Skew Roof Deformation Mechanism in Longwall Gateroads — Concepts and Consequences

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ABSTRACT

A research project was commissioned by the Australian Coal Association Research Program (ACARP) to improve the understanding of tailgate strata mechanics and to provide a more rigorous engineering basis for tailgate support design. A deformation mechanism termed 'skew roof' was defined which relates the regional influence of differential horizontal strata movement (shear) about longwall extraction to gateroads. Confirmation of the mechanism was achieved by field investigations which included measurement of the shear displacement along weak interfaces. Under geological and mining conditions where the skew roof mechanism operated, strata units were found to move progressively further towards the goaf with height into the roof. 3D numerical modelling was used to assess the major geotechnical factors controlling the mechanism and to determine appropriate support strategies within a 'skew roof' environment including the role of cables versus standing supports. The skew mechanism is considered relevant to; all roadways in the vicinity of longwall extraction including the faceline itself, chain pillar design, and support design.

INTRODUCTION

A research project (ACARP, in press) was commissioned to improve the understanding of tailgate strata mechanics and to provide a more rigorous engineering basis for tailgate support design.

A deformation mechanism termed 'skew roof deformation mechanism' was identified which relates the regional differential horizontal movements that occur about longwall extraction to the shear behaviour about gateroads, leading to a range of adverse roadway behaviour. Skew roof has implications for chain pillar design (tailgate positioning) and indeed, all roadways within the vicinity of longwall extraction, including the faceline itself. The implications of the 'skew roof' mechanism to tailgate support design are discussed with reference to the relative roles of long tendons versus standing supports and the importance of support positioning.

The work program comprised a combination of observation, field measurement, laboratory investigations and 3D numerical modelling, predominantly at the sponsor mines of the C12006 Project. Field studies were undertaken at the following mine sites in association with ongoing geotechnical investigations:

- Metropolitan Colliery,
- North Goonyella Mine, and
- Moranbah North Mine.

Measurement of the differential horizontal displacement of roof strata about longwall extraction were undertaken at these mines together with measurement of loads developed in standing supports. Field investigations were supplemented with 3D numerical modelling studies where the sensitivity of the factors driving the skew roof mechanism was examined. A detailed description of the C12006 Project results for each mine is provided in the final project report (ACARP, in press). The purpose of this paper is to convey the key findings that are considered transportable to the broader coal mining industry.

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Problem definition

The C12006 Project was commissioned in response to an industry demand for more rigorous methods of gateroad support design. This reflected an ongoing occurrence of problematic tailgate behaviour against a background of trial and error approaches to support design. This issue is also echoed in overseas coal mines with Barczak (2003) lamenting that:

> *whilst pillar design practices had improved through use of ALPS, problematic tailgate behaviour was still a major concern in many US longwall mines and that optimization of support design would not be achieved through current trial and error practices.*

At two of the sponsor mines in the C12006 Project, the author's own observations and anecdotal information strongly suggested that horizontal movement of roof strata towards the approaching goaf played a more important role than previously considered. As shown in Figure 1a the specific observations of tailgate behaviour suggested that the immediate roof appeared to have been driven towards the block side. The movement was so severe that the immediate roof material was essentially pulverised and flowed out of the roof space between the installed standing supports as shown in Figure 1b. Anecdotal advice suggested that this style of roof behaviour was evident in various forms in many of the Australian coal mines that experienced poor roof behaviour either adjacent to longwall extraction (travel roads) or during approach of the next longwall (tailgates).

SKEW ROOF DEFORMATION MECHANISM

Proposed hypothesis

The 'skew roof deformation mechanism' proposes that under certain circumstances roadways about longwall mining are required, if remaining elastic, to skew. If not for strata softening, rectangular shapes would deform into parallelograms. The propensity to skew is a consequence of a regional gradient of horizontal strata movement towards the goaf, progressively increasing from seam to surface as shown in Figure 2. The affect is regional in that horizontal movements on the surface can extend in the order of kilometres from longwall mining and at seam level the influence can extend over many tens of metres and potentially hundreds of metres.

The direction of the 'skew' is a nett influence of the direction from the roadway to the goaf and the direction of the maximum horizontal stress direction. This may actually cause the nett direction of roof skew to be away from the longwall block side but typically the roof is skewed towards the longwall block being extracted.

The initial roof damage associated with the skew mechanism is slip along interfaces between strata units or along bedding within strata units. The slip is not confined to the immediate roof and floor strata but may extend well beyond the riblines. Most importantly, the regional gradients of horizontal movement may continue to occur and cause more deformation of the already softened strata about the roadway. This introduces a component of displacement control on the subsequent deformation of the softened strata which may impact on the support strategy. The key factors driving the skew roof mechanism are considered to be:

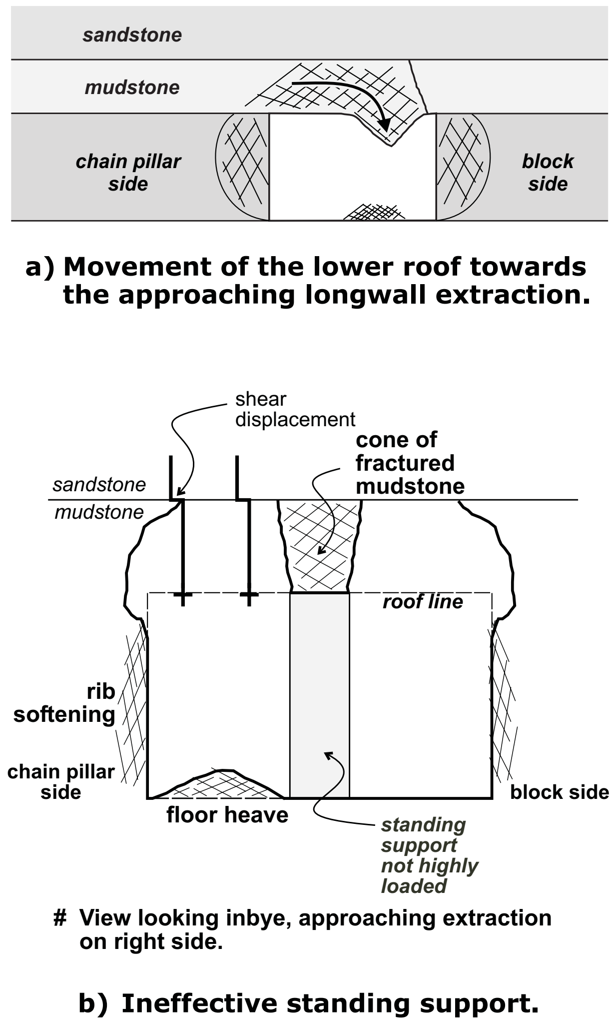


FIG 1 - Typical tailgate roof behaviour observed at Metropolitan Mine prior to investigations.

