INVESTIGATION INTO THE RELATIONSHIP BETWEEN STRATA CHARACTERISTICS AND LONGWALL CAVING BEHAVIOUR

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ABSTRACT: This paper outlines the results of a study to analyse various longwall operations using the Geophysical Strata rating (GSR) to characterize the strata, assess the likelihood of weighting and then correlate this with the various outputs that can be provided by longwall support monitoring analyses. A significant advantage of integrating GSR and longwall datasets is to allow a 3D spatial understanding to be developed between strata characteristics and various support loading related parameters. A caving chart has been developed based on a combination of previous experience in longwall support assessment, strata characterisation, leg pressure data analysis and caving behaviour. The chart provides a link between strata conditions, stresses, panel layout and anticipated support loads via design thresholds that are related to roof convergence. The intent is to provide a means to assess the risk of cavities in the immediate roof and/or the risk of heavy weighting from the overlying roof units.

INTRODUCTION

Massive strata overburden units are known to influence support loading on longwall faces. Past studies of the conglomerates in New South Wales and sandstones in Queensland have identified factors such as unit thickness, proximity to coal seam, immediate roof strength and panel width that may all play a role in support loading and in the development of adverse ground conditions. Other controls such as cut height, cutting method, hydraulic supply, leg pressure control parameters and pressure settings can also influence ground behaviour.

The interaction between longwall supports and the surrounding strata is a complex phenomenon. At present neither empirical nor numerical models can adequately capture the critical factors required to predict strata response. However, recent advances in the ability to analyse longwall monitoring data such as that developed by Longwall Visual Analysis (LVA) provide a potentially large and valuable data source to quantify time related factors. It also provides a means by which to assess how operational practice can influence shield behaviour. There is a need to develop a view to understanding the relative changes in behaviour from one set of conditions to the next. The aim of the ACARP study described here (Medhurst, *et al.*, 2013) was therefore to produce a set of tools and/or indicators that can be used for interpreting key strata caving mechanisms and quantifying its impact on longwall support performance.

Through previous ACARP projects an approach to characterise ground conditions using borehole geophysical logs has been developed. One aspect of this is the Geophysical Strata Rating (GSR), a rating scheme devised for coal bearing strata. Using geophysics data provides a high density and cost effective means of gathering geotechnical information that enables development of 2D and 3D models of strata characteristics. This study aimed to take advantage of GSR estimates to provide a practical means to classify or identify features that affect caving behaviour. Data from three sites were used for the study namely, Moranbah North, Dendrobium and Newlands Mines as they represented a range of conditions and locations. Anecdotal evidence and experience from other sites was also used in the formulation of the outcomes of the study.

LONGWALL EXTRACTION BELOW MASSIVE STRATA

Caving mechanics and the ability to predict caving events in rock strata remains as one of the key challenges in mining geomechanics practice. In massive strata the problem is not only one of predicting caving behaviour, but also of assessing if such behaviour can potentially lead to periodic weight and/or windblast events. In the late 90's a series of well documented studies were undertake to examine the

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caving behaviour of massive strata. This experience was captured in the empirical chart based on Voussoir beam principles (Frith and Creech, 1997), shown in Figure 1.



Figure 1 - Empirical caving chart under conglomerate roof

The concept of fracturing ahead of the face under longwall conditions and behind the face under shortwall conditions, potentially leading to windblast conditions, provides the basis for the design chart shown in Figure 1. In general, this concept remains valid and has served the industry well. However the intensity of periodic weighting, or in some cases a lack of events when anticipated, suggests that a more detailed understanding of the controlling factors at play is required. It is important to note that limited work on the issue of conglomerates has been done since that time. Since then longwall panel dimensions, equipment and operating practices have changed. More recent observations suggest that weighting is not just a function of thickness and width, but also location of units within the sequence and surrounding strata conditions.

