exams, coal rib lines may collapse or be stable, faceroad performance is satisfactory or unsatisfactory and so on. A range of statistical techniques have been developed for analysing data with categorical dependent variables, including discriminant analysis, probit analysis, log-linear regression and logistic regression.

Logistic regression allows for the classification of cases or observations into two (or more) populations based on an outcome, which is referred to as the dependent variable. Logistic regression is able to distinguish which parameters (referred to as the independent variables) are significant predictors of a particular outcome and to then rank and quantify the relative importance of these independent variables on said outcome.

Furthermore logistic regression can determine the most appropriate equation (in relation to those independent variables analysed) to act as a *boundary of separation* between the two populations in terms of the outcome. Within this study that equation is referred to as the *Discriminant Equation,* which can then be used to predict the outcome based on the significant predictors. The statistical software package SPSS was used in relation to these analyses. The statistical component of Microsoft® Excel was utilised for the linear/multiple regression analyses and simple statistical analyses in terms of mean, standard deviation etc.

Linear (Multiple) regression analyses - two pass dataset

Due to space constraints associated with a conference paper it is only the two-pass dataset analyses that are presented herein. The interested reader is referred to Colwell and Frith (2012) for a full description of all database analyses including the maingate/tailgate stables, stables formed utilising a three or even four pass process and maingate/tailgate intersections adjacent to the faceroad.

The two pass (formation) faceroad dataset comprises 207 cases; with 134 considered satisfactory, 33 manageable and 40 assessed as unsatisfactory. With respect to the linear regression analyses only the satisfactory and manageable cases are combined in terms of assessing appropriate levels of roof support. Based on the definition of a manageable case (i.e. "it is where the TARP is being triggered on a more frequent basis and/or there is a need for low to isolated moderate levels of remedial tendon roof support"), it is considered appropriate to include such cases as the outcome will represent an appropriate level of support where a properly considered TARP is in place.

The research associated with the ALTS 2006 project (Colwell and Frith, 2009; Colwell, 2010) clearly indicated that the principal geotechnical drivers which, in combination, essentially dictate the level of roof support required to maintain a stable roof both on development and during longwall extraction are the structural integrity of the immediate roof (as measured by the CMRR) and the resultant stress acting across the roof (σ_R).

With respect to an installation roadway the resultant horizontal stress acting across the roof (i.e. normal to the direction of drivage) is taken to be σ_R-Dev and is estimated by utilising the ratios of the major and minor horizontal stress to the vertical stress (i.e. σ_H:σ_v and σ_h:σ_v respectively) and the angle of σ_H to the direction of drivage while taking into account the stress ratios which best represent the roof section being reviewed.

The initial series of linear regression analyses reviewed total roof support levels in terms of the fully widened section of faceroad under review. In terms of a rock mass classification index the roof support analyses associated with the various ALTS research projects utilised the CMRR as a measure of the structural integrity of the roof and therefore the analyses essentially relate to the primary bolted interval and this is predominantly why the GRSUP calculation is normalised to the bolted interval. With respect to this dataset the primary bolt length ranged from 1.8 m to 2.4 m with an average length of 2.0 m.

In terms of this project it was recognised that for a fully widened faceroad (as compared to a standard roadway width of 4.5 m to 5.5 m) a greater distance into the roof should be reviewed. Therefore in addition to assessing the CMRR (being specific to the bolted interval) for this series of analyses set distances of 2 m, 3 m and 5 m into roof were also reviewed using average values for UR, GSR, RSI, UCS and load bearing capacity (P, MPa). The estimate for σ_R-Dev was also revised in terms of the distance and rock types within the section of roof under review. In keeping with the rationale of normalising the calculation of the GRSUP to the bolted interval (i.e. distance over which the CMRR is calculated), for the greater distances of 3 m and 5 m any longer cables were be normalised to those respective distances.

In terms of 167 combined satisfactory/manageable cases associated with the two pass (formation) faceroad dataset. It was clear from these analyses that the Average UR is by far the superior rock mass classification index with respect to the r^2 value (i.e. strength of correlation in terms of the regression equation).

The analyses also indicate it is beneficial to utilise a roof section greater than the primary bolted interval in assessing the total level of roof support required to maintain satisfactory/manageable faceroad behaviour. The strongest relationship is for GRSUP as a function of Average UR and σ_R-Dev calculated over a roof section 5 m above roofline. Based on the multiple regression analyses the following relationship was found:

$$\text{GRSUP Total}_{5m} = 490.37 \times e^{-0.0427\ \text{Average UR5m}} \times e^{0.0345\ \sigma\text{R-Dev}} \qquad (1)$$

The above relationship is illustrated in Figure 1.