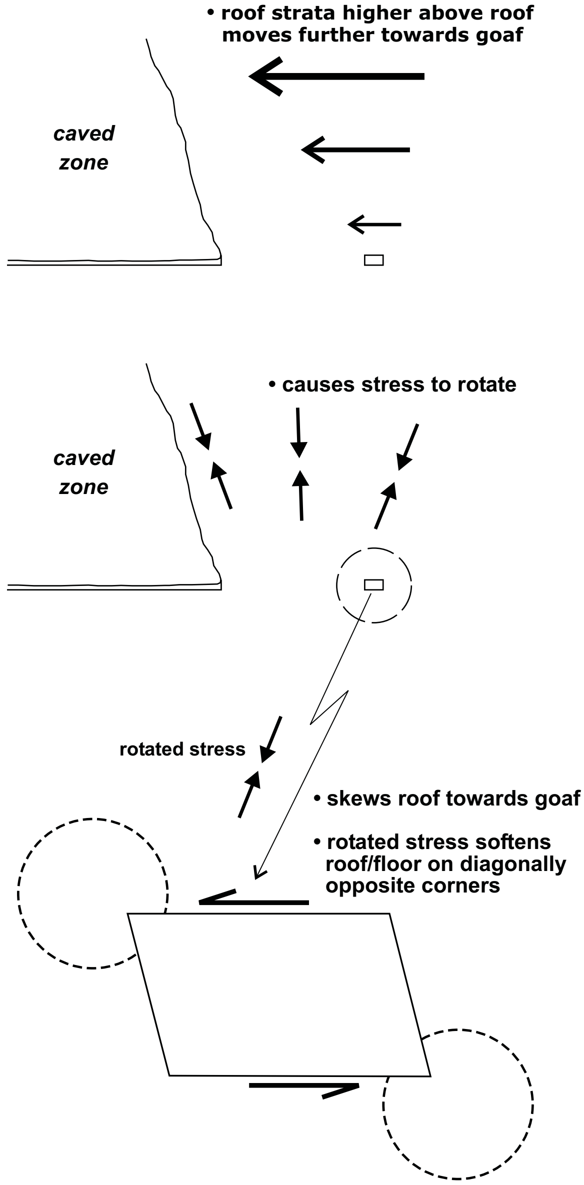


FIG 2 - Simplified model of stress/displacement changes adjacent to goaf. Note: direction and extent of skew varies from mine to mine.

- the magnitude of the vertical and horizontal stresses;
- the shear modulus of the strata pile (shear deformability); and
- the extent of overburden bridging.

Major factors that are considered to influence the extent of roadway damage include:

- the proximity of the roadway to longwall extraction;
- the presence of weak interfaces in the vicinity (several metres) of the roof and/or floor;
- installed artificial support; and
- strata damage about the roadway experienced on initial driveage.

Clearly there are many other factors that may also influence the extent of roadway damage including those factors that impact on roadway damage on initial driveage and all operational factors that impact on the load distribution about the longwall such as powered support capacity and yield setting, etc.

Relationship of skew roof to vertical and horizontal stress changes

The skew roof deformation mechanism overprints the roof deformation mechanisms that are attributed to vertical and horizontal stress changes about longwall extraction. The potentially adverse impact of high vertical pillar loading on roadways has been well established through empirical studies such as ALPS (Mark, 1990, 1992, 1999) and ALTS (Colwell *et al*, 1999). Mills and Doyle (2000) discuss the adverse consequences of high vertical loading on roadway behaviour at Dartbrook Mine using rock mechanics principle centred on the Poisson Effect. Essentially the vertical compression of the pillar results in an increase in horizontal stress in the roof and floor strata. In an elastic environment this is of the order of 33 per cent of the vertical stress increase for most non-coal strata and up to 50 per cent for coal strata (Mills and Doyle, 2000). The increase in horizontal stress may result in overstressing of the roof and floor strata.

The impact of horizontal stress on roadway damage has been well documented (Siddall and Gale, 1992). Essentially elevated *in situ* horizontal stresses may result in overstressing of the roof and/or floor material and contribute to shear along bedding as stresses rotate about the roadway opening. Mine layouts are generally designed to minimise the concentration of horizontal stress about longwall extraction with typically the most favourable extraction orientation subparallel to the maximum horizontal stress direction.

The skew roof mechanism overprints the affects of horizontal stress damage. As stated previously, strata that is already damaged about the roadway is still subjected to the regional differential horizontal strata movements associated with longwall extraction. Under these circumstances the softened strata about the roadway could be considered 'slaved' to the deformation of the host strata. The magnitude and direction of the pre-mining horizontal stress also has a major impact on the direction of 'skew' and the extent to which the skew process impacts on the roadway as will be discussed in greater detail.

In summary the proposed skew roof deformation mechanism operates in conjunction with those deformation mechanisms attributable to changes in the vertical and horizontal stress components. The skew process relates to the *rotation* of the principal stresses out of the horizontal plane.

Supporting data for differential horizontal movement

Surface subsidence monitoring

Reid (1998) measured horizontal movements at the surface of up to 25 mm approximately 1.5 km from longwall mining in terrain surrounding the Cataract Dam where mining had occurred at depths up to 500 m. Reid (1998) also noted that:

> *horizontal movements are typically at least as great as the vertical component, that the maximum horizontal movement occurs soon after undermining and that the movements are generally directed towards the goaf.*

Holla (1997) measured vertical and horizontal surface movements associated with longwall mining in flat and high relief terrain in the Newcastle Coalfields. Horizontal movements of over 260 mm were recorded at distances of half the mining depth and whilst not specifically discussed, the figures presented indicated horizontal movement of at least 20 mm up to 1 km (the limit of the subsidence line) from longwall mining.

Hebblewhite *et al* (1999) noted that monitoring of horizontal surface movements associated with longwall mining at Tower Colliery (450 m deep) recorded horizontal displacement of 60 mm at 1.5 km from longwall extraction.

The reader is directed to these texts for more detailed explanation of the impact of surface horizontal movements however the key point is that significant horizontal movements have been recorded at the surface at great distances from longwall mining.

Numerical modelling

3D numerical modelling has been conducted for three of the sponsor mines associated with the ACARP C12006 Project as listed previously. The modelling approach and detailed discussion of results is provided in the final report (ACARP, in press); however, Figure 3 illustrates a typical cross-section (example from Moranbah North Mine) showing contours of horizontal movement towards the goaf. The figure is separated into three zones from the initial caved area, an area intermediate between caved strata and elastic strata and then the zone of elastic strata. Of most interest here is the region of elastic behaviour which contains the gateroad and which indicates the progressive increase in horizontal movement towards the goaf from below seam level to the surface. The gradient of horizontal movement for the particular case shown in Figure 3 varied from approximately 20 mm at seam level to over 100 mm at the surface. Clearly the extent of this gradient is site specific and some of the key controlling factors are discussed in following sections however the data from surface subsidence monitoring and the numerical modelling both strongly suggest that the gradient of differential horizontal movement from below seam level to surface is significant.

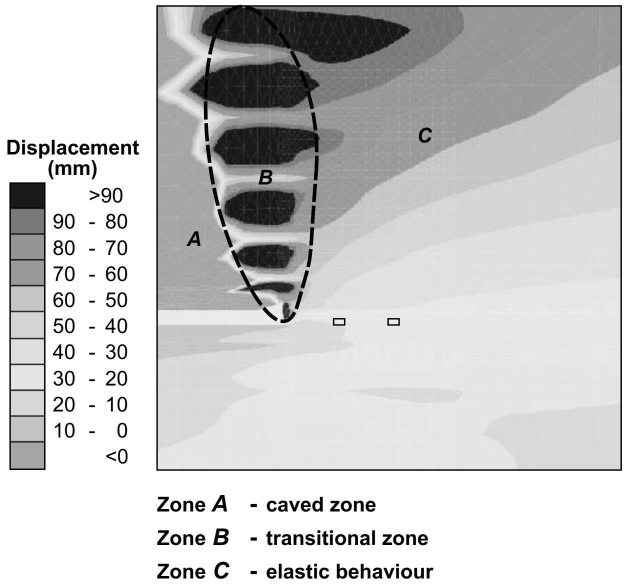


FIG 3 - Contours of horizontal displacement towards the adjacent goaf; 225 m depth. Note: gateroads shown for reference only.

