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PILLAR ABUTMENT LOADING – NEW CONCEPS FOR COAL MINING INDUSTRY

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ABSTRACT: Chain and barrier pillar design for longwall mining and production pillar design for room-and pillar retreat mining have tended to rely on simplistic abutment angle concepts for the estimation of pillar stress increases during and subsequent to extraction. Historically, the underpinning database of monitored abutment loading has been small and displayed considerable variation, leading to the application of a number of mine site-specific approximations and often necessarily conservative assumptions. Also, over the last decade, the trend towards wider longwall faces and narrower room-and-pillar sections in deeper areas has challenged established design practices. However, in recent years, considerable effort has been made both in the US and Australia with regard to expanding the abutment loading database and developing an improved understanding of the pillar loading environment. This paper examines some of the progress made and the implications thereof, with a focus on the derivation of formula for abutment angle prediction.

INTRODUCTION

Since the early 1970s, chain and barrier pillar design for longwall mining and production pillar design for room-and pillar retreat mining have relied very largely on the simple abutment angle (φ) concepts developed by King and Whittaker (1971) and Wilson (1973) for the estimation of pillar stress increases during and subsequent to extraction. A typical representation is shown in Figure 1. This model has been incorporated into numerical and empirical methodologies for pillar sizing.

The early researchers suggested abutment angles of between 16.7^{o} and 25^{o} as being appropriate for design purposes, based largely on comparisons to subsidence results. However, it is generally understood that the link between the abutment angle and any observable angle of break or caving angle is tenuous at best. The abutment angle utilised in the design of pillars is usually only a mathematical convenience, simply the number that best fits with measured pillar stresses and / or observed ground behaviour. It is only loosely associated with the actual physical overburden behaviour. As such, the abutment angle concept implicitly reflects the sum of the outcomes of a complex set of overburden behaviours.

The variance between abutment load and observable ground / caving behaviour is understandable given that in practice:

i) The span to depth ratio of many longwall panels is such that the panel is sub-critical with respect to caving and therefore the calculated abutment load is limited by the half-span of the panel.
ii) Caving characteristics vary with lithology, with weaker, less stiff rock types generally failing at angles closer to the vertical than stronger materials.

Historically, the underpinning database of monitored abutment loading has been very small and displayed considerable variation, leading to the application of a number of mine site-specific approximations and often necessarily conservative assumptions. Although early studies in both Australia and the USA suggested an abutment angle of 21^{o} as being typically appropriate and reasonably conservative for abutment load estimation, field measurements indicate that actual abutment angles are a function of pillar and panel geometry, overburden properties and depth, Hill *et al.,* (2008). Also, over the last decade, the trend to wider longwall faces and (conversely) narrower room-and-pillar sections in deeper areas has challenged established design practices.

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In recent years, considerable effort has been made both in the US and Australia with regard to expanding the abutment loading database and developing an improved understanding of the pillar loading environment. This paper examines some of the progress made and the implications thereof, with a focus on the derivation of more robust design methodologies.

