CHAPTER 6 HIGH HORIZONTAL STRESSES

6.1 INTRODUCTION

As stated in Section 2.7.2, Sources of In-Situ Stresses (p. 64), high horizontal stress is of tectonic origin due to mountain building and continental drift. It occurs all over the world and probably has since the earth was formed. Consequently, it is a norm, not an exception. However, its effect on coal mining in the U.S. was not known until the 1970s.

High horizontal stress in the near east-west direction was found for the first time to cause roof falls and cutters in north-south rooms and heavy rib spalling and tensile roof cracks in the east-west rooms of a northern West Virginia coal mine (Dahl and Parson, 1972). This study is responsible for the dominant trend of east-west oriented longwall panels in most U.S. coal mines, especially in the Pittsburgh seam.

Another study contributed to the awareness of high horizontal stresses and their effects on entry stability: the severe floor heave problems in the Beckley and Sewell seams of southern West Virginia in the late 1970s was by Aggson and Curran, (1978). A series of in-situ stress measurements were performed in five coal mines within a 25-mile area with mine depths from 350 to 1,148 ft (106.7-349.9 m). The maximum principal horizontal stress measured, 1,484-6,109 psi (10.2-42.1 MPa) was much higher than the vertical stress at these depths (Fig. 2.7.6). The results showed that high horizontal stresses were responsible for the heavy directional floor heave, and the researchers recommended slotting at floor center and mine plan re-orientation to solve the problems.

Since then, in-situ horizontal stress measurements have been performed in all coal fields in conjunction with various ground control problems such as mine planning, roof falls, cutter roofs, and horizontal stress abutment/stress shadowing. The solutions developed for those issues include mine plan re-orientation, mining sequence, sacrificial entries, and induced roof caving.

6.2 EFFECTS OF HORIZONTAL STRESS ORIENTATION AND CUTTING SEQUENCE ON ENTRY STABILITY

6.2.1 Field Experience - Horizontal Stress Abutments and Shadowing

During entry development, Gale and Blackwood (1987) found that the percentage of good roof is the highest when the angle, θ, between entry and major principal horizontal stress σ_{h1}, is less than 38^o. The percentage of good roof decreases rapidly when the angle is between 38^o and 65^o and reaches the lowest point when the angle is between 65^o and 90^o (Fig. 6.2.1).

The reason that the entry roof is bad when σ_{h1} is larger than 38^o is attributed to the **horizontal stress concentration** or **abutment**. When the entry is driven parallel to σ_{h1}, the horizontal stress is evenly split on both sides, by-passing the entry, resulting in little or no stress concentration at the entry corner (Fig. 6.2.2A) (SCT, 1995). When σ_{h1} is perpendicular to the entry, the horizontal stress is highly concentrated in front of the face, making it the least stable (Fig. 6.2.2B). When the entry is driven obliquely to σ_{h1}, the advance side of the entry is subjected to high horizontal stress abutment (circles in Fig. 6.2.2C), and the roof condition is bad. Conversely, the stress on the opposite side of the entry is relieved with good roof condition. This is **stress shadowing**.

Underground mapping by Thomas and Wagner (2006) also showed that when the entry intersects the major principal horizontal stress at θ = 30^o to 70^o the majority of roof deformation will concentrate on the side of the entry that the major principal horizontal stress, σ_{h1}, first intersects.

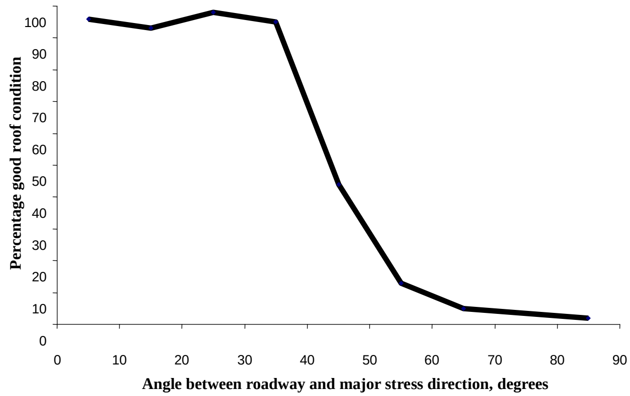


Fig. 6.2.1 Effect of entry orientation, θ, with major principal horizontal stress (Gale and Blackwood, 1987)

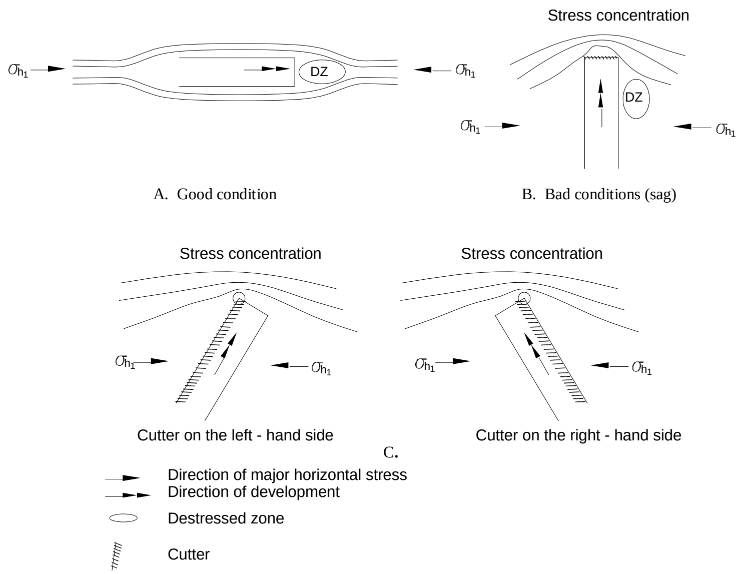


Fig. 6.2.2 Stability of entry when the major principal horizontal stress intersects the entry at different angles (modified from SCT 1995)

Similarly, a longwall panel can be considered as a large opening, and the concepts of horizontal stress abutment and stress shadowing are applicable (Hasenfus and Su, 2006; Mark and Mucho, 1994; Su and Hasenfus, 1995; Thomas and Wagner, 2006). In Fig. 6.2.3, the headgate T-junction of B-panel is subjected to high horizontal stress abutment pressures, because the gob is located to its rear upper-side, causing σ_{h1} to turn and concentrate on the corner. Conversely, on the tailgate, both the left- and upper-sides are gob and thus located in the de-stressed zone. In A-panels, σ_{h1} passes through the gob at the headgate T-junction, thereby relieving the stress. The same is true at the tailgate T-junction, except when the total chain pillar width is too large to transfer the stress-relieving effect of the gob of the previous panel.

