Stability Analysis of Four-Way Intersections of Coal Mine Roadways

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Abstract: A detailed computer analysis was carried out to examine the influence of various parameters on the stability of four-way intersections of coal mine roadways. A number of three dimensional finite element models were developed using data obtained from laboratory test and from field investigations at a coal mine in NSW, Australia. The models were subjected to a three dimensional non-linear solution procedure incorporating the post failure behaviour of rocks. These results were analysed to examine the influence of individual factors such as depth of cover, width of roadway and the horizontal to vertical stress ratio on the stress distribution and displacement induced around the intersection. Based on this study, a procedure for the optimal design of the support system for four-way intersections in underground coal mines is proposed.

Introduction

One of the most important factors affecting the overall success of a longwall mining operation is the stability of gate roadways and intersections. Gate roadway intersections are particularly susceptible to strata control problems due to inherently wide roof spans and excessive induced stresses. This situation is accentuated in the presence of high horizontal stresses, moving abutment pressure zones from retreating longwall faces and the presence of discontinuities. Intersections are formed when the pillars between two roadways or between one roadway and the adjacent panel are connected. The roadway intersections are grouped into two categories; four-way and three-way intersections. In both types of intersection the diagonal roof span is greater than the width of either roadway. Figure 1 shows typical roadway intersections in underground coal mines. The region surrounding a roadway intersection is subjected to a different stress regime than the roof area surrounding a single entry. This may result in a higher incidence of roof falls and rib failures. This paper investigates the application of a three dimensional finite element method to stability evaluation of roadway intersections, in terms of both stress and displacement patterns. The effect of individual parameters such as depth of cover, the ratio of horizontal to vertical stress and the width of the opening on the stability of the intersection were examined. The results were comparable to field observations at an underground site in NSW (Fabjanczyk 1990, Gale 1991, Hematian and Porter 1993).

![four-way intersection](image1)
![three-way intersection](image2)

Figure 1 Intersections in underground coal mining
Previous Investigations of Intersection Instability

Stahl (1961) carried out a detailed study of roadway intersection problems in underground coal mines in the USA and found that 30% of fatalities due to roof falls occurred at roadway intersections even though the exposed roof at these locations rarely exceeded 15% of the total exposed roof. On the basis of the measured convergence at the intersections Stahl (1961) suggested remedial measures such as; use of extra bolts at the trimmed corners of the pillars, use of cross bars at the site of scaly roof and the occasional use of cross bars on the approach to the intersection where shear cracks occurred in the roof along the pillar / roof interface.

From 1974 to 1978, Langland (1976 and 1978) carried out comprehensive investigations into the stability of roadway intersections using analytical and numerical modelling techniques. The input parameters for these investigations were obtained by laboratory testing of rocks and the results verified by field observations. The field work in this study was particularly concentrated on the shape and dimensions of roof falls and measurement of roof convergence, roadway closure and load on selected roof bolts. It was observed by Langland that roof sag (relative displacement of strata layers, including shear) and load on the bolts were a maximum at the pillar edges and at the corner of the intersection where shear stress was a maximum. Total closure, however, was a maximum at the centre of the intersection. It was further observed that the development sequence had a significant influence on the structural stability of the roof. The roof convergence rate was a maximum during the first few days after excavation and eventually slowed down after 20 to 30 days. Limitations of the finite element analysis were; no consideration of a realistic failure criteria and no consideration of post-failure behaviour.

Peng and Okubo (1978a and b) carried out site specific studies of roof falls at three-way and four-way intersections in the Pittsburgh seam in the USA which was followed by numerical modelling of the intersections using the finite element program NASTRAN. On the basis of these studies it was revealed that there is an arching zone within a roof fall which requires additional support. The maximum displacement occurred at the centre of the intersection and small tensile stresses were induced at the centre of the intersection and along the centre line of the entries. It was suggested that in order to control the propagation of roof falls at roadway intersections within the arch zone the roof bolt pattern should be designed to carry the weight of broken rock by suspending it from the overlying intact main roof. It was suggested that the length of the roof bolts at the central region of the intersection should be half the width of the entry and those in the corner region should be one quarter of the entry width. The load carrying capacity of the bolt at the centre region should be half the unit weight, \( \gamma \), times the width of the intersection, \( w \), (0.5\( \gamma \)\( w \)); double that required at the corners. When the roof strata is thinly laminated, roof bolting would be effective by the process of beam building, produced by activating the frictional shear resistance along the bedding planes, thereby preventing inter-bed sliding. The maximum shear resistance required on the horizontal plane was found to be somewhere between the centre and the corners of the intersection.