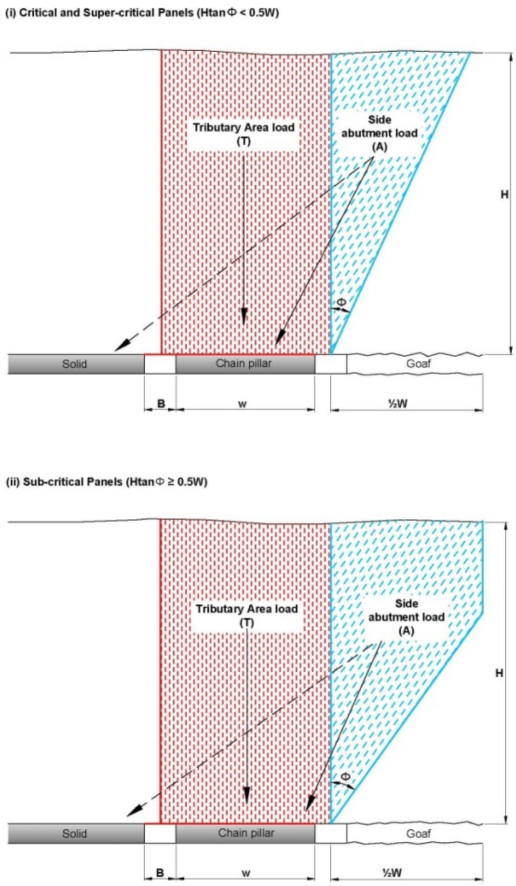

Figure 1: Schematic of side abutment loading model

THE EXPANDED DATABASE

A joint Australian and US longwall database has been compiled that incorporates the published work of Mark (1992), Colwell (1998) and Vandergrift and Conover (2010), as well as the outcomes of projects conducted by Golder Associates for industry clients from 2008 onwards. The data set is deliberately limited to measurements obtained from stress cells installed in the pillars, rather than the roof above the pillar, as the latter tend to show considerably more scatter, which is largely regarded as a function of the measurement technique.

The longwall database therefore covers:

- 29 sites,
- 6 coalfields,
- 13 seams,
- seam depths of 125m to 533m,
- roadway heights of 2.0 m to 3.6 m and
- panel widths of 105 m to 310 m (centres).

Most of the Australian data involves twin entry gate road systems, whereas the US data is from three and four entry systems. For the purpose of estimating an equivalent twin entry chain pillar dimension, the individual pillar widths for the multiple entry systems have been added together, plus the width of the intra-pillar entries, to arrive at an apparent combined pillar width 'w' for analytical purposes. This distance is considered a reasonable approximation of what the over-burden 'sees' around the extracted area. In the multiple entry systems, goaf-side yield pillars are excluded from the analysis of maingate (i.e. side) abutment loading. Applying these criteria, apparent pillar width varies between 24 and 110 m in the side abutment loading database.

Figure 2 illustrates the frequency distribution for the abutment angle (φ) database. The abutment angle averages 14°, with a minimum of 4° and a maximum of 27°.

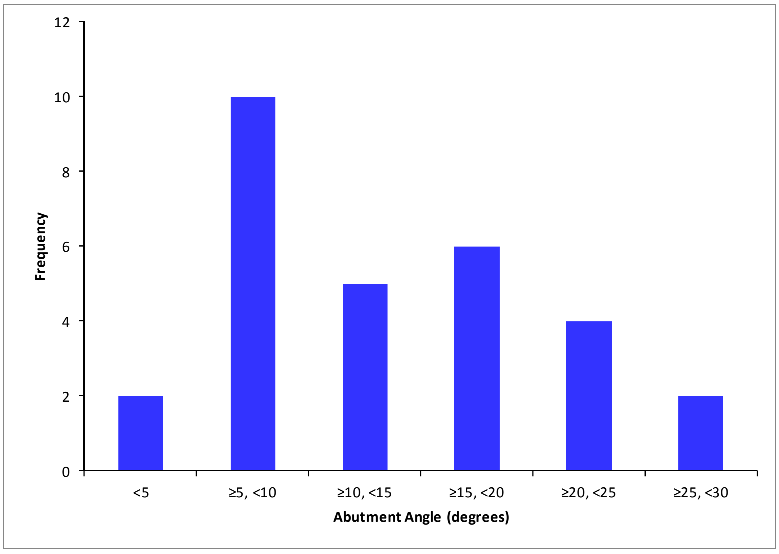

Figure 2: Frequency histogram for abutment angles in the expanded database

Figure 3 illustrates the variation in measured abutment angle versus depth (H). It can be seen that the measured abutment angle tends to reduce with increasing depth, although there is considerable scatter to the data. In particular, in the Western USA, as well as those areas of NSW in which depth exceeds 300m and the upper overburden is dominated by competent sandstone units, field studies strongly indicate that the measured abutment angle reduces as depth increases. A potential explanation is that traditional abutment angle models overstate the magnitude of abutment load at increasing depths of cover, which suggests that an increased proportion of the load is transferred elsewhere (i.e. to the goaf). Tulu and Heasley (2012**)** have suggested the relationship between abutment angle and depth summarised in Table 1.

