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DEVELOPMENT OF A CAVITY PREDICTION MODEL FOR LONGWALL MINING

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ABSTRACT: Advancements in technology over the past decade, in data collection and computer modelling systems, have created opportunities to develop and improve the current methods of predicting roof stability issues in longwall mining operations. The ability to accurately predict roof instabilities and cavity developments has great benefits for the coal industry. Early prediction will allow for appropriate actions to be taken to avoid such events, removing the potential for harm to personnel and loss of production. A case study of Moranbah North Mine, investigating the causes of roof stability issues, concentrating on the development of roof cavities in the longwall face is presented. Results from an investigation of the effect of particular geological factors on the occurrence of such instability events are recorded. From the investigation a stability index was developed from geological data collected from boreholes on site. A hazard map was developed, using the index, to indicate areas in the roof where failures and cavities were most likely to occur. Although some correlations were found between the index and geological factors, the results were not entirely satisfactory as some important factors had not been included in the prediction model which is still being improved.

INTRODUCTION

Roof stability issues and the development of cavities in the immediate roof are a key concern for underground longwall mines. New technologies have enabled a greater knowledge and understanding of geological factors and *in situ* stresses in an underground environment, leading to a more accurate prediction of roof stability. These facilitate a safe working environment, which is imperative to all mining operations.

An investigation into the effects of particular geological factors on the development of cavities at Moranbah North Mine was conducted. The geological factors investigated included:

- Seam thickness;
- Depth of cover;
- Sandstone thickness;
- Interburden thickness; and
- Faulting.

These factors were used to develop a prediction model that highlights areas of concern along a longwall panel. The prediction model was developed using borehole data collected at the site. The prediction model was compared to data collected from the longwall chocks using Longwall Visualisation Analysis (LVA) software, to identify whether a correlation existed between the known cavity events and the prediction model developed. An accurate indicator will allow time for actions to take place to eliminate or at least reduce potential roof-stability issues or developing cavities and to avoid major time losses.

LONGWALL MINING

Longwall mining is the most common method of underground coal extraction used in Australia today. Longwall mining extracts coal in large rectangular blocks, defined during development, in a single continuous operation (Aziz, *et al.,* 2007). Each block of coal, known as a panel, is developed by driving a set of headings on either side of the panel off the main access roads. The start of the working face is created by the joining of these roadways. The longwall face is supported by hydraulic roof supports, whose main function is to provide a safe working environment as the coal is extracted and the longwall equipment advances. A goaf is formed as the immediate roof is allowed to collapse behind the mined out area. Figure 1 shows a schematic of a typical longwall retreat method.

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When designing a longwall panel layout, along with coal property boundaries, several factors will dictate the final result. Peng (2006) listed the following factors:

- Reserve;
- Panel dimensions;
- Geology;
- In-situ (horizontal) stresses;
- Multiple seam mining;
- Rivers/streams or lineaments; and
- Surface subsidence.

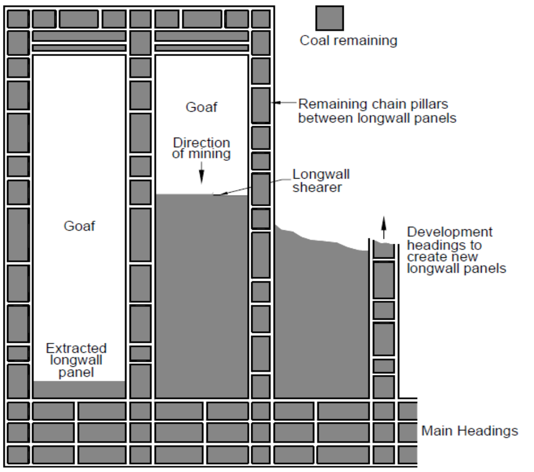

Figure 1 - Longwall retreat mining (Mine Subsidence Engineering Consultants, 2007)

GEOLOGICAL FACTORS

Seam attributes

Longwall units are better suited to regular seam trajectories as undulating seams cause issues because of irregularities in the roof and/or floor. Such instances can affect the stability of the structure or the quality of the product (Carroll, 2005). In general longwall mines have been developed in relatively flat lying seams, with inclinations of not more than 10°. With developing technologies and the increasingly strong coal market, seams dipping 15% to 20% are becoming more economically and physically viable to mine.