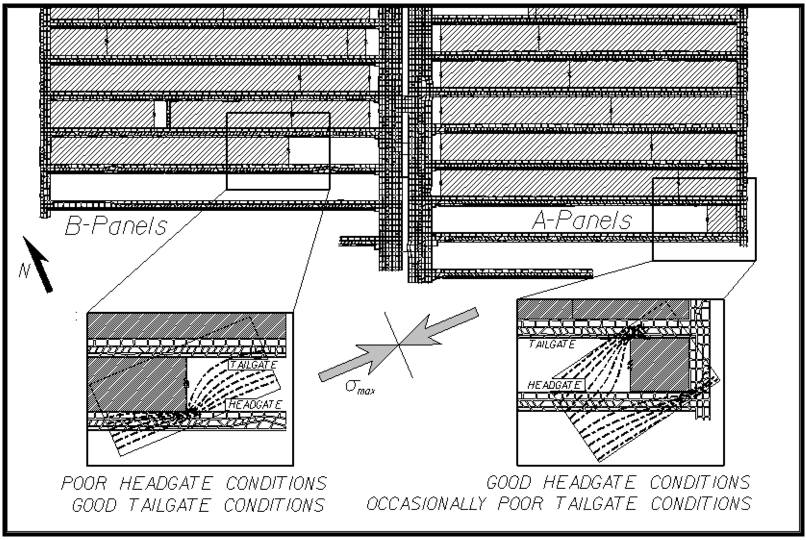


Fig. 6.2.3 Horizontal stress abutment and shadowing for head- and tail-gates (Hasenfus and Su, 2006

Horizontal stress abutments and shadowing also affect bleeders, set-up rooms, recovery rooms, and staggered panel intersection areas as shown in Fig. 6.2.4 (Hasenfus and Su, 2006), where σ_{h1} is applied in the east-west direction. For right-handed faces, the headgate T-junction (A) is always subjected to high horizontal stress abutment pressure, while the tailgate T-junction is in the de-stressed zone. The protruding sides of the set-up room, bleeders (B), recovery rooms, and bleeders (C) are also located on the horizontal stress abutment zone. For left-handed faces, the headgate and tailgate T-junctions are located in the shadowing zone (see also B-panels in Fig. 6.2.3). The protruding sides of the recovery rooms, bleeders (D), set-up rooms, and bleeders (E) are located at the stress abutment zones. When the bleeder end of the left-hand panel is offset for whatever reasons, F becomes a pinch point where the horizontal stress abutment pressure increases continuously as the face retreats toward and approaches it (JS Chen et al., 1998; Miller, 1998), causing ground control problems. The left- and right-hand longwall panels refer to the panels when standing at the face looking outby, the headgate is on the left and right sides, respectively (Peng, 2006).

In the Pittsburgh seam, longwall panels are oriented east-west with the major principal horizontal stress oriented at N65^{o}E to N90^{o}E. Consequently entries in the gateroad system are driven 17^o to the major principal horizontal stress resulting in good roof condition during development. However, the crosscuts developed at 60^o to the entries experience some roof control problems. Since the crosscuts are spaced at 135-145 ft (41.2-44.2 m) intervals, the linear footage of entries developed in the better orientation (17^o or 26^o to σ_{h1}) is about 2.1-2.3 times that of crosscuts developed in the worse orientation (43^o or 86^o to σ_{h1}) (JS Chen et al., 1998). Gateroads driven at an angle greater than 50^o to σ_{h1} exhibited roof bolting problems, such as bearing plate deformation, strap buckling, and overbreak on the more highly stressed side of the entry and required higher bolt density (Cassie and McLennan, 1997). Conversely, gateroads driven at less than 50^o exhibited smooth roof profiles.

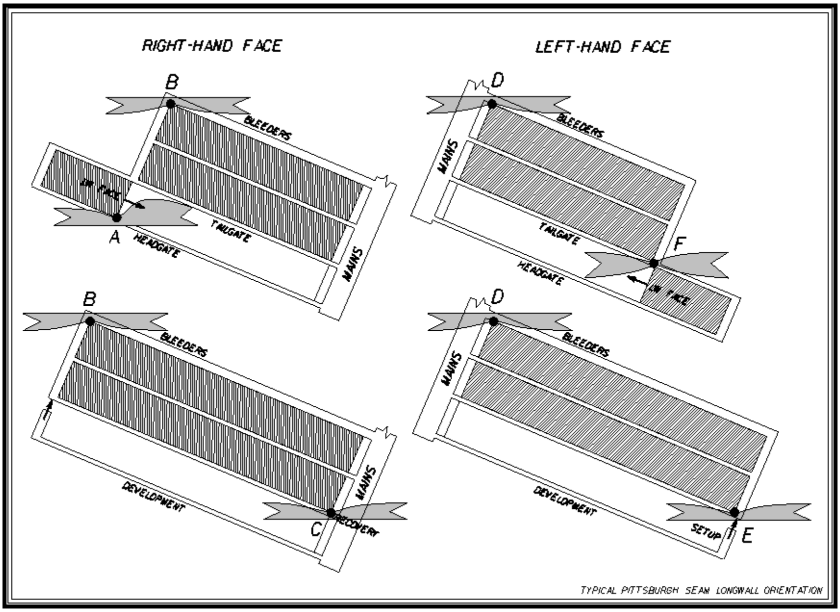


Fig. 6.2.4 Horizontal stress abutment location for longwall panels (Hasenfus and Su, 2006)

In the Illinois coal field, when entries were developed perpendicular to σ_{h1}, orienting at N86.3^{o}E, numerous roof falls occurred at and outby the face during mining and the rejects increased to more than 50 %. (Blevins and Dopp, 1985). When the entries were turned to intersect σ_{h1} at 45^o, the roof crushing that occurred during mining was almost completely eliminated. In the eastern coalfield, Lizak and Semborski (1985) found that maximum roof stability areas lie within $\pm 30^o$ of σ_{h1}; intermediate roof stability areas lie between 30^o and 60^o on both sides of σ_{h1}; and minimum roof stability areas lie from 60^o to 90^o on both sides of σ_{h1}, which was confirmed by computer analysis (see Fig. 6.2.7).