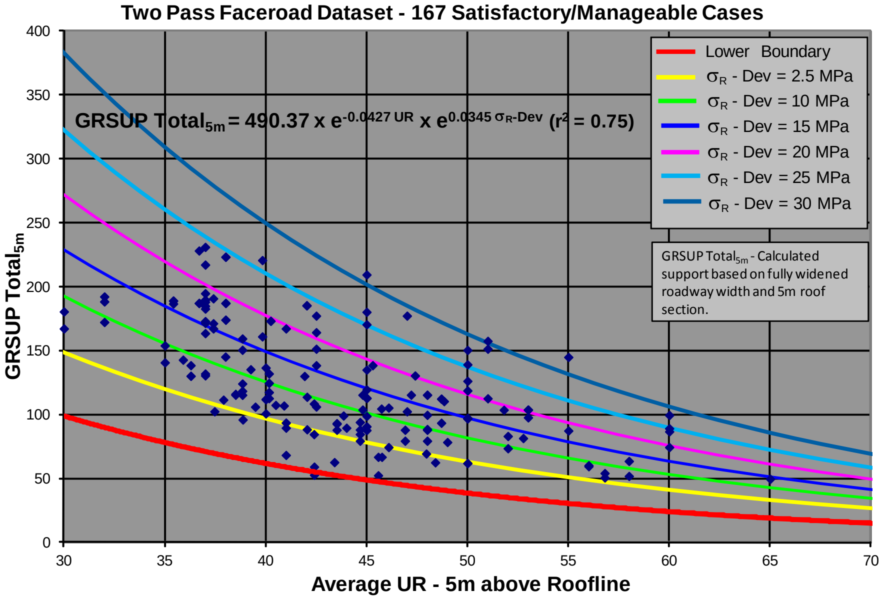

Figure 1 - GRSUP Total$_{5m}$ v's average UR and σ_R-Dev - two pass dataset

Another important aspect in relation to faceroad roof support design is to determine the appropriate level of roof support to install within the 1st pass drivage prior to widening. It was decided to plot GRSUP calculated over a 5 m roof section for both 1st pass and with respect to the fully widened roadway width (i.e. GRSUP Total$_{5m}$).

Figure 2 indicates that approximately 65% of the total roof support capacity installed within the fully widened faceroad (as measured by GRSUP 1st Pass*$_{5m}$ with respect to GRSUP Total$_{5m}$) is installed within the 1st pass drivage prior to widening to achieve a satisfactory/manageable outcome. The statistical analyses associated with the combined 167 satisfactory/manageable cases clearly indicate that a viable design methodology for longwall installation roadways can be developed.

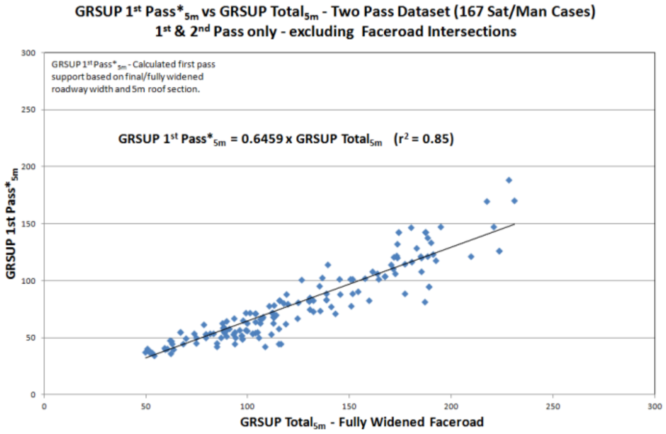

Figure 2 - GRSUP 1st Pass*$_{5m}$ v's GRSUP Total$_{5m}$ - two pass dataset

Logistic regression analyses - two pass dataset

To undertake binomial logistic regression with a multinominal outcome (i.e. satisfactory, manageable and unsatisfactory), it was decided to eliminate the manageable cases (i.e. 33 cases) and compare the satisfactory cases (i.e. 134 cases) to the unsatisfactory cases (40 cases) thereby providing a dichotomous outcome. Therefore the resultant *Discriminant Equation* would potentially represent a design equation approximating a manageable outcome (i.e. effectively a *boundary of separation* between the two populations).