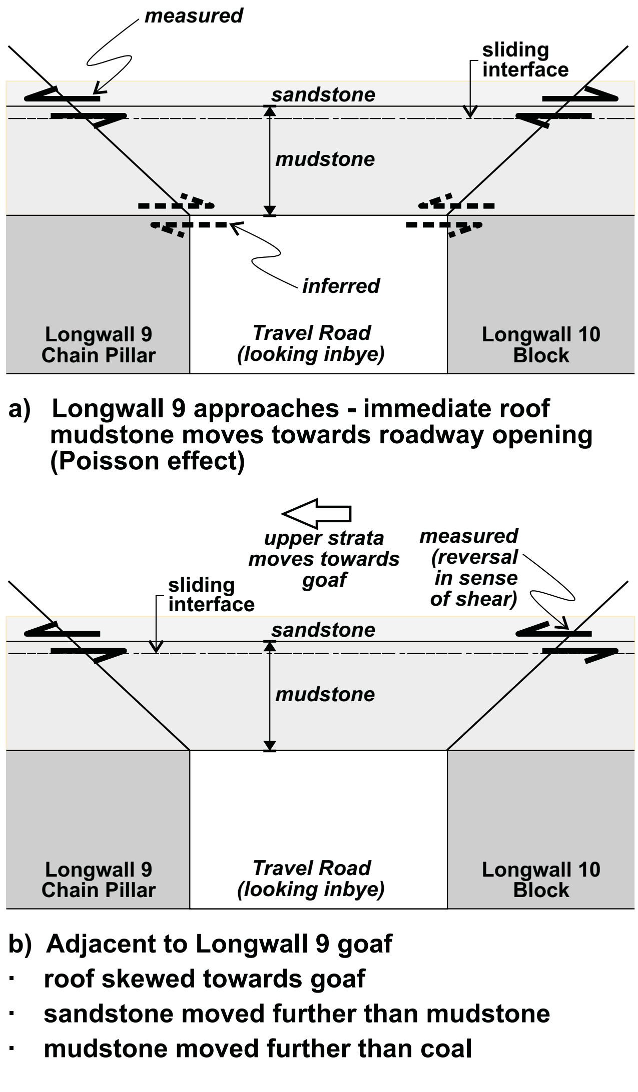


FIG 4 - Relative movement – Travel Road, Longwall 9, Metropolitan Colliery.

Field measurements at seam level

The relative horizontal movement of strata about gateroads adjacent to longwall extraction was conducted at the three sponsor mines adjacent to longwall extraction (full side abutment loading) for each of the mines and also under tailgate loading at Metropolitan Colliery.

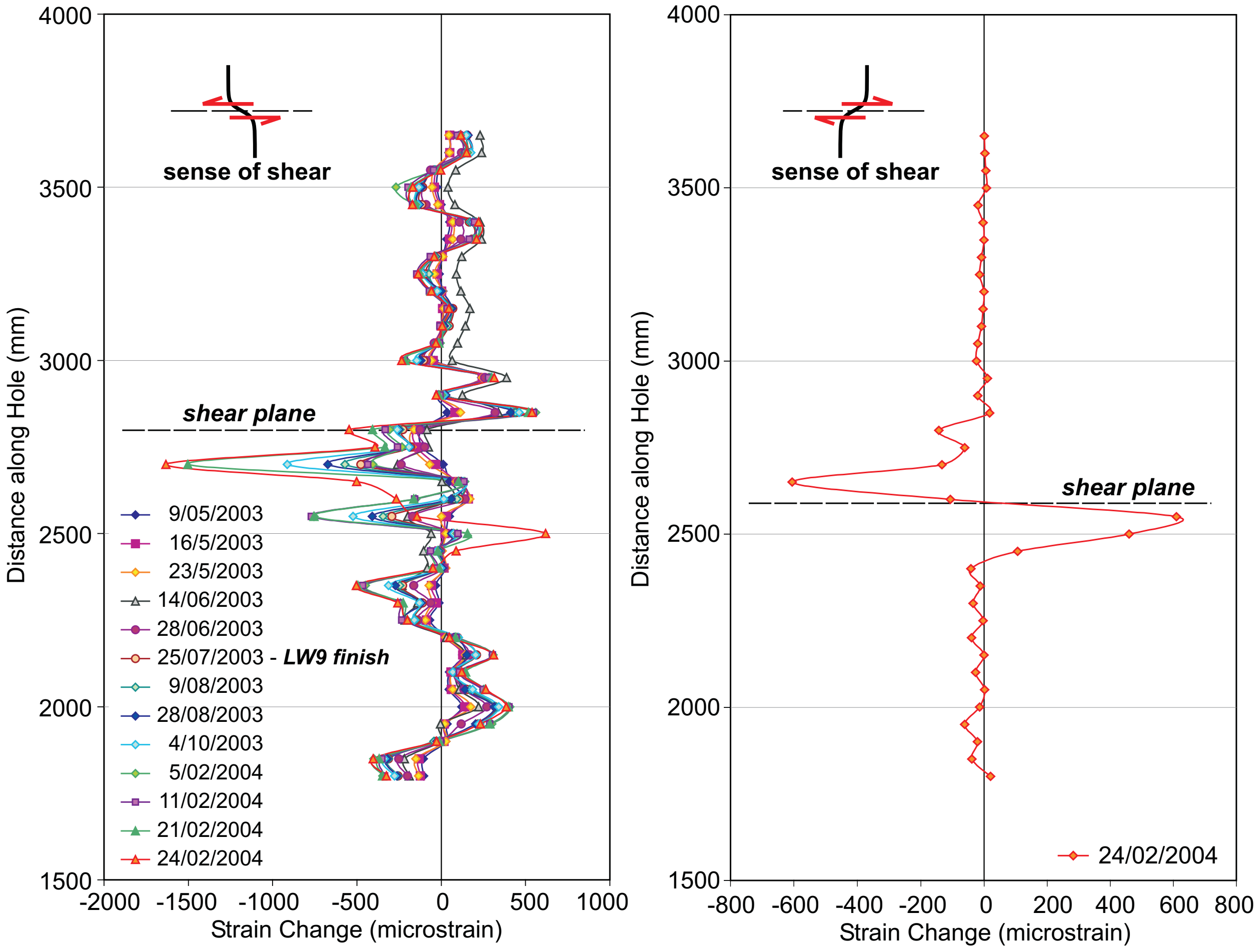
At each monitoring site the array of field instrumentation included shear strips installed at 45° over the riblines. Each shear strip comprised 72 strain gauges (36 each side) at 50 mm intervals on a stainless steel bar over a total length of 2.0 m. The bar was sealed within a rectangular housing and grouted into a 60 mm diameter hole. Shear displacement of the strata causes the bar to bend and the magnitude of shear displacement is calculated through the differences in strain developed either side of the bar. Prior to installation of the shear strips, candidate locations for shear displacement were identified through roof coring and in each case a clear candidate was identified.

The location of the shear strips in relation to the roof geology at Metropolitan and the sense of movement during approach of the adjacent longwall and then behind the goaf are shown in Figure 4. For the sake of brevity, only the shear strip data for Metropolitan Colliery is provided in the Appendix (and Figure 5). The complete shear strip data in terms of the strain changes measured and the cumulative displacements for each of the mines is provided in the final project report (ACARP, in press).

The shear strip data clearly shows the presence of a shear plane (indicated by the 'Z' shape) that developed with extraction of the adjacent longwall. The shear horizon coincided with the candidate location identified from roof coring.

During approach of the adjacent longwall the sense of shear was lower roof towards the roadway centreline which is consistent with that expected from vertical loading and flexure of the lower roof layer as shown in Figure 4. Note that the sense of shear between the lower and upper roof layers is opposite on each side of the roadway at this stage. As mining drew level and passed the monitored site, the sense of shear reversed on one side of the roadway such that the sense of movement was consistent with the upper layer moving further towards the adjacent goaf compared with the immediate roof layer. This was consistent with the skew roof mechanism. At this stage in the mining cycle the magnitude of shear displacement was approximately 5 mm and no discernible roof damage was observed.