The thickness of a coal seam is another major contributing factor in the selection of the longwall mine design. Economically, maximising the recovery in thick seams can prove to be highly beneficial; however mining thick coal seams can often lead to roof stability issues that must be alleviated to maximise the benefits. Geological anomalies, that in some way affect the coal seam, have serious implications for the successful implementation of a longwall extraction method. These include faults, folds, sandstone channels, clay veins, and fractures (hill or mountain seams). It is important that these occurrences are identified, by mapping their locations using geophysical methods or at least determined panel by panel during gate road development. Locating the anomalies will have a strong influence on the layout of the main headings and working panels.

Floor and roof characteristics

Good roof and floor strata conditions are preferred for fast moving longwall operations. It is important to determine the properties of the near seam strata during the investigation stage, and ensure that the properties defined are not restricted to uniaxial compressive strength (UCS) and tensile strength. According to Medhurst (2005), roof stability is a function of lateral confinement, generated by the support resistance and the coal seam. This is of particular importance in areas of weak immediate roof. Confinement generates an increase in shear strength of rocks. Hence the coal seam and support legs of the longwall become the main abutments for arching of the immediate roof strata and the canopy provides active pressure within the arch zone. If the abutment is lost, the support system will break down. Roof material properties and orientations must be accurately tested to determine the forces to which the longwall supports will be exposed. As the longwall face advances, the vertical forces that were once being applied to the coal will now be directed towards the mining face and also to the armoured supports. Thus, the equipment selected must take into account the yield capabilities of the roof relative to the imposed loads.

Another predominant issue related to underground coal mining and roof stability is the presence of massive overburden strata. Periodic weighting issues can be caused by the presence of massive sandstone channels in the overlying strata. The distance of the massive strata unit from the seam influences support loadings that develop. The strength, distribution and character of massive sandstone structures in the roof lead to several issues when longwall mining, including (Medhurst, 2005):

- Cantilever effects that overload supports under 'massive' conditions (including panel start-up);
- Detachment of large blocks that are able to overload supports; and
- Development of small blocks in the tip-to-face area disrupting cutting.

The occurrence of roof cavities can also be attributed to a combination of roof guttering due to multiple yielding events, resulting in poor set conditions, and low set pressures on subsequent shears. The development of cavities generally occurs over two to three load cycles. In some cases when cycle time has increased long enough, for example due to planned maintenance or machine breakdown, cutting can deteriorate into cavities within a single load cycle.

Technical considerations

Roof stability in longwall operations can be affected by several operating factors including:

- Canopy tip-to-face distance;
- Hydraulic supply and control settings; and
- Cutting height.

All of these factors should be taken into account when developing the roof stability model, as each can be resolved by modifying and improving operating techniques. The chances of roof instability issues arising can be reduced by ensuring all operational factors are observed in areas of concern. This will ensure a safer working environment and reduce or eliminate lost time due to operational issues.

PAST STUDIES

Extensive research into the geological factors and roof stability of longwall mines has been performed over the years. From this research many prediction methods and rock mass classification systems have been developed. Quantifying the critical geological factors when evaluating roof stability can be difficult due to the varying geological and structural settings of different deposits. According to Peng and Chiang (1984), various geological factors have been investigated in an attempt to classify the roof strength, including; lithological sequence, roof convergence, unsupported time durations before caving, seismic wave velocity, drill core strength, average frequency of bedding planes and rock strength, and bed separation resistance.

Coal mine roof rating (CMRR)

One example of a rock mass classification method is Coal Mine Roof Rating (CMRR). As this method was developed for US coal mines it lacks adequate boundary definition for low strength lithologies, such as those common to Australian coal seam strata (Hatherly, *et al.*, 2009). Major roof disruptions such as faults or shears are not included in the assessment. The CMRR can be determined from either underground exposures, including roof falls and overcasts, or from exploratory drill cores. The main parameters measured according to Mark and Molinda (2005) are:

- The uniaxial compressive strength (UCS) of the intact rock;
- The intensity (spacing and persistence) of bedding and other discontinuities;
- The shear strength (cohesion and roughness) of bedding and other discontinuities;
- The moisture sensitivity of the rock; and
- The presence of a strong bed in the bolted interval.

Secondary factors to be considered include the number of layers, groundwater, and surcharge from overlying weak beds. All these factors are individually rated, and the summation of these make the final generated CMRR, in the range from zero to 100 (zero being weak and 100 being very strong).