Frith (1996) provides a detailed discussion of the classic periodic weighting mechanism in which tensile fracturing occurs ahead of the face due to self-weight cantilever loading. The discussion is extended to show the potential of bedding plane shear on underlying laminated material as a result of the tensile fracturing via a mechanism of the lowering of the neutral axis of the overlying massive strata beam. Albeit somewhat academic it raises the question of whether bedding plane shear occurs before or after the development of tensile failure leading to weighting events. The short answer to this question is that both scenarios can occur and in fact, leads to the heart of understanding the interplay between strata conditions, support characteristics and operating practice.

Experience in the weaker, thick seams of the Bowen Basin show that weighting issues are most prominent where "soft" forward abutments can develop via shear ahead of the face due to factors such as excessive horizontal stress conditions, high cut heights and significant face spall, stress relaxation due to prolonged face stoppages and/or poor longwall operating performance. The potential for periodic weighting is not only dependent upon thickness and strength of massive roof units, but also the thickness and character of interburden, including position of weakness planes. In other words this might be a case where bedding plane shear due to the presence of unfavourable strata conditions is a key factor in the damage of overlying laminites and the main source of cavities.

The rate of retreat is also critical. Where conditions might have otherwise been considered reasonable, a slow retreat rate or lack of adequate set pressure may allow excessive convergence of overlying strata leading to tensile fracturing. In this case, the classical mechanism may be relevant in which the development of poor immediate roof conditions are essentially mining induced. A typical scenario might be that shown in Figure 2.



Figure 2 - Caving mechanism under slow retreat and/or poor roof conditions

Previous studies show that shearing and cavity development often occurs in the presence of a weak layer within the lower 2 m to 3 m of the roof horizon (Medhurst, 2005). This is related to how far the influence of active pressure from the supports is able to extend into the roof. The background rate of roof convergence is also important in controlling roof stability and can sometimes be related to the impact of a slow retreat rate or the effect of soft roof.

At Moranbah North, microseismic monitoring showed that shear events had occurred up to 40 m ahead of the face (Strawson and Moodie, 2007). Up to 40 m of overlying sandstones were also present, but in this case the presence of a weak immediate roof provided an area of high propensity for cavity development. Comparison of examples from the conglomerates in NSW and sandstones such as at Moranbah North show how different outcomes can occur despite relatively similar massive unit characteristics and panel dimensions. In essence, a one size fits all solution to longwall ground control problems is an elusive goal without due consideration of strata and operating conditions.

SHIELD MONITORING

Leg pressures

Longwall leg pressure monitoring has in various forms been used in Australia for over 20 years. Peng (1998) characterised pressure changes within a mining cycle into three major types: increasing, steady and decreasing types, shown in Figure 3. The increasing type was described to be representative of a relatively intense roof loading. The steady type is denoted as relatively weak roof loading, and the decreasing type being of extremely weak roof and/or the presence of too much rock/coal debris between the canopy/roof, base/floor or due to leg leakage.

An inherent characteristic of the support loading cycle is its relationship to the overlying roof conditions. In general, whilst variations on this behaviour exist, the plots show an initial high load rate period where the supports are seated against the roof; which will depend on the set pressure applied. A second long period of constant load rate that reflects the stiffness and load transfer capacity of the overlying roof, and a third, high load rate component, which in most cases is normally associated with the cutting cycle, increase in tip-to-face span and lowering of the adjacent shield.

The time weighted average leg pressure represents the most common and traditional means of assessing support resistance over a load cycle. Several features of longwall support response can usually be identified such as whether there is adequate set pressure or if the support is being

overloaded due to a number of repeated yield cycles (Trueman, *et al.*, 2005). One key aspect however, is the change in load over a given time span. A measure of loading rate provides a measure of roof stability as it reflects the rate of strata movement.



Figure 3 - Pressure changes in a shield supporting cycle

One difficulty in assessing load rates is setting criteria for the calculation of initial load rate, steady state load rate or final load rate. For each case, a change in state in the pressure record has to be estimated or a time cut-off has to be defined, e.g. initial rate over 10 mins. This cut-off is an arbitrary measure and to various extents can produce significant variation depending upon the consistency of operating characteristics between operators, panels or even different mines.