Most discussion on the effect of high horizontal stress considers only entry stability with little emphasis on crosscut stability. Since in most mine plans entries and crosscuts are developed perpendicular to each other, a good stress orientation for an entry is bad for the crosscut. This conflicting effect can be reduced to some extent by driving the crosscuts obliquely to the entry direction. By orienting the entry such that $\theta \leq 30^o$ with respect to σ_{h1}, crosscuts can be driven by turning toward, and at shallow, oblique angles to, σ_{h1}. An example is shown in Fig. 6.2.5 (Hasenfus and Su, 2006). Cutter conditions occurred in the crosscuts between the 3rd and 4th entries (Fig. 6.2.5A, counting from the left). A roof fall occurred on the 3rd entry at the intersection and last open crosscut when passing under a stream (Fig. 6.2.5A), because the crosscut was driven nearly perpendicular to σ_{h1}. Conversely, when the crosscuts were turned to σ_{h1} direction (Fig. 6.2.5B) such that θ between σ_{h1} and the crosscut direction ranges from 30^o to 40^o, there was no reported roof instability under the stream. It must be emphasized, however, that this method may only be beneficial for certain cutting sequences, for instance the right-handed longwalls in the Pittsburgh seam (Hasenfus and Su, 2006).

During longwall retreat as the face advances to pass a pillar, the horizontal stress abutment in the headgate increases on the inby side and reduces on the outby side of a crosscut (Fig. 6.2.6) (Thomas and Wagner, 2006). The horizontal stress will be relieved on the headgate when the face retreats outby of the crosscut. This is **stress pinching**.

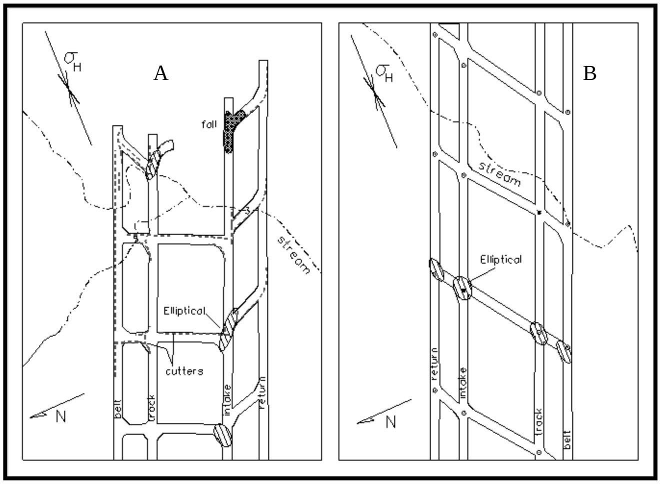


Fig. 6.2.5 Crosscut orientation of two 4-entry gateroad development (Hasenfus and Su, 2006)

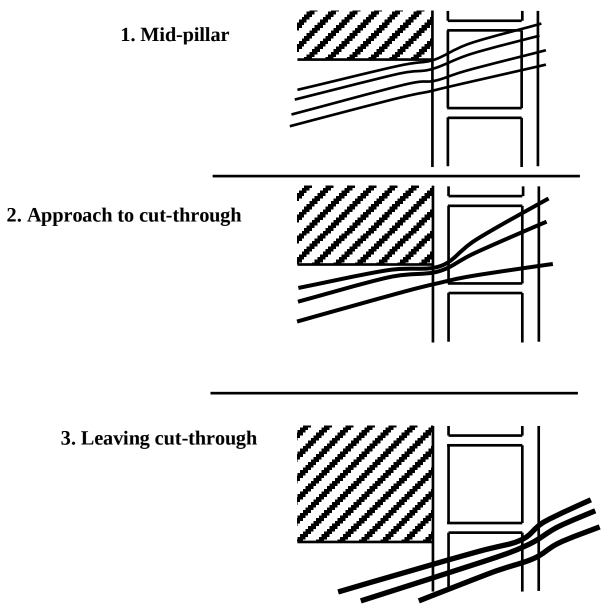


Fig. 6.2.6 Stress pinching on the headgate (Thomas and Wagner, 2006)

6.2.2 Computer Modeling

The effect of orientation of entry and longwall panel layout has been studied extensively in the past decade (HJ Chen and Peng, 1998, 1999 and 2000; Gadde and Peng, 2004; Su and Hasenfus, 1995; Y. Wang and Peng, 1996; Y. Wang and Stankus, 1998). In terms of high horizontal stress, the complete set of factors affecting stress distribution around the entry/crosscut include magnitude and orientation, θ, of the major principal stress; ratio of major principal stress to vertical stress *(*σ_{h1}/σ_v*;)* and ratio of major to minor principal stresses *(*σ_{h1}/σ_{h2}*.)*.

1. Effect of Orientation, θ

Most modeling studies only involved the orientation effect, and their results agreed that when the angle θ is less than 40°- 45°, entry stability is good, but crosscut stability is bad; when θ is larger than 45°, entry stability is bad, but crosscut is good, assuming the entry and crosscut are perpendicular to each other.

Since entry stability problems are not restricted to the development face area, evaluation of the effects of entry orientation must include as many locations of the development layout as possible in order to get a complete picture of the effect of σ_{h1} orientation. In addition to the face area, Gadde and Peng (2004), using the Hoek-Brown criterion, evaluated the stress distributions for cross sections one entry-width depth into the roof and ribs for an area within 100 ft (30.5 m) outby the faces, plus an intersection. They found that near the face, the stresses concentrate on the side where σ_{h1} passes through the solid coal. The stress concentrations extend to about 5-10 ft (1.5-3 m) on either side of the face, after which the asymmetry is reduced. Considering the different distribution patterns of the derived safety factors for different strata and cross sections at various distances from the face, Fig. 6.2.7 shows the effect of σ_{h1} orientation on entry/crosscut stability; $\theta \leq \pm 30°$, between 30° and 60°, and between 60° and 90° are highly favorable, moderately favorable, and unfavorable, respectively.