The site continued to be monitored during approach of the next wall and the sense of shear continued (upper roof towards the adjacent goaf) until a clear reversal became evident on the block side when the next longwall approached between 52 m and 36 m from the monitored site. The reversal was clearly detected as shown in Figure 5 where Figure 5a illustrates the strain changes from installation and Figure 5b illustrates the strain changes and sense of shear using the readings when the approaching wall was >50 m from the site as the reference.



(a) Strain changes using initial readings as reference.

(b) Strain change on block side from Longwall 10 at 52 m inbye and 36 m inbye (readings at 52 m used as a reference).

FIG 5 - Strain changes – Longwall 10 block side, Longwalls 9 and 10 extraction.

The shear strip results from the central heading adjacent to longwall extraction at Moranbah North Mine are summarised in Figure 6 which also showed a similar style of shear behaviour as that evident at Metropolitan Mine. In this case shear movement occurred along the Rider Seam/stone interface. Initial shear displacement on approach of the longwall and at least 81 m behind the wall was dominated by vertical loading, roof flexure and associated Poisson effects and then between 81 and 195 m behind the adjacent goaf, the strata above the shear plane moved towards the goaf relative to the strata below on both sides of the roadway. The shear movement was greater on the block side which is also consistent with the inferred rotation of the principal stresses as shown in Figure 2.

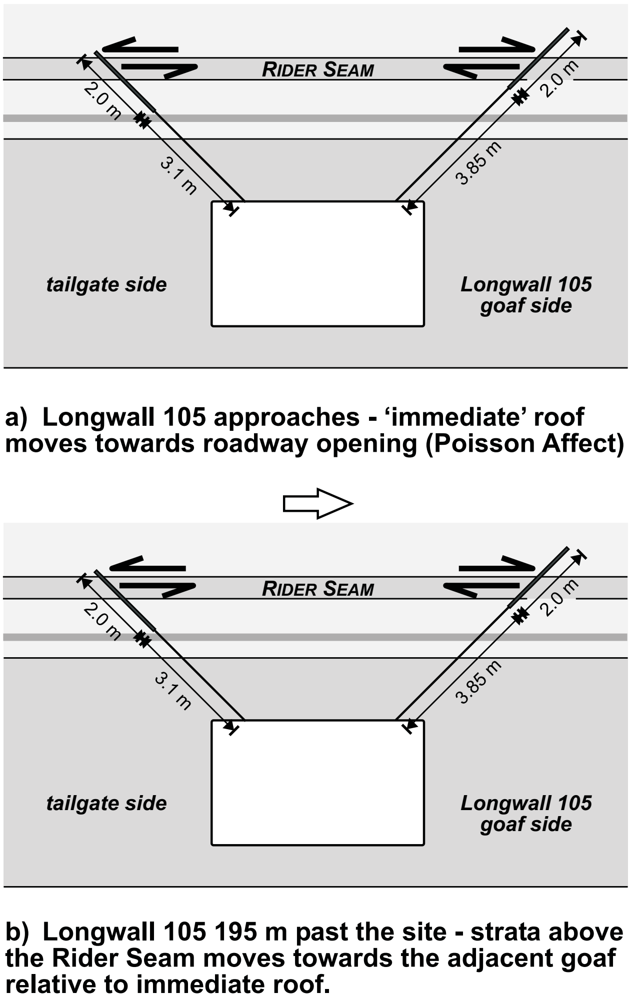


FIG 6 - Relative movement about the central heading during extraction of adjacent longwall – Moranbah North.

The shear strip results from North Goonyella associated with adjacent longwall extraction are summarised in Figure 7. The data suggested a reversal in the sense of shear across the thrust plane consistent with skew roof behaviour after the wall had passed by 75 m however the results are considered to be influenced by general softening about the roadway and are far from convincing. It is considered possible on the basis of field observations and numerical modelling that the shear inferred about the roadway may reflect the development of high angle zones of bedding developed at or beyond the riblines. The remaining shear strips installed across the coal/stone interface were consistent with behaviour expected from the Poisson effect.

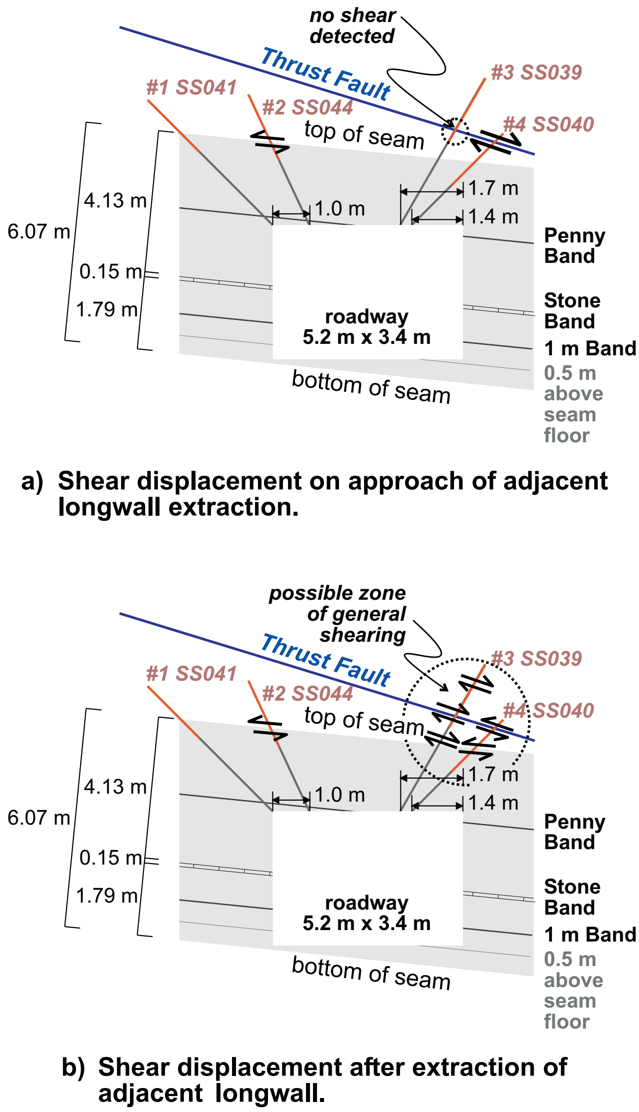


FIG 7 - Sense of shear about the travel road on approach and after extraction of the adjacent longwall.

Field results summary

Each site clearly detected the presence of shear along weak interfaces about the roadways associated with adjacent longwall extraction. This in itself has implications for both roadway and pillar behaviour however the key objective of the fieldwork was to establish whether or not strata units higher into the roof moved further towards the goaf in response to a regional gradient of horizontal movement from seam to surface (skew roof mechanism). The skew roof mechanism was convincingly indicated by the shear strips at Metropolitan Colliery on approach of adjacent longwall extraction and then under tailgate loading conditions. At Moranbah North Mine the skew behaviour was detected but much later relative to adjacent longwall extraction (>81 m behind the goaf). At North Goonyella Mine the results were not conclusive in relation to the operation of the skew roof mechanism and it is considered more likely that the shear detected was a consequence of general softening and mobilisation of structured ground.

DISCUSSION

Factors influencing skew roof mechanism

The proposal that progressively increasing horizontal movement towards the goaf from seam surface may impact on gateroads was confirmed through field measurement. The regional horizontal movements imposed relative movement about the roadways such that the roadway roof moved towards the goaf more than the floor and layers higher into the roof moved further than immediate roof layers, all other things being equal. The extent of the relative movement and consequential slip along bedding varied considerably between the three mines and the following discussion presents the findings of work conducted to better understand the underlying factors driving the skew roof process.

The driving force for shear displacement is shear stress. The shear stress generated in the plane of bedding is the driving force behind slip along bedding.