Hanna et al (1985, 1986a and b) carried out field investigations to determine failure modes and stress-displacement relationships around roadway intersections and to establish engineering guide lines for the design of safer intersections. The field work consisted of instrumenting and monitoring roadway intersections before, during and after intersection development. The effect of re-orientation of the mine entries, modification of the bolting pattern and alteration of the mining sequence and geometry on roadway stability was examined. The study indicated that horizontal stresses were the main cause of rock shear in the fractured zone, and this shear failure gradually propagated into the roof until it intersected a weak plane above the bolt. Figure 2 shows a typical shear failure at a roadway intersection (Hanna et al, 1986b). It was observed that at the site of high horizontal stress, longer roof
bolts resulted in higher falls and it was found effective to anchor the bolts outside the failure envelope. A roof bolting pattern using 3m long bolts close to the rib sides and 1.5 m long bolts at the centre of the roadway reduced the occurrence of roof falls significantly.

Figure 2 Shear failure at intersections (Hanna et al 1986b).

Stability Evaluation of Intersections Using Three Dimensional Finite Element Models

The procedure used in the stability analysis of intersections consisted of four basic steps (figure 3) as follows:

(a) define the mechanical properties of the materials, the geometry of the structure and the virgin stresses,

(b) determine the stresses and displacement induced around the structure,

(c) assess the stability of the intersection,

(d) if unstable conditions exist, design an appropriate support system or change the geometry of the structure.
A series of 3-D computer models were developed using the vertical stress, the ratio of horizontal to vertical stress and the width of opening as variables. By assuming symmetrical conditions around the intersection, one quarter of the structure was modelled using 8-node solid elements. For a 6m x 6m x 3m high intersection, 5932 elements and 8225 grid points were used. The computer running time for processing the model was just under 4 hours.

A general view of the intersection is illustrated in figure 4 and the rock properties are given in table 1. At least 400 megabytes of computer memory were required to run each of these models. The model used the eight loading configurations shown in table 2; loads being applied by using uniform pressure on the internal free faces. This technique of loading reduced the size of the model and eliminated boundary effects from the results.

Table 1 Properties of rocks encountered in three dimensional models.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Thickness (m)</th>
<th>E (GPa)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>sandstone (roof)</td>
<td>12.0</td>
<td>18.00</td>
<td>0.2</td>
</tr>
<tr>
<td>coal</td>
<td>3.0</td>
<td>4.0</td>
<td>0.3</td>
</tr>
<tr>
<td>mudstone (floor)</td>
<td>10.0</td>
<td>16.00</td>
<td>0.22</td>
</tr>
</tbody>
</table>
To examine the effect of depth on the stress distribution at the mid-height of the pillar an average strata density of 2.5 MPa / 100m depth was assumed. The models were analysed under four different vertical stresses; $\sigma_z = 5.0$, $7.5$, $10.0$ and $12.5$ MPa corresponding to 200, 300, 400 and 500m depths.

Table 2 Loading conditions applied to the three dimensional models.

<table>
<thead>
<tr>
<th>Loading conditions</th>
<th>$\sigma_z$ (MPa)</th>
<th>$\sigma_y$ (MPa)</th>
<th>$\sigma_x$ (MPa)</th>
<th>$K_y$ ($\sigma_y/\sigma_z$)</th>
<th>$K_x$ ($\sigma_x/\sigma_z$)</th>
</tr>
</thead>
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<tr>
<td>SUB1</td>
<td>5.0</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SUB2</td>
<td>7.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SUB3</td>
<td>10.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SUB4</td>
<td>12.5</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SUB5</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>SUB6</td>
<td>10.0</td>
<td>10.0</td>
<td>20.0</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>SUB7</td>
<td>10.0</td>
<td>10.0</td>
<td>30.0</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>SUB8</td>
<td>10.0</td>
<td>10.0</td>
<td>40.0</td>
<td>1.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Stress distribution at the mid-height of the pillar

Vertical stress concentrations at the mid-height of the pillar were computed for the various loading conditions. The results are presented, figure 5, as contours for various stress concentration ratios (σ/σ₀; where σ₀ is the induced vertical stress).