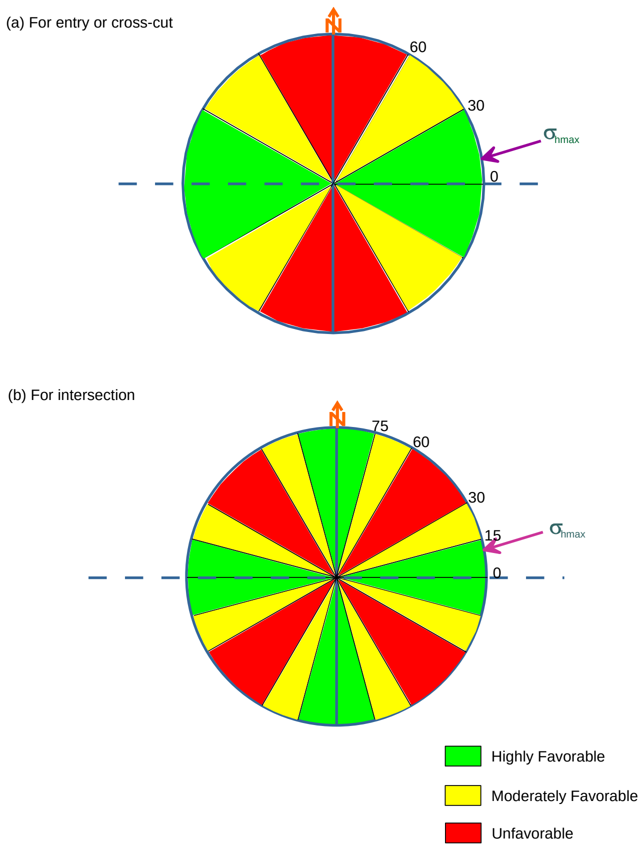


Fig. 6.2.7 Layout orientations and associated ground conditions with respect to σ_{h1} for entry/crosscut (upper) and intersections (lower) (Gadde and Peng, 2004)

When $k = \sigma_{h1}/\sigma_v$ (i.e., ratio of major principal horizontal stress to vertical stress) is greater than one, improvement of the stress field at the face area by changing the orientation is less than 10 %. Conversely, when k is less than one, the stress field improves 236 % for the entry. Therefore, orientation effect applies both to low and high horizontal stress fields.

2. Effect of Biaxial Horizontal Stresses

The ratio of measured major to minor principal horizontal stresses ($l = \sigma_{h1}/\sigma_{h2}$) varies from 1 to 4 (Fig. 2.7.7). According to Gadde and Peng (2004), when $k = \sigma_{h1}/\sigma_v$ is less than one; the effect of l is more noticeable. But when k is greater than one, l has little influence on roof stability. The change of safety factor in the roof and ribs is a function of k, θ, and the location in the roof and distance outby the face. In general roof stability decreases with increasing l for a constant k.

6.2.3 Methods of Relieving Horizontal Stress Abutments

Analysis of Figs. 6.2.3 - 6.2.6 indicates that the effect of horizontal stress abutments can be reduced by mine plan layout and mining (cutting) sequencing.

1. Sacrificial Entry, Pillar Width, and Zone of Influence

Operational experience showed that in certain areas of high horizontal stress, the first entry driven into the virgin stress field tends to experience roof damage, while the adjacent entries driven subsequently encountered satisfactory ground conditions. On a larger scale, the first longwall or room-and-pillar panel in a virgin reserve is subjected to higher horizontal stress effects than the subsequent panels. This indicates horizontal stress can only be fully transmitted through intact rock. Roof falls, roof softening, fractured ground, and gobs reduce the horizontal stress, or **stress shadowing**. Sacrificial entries, caving chambers, and roof and/or floor slotting have been employed for this purpose. "Sacrificial" means the first entry driven in the virgin stress field suffers roof damage, relieving the stress on the subsequent entries.

Severe cutter roof falls occurred along the whole length of the belt entry of a three-entry longwall development in northern West Virginia (Aggson and Mouyard, 1988). So the decision was to drive the 2nd (middle) entry in a high arched shape to relieve the horizontal stress on the 1st (belt) entry. The arched entry was 15 ft (4.6 m) high and driven 60 ft (18.3 m) ahead of both the 1st and 3rd entries. The roof was supported by yieldable arches such that the roof would continue to fall to an ultimate height of about 25 ft (7.6 m). Stress measurements indicated that the zone of stress relief extended at least 80 ft (24.4 m) from the arched entry (Fig. 6.2.8). The mine was about 600 ft (182.9 m) deep. Entries/crosscuts were 18 ft (5.9 m) wide, and the two rows of chain pillars were both 30 ft (9.1 m) wide and arranged in a staggered manner. This agreed with Australian experience that meaningful stress relief can only be obtained when the pillar between the sacrificial entry and the entry to be relieved is reduced to 26.3-29.5 ft (8-9 m) (Matthews et al., 1992). However, numerical analysis showed that in order to produce such a large relief zone, bedding plane slippage must have occurred (Ahola et al., 1991; Ahola and Kripakov, 1987). In fact, a small amount of slip between the immediate roof bedding layers into the caved entry decreases the maximum shear stress significantly more than the arched entry alone. It must be noted that with the current practice of mining operations in U.S. coal mines, this approach is time consuming and expensive to implement.