Longwall shield-strata interactions

A study released in 2010 by Trueman *et al*. (2010) attempts to quantify the impact of cover depth and panel width on longwall shield-strata interaction. The investigation used recently developed shield load cycle analysis theories, allowing factors influencing shield loading to be isolated and to quantify the interaction between the shield and strata. Five sets of historical data from different mines were back analysed, as well as strata delay data for the longwall faces. Also included in the investigation was an assessment of the near seam overburden geology for each of the sites.

Maps of the critical load cycle parameters implicit to the utilised analysis methodology were provided using Longwall Visualisation Analysis (LVA) software. The LVA software was modified such that it presented the outputs as the individual load cycles for every shield rather than to a time or chainage basis, allowing for the load cycle analysis to be conducted (Trueman, *et al*., 2010). The investigation found that the presence or absence of thickly bedded to massive units in the immediate roof had the greatest impact on shield loading. The analysis showed that once the thickly bedded to massive sandstone units exceeded 20 m in thickness high level periodic weighting and periodic shield overload occurred. The periodic weighting transitioned between low and high once the sandstone bodies exceeded 16 m. The height of the massive bodies above the shield that still had influence on loading was observed to exceed 70 m. By comparing the data from the five different mines this study concluded that, within the range of the data investigated, depth on its own did not majorly affect the loading on the shields.

All longwall widths examined in the study showed the potential for shield overload. However, the reduced cycle time associated with narrower panel widths was found to have a significant effect on roof control if periodic support overload occurs (Trueman, *et al.,* 2010). This was due to the reduced number of yields and the subsequent roof degradation. The investigation also highlighted the significance of shield maintenance and operation on the shield loading environment. Increased load on the adjacent legs and supports can result from inadequate maintenance of the shields. When set conditions deteriorate, leading to low set pressures, roof control problems were experienced due to the destruction of the mechanical interlock of the strata above the supports.

CASE STUDY - MORANBAH NORTH MINE

Moranbah North Mine

The data used from this investigation related to longwall 108 at Moranbah North Mine. A plan layout of the mine is shown in Figure 2 and longwall 108 is indicated.

Moranbah North is an underground coal longwall mine, located approximately 18 km's north of the town of Moranbah, Central Queensland. Anglo Coal Australia manages and operates the mine which began operations in 1998. The operation mines approximately 4.5 Mtpa of hard coking coal from the Goonyella Middle (GM) Seam to the northern end of the Bowen Basin.

Previous longwall blocks at Moranbah North have been plagued by a series of weighting events that have been linked to poor longwall face stabilities (AMC Consultants Pty Ltd, 2006). These weighting events have led to significant delays in production, resulting in below-plan performance of the longwall. The incidence of cavities developing in the longwall face has been identified as a result of these weighting events. Such cavities have ranged in depth from a few centimetres to metres in the roof and have spanned from one shield to tens of shields in width. Previous investigation of the cavities has also indicated a potential link between cavity development and poor set pressures of the longwall shields and also horizon control.

Longwall visualisation analysis software data

Real time data was collected from the longwall chock legs, and then recorded in LVA software. The data set obtained from the longwall chock legs measures the pressures at the mining face as it progresses. Data is taken from each of the legs that span across the whole of the longwall and is recorded every minute. This data can be sourced using the LVA program, which collects live data and shows values for a variety of measurements including:

- Time weighted average pressure (TWAP);
- Initial loading rate;
- Yield; and
- Low set pressure.

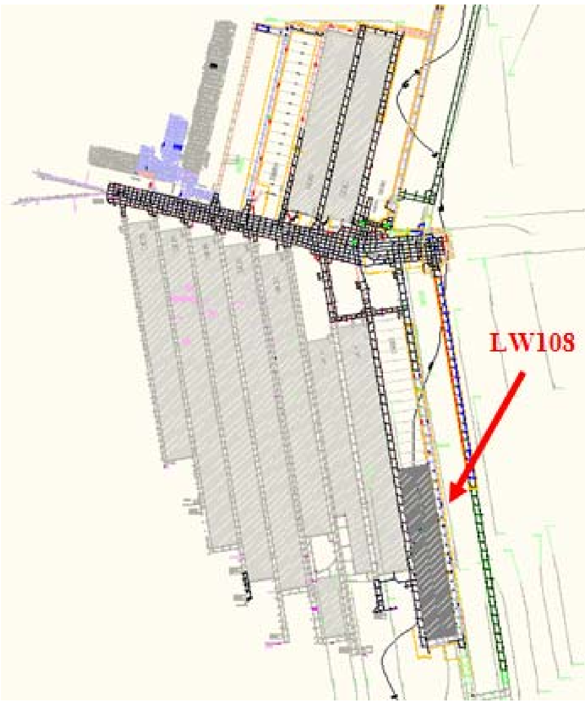

Figure 2 - Moranbah North Mine plan

Geological data

The second source of data used in this investigation was geological data collected at Moranbah North. The geological data used included:

- Seam thickness;
- Depth of cover;
- Sandstone thickness;
- Interburden thickness; and
- Faults.