The three mines represent a range of mining and stress environments as summarised in Table 1. The skew roof behaviour was greatest at Metropolitan which implied that either depth and/or horizontal stress may have been contributing factors. Moranbah North and North Goonyella represent similar mining geometries with the major differences being that the horizontal stress is somewhat higher at Moranbah North and also the orientation of the maximum horizontal stress with respect to mining is significantly different. The range of variables in the field sites also included other factors such as average rock stiffness of the strata pile from seam to surface, rock stiffness contrasts of the immediate roof strata, presence of structure and variation in the strength of interfaces.

3D numerical modelling of the three sponsor mines provided a measure of the shear stress that would have been imposed on the gateroads during extraction of the adjacent wall (under full side abutment loading). The shear stress obtained from modelling represents the nett outcome of the competing influences listed above. It was considered important to use the 3D code so that the effects of longwall extraction oblique to the principal stresses would be captured. Skew of the rectangular roadway can be visualised as a combination of skew both across and along the roadway and each of these components contributes (by vector addition) to shear stress in a given plane.

Figure 8 is a contour of total shear stress resolved in the plane of bedding (horizontal in these cases) for the same modelled scenario as that shown in Figure 3. The 1 MPa contour is highlighted and the area containing shear stress along bedding greater than 1 MPa is shaded. Any roadway positioned within the shaded region would be expected to experience shear along bedding to some extent (clearly this depends on the shear strength of the interface). The actual position of the gateroad in this case is also shown in the figure and clearly the likelihood of slip along bedding was high.

The distribution of shear stress along bedding away from the goaf is summarised in Figure 9 which also includes the distribution obtained from modelling conducted for Metropolitan

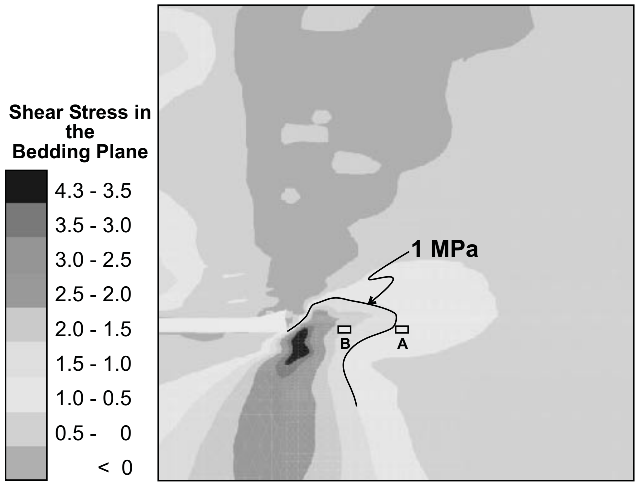


FIG 8 - Contour of shear stress in the plane of bedding under full side abutment loading – Moranbah North, 225 m depth. Note: roadways shown for reference only. Shaded area represents region in which high potential exists for shear along bedding in the roof and floor of a roadway.

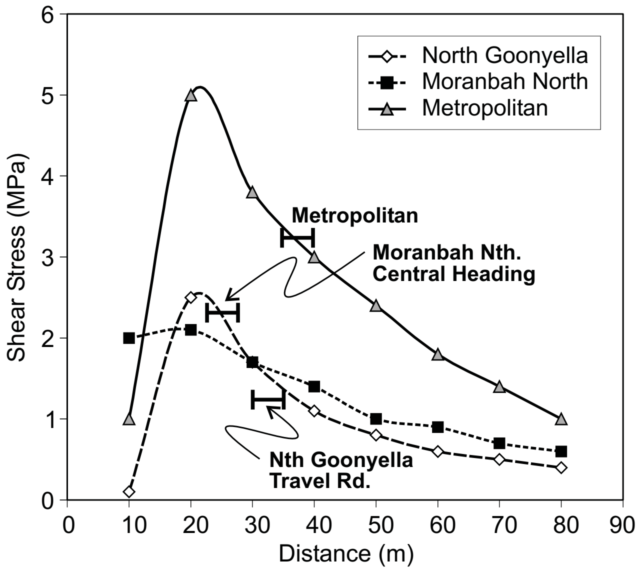


FIG 9 - Modelled shear stress on bedding versus distance from goaf edge – side abutment loading.

TABLE 1

Background data for the three sponsor mines.

Mine	Depth of cover (m)	Longwall width (m)	Pillar width (centres) (m)	Tectonic setting
Metropolitan	500	155	40	Relatively high horizontal stress environment. 30° maingate stress concentration.
Moranbah North (three heading layout)	225	250	30 and 25	Relatively moderate horizontal stressfield. 0 - 25° tailgate stress concentration.
North Goonyella	250	250	35	Low to moderate horizontal stresses. 30° maingate stress concentration.

Colliery and North Goonyella Mine and the respective gateroad positions. The figure shows that the magnitude of shear stress imposed on Metropolitan gateroads adjacent to longwall extraction was significantly high than Moranbah and North Goonyella. Whilst the Moranbah North and North Goonyella distributions were similar, the central heading of the former mine was located within a region of higher shear stress. The modelled distributions suggests that slip along bedding would be expected about any roadway located within 40 to 50 m of the goaf edge at North Goonyella and Moranbah North and over 80 m from the goaf edge at Metropolitan Colliery!

To better understand the factors resulting in the difference between shear stresses at different mines, a desk top study was undertaken to examine the impact of depth, rock stiffness (shear deformability of the strata) and *in situ* horizontal stress on shear stress about longwall extraction. The study was conducted using the 2D Flac code and therefore no 'out of plane' shear stresses were modelled. The strata section used was a generic case, simplified such that the only two rock types were coal and another rock type whose properties were varied. The pre-mining horizontal stress was input according to Equation 1, which scales the horizontal stress according to depth and a tectonic stress component. The study is described in detail in the ACARP C12006 Final report (ACARP, in press) and only the key findings are discussed here.

$$\sigma_{Htotal} = \sigma_v * \left(\frac{v}{1-v}\right) + TSF * E \qquad (1)$$

where:

σ_{Htotal} is the horizontal stress

σ_v is the vertical stress

v is the Poisson's Ratio

TSF is the tectonic stress factor

E is the Young's Modulus

Figure 10 shows the shear stress in the roof of a hypothetical roadway located 40 m from the goaf edge for the generic case modelled for a range of depth and rock stiffness and tectonic stress factors (TSF). The first point in each curve is a TSF of 0.2, which would represent a very low tectonic stress environment and the last point is a TSF of 1.4, which represents a high horizontal stress environment. The figure shows that:

- for a given rock stiffness and depth, shear stress generally increases with the magnitude of the pre-mining horizontal stress;
- for a given depth and horizontal stress, shear stress increased with shear modulus with much greater sensitivity in the E = 5 to 12 range compared with E = 12 to 20 range; and
- for a given rock stiffness and pre-mining horizontal stress, shear stress was not related to depth of cover.

The sensitivity study highlighted that the interrelationships between shear stress and depth of cover, rock stiffness and horizontal stress are complex and that evaluation of the propensity of any given environment to exhibit skew roof behaviour requires a numerical approach to gain an understanding of the interaction between competing influences.

One of the important findings of the sensitivity study was the lack of a clear relationship between potential skew roof deformation and depth of cover. This suggests that problematic gateroad behaviour can occur at depths below that suggested from analysis of vertical loading alone and conversely that increased depth may not necessarily make skew roof behaviour worse.