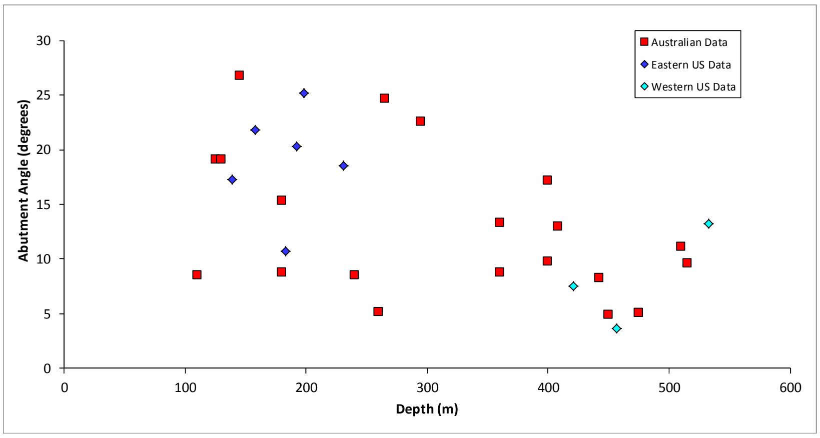

Figure 3: Variation in measured abutment angle versus depth

Table 1: Abutment angle concept according to Tulu and Heasley (2012)

Depth (H, in metres)	Abutment Angle (φ, degrees)
H ≤ 274	21
274 < H ≤ 625	$21 \times (H/274)^{-1.59}$

Figure 4 illustrates the variation in measured abutment angle versus chain pillar width (w). No correlation is apparent for pillar width in isolation. However, Figure 5 illustrates the variance in abutment angle for single side abutment loading versus chain pillar width to depth ratio; from this it can be seen that the measured abutment angle tends to reduce with reducing pillar width and increasing depth. The relationship is stronger than that with respect to depth alone. A possible explanation is that as chain pillar width and therefore stiffness reduces, the ability of the pillar to attract the side abutment load reduces and a greater proportion of this load is redistributed to larger, stiffer blocks of coal (i.e. the adjacent barrier or unmined longwall block). However, the measurement process usually includes an attempt to measure the component of load on the block side, as well as the pillar itself. It would seem that in deeper mines with stiffer overburden, the extent and proportion of the load re-distributed to the solid is greater than either can be measured or is suggested by widely applied stress distribution approximations, such as the abutment influence zone parameter (D) defined by Peng and Chiang (1984) and the associated square decay function for abutment stress defined by Mark (1992). In other words, some of the abutment load may go further afield, where it is unmeasured. There is some evidence for this in the deeper mines of the Western USA (Larson and Whyatt, 2012), as well as from one Australian mine at a depth of 400 m, viz:

- 75 m wide pillar: measured abutment angle 17^{o}
- 25 m wide pillar: measured abutment angle 10^{o}

However, at depths of <350 m, the available evidence suggests that the stress distribution defined by Mark (1992) remains a reasonable approximation.