Each of these factors has shown to have some effect on the stability of the roof in a longwall mine and also the development of cavities in the longwall face. The analysis of these parameters aims to determine a more accurate way of predicting such events by developing indicators to highlight areas of concern.

The geological data was collected using borehole sampling. Over a lease area numerous boreholes are drilled and core samples are extracted to be analysed to determine vital information about a potential mine. The relevant data to this investigation is the geological properties of the coal and surrounding strata. Figure 3 shows a section of the tailgate view of longwall 108 and the surrounding rocks. This figure also shows the geophysical logging which is used to determine the properties and type of the rock.

Seam thickness

The seam thickness simply describes the thickness of the seam being mined. At Moranbah North, the Goonyella Middle (GM) seam is being mined. The GM seams thickness fluctuates between 5.2 m and 6.4 m, within the mining lease. The mining height is approximately 4 m.

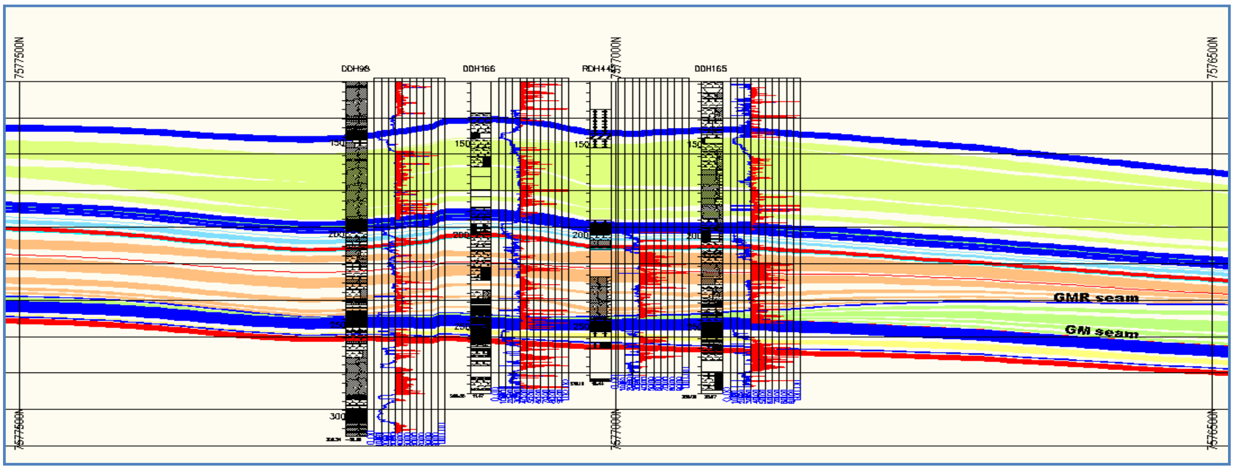

Figure 3 Longwall 108 Tailgate section

Interburden thickness

A rider seam which is called the Goonyella Middle Roof (GMR) seam splits off the GM seam. This seam is approximately 0.3 m thick, and rides approximately 0.5 m above the GM seam, until it splits off and the interburden beings to increase.

Overburden thickness

The overburden at Moranbah North consists of coal seams, siltstone, sandstone and claystone. On top of this is approximately 60 m of tertiary sediments consisting of poorly consolidated sands and clays with occasional basalt flows (Carroll, 2005). The depth of cover increases to the east of the mining lease.

Sandstone bodies

Three major sandstone bodies exist within the overburden. These were investigated to determine their effect, if any, on the occurrences of roof instabilities and cavity development. The three sandstones examined are named MP/MR20, MP/MR42 and MP/MR41.

Faults

Some minor faults were detected within the Longwall 108 block. These were also examined to determine if they contributed to the previous occurrences of roof instabilities at Moranbah North.

Eliminating data inaccuracies

Before analysis of the data could take place, any potentially erroneous data had to be eliminated to assure all results were as accurate as possible. In relation to the LVA records, from observation of the graphs produced, it was obvious that errors occurred in the recording of data at the beginning of the longwall development, which can be seen in Figure 4. This section of the data was excluded from the investigation.