Figure 5 Typical stress concentration pattern at the mid-height of the pillar for a 6m x 6m intersection.

The normalised stress concentration pattern at the mid-height of the pillar was similar for all depths. As expected the maximum stress concentration increased slightly as the roadway width increased, but the location of the maximum was the same. The extent of the zone of influence of the intersection may be estimated from the following:

\[ L \gamma = 1.2W_v, \quad L_x = 0.95W_v - 1.162 \quad \text{and} \quad r = 4.6 \text{ to } 6.0 \text{ m, where; } \quad \text{Eq}(1) \]

\( L \gamma = \text{extent of zone of influence along the y-roadway,} \)

\( L_x = \text{extent of zone of influence along the x-roadway,} \)

\( r = \text{radius of influence of intersection over the pillar,} \)

\( W_v = \text{width of the individual roadways.} \)

Stress concentration 0.5m above the roof line

The normalised stress concentration pattern 0.5m above the roof line, figure 6, was similar for various depths. The influence of the intersection over the pillar and along the roadway can be expressed in terms of roadway width as given in equations 2 and 3 respectively.

\[ r = 3.6W_v \quad (\text{influence over the pillar}) \quad \quad \text{Eq}(2) \]

\[ L = 1.7W_v \quad (\text{influence along the road}) \quad \quad \text{Eq}(3) \]
The highest stress concentration was located over the edge of the pillar and its value was around 1.4 to 1.6 times the vertical stress; about 20% more than that occurring above an individual roadway.

![Diagram](image)

**Figure 6** General stress concentration pattern on a plane 0.5m above the roof for a 6m x 6m intersection.

**Stress distribution directly above intersections and individual roadways**

The destressed zone above the intersection and the roadways are as shown in figure 7.

![Diagram](image)

**Figure 7** General shape of the destressed zone: (a) over the intersection, (b) over the individual roadways.

It may be noted that the stress distributions at both sides of the intersection along the x-axis and the y-axis were similar. The height, h, and the width, 2d, of the destressed zone depends upon the width of the opening and the stress concentration ratio, \( \sigma_j/\sigma_p \), as shown in figures 8a and 8b.
Figure 8(a) Relationship between roadway width, $W_0$, and the height of the destressed zone for various stress concentration ratios, $\sigma/\sigma_v$.

Figure 8(b) Relationship between roadway width, $W_0$, and the width of the base of the destressed zone, $2d$, for various stress concentration ratios, $\sigma/\sigma_v$.

Roof Closure

Contours of displacement along the roof line are shown in figure 9. It may be noted that the maximum closure of the roof occurred at the centre of the intersection; its value influenced by the vertical stress distribution for various cover loads.

Figure 9 Roof sag for a 6m x 6m roadway intersection.
Based on regression analysis, the closure at the centre of the intersection can be estimated as follows:

\[ d_c = H_o[ -0.15 + (0.77 + 0.26W_o) \frac{\sigma_v}{E_{coal}} ] \]  ...Eq(4)

where;
- \( d_c \) = closure at the centre of the intersection (mm)
- \( H_o \) = height of the seam (m)
- \( W_o \) = width of the roadway (m)
- \( \sigma_v \) = virgin vertical stress (MPa)
- \( E_{coal} \) = elastic modulus of coal (Gpa)

**Floor heave**

Figure 10 shows the vertical displacement of the floor in the vicinity of the intersection.

![Figure 10 Floor heave at a 6m x 6m intersection.](image)

It was observed that floor heave was much less than the corresponding values for roof closure. The maximum value for floor heave can be estimated using equation (5), which was derived from regression analysis of the maximum floor heave for various roadway widths.

\[ d_h = H_o[ -0.85 + 0.17W_o + 0.53\sigma_v/E_{coal} ] \]  ...Eq(5)

where;
- \( d_h \) = heave at the centre of the intersection (mm)

The above equation does not take account of variations to the elastic modulus of the roof and floor as these were held constant during the analysis. It would be a simple matter to vary the modulus of the roof, floor or both if so desired.