Another aspect is that when calculating load rates longwall data are inherently "noisy". Crisafulli and Medhurst (1994) have addressed this issue by developing a continuous load rate estimation algorithm that takes account of sharp changes in the pressure record due to operational influences or measurement errors. A comparison is shown in Figure 4.

The top plot shows the pressure record. The time difference calculation is shown at the bottom. This represents the standard calculation that would be done in excel, in which the difference between pressure measurements at each minute is calculated. Notice how extremely high load rates are estimated (> 50 bar/min) due to the support resets and other signal discontinuities, producing a "noisy" estimate. The centre plot shows the continuous load rate calculation. This method removes the signal discontinuities and provides a smoothed estimate of load rate that is reflected by the rate of overlying strata movement. In this case load rates in the order of 4 bar/min are shown which is more representative of the pressure record.

Estimation of load rates provides a measure of strata response and reflects the rate of overlying roof convergence. In a pre-yield condition load rates can be directly related to convergence rates. However if the support is in yield, measures such as yield counts have been used since they present an indirect measure of load rate and hence convergence rates.

Convergence based triggers are routinely used for strata control purposes. Until recently however, such measurements have been difficult to obtain in a longwall environment. In the absence of direct convergence measurements, estimation of critical load rates or yield counts or combinations thereof have provided the most useful stability measures as they reflect the potential to reach the point of critical roof convergence.

Roof convergence

The typical response in a strata control environment is to install more support when a trigger is reached. This is generally not an option in a longwall environment leaving only the ability to keep moving or lowering cut height to alter the loading conditions. In this case a greater reliance on a predictive model of

longwall ground response is required in order to take preventive action. This is an important consideration for support design and operational planning.



Figure 4 - Load rate estimation using continuous and time difference methods

One approach used to assess roof support response requires introduction of the Ground Response Curve (GRC) concept (Medhurst and Reed, 2004). The GRC was originally developed by the civil tunnelling industry to optimise ground support practices in weak ground. The advantage of this approach is that ground behaviour and support set-to-yield characteristics can be assessed together. The general concept is illustrated in Figure 5.

It is important to note that total roof convergence is made of two components, initial roof convergence before the support is set in each the Lower-Advance-Set (LAS) cycle and the roof convergence during the cutting cycle as demonstrated in Figure 5. An estimate of initial roof convergence is important for understanding the impact of the LAS cycle on roof stability. A high level of initial roof convergence gives a lower margin for controlling the roof and more demand on support load to limit the roof reaching critical convergence levels.

Unfortunately, initial convergence cannot be measured directly, even via convergence monitoring, as it occurs at the faceline as part of the LAS cycle. However an estimate can be made if there is some measure of the convergence rate of the overlying strata and a timeframe in which to estimate the amount of movement. As previously mentioned a high load rate spike is often detected at the end of the cutting cycle as shown in Figure 3. This pressure increase provides an indirect measure of initial convergence.

A measure of the set-to-yield convergence for a nominated set pressure is normally provided with the technical specification of the supports. An analysis of leg stiffness from several modern support designs shows a typical set-to-yield leg closure ranging from 1.1 to 1.5 mm for every 10 bar of pressure increase. This equates to an average leg stiffness of about 8 bar/mm resulting in leg closures of 6.5 mm to 13 mm for a 50 bar to 100 bar set-to-yield pressure range. Any given pressure change can then be equated to a value of roof convergence from the longwall monitoring data.

A typical example might be a pressure spike of 20 bar over a period of 45 s after the shearer goes past and the support is advanced. This equates to a pressure increase of up to 30 bar/min or 200 mm/hr. At a nominal shear speed of 10 m/min and an exposed roof of say 10 supports (20 m), this suggests an unsupported roof area (after the cut) for about 2 mins. At 200 mm/hr this gives about 7 mm of roof movement. Analyses of this type over several sites suggests about 50% of initial roof convergence occurs due to seam compression and the other 50% from the LAS cycle. In this example, the total initial roof convergence would be about 15 mm.