The presence of zeros in the LVA raw data caused problems when modelling the data using Surfer™. This was due to the fact that the program interpolates between points. Instances in the data that show almost instantaneous drops of pressure from close to 400 bars to zero indicate errors occurring in the recordings taken from the chock legs. These errors are most likely due to faults in the technology. Hence, all zeros were removed from the data set.

The geological data had to be modified after it had been contoured in Surfer and new grid files were developed. Surfer™ is an interpolation program which turns scattered X, Y and Z data into maps and contours (Golden Software, 2010). In doing so, some of the data points generated in Surfer™ became negative. This is obviously impossible as all parameters were thicknesses. Thus all values that recorded a negative value were excluded.

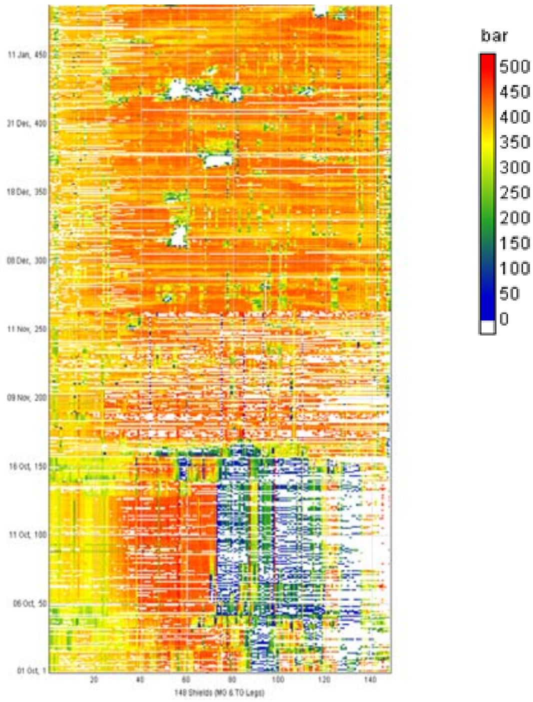

Figure 4 - Errors in LVA data

Data analysis

Longwall visualisation analysis software data

Due to the fact that the pressures were measured every minute, the data collected from the LVA software produced tens of thousands of rows for each of the longwall chocks. As such large quantities of data cannot be handled by Surfer^{TM}, the data had to be condensed, by averaging all readings recorded in relation to the chainage, using a macro developed in Windows Excel^{TM}. Once the data had been condensed, it was then organised into three columns representing easting, northing and chock pressures. Once again a macro was used to organise the data.

Once organised into columns the easting's and northing's had to be changed to replicate the coordinate system of the geological data so it could be accurately compared. The geological data used included the longwall block and some surrounding areas, as the longwall is positioned at an angle approximately 20^{o} west from north. Hence the LVA data had to be rotated to this angle so an accurate comparison could be made. A two-step process was applied for this rotation.

First the easting's and northing's had to be changed, such that the bottom left hand corner of the LVA data corresponds with the bottom right hand corner of the longwall block true coordinates. This coordinate point was to be the point of rotation for the LVA data. Once this point was determined each of the easting and northing points were changed by adding the distance along the length or the width of the longwall block to the coordinate. Two equations were then used to rotate each of the points by 110^{o}, such that it is orientated the same as the geological data. The rotation equations are shown as Equations 1 and 2.

(1)

(2)

After rotating the data set to align with the longwall panel, a contour map was generated using Surfer^{TM}. This contour map is shown in Figure 5. The lower pressures (red) indicate where cavities have occurred, as the pressure on the chocks is less due to the void created above.

Geological data

The raw borehole data was imported into Surfer^{TM} where grid files were developed for each of the data sets. A rectangular area that encompassed longwall 108 block was selected from the mine plan to determine maximum and minimum of the easting and northing coordinates. The maximum and minimum coordinates were then used in surfer when developing the grids to reduce the area being investigated. The new grids were developed such that the easting and northing points for each data set were identical. This allows for easy comparison and combining of the data. These grids were exported to excel including the new 'Z' values interpolated by Surfer^{TM}. This was performed for the seam thickness, depth of cover, interburden thickness and sandstone thickness. The effect of faulting was examined simply by overlaying the LVA data with a map showing where faulting had been detected.