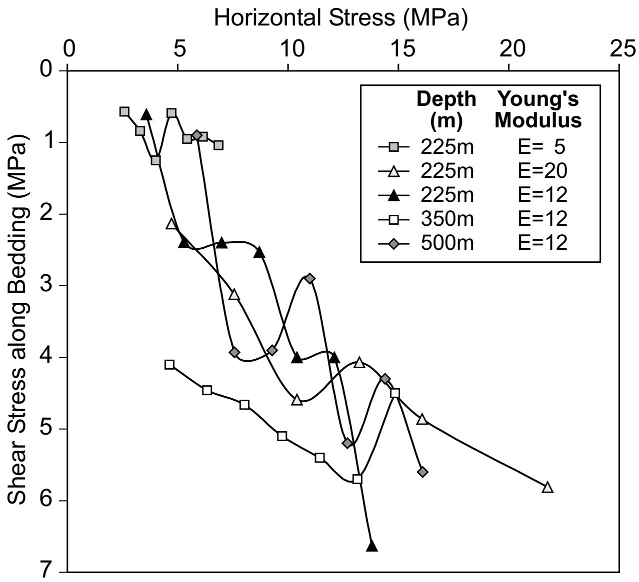


FIG 10 - Modelled shear stress 40 m from the goaf edge for a range of depths, rock modulus and horizontal stress.

Skew roof at the tailgate/faceline corner

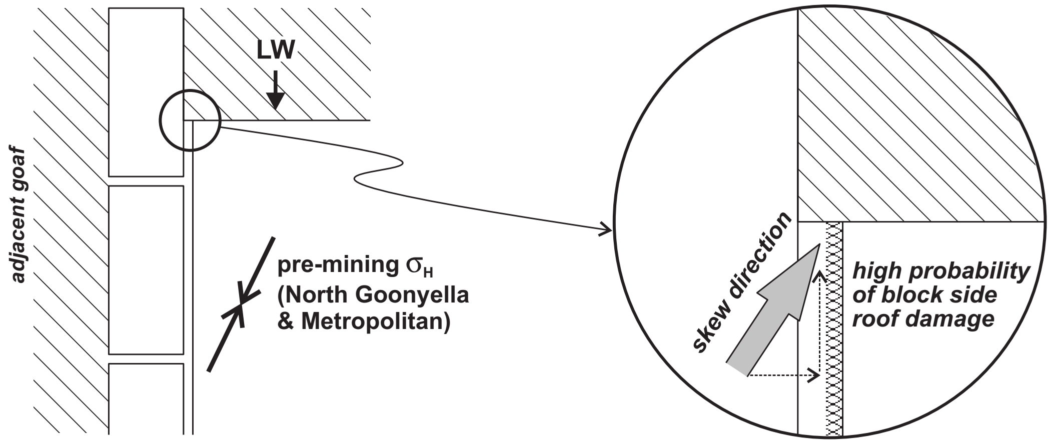
The preceding discussion developed the general concepts of the skew roof behaviour for the relatively simple extraction geometry of an adjacent goaf ignoring end effects.

The extraction geometry at the tailgate corner is considerably more complex however the general concepts already developed still apply. The 3D numerical modelling work conducted for the three sponsor mines indicated that the direction of the shear stresses resolved in the plane of bedding (the skew direction) was influenced by both the direction to the approaching goaf and the pre-mining horizontal stress direction. This is conceptually illustrated in Figure 11 for a range of extraction orientations with respect to the maximum horizontal stress. It is interesting to note that whilst there would usually be a component of skew movement towards the block side, under some circumstances there can be a component of movement away from the block side.

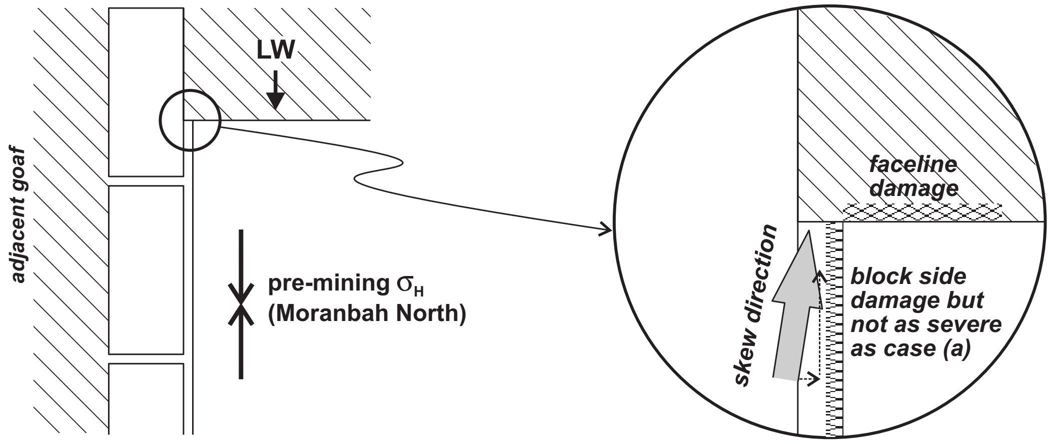
Figure 12 is a summary plot showing the distribution of shear stress along bedding in the tailgate roof versus distance to the faceline for the three sponsor mines. Based on the general assumption that 1 MPa shear stress would be sufficient to generate shear along bedding in the roof or floor of a roadway, the distributions suggest that shear behaviour would be expected at Metropolitan and Moranbah North with the former being more extensive. In contrast, the shear stress about the tailgate at North Goonyella would not be expected to be as high. This is mainly a consequence of the magnitude and orientation of the maximum horizontal stress direction.

Style of damage from skew roof behaviour

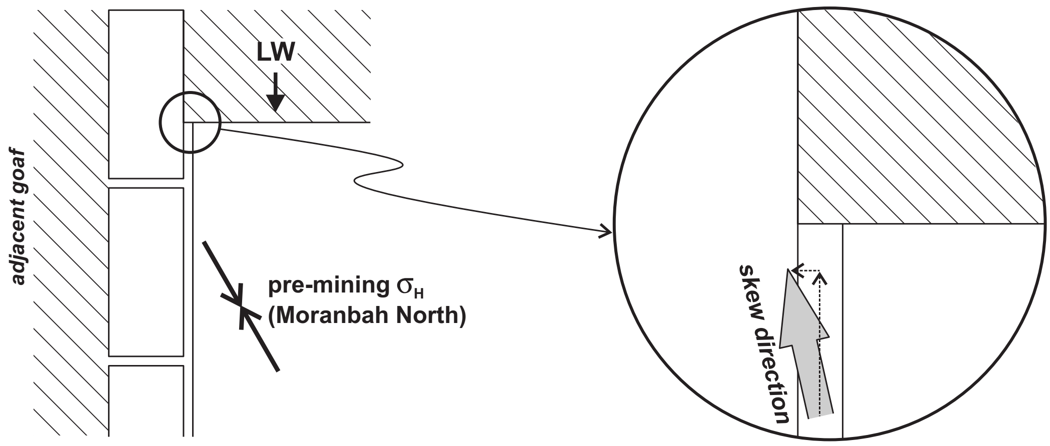
The preceding discussion presented some major factors contributing to the generation of shear stress about roadways in the vicinity of longwall extraction. The likelihood of the imposed shear stress causing slip along bedding and consequential adverse roof behaviour is itself dependent on many factors. Clearly the strength of the interfaces is a major factor. The following discussion is based on the assumption that a weak interface is present within the immediate 5 m of roof or floor and that the shear stresses are such that the skew roof mechanism is operating.



a) Maingate stress notch - high component of movement towards the block side.



b) Maximum σ_H parallel to heading - high component of skew along the gateroad (very bad for cut-throughs and faceline
- small component across the gateroad



c) Tailgate notch - potential component of movement away from block side

FIG 11 - Conceptual model of skew direction caused by direction of extraction with respect to the maximum horizontal stress orientations.