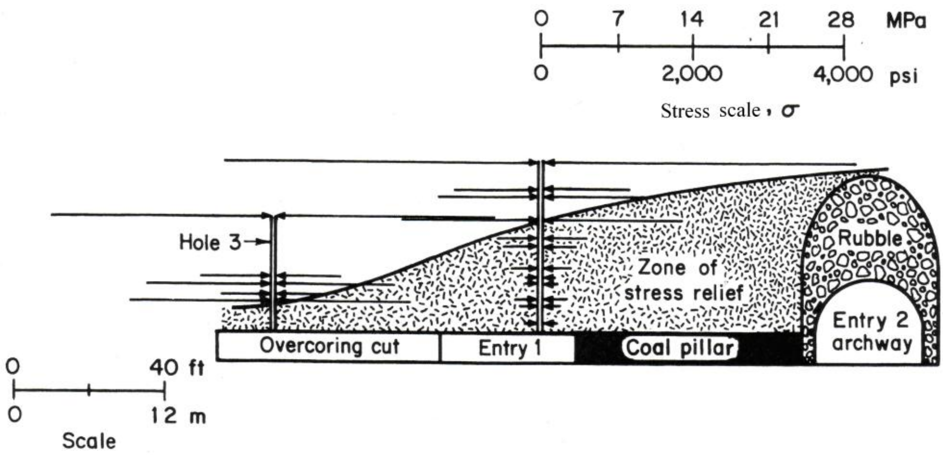


Fig. 6.2.8 Stress relief created by an arched entry (Aggson, 1988; Aggson and Mouyard, 1988)

Since the horizontal stress is transmitted through intact rock strata, the total chain pillar width in the gateroads is a critical factor in governing the effect of mined-out gobs in longwall stress shadowing. Wider pillars will decrease the effectiveness of stress shadowing. Su et al., (2003) monitored the three-dimensional roof stress at the headgate adjacent to the pillar-side ribs with three different headgate-side pillars, i.e., 100 ft (30.5 m), 80 ft (24.4 m), and 60 ft (18.3 m) centers (Fig. 6.2.9). The longwall panels were oriented 31^o to the east-west major principal horizontal stress. In the 3-Right headgate where the 100 ft (30.5 m) centers pillars were used, the east-west horizontal stress concentration in the headgate roof was detected to increase rapidly when the face reached to within 130 ft (39.6 m) inby. The stress meter was destroyed when the face reached to within 30 ft (9.1 m) of it, indicating potential roof instability ahead of the face. In the 4-Right headgate where the 60 ft (18.3 m) centers headgate-side pillars were employed, the east-west horizontal stress concentration in the roof was insignificant before the face passed the stress meter. The roof stress changes for the 80 ft (24.4 m) centers chain pillars fall between those of 100 ft (30.5 m) and 60 ft (18.3 m). Therefore, the 60 ft (18.3 m) pillars served to reduce the east-west horizontal stress concentration of the headgate roof ahead of the face of the right-handed longwalls, resulting in a stable headgate T-junction.

In a four-entry yield-abutment-yield gateroad development system when the gateroad is driven perpendicular to an extremely large σ_{h1}, the No.1 (belt) entry driven in the virgin ground ahead of the other three entries always had cutters on the solid side. When both the 1^{st} and 4^{th} were driven ahead of others, cutters occurred in both entries (Khair, 1992).

Australian experience showed that the 2^{nd} entry driven within 82 ft (25 m) of the 1^{st} entry, which had suffered roof deformation and created a stress-relieved zone, exhibited significantly improved stability (Fig. 6.2.10) (Matthews et al., 1992)

Similar experience was reported in the United Kingdom using a sacrificial entry, 15.5 ft (4.7 m) wide, to develop a stable set-up room, 20.3 ft (6.2 m) wide, with a pillar 49.2 ft (15 m) wide between them (Cassie and McLennan, 1997). The sacrificial entries were driven before the respective set-up rooms. Fig. 6.2.11 shows the roof movement in terms of height of softening and continuing movement with time. In comparison, the sacrificial entries have suffered a considerable amount of roof displacement, while the set-up rooms experience only minor roof displacement.

Using a physical scale model simulation, Goharui et al., (1992) showed that under a predominant horizontal stress field, the pillar width-to-height ratio does not affect the stability of the pillars. Consequently mine design under such conditions should aim to achieve minimum roof and floor failures of openings.

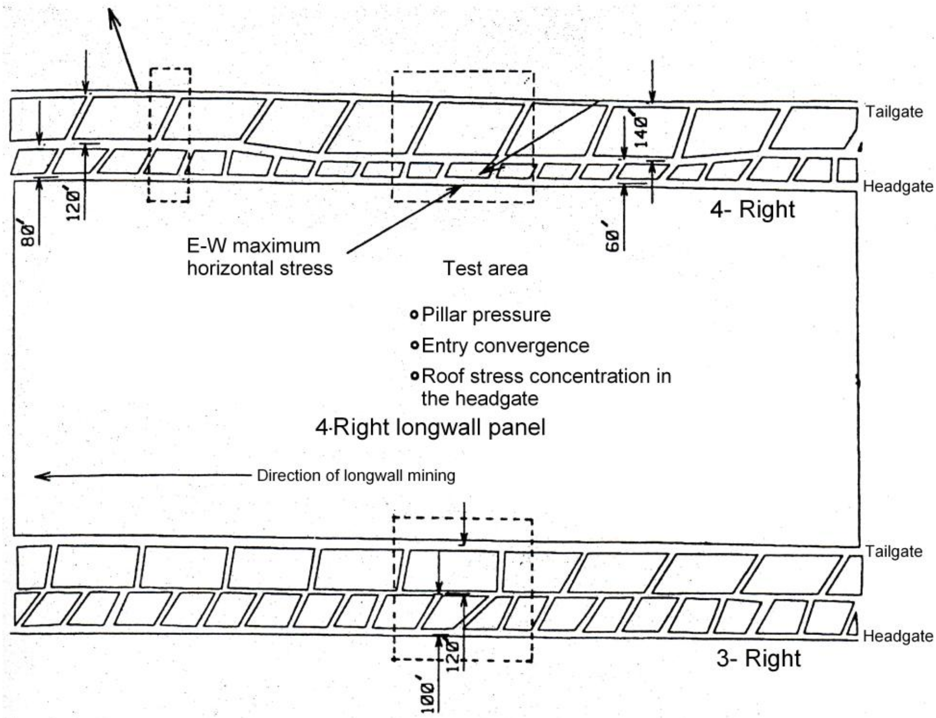


Fig. 6.2.9 Test areas for the effect of 100 ft (30.4 m), 80 ft (24.4 m), and 60 ft (18.3 m) headgate-side chain pillars on horizontal stress transfer (Su et al., 2003)

2. Longwall Sequencing

There are two ways to arrange the mining sequence in longwall mining to utilize the benefits of stress shadowing (Hasenfus and Su, 2006): (1) sequential development of panels around a set of mains to maintain a constant shadow for the longwall face headgate area, and (2) development of critical sections in the previously-created longwall gob shadow. The best headgate roof condition during longwall retreat can be achieved if the longwall panel mining sequence and retreat direction shown in Fig. 6.2.12 (H J.Chen et al., 1998; Y.Wang and Peng, 1996) is employed. Among all the development workings in longwall mining, the gate entries have the longest linear footage per panel to maintain. So they are the most difficult ones to control during longwall retreat. Therefore, longwall gate entries should always be designed with a small angle to the major principal horizontal stress to minimize the probability of failure on development. Most importantly, both the longwall panel mining sequence and retreat direction should be designed such that the newly formed gob relaxes the major principal horizontal stress concentration in the outby headgate entry roof during longwall retreat.