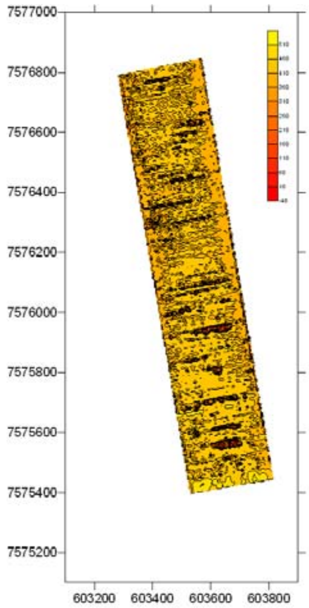

Figure 5 - LVA data contour

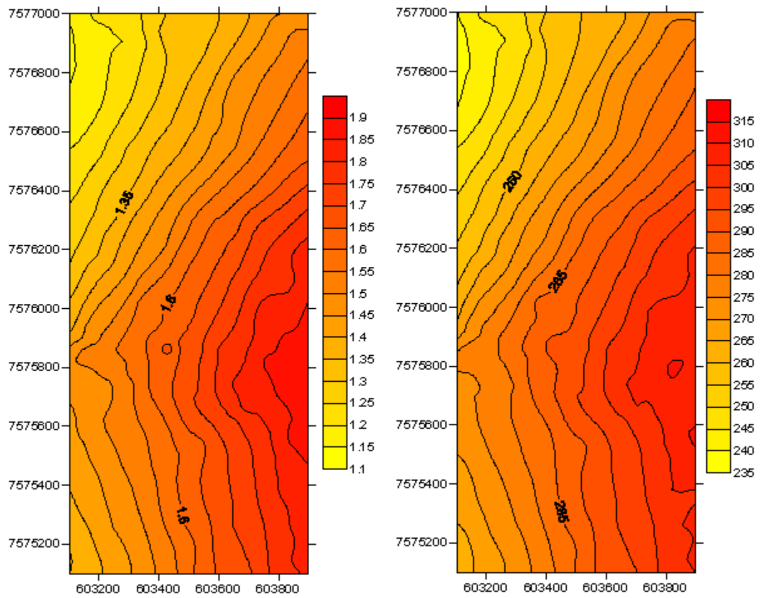

Figure 6 - Index contour and original data contour of overburden thickness

Developing the prediction model

Geological index

To develop a prediction model the data for the seam thickness, depth of cover, interburden thickness and sandstone thickness had to be scaled such that their effect was comparable to the other parameters. As the effect of the thickness of the geological parameters on roof instabilities and cavity developments did not follow a simple linear relationship, the thickness values were scaled to a value between one and ten using an exponential relationship to determine the indexes. Figure 6 shows a comparison between the index contour and the original contour for the overburden thickness.

Weighting of individual parameters

A weighting factor was applied to each of the individual geological indexes to account for the different effects each had on the roof stability. To determine the weighting of each of the factors, contours of each index were developed and compared with the LVA data. Figure 7 shows the overburden thickness index contour overlaid with the contour produced from the LVA data. With reference to Figure 5, it can be seen that there is little correlation with the individual cavities that have occurred. However, there is some correlation with the depth of cover and the frequency of cavities. As the depth of cover decreases the number of cavity events also decreases.

Figure 7 shows an example of how the weighting factors were determined. Little correlation was found between the parameters investigated. Those that showed the most correlation were the seam thickness, overburden and interburden thickness. One major relationship that was identified was that as the thickness of the overburden and interburden increased the frequency of the cavities also increased. The sandstone bodies showed little correlation, if any. However, each of the sandstone bodies had relatively constant thicknesses, with few peaks or plateaus that the cavities can be compared to.

From the examination of each individual contours it was decided that the weighting factors applied to each of the individual parameters would be:

- Seam thickness = 0.7;
- Overburden thickness = 0.8;
- Interburden thickness = 0.9;
- MP/MR41 sandstone thickness = 0.4;
- MP/MR42 sandstone thickness = 0.5; and
- MP/MR20 sandstone thickness = 0.3.