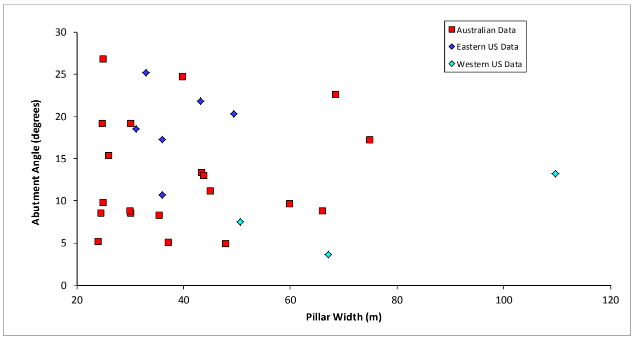

Figure 4: Variation in measured abutment angle versus chain pillar width

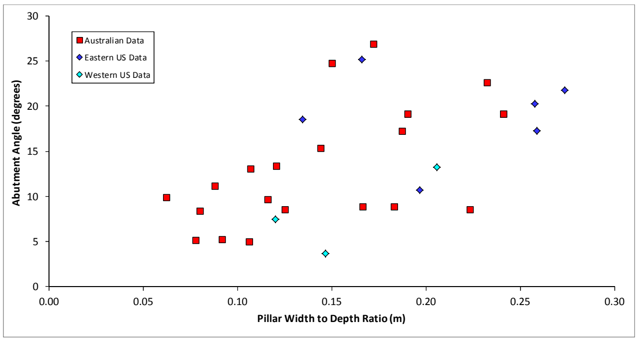

Figure 5: Variation in measured abutment angle versus chain pillar width to depth ratio

Figure 6 illustrates the variation in measured abutment angle versus panel width (W). Although no correlation is apparent, overburden stiffness and load transfer capabilities at a given depth are a function of panel width; increasing overburden "arching" or spanning would be expected at reducing panel width to depth ratios. Figure 7 confirms a weak trend of increasing abutment angle at increasing panel span to depth ratio; low abutment angles are generally associated with panels that would be considered "sub-critical" in subsidence terms (and especially at W/H ratios of <1). This is an important consideration in the Australian industry, where (as in the US) average longwall panel spans are progressively increasing. Also, in Australia at least, although depth may be increasing in the case of individual mines, the average longwall industry depth has remained at around 300 m for over 15 years. The implication is that an increasing proportion of Australian longwalls are migrating from sub-critical to super-critical loading environments.

The highly complementary nature of the US and Australian data is clearly evident from the plots; in particular, the Western US outcomes are highly consistent with deeper NSW experience.

The influence of various parameters on the abutment angle has been further assessed using Multiple Linear Regression (MLR). The general purpose of this statistical process is to determine a linear relationship between several predictor variables (dimensional parameters) and the response variable (abutment angle). A series of analyses were undertaken, from which it was ascertained that the abutment angle is best predicted by:

- depth (H)
- chain pillar width (w)
- panel span (W) to depth ratio (i.e. W/H)

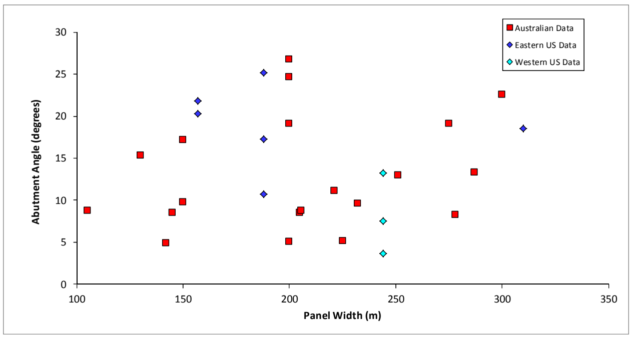

Figure 6: Variation in measured abutment angle versus panel width

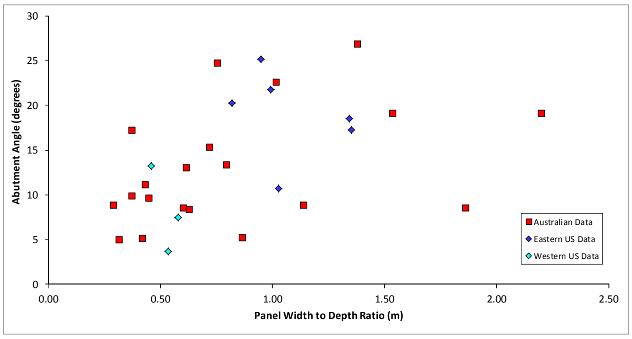

Figure 7: Variation in measured abutment angle versus panel width to depth ratio

Panel span on its own was found to be not statistically significant. The analysis was refined by removing the following cases from the data set:

- two cases in which multi-seam interaction is considered to have resulted in unusually low and otherwise unrepresentative abutment angles and
- two cases in which the spanning properties of the overburden again resulted in unusually low, unrepresentative abutment angles.