**Effect of horizontal stress on the stability of an intersection**

The effect of horizontal stress on the stability of a 6m x 6m intersection was examined by analysing a series of models under four different ratios (1, 2, 3 and 4) of horizontal to vertical stress, \( K \), for a constant vertical stress of 10MPa. Values of \( K = 1 \) or 2 are common in many underground coal mines and the higher range, \( K = 3 \) or 4, is representative of the conditions at Ellalong colliery. It may be realised that the vertical stress concentration at the mid-height of the pillar for values of \( K > 1 \) are no longer symmetrical (figure 11). The variation of stress is more pronounced along the y-axis which is perpendicular to the direction of maximum
horizontal stress. There are some tensile zones along the rib side, and when $K > 2$ the thickness of the tensile zone increases as $K$ increases. This tensile zone on the surface of the rib may manifest itself as severe spalling, therefore side reinforcement, such as wooden dowels, must be longer for roadways in the y-direction than for roadways in the x-direction.

$$K_{\text{max}} = 2$$  $$K_{\text{max}} = 4$$

Figure 11 Stress concentration contour lines at the mid-height of the pillar under different horizontal stresses.

The stress concentration at the mid-height of the pillar for intersections from 4m x 4m to 6m x 6m are shown in Figure 12. This shows that the maximum stress concentration is located close to the pillar corners and extends further along the x-roadway as $K$ increases. Also, the width of the stressed zone along the y-roadway is greater than that along the x-roadway. It may also be noted from Figures 11 and 12 that the width of the disturbed zone over the pillar is influenced by both the horizontal to vertical stress ratio and the width of the roadway.

Figure 12 Effect of intersection dimensions and horizontal stress on the stress concentration at the mid-height of the pillar.
The stress distribution on a plane 0.5m above the roof line (figure 13) shows the marked influence of the ratio of horizontal to vertical stress. For $K = 1$ the stress contour line 0.1 $\sigma_z$ was located over the roadway, indicating destressing, whilst the 1.1 $\sigma_z$ line was very close to the rib line. As the K value increased from 1 to 4, the stress pattern changed along the y-direction whilst that in the x-direction (parallel to the major horizontal stress) remained essentially the same. Implicitly, there was the possibility of a larger failure zone over the y-roadway because of the higher stress concentration close to the roof line.

**Figure 13 Vertical stress contours 0.5m above the roof line.**

The vertical stress pattern within the roof on the x and y-side of the intersection were studied by plotting the destressed zone over the intersection and individual roadways as shown in figure 14. This analysis showed that the destressed dome along the x-roadway flattened significantly with increased horizontal stress ($\sigma_x$), whereas the dome shape was still dominant along the y-roadway.

Further analysis was carried out by Hematian (1994) in an attempt to estimate the height and radius of the base of the destressed zone above the intersection and along each of the roadways. Figure 15 shows the radius of influence and the shape of destressed zone defined by the height, length and curvature of the 0.5 $\sigma_z$ contour line. The above study also showed that the height of the destressed dome increases with roadway width, $W_0$ and decreases with an increase in the principal stress ratio. The length of the base of the destressed dome decreases in the y-direction and increases in the x-direction for various $W_0$ as the stress ratio increases from 1 to 4. Previous research (Peng and Okubo, 1978) proposed that the contour 0.1 $\sigma_z$ be the upper boundary for potential fall zones, however, observations at Ellalong Colliery suggested that the contour 0.3 $\sigma_z$ would more confidently define the outline of a potential roof fall cavity. Regression analysis of the results for various intersection configurations indicated that the height of the dome may be estimated from the following equations:

\[
\begin{align*}
    h_{0.3} &= 0.9W_0 - 0.2K - 0.7 \quad \text{...Eq (6)} \\
    d_{0.3} &= 0.7W_0 - 0.4 \quad \text{where;} \quad \text{...Eq (7)}
\end{align*}
\]

- $h_{0.3}$ = height of destressed zone defined by 0.3 $\sigma_z$ contour line (m)
- $W_0$ = width of the roadway (m)
- $K$ = ratio of horizontal to vertical stress
- $d_{0.3}$ = radius of the base of roof fall (m)
Figure 14 Destressing of the roof along the x and y-roadways.