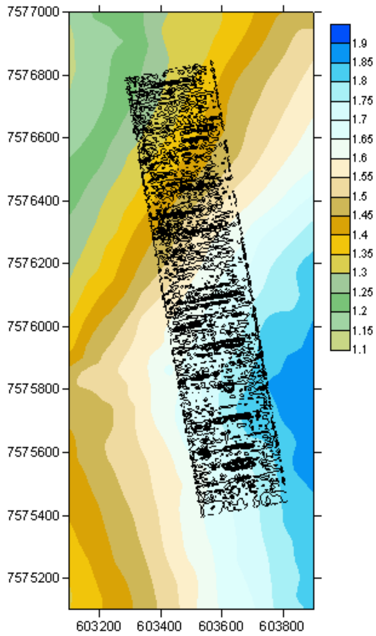

Figure 7- Overburden thickness index contour

To determine the index Equation 3 can be used.

$$I = STi * W_{ST} + OTi * W_{OT} + ITi * W_{IBT} + ST41i * W_{ST41} + +ST42i * W_{ST42} + ST20i * W_{ST20} \quad (3)$$

Where: *STi*: Seam thickness index;
OTi: Overburden thickness index;
ITi: Interburden thickness index;
ST41i: MP/MR41 sandstone thickness;
ST42i: MP/MR42 sandstone thickness;
ST20i: MP/MR20 sandstone thickness; and
W: weighting factors relevant for each of the parameters.

Each of these weighing factors was applied to the index values before they were summed to produce the prediction model.

Prediction model

Figure 8 shows the prediction model that was produced after each of the parameters had a weighting factor applied. Greater correlation can be seen from the prediction model compared to the individual parameters. The red arrows show where there was good correlation between the prediction model and the LVA data. The green arrows indicate significant cavities that occurred that were not highlighted in the prediction model. It must be noted that these cavities still exist in an area with a relatively high index number. No major cavities have occurred in areas that have achieved a low index value.

The prediction model produced showed minor correlation with the cavity events that were recorded using the LVA technology. Thus it can be deduced that the thickness of the seam and surrounding strata contained within the roof have little to no effect on the occurrence of roof cavities and unstable roof conditions as individual components. When combined, more correlation with known cavity events was detected. Poor roof conditions are expected in areas where the longwall chocks are exposed to high pressures. This implies areas where the overburden is extensive, and areas where thick bodies of high density strata exist within the roof. This leads to large amounts of weight force being applied to the immediate roof just above the coal. Such weighting issues can lead to events such as:

- Cantilever effects that overload supports under 'massive' conditions;
- Detachment of large blocks that are able to overload supports; and
- Development of small blocks in the tip-to-face area that disrupt cutting (Medhurst, 2005).

These effects are amplified if the strata unit is close to the seam. This justifies the correlation with the increasing depth leading to the increasing numbers of cavities.

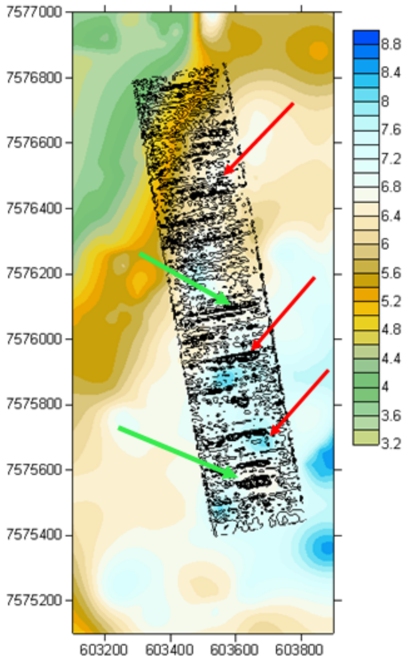

Figure 8 - Prediction model

One feature that could account for poor correlation with the geological data is lateral confinement, built up when coal is left in the roof. Leaving a thick layer of coal in the roof has been proven to alleviate roof instabilities issues when utilising a longwall mining method, particularly in thick seam mining. This method is applied at Moranbah North as the GM seam is relatively thick and highly variable in parts.

One other issue that could account for poor correlation is the fact that the geological data was extrapolated, using common estimation methods, from boreholes which were spaced relatively far apart. Boreholes for the purpose of determining the properties of the seam and surrounding strata are very costly, thus the minimum necessary boreholes are taken. The contours created from the borehole data simply predict the properties of the strata, where as geology is unlikely to follow such a mathematical model.

As a result of this investigation, it seems possible to predict the modelling areas of a longwall face that may be subjected roof instability.

Faulting

One factor not included in the prediction model was the presence of faulting and its potential effect on the stability of the roof. Figure 9 shows the faulting map of longwall 108 overlaying the LVA data contour. The two arrows indicate where a fault has corresponded with a cavity event. The further right example is one case where it was not previously indicated by the prediction model. The left example did fall on a point which was indicated as relatively high risk according to the model. The green arrow is pointing to a relatively significant fault that extends through the width of the panel. At this point no cavities were recorded.