The resulting predictive formula is as follows:

Abutment angle, $\varphi = 21.62 - 0.0221H + 0.0725w - 6.23C$
Where C = Panel span criticality, defined by:
$C = 1$, when $W/H < 0.75$ and
$C = 0$, when $W/H \geq 0.75$

Figure 8 presents the measured and predicted abutment angles using the above formula for the sub-set of 25 cases from the database. The coefficient of determination for multiple regression (i.e. R^2 value) is favourable, at 0.65. The analysis indicates that:

- As depth increases, the abutment angle reduces (consistent with the Australian and US findings).
- As the panel width to depth ratio increases, the abutment angle increases.
- As pillar width increases, the abutment angle increases.

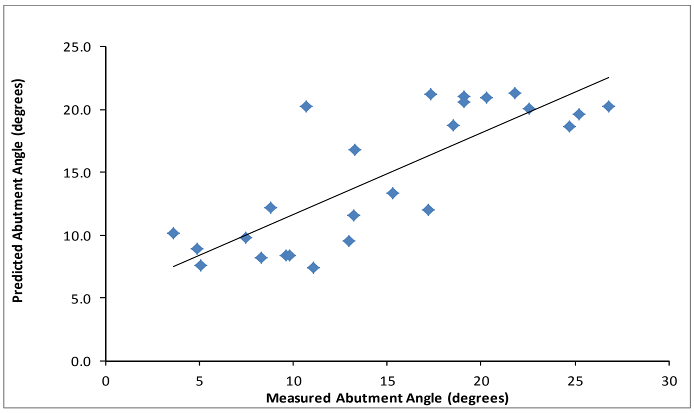

Figure 8: Predicted versus Measured Abutment Angle

This abutment angle formula and the associated concepts find application in:

- The design of chain pillars and associated gateroad support.
- Barrier pillar design.
- The design of total and partial pillar extraction systems.
- Subsidence analysis and control for partial extraction systems.

Other aspects of the database that are useful with respect to pillar and support design relate to the front and tailgate abutment loading factors. Specifically:

i) The measured front abutment loading factor for pillars at the maingate corner of the longwall face ranges from 0.02 to 0.63, with a mean of 0.28 and a standard deviation of 0.16. Measured results are typically well below the factor of 0.5 that is commonly applied in the industry. This factor was found to be highly mine specific and not to relate strongly to the geometrical factors influencing the abutment angle.
ii) The measured tailgate abutment loading factor or "multiplier" for pillars at the tailgate corner of the longwall face ranges from 1.3 to 3.8, with a mean of 1.9 (1.7 ignoring one outlier). Measured results are typically higher than the factor of 1.5 commonly applied in the Australian industry. This factor was also found to be highly mine specific and not to relate strongly to the geometrical factors influencing the abutment angle.

STRESS MEASUREMENT CASE STUDIES

Apart from contributing to the increasing usefulness of the database as a whole, individual stress measurements provide invaluable data for enhanced design on a mine specific basis. This is illustrated by the following three examples from three contrasting geotechnical environments:

- Mine A: A gassy mine employing a three heading gateroad layout.
- Mine B: A deep mine utilising twin heading gateroads.
- Mine C: A moderately shallow multi-seam mine utilising twin heading gateroads.

Mine A

Figure 9 shows the pillar and stress cell array for Mine A, which was operating at a depth of 295m. Figure 10 illustrates the profiles for the changes in vertical stress associated with both front and side abutment loading.

From this information it was possible to determine that:

- The abutment angle was 23°.
- The ratio of front to side abutment loading was 0.3.

It is also possible to demonstrate, by coupling the stress measurement results to a broader review of the geotechnical environment that, with respect to the maintenance of tailgate serviceability, the chain pillars were over-designed (i.e. it would have been possible to reduce the pillar system width by up to 10 m).