Figure 15 Radius of influence and extent of destressed zone over the individual roadways.
Design of Support Systems for Four Way Intersections

Design of an appropriate support system depends upon the potential mode of failure at the intersection. The state of stress, width of roadway, structure, nature and properties of the surrounding strata all have appreciable influence on the stability of the intersection. Past experience has indicated that potential modes of failure at intersections are as follows:

(i) dome shaped failure in massive roof or thicker beds under a low stress regime;

(ii) shear failure along the bedding planes in a laminated roof and a high horizontal stress environment;

(iii) guttering of the roof at the pillar edge and corners of the intersections in high horizontal stress regimes.

Where a dome type of failure is anticipated above an intersection, the height of the dome and the radius of the base of the unstable zone should be estimated from the appropriate stressed contour line over the intersection, also taking into account the width of the roadways and the stress state (equations 6 and 7). To help prevent dome type roof falls installation of longer and a greater number of bolts at the centre of the intersection is suggested. In the second case, when the horizontal shear stress exceeds the frictional resistance offered by the bedding plane, more bolts need to be located near the side wall where the maximum shear stress occurs on the bedding planes. In a high horizontal stress field where guttering type failures are more pronounced, long inclined bolts should be installed over the abutment to prevent guttering.

Figure 16 shows an intersection with the various failure zones highlighted. Guttering usually occurs over a 0.5m to 0.7m wide strip parallel to the rib edge, normal to the direction of the highest horizontal stress and extending vertically into the roof. The most probable location of the zone where sliding type failure may occur is somewhere between 0.2 to 0.4 \( W_o \) from the centre line. Dome or arch type failure usually covers the entire width of the roadway and extends to a height of 0.5 to 1.0 \( W_o \).

![Figure 16 Locations of various modes of failures at four-way intersections](image-url)
Figure 17 highlights three zones where more attention has to be paid to the sequence of development and support intensity and pattern in order to control instability. Zone 1 has conditions similar to an individual roadway and as such the support requirements are the same. Zone 2 within the roadway intersection experiences increased strata loading by some 20%, therefore this zone requires longer bolts with closer spacing and increased load ratings. In the centre area of the intersection, zone III, strata loading is severe. Normally bolts in this area should be 50% longer than that in zone II and also their load bearing capacity must be increased accordingly.

![Diagram of zones of instability at four-way intersections.](image)

Figure 17 Zones of instability at four-way intersections.

It is suggested that in high horizontal stress fields, the roadway running parallel to the high horizontal stress should be driven first and the support for the completed intersection be installed before the other roadway is driven. It is suggested that installation of inclined roof bolts near the rib and the use of w-straps parallel to the pillar edge would help maintain structural stability of the intersection.

Conclusions

From analysis of the results from the three dimensional models of intersections a number of conclusions can be drawn:

(i) The normalised stress concentration pattern around an intersection is similar for various depths of cover. The maximum value of the resultant stress increases with the increase in depth. Dimensions of the abutment zone around the intersection are a function of the state of stress and roadway width. The radius of influence of the abutment zone around an intersection is twice the opening width measured from the centre of the intersection.

(ii) The highest stress concentration rate at the mid-height of the pillar was around 2.0 \( \sigma_z \) and dependent upon the roadway width. The diameter of the abutment zone at the mid-height of the pillar was equal to the opening width measured from the pillar edge.
(iii) The distressed zone in the roof of a four-way intersection has a dome shaped configuration which expands further into the roof with increasing roadway widths. This in turn results in a higher potential failure zone at the intersection. The height of the apex of the failure zone decreases with an increase in the horizontal stress.

(iv) The maximum roof closure and floor heave occurs at the centre of the intersection and is dependent on the vertical stress, width of opening and the mechanical properties of the surrounding strata. The maximum change of heave and closure occurs over the rib line which in turn induces tension at these locations.

(v) The area around an intersection can be divided into three regions, each region having different support requirements. The region outside the radius of influence of the intersection should have the same support as the individual roadways. The support system within the area of influence of the intersection should be increased by installing longer roof bolts at closer spacing with a corresponding increase in load carrying capacity. Support in the central region of the intersection should be further enhanced with a further increase in bolt length and capacity.

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References