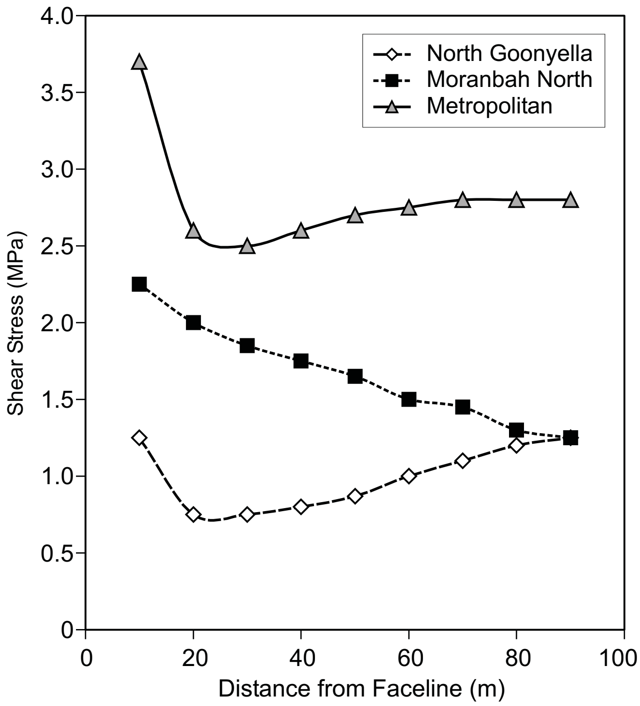


FIG 12 - Distribution of shear stress about the tailgate versus distance from the longwall faceline.

The key aspects of damage associated with the skew roof mechanism:

- increased shearing along weak interfaces in the roof beyond the riblines on the goaf side of the roadway;
- increased shearing along weak interfaces in the floor beyond the riblines on the other side of the roadway;
- increased roof damage typically on the goaf side of the roadway (naturally pre-existing roof damage may continue to focus subsequent damage); and
- increased floor damage on the same side of the roadway as the roof damage.

Potentially the most important characteristic of the skew roof mechanism is the perfectly plastic behaviour (displacement driven) of the softened strata about the roadway. The strata surrounding the roadway will differentially move towards the goaf whether or not the roadway is present. If the movement was simple translation without a shear component, then an observer underground would scarcely notice however the shear deformation demands a change of shape in the host strata irrespective of the presence of the roadway or surrounding softened strata.

IMPLICATIONS FOR SUPPORT DESIGN

Tailgate roadway behaviour is sensitive to a combination of vertical, horizontal and under some circumstances shear stress changes (skew roof) associated with longwall extraction. The roof strata moves laterally towards the adjacent goaf under side abutment loading and under tailgate loading the movement changes direction towards the approaching goaf. In addition to this movement, the vertical loading of the ribs causes rib softening which increases the effective span of the roof and floor and also induces further lateral movement in the roof and floor according to the Poisson effect.

One of the key objectives of the support design should be to reduce the lateral strata movement towards the block side as far as possible. The 'collision' of the immediate roof strata against the block side causes roof and floor damage by itself and exacerbates any other primary drivers of roof damage such as horizontal stress increases or elevated pillar loading. If the lateral strata movement cannot be reduced sufficiently, then protection of the block side should be considered, potentially accepting increased damage on the chain pillar side of the roadway. This strategy has proven to be an effective method to manage skew roof style of behaviour at Metropolitan Mine. The method seeks to prevent damage propagating from the tailgate along the faceline and provides a stable section of roadway for a second means of egress.

Protecting the block side

The positioning of standing support in a line rather than in a staggered pattern is considered to be an effective means of predisposing the roof or floor damage to occur on the chain pillar side rather than the block side. Essentially the lateral movement of the immediate roof strata 'collides' against the artificial barrier presented by the line of standing supports rather than against the block side. The following aspects are critical to achieving an effective artificial barrier:

- The standing supports must be placed close enough to interact as a pattern. This typically ranges from 3 to 5 m but should be confirmed for the conditions specific to each mine.
- The integrity of the immediate roof must be maintained as far as possible. This impacts on the primary roof bolt density. It is considered unlikely that a four-bolt pattern would maintain an acceptable level of roof integrity under skew roof conditions.
- The integrity of the roof skin is critical. Strong mesh is considered an essential component for this strategy with the use of suitable bolt plates such that high collar loading does not result in premature failure of the bolt/plate/mesh system.
- The line of standing supports should be biased towards the block side.
- The standing supports should be engaged as early as possible by the roof to floor convergence. This is achieved by early installation, tight packing and pre-stressing with inflatable packers.
- Cable bolts should be used to assist with maintaining roof integrity on the block side however their ability to limit lateral strata movement associated with skew roof is considered to be limited.

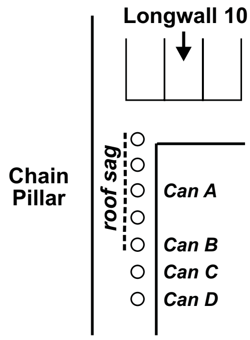
Figure 13 illustrates the successful use of this strategy at Metropolitan Colliery. Note the excellent roof conditions on the block side of the supports as the lateral movement of the immediate roof essentially collides against the barrier developed by the line of standing supports.

Role of cable bolts

Cable bolts are considered to be an excellent product to reduce strata dilation, particularly when this occurs above the bolted horizon. The ability of cable bolts to reduce lateral shear displacement is considered to be limited. Unfortunately under circumstances where skew roof deformation is active, a simple substitution of cable capacity for standing support capacity would be an inappropriate design choice.

It is highly recommended that standing supports are used to control the lateral strata behaviour or to reduce its impact rather than cables. Cable bolts would perform an important function on the block side by maintaining roof integrity. When used in conjunction with standing supports, the cables on the block side are theoretically operating in a zone of reduced shear displacement which would enhance their longevity and performance.

a) Can A, approximately 10 m outbye.



b) Can B, approximately 16 m outbye.

c) Can C, approximately 19 m outbye.

d) Can D, approximately 22 m outbye.

FIG 13 - Views of tailgate looking inbye – roof conditions on block side of supports significantly better than chain pillar side.

Future support improvements

Numerical modelling conducted as part of this project sought to determine the influence of support aspects such as positioning, stiffness, strength and timing of installation. This work will be reported in more detail elsewhere however the results suggest that a substantial increase in support stiffness and capacity (to at least 350 tonnes and potentially up to 500 tonnes) would be required to have an impact on the skew roof mechanism. The impact of such support capacity would need to be evaluated against other aspects such as supports punching into the roof.

Significant improvement to the stiffness of existing support systems would be expected to result from active setting of the supports against the roof. Use of inflatable packers would be expected to offer significant benefits in terms of support performance compared with existing methods of base construction. Pre-stressing the supports in this way also removes that component of roof to floor convergence required to 'seat-in' the support. This was found to be in the range 20 to 50 mm which would allow significant loss of roof strength prior to the supports being effectively engaged.

CONCLUSIONS/RECOMMENDATIONS

A roof deformation mechanism termed 'skew roof' has been investigated through observation, field measurement and 3D numerical modelling. As the term suggests, the immediate roof layers in the vicinity of longwall extraction may move further towards the adjacent or approaching goaf relative to the floor. Similarly, higher strata layers move further than layers closer to the roof. In extreme cases the immediate roof layer is 'driven' towards the goaf under displacement (unstoppable) control.

The skew roof mechanism is driven by the rotation of the principal stresses out of the horizontal plane about longwall extraction, thereby imposing excessive shear stress on (near) horizontal bedding. The key factors driving the skew roof mechanism are considered to be:

- the absolute and relative magnitudes of the vertical and horizontal stresses;
- the shear modulus of the strata pile (shear deformability); and
- the extent of overburden bridging.

The skew mechanism overprints other influences such as vertical loading of chain pillars and associated Poisson effects and exacerbates the affects of horizontal stress changes.

Control of tailgates subjected to skew roof behaviour is currently limited to protection of the block side, considered to be the most critical area to safe egress of personnel and manageable faceline conditions. Standing supports are considered to be the 'front line' support strategy with emphasis on appropriate positioning (biased to the block side), interaction as a pattern and maximising effectiveness through early placement and pre-stressing. Primary bolts, roof mesh and long tendons have important roles to play in maintaining the integrity of the immediate roof layers to allow the standing supports to interact effectively.