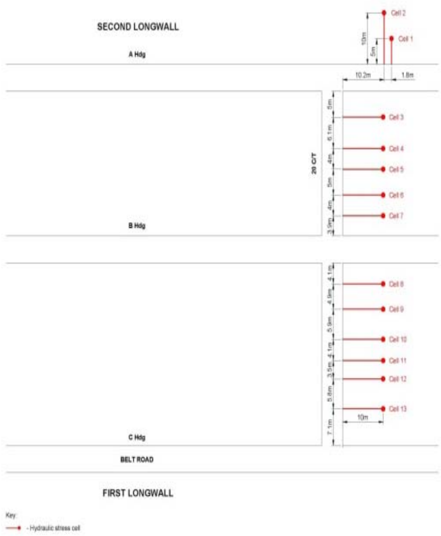

Figure 9: Mine 'A' Stress Cell

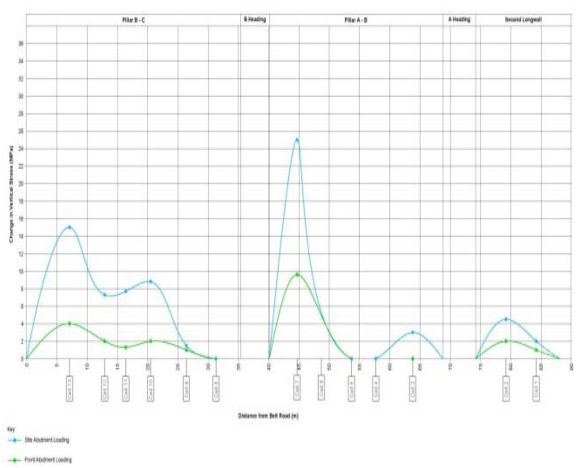

Figure 10: Mine 'A' Vertical Stress Changes due to Abutment Loading

Mine B

Figure 11 shows the pillar and stress cell layout for Mine B, which was operating at a depth of 510m. Figure 12 illustrates the profiles for the changes in vertical stress associated with front, side and tailgate abutment loading.

From this information it was possible to determine that:

- The abutment angle was 11^{o}.
- The ratio of front to side abutment loading was 0.4.
- The ratio of tailgate to side abutment loading was 1.3.

Unusual features of the stress profile are the "triple hump" and the concentration of stress on the travel road side of the chain pillar during side abutment loading. This atypical profile was later effectively replicated by a second set of stress measurements in a subsequent gateroad.

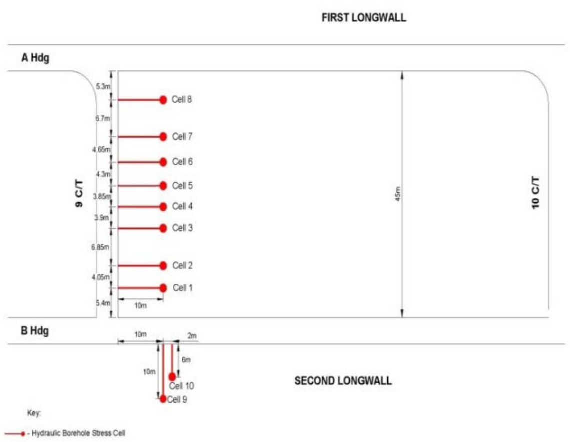

Figure 11: Mine 'B' stress cell array

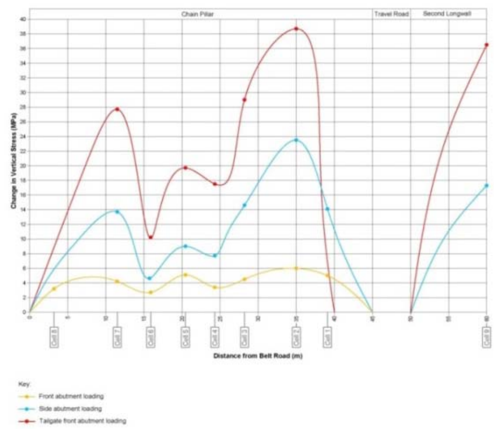

Figure 12: Mine 'B' vertical stress changes due to abutment loading

Mine C

Figure 13 shows the pillar and stress cell layout for Mine C, which was operating at a depth of 110 m. Figure 14 illustrates the profiles for the changes in vertical stress associated with front, side and tailgate abutment loading.