Figure 5 - Ground response curve

The second aspect is set-to-yield convergence. For an 80 bar set-to-yield range this might result in an additional 10mm of roof movement. However if a low set pressure is applied, e.g. giving say a 160 bar set to-yield range, the convergence will double to 20 mm. Combined with an estimate of initial convergence this shows how low set pressure can result in a significant amounts of roof movement.

The third aspect is post-yield roof convergence. Obviously direct convergence measurement will provide the best answer. But if such information is not available, a minimum value of roof convergence can be estimated via the pressure drop in each yield cycle. For example a 10 bar pressure drop during yield and then an increase back to yield pressure equates to 2 x 1.5 mm; or a minimum of 3 mm leg closure for every 10 bar yield cycle. Depending upon the flow rate in the yield valve and the convergence rate of the strata, the roof convergence may be greater. Nevertheless the preceding discussion shows why combined measures of set pressure, load rate and yield cycles such as the Cavity Risk Index (Hoyer, 2012) give some measure of roof stability, since they all indicators of reaching some level of critical roof convergence.

LONGWALL CAVING ASSESSMENT

Strata characterisation

Through ACARP projects C15019 (Hatherly, *et al.*, 2008) and C17009 (Medhurst, *et al.*, 2010) an approach for characterising ground conditions using borehole geophysical logs has been developed. One aspect of this is the GSR, a rating scheme devised to allow coal bearing strata to be quantitatively assessed in every borehole that is geophysically logged. Table 1 shows an indicative range of rock quality as it relates to GSR.

The GSR allows a full analysis of overburden characteristics to provide 2D and 3D models of strata conditions. This provides the opportunity to correlate strata conditions with longwall support response. Each longwall face will operate over a given set of panel dimensions, stresses and ground conditions, which can be represented in the ground response plot in Figure 6. The ability to develop a cave prediction model therefore relies upon the active zones defined by four variables namely, strata conditions (GSR), support behaviour/characteristics, support load/stresses and convergence limits. It then becomes feasible to define a relationship between these variables for assessing caving and roof stability.

GSR I	Description	
0	15	Very poor
15	30	Poor
30	45	Fair
45	60	Good
60	80	Very good
80	100	Extremely good

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Figure 6 - Ground response over active longwall panel

The first task in providing an assessment of the caveability of overlying strata is to establish suitable parameters for strata characterisation. In accepting GSR as a measure of changing strata conditions, it then becomes a question of how it is to be used. Australian experience shows that severe periodic weighting effects tend to develop where massive strata units are present, i.e. where a single unit or series of combined units are greater than 15 m to 20 m thick as reflected in Figure 1. This can lead to heavy weighting, windblasts and/or face stability issues.

There is significant evidence to suggest that the potential for cavity development at the faceline is more pronounced in the presence of weak immediate roof conditions. This can be due to the inherent conditions, or by mining induced shear or fracturing from localised mining induced stresses or periodic weighting effects. As discussed previously, the potential for cavity development is particularly high in the presence of massive strata overlying a weak immediate roof unit.

Shearing and cavity development often occurs in the presence of a weak layer within the lower 2 m to 3 m of the roof horizon. The influence of poor roof conditions can also often be observed to reach up to 5 m under failure conditions. The overall zone of influence for caving assessment therefore could be separated into two basic zones comprising the immediate roof above the supports and the main roof that may contain massive units from 15 m up to 50 m thick. In keeping with industry experience, a 30m interval has been selected to represent the main roof and a 3m interval for the immediate roof as shown in Figure 7. Median values are chosen in preference to averages since they are less prone to the influence of outliers.

The presence of coal roof can shield the face from high stresses and influence roof stability. A stress correction factor is proposed to account for the additional stability provided by a coal roof. In this case, where the thickness of coal is at least 1m thick above the cutting horizon, the median GSR value for the proportion of coal in the roof should be multiplied by a factor of 1.4. This factor relates to the stress transfer capability of a fixed end beam in a low stress environment.