However, significant increases in the existing strength and stiffness of standing supports is considered necessary to achieve better control of problematic tailgates.

The determination of the potential impact of skew roof behaviour and development of an appropriate support strategy remains a 'horses for courses' proposition, requiring observation of strata behaviour, field measurement of support loading and strata interaction and numerical modelling which should be 3D to properly simulate the full 3D stress changes.

The skew roof mechanism should also be a consideration in pillar design, mine layout and the potential impact on the longwall faceline itself. Computational advances allow the reasonable 3D simulation of the tailgate environment and evaluation of any conceivable support strategy. This provides a rigorous basis to optimise pillar width against support effort.

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APPENDIX
SHEAR STRIP RESULTS – METROPOLITAN MINE

Note that the reference location (zero displacement) is the base of the shear strip however since the absolute position of the shear strip is not known, the 'Y'-axis in the cumulative displacement plots could be moved to the right or left. This does not alter the sense of shear but would affect the absolute position of the shear strip itself. In other words, the absolute location of the shear strips is not known relative to a fixed reference.

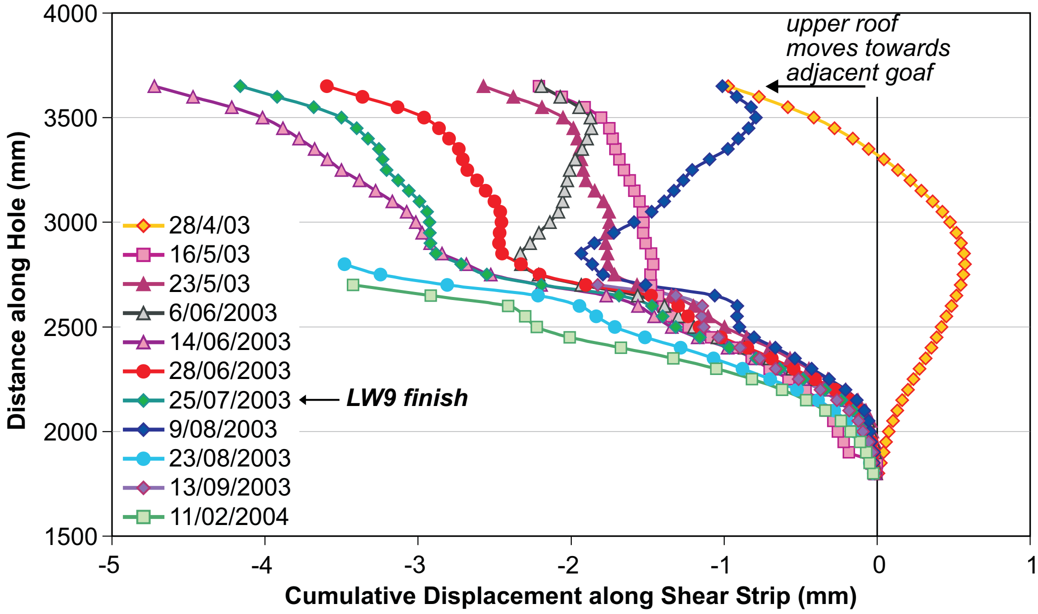

FIG A1 - Cumulative displacement – chain pillar side during extraction of Longwalls 9 and 10.

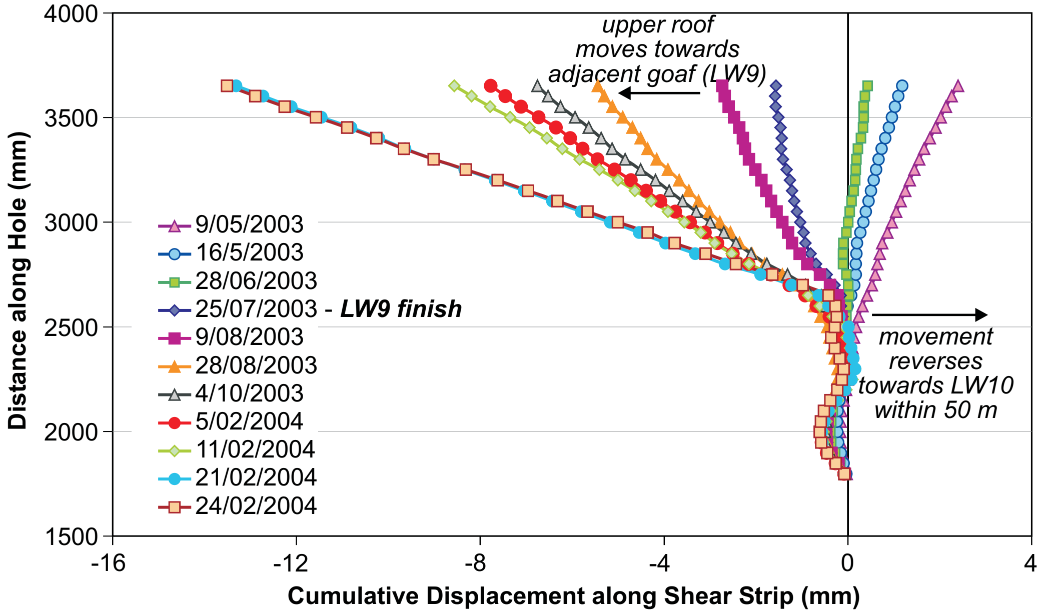

FIG A2 - Cumulative displacement along shear strip – block side during extraction of Longwalls 9 and 10.

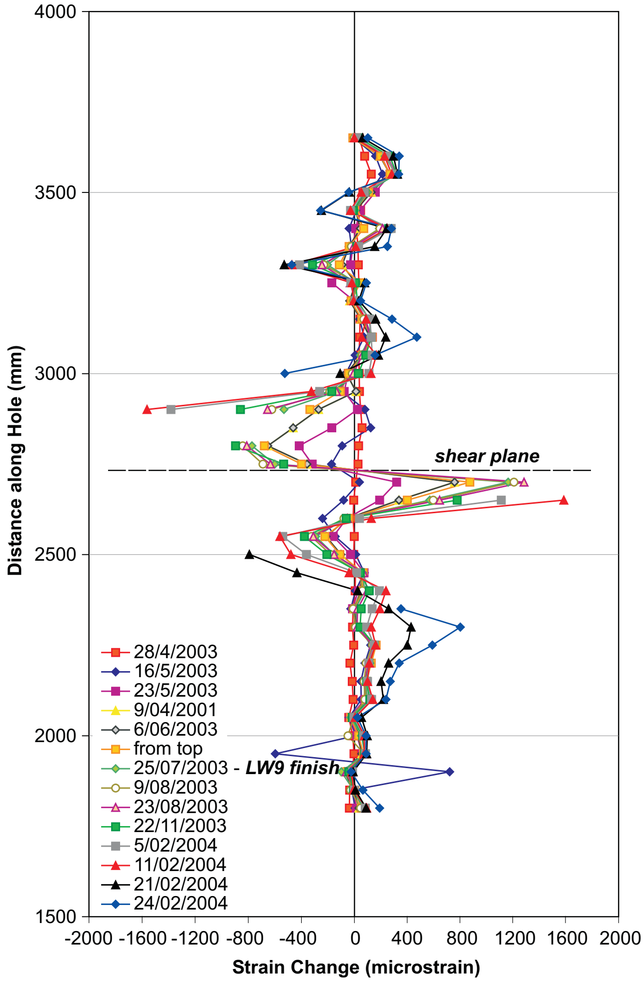

FIG A3 - Strain change on chain pillar side after extraction of Longwalls 9 and 10.