From this information it was possible to determine that:

- The abutment angle was 9^{o}.
- The ratio of front to side abutment loading was 0.2.
- The ratio of tailgate to side abutment loading was 1.9.

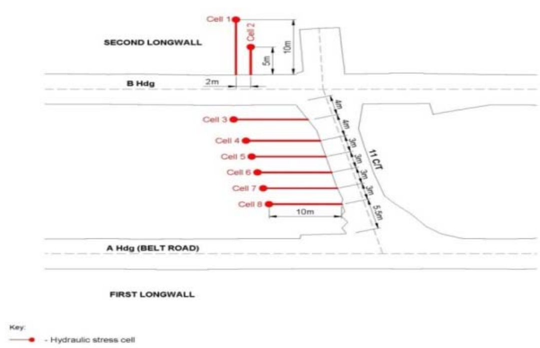

Figure 13: Mine 'C' stress cell array

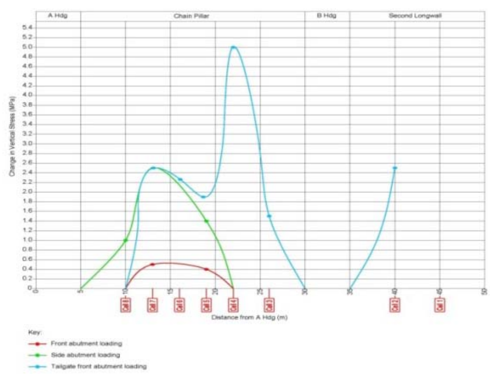

Figure 14: Mine 'C' vertical stress changes due to abutment loading

The low abutment angle and generally favourable loading environment is a direct function of the location of the monitoring site beneath an overlying longwall goaf. Similar to Mine A, it is again possible to demonstrate, from the stress measurement and an assessment of the geotechnical environment that, with respect to the maintenance of tailgate serviceability, the chain pillars were significantly over-designed (i.e. it would have been possible to reduce the pillar system width by at least 5 m).

GAINING INFORMATION

Stress measurement is just one tool for the analysis of system performance. In this regard, the generation and application of complementary data sets has proven powerful for mining layout design, ground control and long-term stability analysis. Examples of complementary approaches include:

i) Monitoring pillar deformation using mapping, borescope and extensometry techniques. The information generated: (a) facilitates the definition of peripheral yield zones and therefore the pillar stress profile and abutment angle, (b) provides base data for rib support design, (c) enables the quantification of long-term pillar behaviour and (d) provides input for further analysis of pillar strength and performance.
ii) Numerical modelling of pillar stress and ground deformation. For example, in the LaModel program, a coal mining specific software (Heasley *et al.,* 2010), it is possible to utilise the calculated or measured abutment angle in the analysis of stress and ground deformation. This involves the definition of the goaf material properties, in which the percent of overburden load applied to the goaf is inputted. This is a function of abutment angle, panel width and depth. The information generated can: (a) facilitate the assessment of long-term pillar stability, (b) contribute to the estimation of subsidence (and can be calibrated to actual subsidence results) and (c) assist in defining input material parameters for future mining layout optimisation.

CONCLUSIONS

This paper has examined some of the progress made in recent years with regard to understanding the vertical stress re-distribution around extraction panels and in particular the prediction of the abutment angle. The derived abutment angle formula is considered to be widely applicable and facilitates both improved pillar designs and the determination of associated ground support requirements. In most environments, site-specific stress measurement and related analyses represent a significant opportunity to further optimise mining layouts and ground support design.

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