Figure 7 - Basis of strata characterisation for caving assessment

Caving assessment

A critical aspect for caving assessment is the influence of panel dimensions and stress. For sub-critical panel layouts longwall supports are unlikely to experience full cover depth conditions. The ability of a massive unit to create a cantilever or the ability of a weak immediate roof to become unstable will be related to both the depth and panel width. This introduces the concept of Equivalent Depth (ED) in which a reduction in full depth conditions can be used to account for sub-critical panel layouts.

Using the concept shown in Figure 6, an analysis was undertaken of longwall support loads, critical convergence levels, ground conditions, panel dimensions and cover depth using data from a large proportion of longwall operations in Australia. A corresponding relationship between GSR and ED for a range of longwall support conditions was subsequently determined. This is shown in Figure 8.

Figure 8 is based on a combination of previous experience in longwall ground response, GSR analysis, analysis of leg pressure data and caving behaviour. The stable to transitional boundary represents a zone of increasing roof convergence and can vary locally, hence "transitional". Longwall support capacity thresholds are also shown and represent the yield density (before the cut) in t/m² required to maintain acceptable levels of roof convergence.

The ED can be estimated using the formula shown in the bottom right hand corner of Figure 8; and takes account of the effect of panel width and depth on support loading. The GSR is chosen as the median value over a given roof interval. This can be used to assess the risk of cavities in the immediate roof and/or the risk of heavy weighting from the overlying roof units as defined in Figure 7.

The majority of Australian operations present data in the lower half of the design curves, although several proposed operations are planning to mine at considerable depths. In order to obtain some representative guidelines for the greater depths, data for several proposed operations were used along with some international data where available. In particular, a useful dataset from a colliery in Canada was provided for the study that included longwall mining beneath massive strata at depths greater than

700m (Payne, 2013). Such data provided additional information for defining curves where the ED was in excess of 300 m.



Figure 8 - Summary of caving response for Australian longwall operations

Assessing risk

Longwall face cavities generally develop as a result of excessive roof convergence, which can be caused by several inter-related factors including:

- · Poor setting loads, canopy contact and/or horizon control during operation of supports
- Presence of weak, sheared, faulted ground and/or damaged roof from overlying weighting behaviour and/or mining induced behaviour such as increased loading due to stress notching
- Increased tip-to-face roof spans due to excessive face spall due to high abutment loading from overlying weighting behaviour, poor face alignment and/or other mining induced factors
- Inability to support the roof due to non fit-for-purpose support characteristics or inadequate hydraulic supply system attributes
- Insufficient support capacity leading to excessive yielding during operations

A one size fits all solution to assessing risk is therefore a challenging task. Nevertheless on the basis of the summary design chart an assessment can be made. For the purposes of cavity risk analysis, it is suggested that the chart may be used in a staged process, namely

- 1. Plot immediate roof GSR vs ED to assess stability
- 2. Plot main roof GSR vs ED to assess stability
- 3. A first pass assessment can then be based on thresholds of immediate roof and main roof.

An example is shown in Figure 9. This represents a typical weak roof, strong overlying strata scenario of typical panel dimensions and depth with a median GSR of 30 for the immediate roof and a main roof GSR of 60. Assuming an installed support density of 110 t/m², the chart suggests that the immediate

roof will be prone to cavities and the overlying strata may cause some periodic weighting that could overload the supports.



Figure 9 - Caving chart example

As roof conditions and/or stresses change as a panel is mined different points may be plotted on the chart. The chart can therefore be used as a broad scale assessment of the potential for cavities and/or periodic weighting. Table 2 provides a guideline for undertaking a first pass risk assessment based on a point plotted on the caving chart.