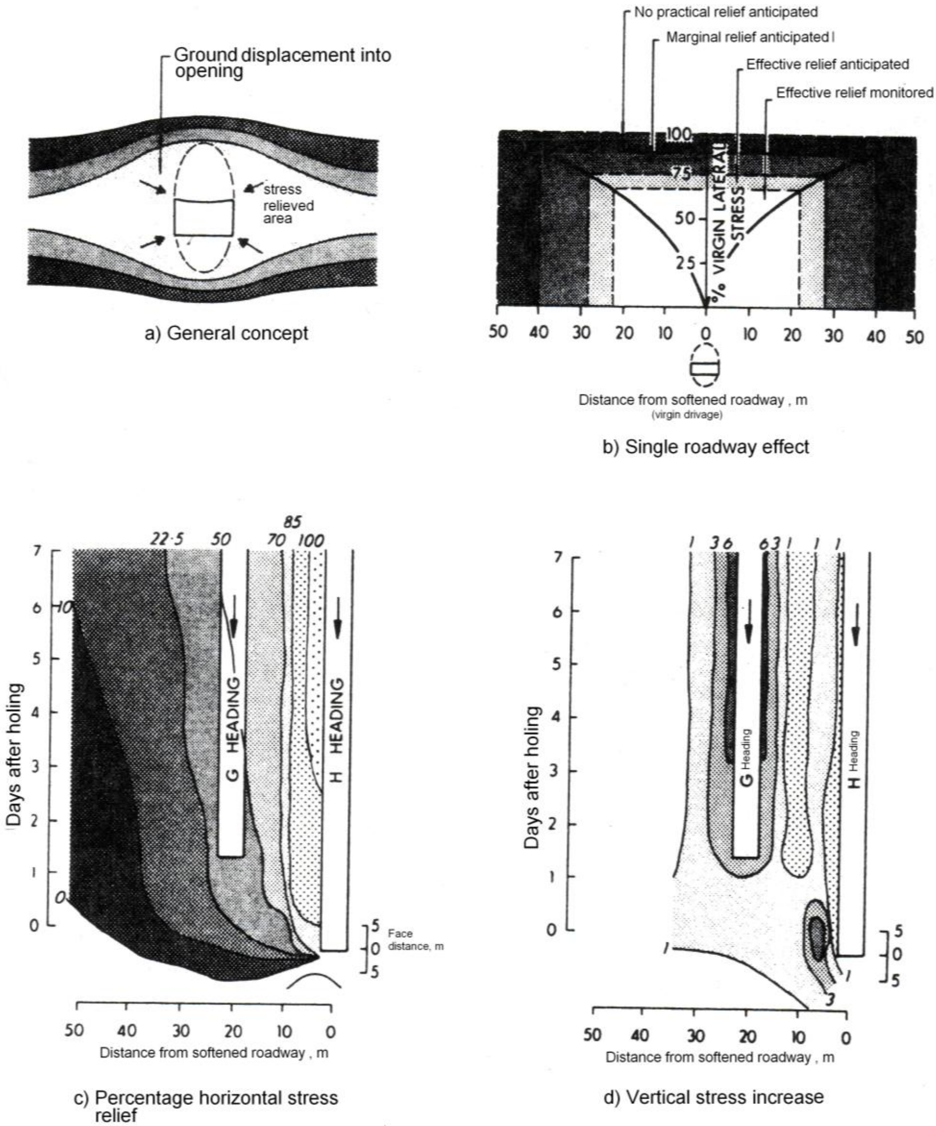


Fig. 6.2.10 Development of sacrificial entry for headgate entry (Matthews et al., 1992)

3. Advance and Relief Method

The advance and relief method has also been used to relieve the high horizontal stress effect (Chase et al., 1999, Dolinar et al., 2000). This method involves the extraction of one or more rows of pillars or a sacrificial entry on one side of the panel or entry during development. Fig. 6.2.13 shows an example, where the panel was developed by the continuous haulage method (see Fig. 1.3.7 on p. 9) at 100^o to σ_{h1}, a direction most damaging to the entries. In fact, roof falls up to 2,000 ft (609.6 m) long and 30-35 ft (9.1-10.7 m) high occurred on the entries. During panel development, pillaring was conducted on the right side of the panel, 100-120 ft (30.5-36.6 m) wide. Due to roof caving of the pillaring section, a stress reduction of 800-1,200 psi (3.4-8.3 MPa) was obtained at a distance 120 ft (m) from the cave, which represented a reduction of up to 50 % of the maximum principal horizontal stress and allowed for retreat mining in the stress relief section with no roof falls or floor heave. The width of the stress relief zone is 250-500 ft (76.2-152.4 m) or 7-14 times the caving height of 35-37 ft (10.7-11.3 m) of the pillared section.