The uneven nature of the outcome (i.e. 134 satisfactory cases v's 40 unsatisfactory cases) limits the ability of most statistical techniques to discern an unbiased result. With respect to logistic regression a significantly greater weighting would be given to the satisfactory cases in terms of the resultant *Discriminant Equation*, which could potentially result in a design equation or methodology that does not adequately address the more difficult conditions.

However a facility exists within SPSS to weight cases and in this instance it was decided to weight the unsatisfactory cases by a factor of 3. This results in a simulated database (for analysis) of 134 satisfactory and 120 unsatisfactory cases. Numerous statistical analyses were performed on the two-pass data set. The interested reader is referred to Table 7.2 of Colwell and Frith (2012) which contains a sample of the various parameters utilised during these analyses (many more were assessed) and details the range as well as mean and standard deviation.

The two best predictors of the final outcome were the AMCMRR FOS values calculated in relation to the 1st pass against both buckling and compressive yielding of the roof material over a distance of 5m above the roof line and in relation to the 1st pass roadway width. When utilising an AMCMRR FOS value associated with the 1st pass drivage for the purpose of this study i.e. as an index/predictor of the fully widened roadway outcome to assist with the design process, it is considered far more practical in terms of the eventual design methodology to simply use one or the other index rather than both.

From a statistical point of view there was essentially no difference in relation to which FOS value was utilised, however from a geotechnical point of view the FOS calculated in relation to compressive yielding of the roof material is considered more appropriate as it limits the mechanical advantage applied within the load balance calculation by the yield strength of the rock units over the 5 m interval. The resultant *Discriminant Equation* incorporating AMCMRR $FOS_{5m\text{-}yield}$ is:

$$z = 3.339\ FOS_{5m\text{-}yield} - 4.745 \qquad (2)$$

The value z is referred to as the predicted log odds value. When z is less than zero one would predict/classify the case as unsatisfactory and when greater than zero the case would be predicted as satisfactory. Equation 2 successfully classified 105 of 120 weighted unsatisfactory cases (therefore in actual fact 35 of 40 unsatisfactory cases or 87.5% correct) and 107 of the 134 satisfactory cases (79.9% correct) for an overall classification success rate of 81.6%. Equation 2 can be rearranged so that the design variable $FOS_{5m\text{-}yield}$ relating to a manageable outcome can be calculated i.e. $FOS_{5m\text{-}yield} = 4.745/3.339 = 1.421$

The above findings essentially indicate that if on the 1st pass $FOS_{5m\text{-}yield} > 1.421$ then it is more likely that the longwall installation roadway will be manageable following widening, however when $FOS_{5m\text{-}yield} = 1.421$ this also means there is 50:50 chance of the outcome (i.e. fully widened roadway performance) being satisfactory or unsatisfactory.

It is extremely important to recognise that in this way $FOS_{5m\text{-}yield}$ associated with the 1st pass drivage is being used as a predictor of the eventual outcome and not as a Factor of Safety. To emphasise this point; in developing the design methodology $FOS_{5m\text{-}yield}$ is not referred to as a Factor of Safety, it is referred to as the 1st Pass Reinforcement Index or $RF_{5m\text{-}yield}$.

Further analyses were undertaken specifically relating $RF_{5m\text{-}yield}$ to other roof performance indices. For example Figure 3 plots the Surge (mm, being defined as the initial increase in vertical roof displacement post-widening) against $RF_{5m\text{-}yield}$, Figure 4 plots the Creep Rate (mm/d being defined as the vertical roof displacement rate subsequent to the initial Surge) against $RF_{5m\text{-}yield}$, while Figure 5 plots Height of Softening (HOS), which is defined as the distance into the roof where the measured displacement first exceeds 1mm, against $RF_{5m\text{-}yield}$.

With respect to Figure 4 it should be noted that in relation to the unsatisfactory cases there were two instances where there were falls and as such the creep rate was extremely high! In addition there were two other cases where creep rates of 8.33 and 18.44 mm/d were recorded requiring the use of standing support to avert a fall. So as not to overly increase the y-axis (and lose the visual detail for creep rates of < 0.5 mm/d), these four cases have been given a nominal creep rate of 2.5 mm/d.