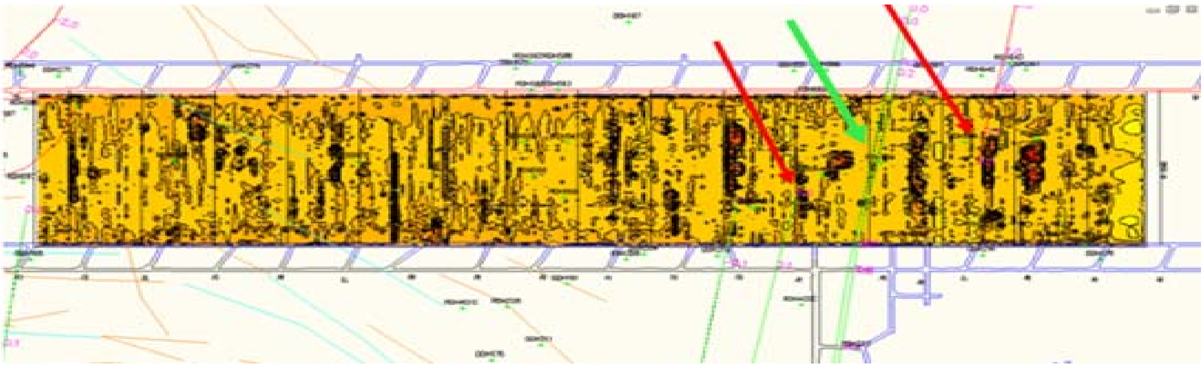

Figure 9 - GM seam structure map

CONCLUSIONS

Longwall mining is the most common method of underground coal mining used in Australia today, with the method becoming ever more prevalent and adaptable to coal seams that were previously too difficult to mine. As such, determining the cause of stability issues that lead to compromised safety of employees and lost production time is of high priority to the coal industry.

This research project, conducted on the evaluation of cavity developments at Moranbah North Mine, aimed to determine the cause of roof instabilities and cavity developments that have plagued the mine site in the past. The knowledge gained from prior literature emphasised features of the coal seam and surrounding strata that contribute to roof instabilities and the development of cavities at the longwall face. Using these features a prediction model was developed, which aimed at accurately highlighting areas prone to instability within the roof and the development of cavities.

Indexes of the geological data were developed for the purpose of developing the prediction model. The geological data was scaled to a value between one and ten, to ensure no feature would overshadow the other contributing factors. Each of these geological factors was then compared with longwall pressure data collected using LVA software. The LVA data showed historical data collected as production on longwall 108 at Moranbah North mine progressed. From the pressure data, the areas where cavities had occurred during mining were able to be identified.

Little correlation was found to exist between the individual geological properties and known cavities that occurred along longwall 108, with the overburden and interburden showing the greatest correlation. The sandstone bodies showed little to no correlation. With this knowledge each parameter was weighted accordingly, and then all indexes were combined to produce the final prediction model.

Some correlation was identified between the LVA data and the prediction model developed using the geological data. Three of the known cavities occurred in areas that were highlighted as high risk areas in the prediction model. However, two cavities occurred in areas that were only considered a moderate risk. No cavities occurred in areas that were calculated to be low risk areas by the prediction model.

The prediction model failed to take into account faulting as a potential contributor to roof instability. The LVA contour was compared to a map that showed the significant faults that affected the longwall 108 panel. Two of the known cavities corresponded to faults that existed. However, one significant fault that spans along the width of the panel did not cause any roof instability issues. As these faults were known to the operators of the mine, some precautions may have been taken to alleviate any issues associated with this particular fault, however this fact is not certain.

It is suggested that the lack of correlation between the model and the pressure data may be a result of the thick seam mining method applied at Moranbah North mine. By leaving a thick layer of coal in the roof, a method proven to alleviate some instability issues when applying a thick seam mining method, higher lateral confinement stresses may have offset the pressures being exerted by the overlying strata. In addition, the potential for inaccuracies to exist in the contour plots of the coal seam and roof strata as a result of the distance between boreholes, could have contributed to the lack of correlation.

The research on developing a model for predicting longwall roof instability continues. The model will be further improved by incorporating the additional geological and operational parameters. It is hoped that the new model will provide a better indication of where roof failures might occur for longwall mining operations.

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