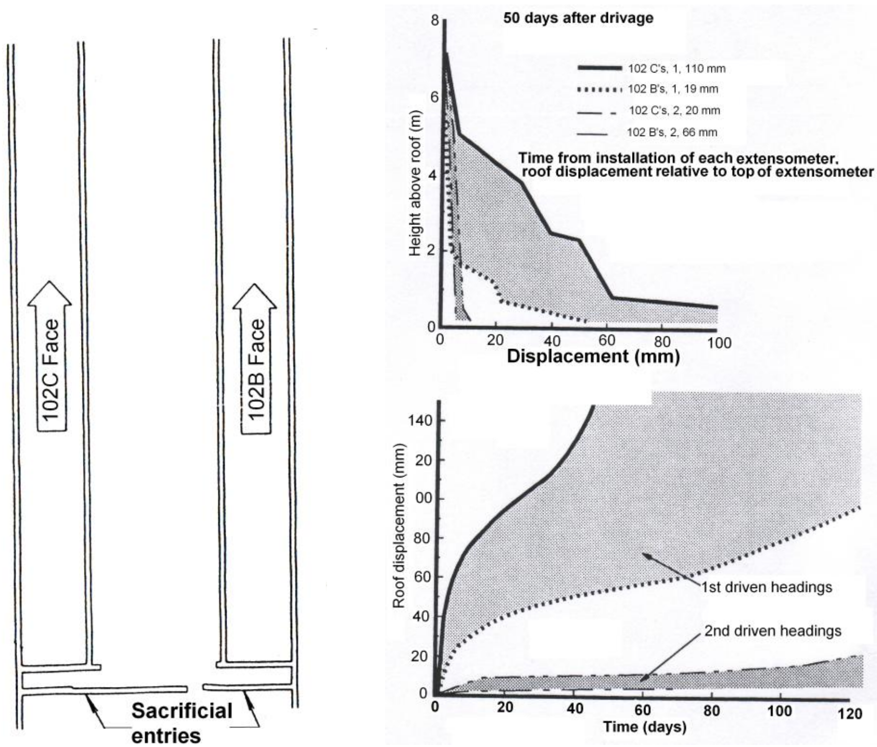


Fig. 6.2.11 Development of sacrificial entries for set-up rooms (Cassie and McLennan, 1997)

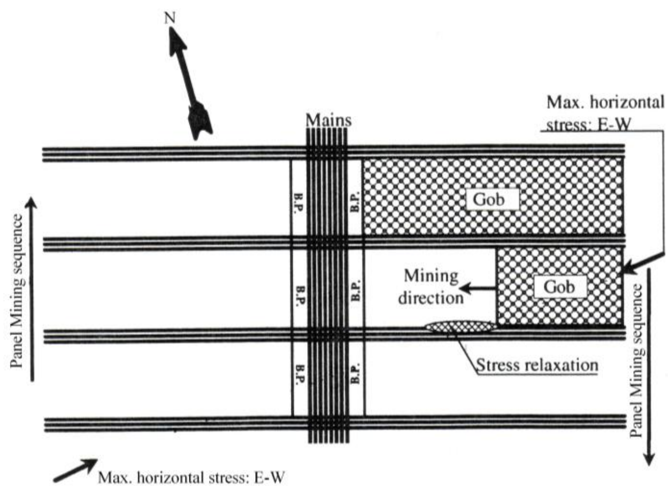


Fig. 6.2.12 Horizontal stress relaxation over the outby headgate during longwall retreat (HJ Chen et al., 1998)

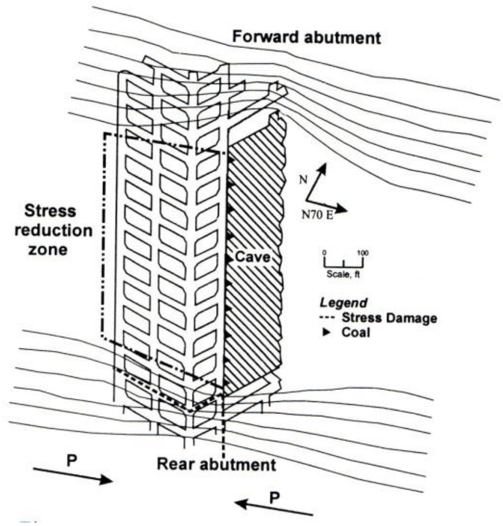


Fig. 6.2.13 Advance and relief method (Dolinar et al., 2000)

Numerical modeling analysis (Maleki et al., 2003a) showed that because of cave geometry in the advancing panel, horizontal stress concentrations occur near the cave line both in front of the face and to the sides. The horizontal stress concentration reaches 1.7 times the far-field, in-situ stress ahead of the face. This requires additional supports. In the next advancing panel located within the shadow zone of the gob, horizontal stresses are significantly reduced in the roof. The width of the relief zone depends on caving height, rock mass properties and panel layout.

6.2.4 Roof Falls and Floor Heaves

In recent years, roof falls tend to be attributed to high horizontal stresses (Keim and Miller, 1999; Mark et al., 2004). Most were justifiable, but there were many cases where roof falls could not be caused by high horizontal stresses (Peng, 1999; van der Merwe, 2000). It must be emphasized that rock failure in general is due to the fact that the stress applied on it exceeds its strength. If the rock strength is low, even low stress will cause it to fail.

Keim and Miller (1999) reported that the gateroad entries and crosscuts were oriented at N35^{o}E and N55^{o}W, respectively, that among the 183 roof falls recorded in a northern West Virginia longwall mine, 99 were oriented at N35^{o}E, 54 were oriented N55^{o}W, and the orientation of all others could not be determined, and that the major principal horizontal stress was oriented east-west. Clearly, the entries were oriented in the least favorable direction, and the crosscuts were oriented at a moderately favorable angle when the major principal horizontal stress was along the east-west direction (see Fig. 6.2.7, p. 293).

Jeremic (1981) studied the effects of lateral tectonic stress on roof falls and floor heave at western Canadian mines. He found that:

1. When roadways are perpendicular to lateral tectonic stress,
   A. The roof failed in two ways: sliding along bedding planes in thinly laminated carbonaceous shale and siltstone, and shearing at a low angle or along small faults in thick bedded siltstone and sandstone (Norris, 1978).

B. The floor coal heaved and formed an anticline structure with inclined axis (Fig. 6.2.14). Floor heave is accelerated by the presence of lateral compression.

C. Rib extrusion was up to 4 in. (100 mm) deep immediately after development, and reached up to 5 ft (1.5 m) deep one year after development; the rate of rib extrusion coincided with floor heave and rate of roof separation

2. When roadways are parallel to lateral tectonic stress,

A. Deformation and roof failure are less severe. The stand-up time for carbonaceous shale and thinly laminated siltstone was a matter of hours, while that of sandstone was days or weeks.

B. The floor coal may heave like gentle anticlines, having concentric internal structure (Fig. 6.2.15) or displaced along joints (Fig. 6.2.16).