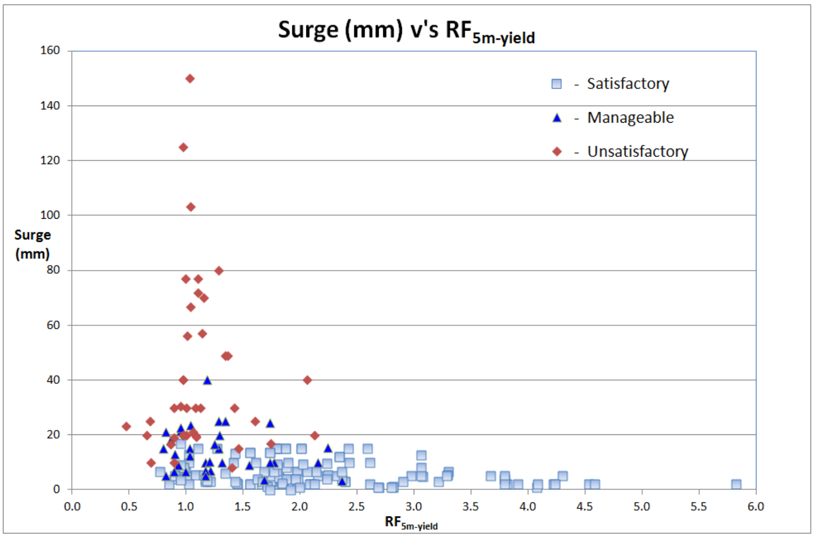

Figure 3 - Surge (mm) v's $RF_{5m\text{-}Yield}$

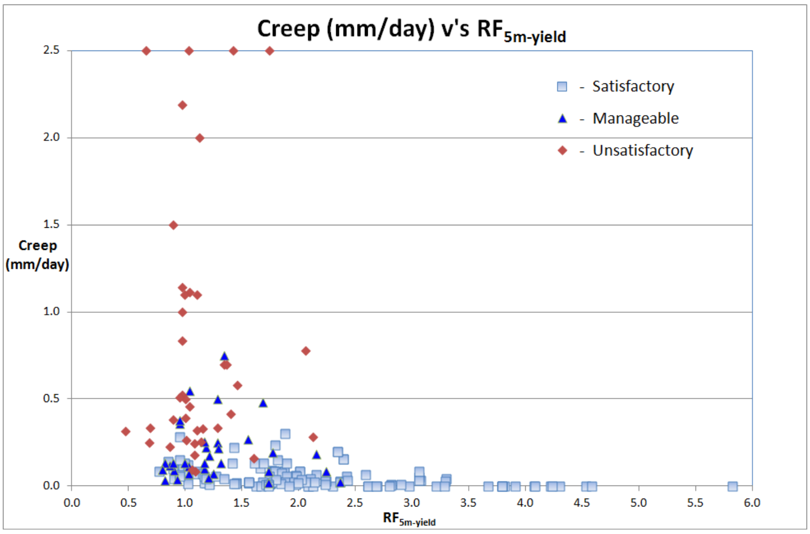

Figure 4 - Creep Rate (mm/d) v's $RF_{5m\text{-}Yield}$

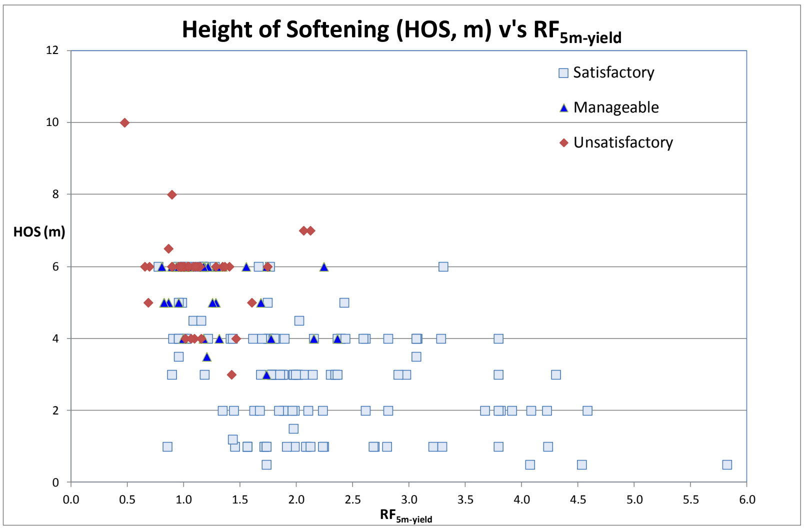

Figure 5 - Height of Softening (HOS, m) v's $RF_{5m\text{-}Yield}$

DISCUSSIONS

The linear (multiple) regression analyses clearly demonstrate that the principal geotechnical drivers which, in combination, essentially dictate the level of roof support required to maintain a stable roof are the structural integrity of the immediate roof and the resultant stress acting across the roof. This being totally consistent with previous research associated with the development of ALTS (Colwell and Frith, 2009) and essentially consistent with the findings of Thomas (2010).