Threshold	Main Roof < Transitional	Transitional < Main < Heavy	Main Roof > Stable
Immediate Roof <	Cavity High, Weighting	Cavity Moderate,	Cavity High, Weighting
Transitional	Low	Weighting Low	High
Transitional <	Cavity Moderate,	Cavity Low, Weighting	Cavity Moderate,
Immediate < Heavy	Weighting Low	Low	Weighting High
Immediate Roof >	Cavity Low, Weighting	Cavity Low, Weighting	Cavity Low, Weighting
Stable	Low	Low	High

 Table 2 - Summary of caving risk

The caving chart provides a link between support load, roof conditions and support requirements via design thresholds that are related to roof convergence. The risk matrix is useful as a first pass but does not address variation in support loading across the face and/or high/low loading or convergence rate of the supports and its effect on roof stability during operations. It therefore provides a guide and starting point for site based analysis and the use of real-time longwall monitoring data.

Site-based analysis

As per the example outlined one approach that can be used to assess cavity risk is to superimpose the effect of changing roof conditions on the caving chart as a function of longwall retreat. Figure 10 shows an example from Moranbah North.

In this case GSR values plotted from the model at every 25 m are superimposed on the chart. The results show the variation in cavity risk and reflect the potential for increased roof convergence in the weaker roof zones.



Figure 10 - Caving chart showing change in roof conditions

An alternative is direct roof convergence measurement and/or estimates of roof convergence and convergence rates using leg pressure data as discussed previously. Past experience suggests that cavity development starts to occur when roof convergence is in the range of 30 mm to 50 mm at most operations. Examples are provided in the ACARP study (Medhurst, *et al.*, 2013) that outline the use of loading rate and convergence rate analysis for estimating time related strata relaxation and critical convergence thresholds. Each requires site specific considerations.

The collective theme and key consideration through various methods is a measure of convergence. The caving chart is a broad scale measure that reflects the impact of roof conditions on support response. The CRI method as it applies to existing operations is an index measure of convergence obtained from leg pressure data combined with some basic parameters that relate to support load and continuity of prevailing conditions across the face. A third approach considers convergence more directly from leg pressure data through conversion from leg stiffness data.

The direct convergence estimate approach will be augmented in future by convergence monitoring. This will be a useful advancement. It is likely however, that accuracy of convergence monitoring may be limited and leg pressure conversions will be useful for estimating to the 1 mm accuracy required.

CONCLUSIONS

Longwall face stability depends upon a range of geotechnical conditions, operational factors and the mechanical constraints of the longwall system. It is therefore sometimes difficult to determine the relative importance of these three main influences and their degree of interaction when assessing risk of instability. In this regard "a one size fits all" solution to longwall ground control problems is an elusive goal without due consideration of strata conditions and operating practice.

A caving chart has been developed based on a combination of previous experience in longwall support assessment, strata characterisation, leg pressure data analysis and caving behaviour. The chart provides a link between strata conditions, stresses, panel layout and anticipated support loads via design thresholds that are related to roof convergence. The intent is to provide a means to assess the risk of cavities in the immediate roof and/or the risk of heavy weighting from the overlying roof units.

Measures of convergence/convergence rate either directly or indirectly combined with a measure of load cycle times provides a mean to estimate convergence over a shear or multiple shears. This leads to the ability to determine whether the roof strata are near critical convergence levels.

Whilst achievable, continuous load rate analysis requires sophisticated smoothing algorithms to remove pressure spikes and other data discontinuities commonly present in longwall data. However when

measures of continuous load rate become available various parts of a shield's load cycle can be interrogated to help define support response.

The caving chart can provide the broader setting for design, risk assessment and planning whilst longwall monitoring data can be used to disseminate key parameters from the daily records. A direct convergence estimate using leg pressure data will obviously be augmented in future by convergence monitoring.

Convergence estimates from any particular shield alone however is unlikely to provide the necessary detail for a reliable real-time cavity risk indicator. A more sophisticated algorithm that uses each part of the load cycle in conjunction with continuous load rate and direct convergence measurement will be required for short-term longwall face stability assessment. Future algorithms will also need to incorporate factors such as the influence of load sharing from adjacent supports, standing time and the influence of varying set pressure on each load cycle. This is likely to require site-specific assessments that take account of operating practice, longwall support configuration and prevailing ground conditions in order to provide a reliable quantitative outcome.

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