The strength of the relationship between GRSUP Total_{5m} as a function of the Average UR (over the first 5 m of roof) and σ_R-Dev (i.e. equation 1 and as depicted in Figure 1) would be considered strong to very strong with a correlation (i.e. r^2 value) of 0.75.

The logistic regression analyses in conjunction with the very simple mean and standard deviation analyses (reported in Table 7.2 of Colwell and Frith, 2012) as well as plotting $RF_{5m\text{-}yield}$ against other roof performance indices (refer Figures 3, 4 and 5) illustrate that the 1st Pass Reinforcement Index, $RF_{5m\text{-}yield}$ can be effectively utilised as a part of the design process.

Furthermore in relation to the level of reinforcement required with the 1st pass drivage prior to widening, Figure 2 very strongly indicates that approximately 65% of the total roof support capacity installed within the fully widened faceroad (as measured by GRSUP 1st Pass*_{5m} with respect to GRSUP Total_{5m}) should be installed within the 1st pass drivage prior to widening to achieve a satisfactory/manageable outcome. Furthermore it was found that on average 64.5% was utilised with respect to the satisfactory cases and 61.9% in terms of the manageable cases, while there was a significant drop to 54.2% in relation to the unsatisfactory cases.

All of this information, in addition to the very strong relationships that already exist within ALTS (so as to achieve satisfactory standard width roadway conditions while accounting for variances in the structural integrity of the roof and applied stress), indicated that a robust design methodology for installation roadways would be developed. This proved to be the case resulting in ADFRS (Colwell and Frith, 2012).

CONCLUSIONS

In relation to other strata control issues, such as coal mine pillar and roof support design (for standard roadway widths), there has been comparatively very little research undertaken in relation to the geotechnical design and management of longwall installation roadways. As a result, in terms of a satisfactory outcome, faceroads within Australia have been quite problematic and by way of example of the 207 cases associated with the two-pass dataset, 40 resulted in an unsatisfactory outcome involving the use of standing support, PUR and/or high levels of remedial tendon support with two faceroads "lost" and having to be re-driven due to major roof falls.

The authors were also aware of several other faceroads that were abandoned in recent years due to major roof falls however due to a lack of site specific information unfortunately they could not be included in the database. Nonetheless *a failure rate* of approximately 20% is judged to be unacceptable. The authors' contend the principal reason for such a failure rate is the clear absence of suitable design equations that relate the required levels/type of roof support as a function of the competency (or some valid measure of the competency) of the roof and the horizontal stress acting across the roof.

Thomas' (2010) findings in a way essentially represented our industry's state of empirical knowledge prior to this study. The strength of the relationships found by Thomas (2010) when plotting his roof support indices (RDI and SRDI) against a "*measure of the roof's propensity to buckle"* (being the SSR - Stress Strength Ratio) would, for geotechnical design, be considered weak to moderate at best with r^2 values of 0.499 and 0.325 respectively and reinforced the need for suitable design equations with strong correlations around which can be engineered a credible design methodology.

The design methodology resulting from this study is called *ADFRS* and now fills the gaping void that existed in the Australian underground coal industry with respect to the geotechnical design and management of longwall installation roadways. ADFRS is based on a sound mechanistic understanding of the roadway development and widening process and the design equations (with strong to very strong correlations) are fully consistent with measured roof behaviour.

Over the last two decades (particularly subsequent to the findings associated with the Moura disaster in 1994, i.e. Windridge, 1995), 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, roadway and longwall hazard plans and in relation to ground support, the categorisation of various zones as a part of the mine manager's support rules.

The ADFRS Design Methodology has been formulated to complement the mine site risk management approach to strata control/management. However because there are factors affecting longwall installation roadway behaviour that are either specific to or more pronounced at an individual colliery, it is imperative that the ADFRS design recommendations, resulting in the formulation of a ground support design strategy, be assessed within the framework of a properly facilitated mine site risk assessment and that a properly considered TARP is in place prior to any development taking place.

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