C. Rib deterioration was only half of that of roadways perpendicular to lateral stress.

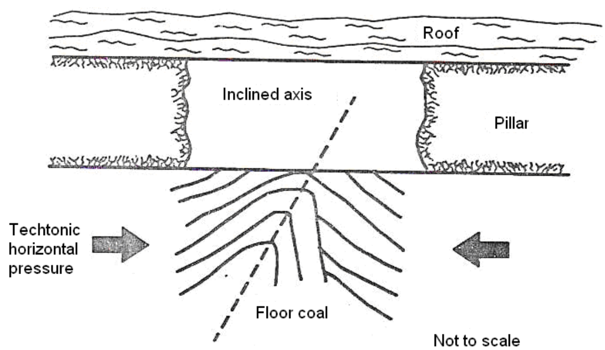


Fig. 6.2.14 Floor coal heave assumes the form of an anticlinal structure when roadways are perpendicular to lateral tectonic stress (modified from Jeremic, 1981)

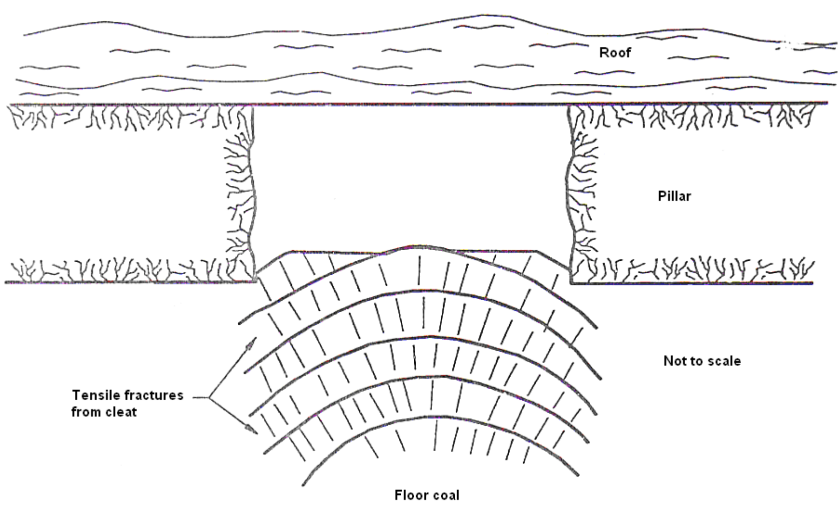


Fig. 6.2.15 Floor coal heave assumes the form of gentle concentric anticlines when roadways are parallel to lateral tectonic stress (modified from Jeremic, 1981)

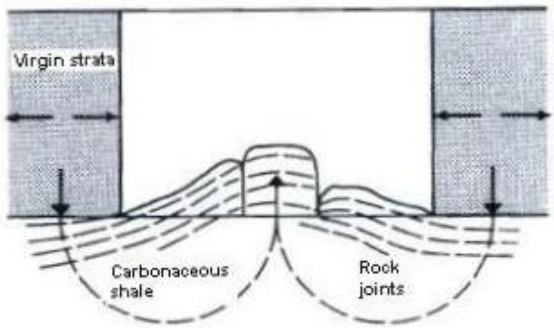


Fig. 6.2.16 Floor coals (or carbonaceous shale) heave along joints when roadways are parallel to lateral tectonic stress (modified from Jeremic, 1981)

3. Roadways oblique to lateral tectonic stress
   A. The roof behaved like a voussoir beam and remained stable even though roadways in this direction intersect small faults.
   B. Floor heave was minimum and, when it occurred, assumed the form of a chevron fold (Fig. 6.2.17).
   C. Roadway ribs were stable except at intersections where the corner ribs parallel to lateral tectonic stress sloughed badly, while the other corner ribs suffered only minor sloughing

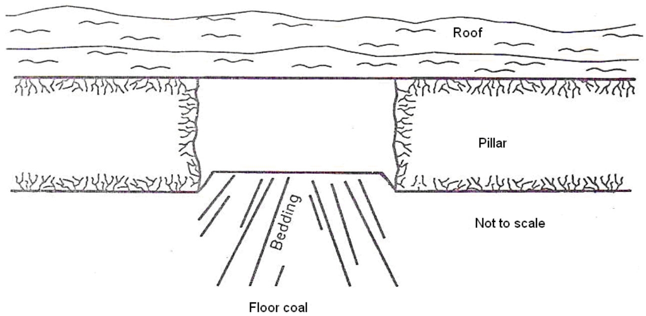


Fig. 6.2.17 Floor coal heave assumes a typical chevron fold when roadways are oblique to lateral tectonic stress (modified from Jeremic, 1981)

6.2.5 North-South Longwall Panels in Predominantly East-West Oriented Horizontal Stress Field

There is a generally accepted concept among the longwall operators that north-south panels will not work. This is why a great majority of U.S. longwall panels are laid out near or along the east-west direction. Can a north-south oriented panel or a panel oriented at high angles to the east-west direction be successfully mined? The answer is a positive "yes." There are plenty of examples to support the positive answer.

Figure 6.2.18 shows a longwall mine panel layout map in the central coalfield. Three stress measurements in the room-and-pillar workings (marked A in Fig. 6.2.18) were made and the average was (Ingram and Molinda, 1988):

Maximum principal horizontal stress, σ_1	= 1,300 – 1,700 psi
Minimum principal horizontal stress, σ_2	= 500 psi
Orientation of σ_1	= N74^{o}E and N85^{o}E
Depth of stress measurement	= 510 ft and 600 ft

Therefore, the maximum principal horizontal stress is twice or more than that of vertical stress due to overburden rock weight. Since it is highly biaxial, the magnitude of stress changes rapidly with panel orientation. According to Fig. 6.2.7, longwall panels (or the retreat mining direction) should be oriented within ± 30^o from the direction of σ_1 in order to avoid stress damage on the gateroad entries/crosscuts.

In Fig. 6.2.18 there are 10 longwall districts with the following panel orientations:

1. South of sandstone channel	1 district of north-south panels
	1 district of east-west panels
	1 district of N50^{o}E panels
	2 districts of N60^{o}W panels
2. North of sandstone channel	2 districts of N63^{o}W panels
	1 district of N23^{o}W panels
	1 district of very large district of east-west panels
3. West reserve	1 district of N50^{o}E panels

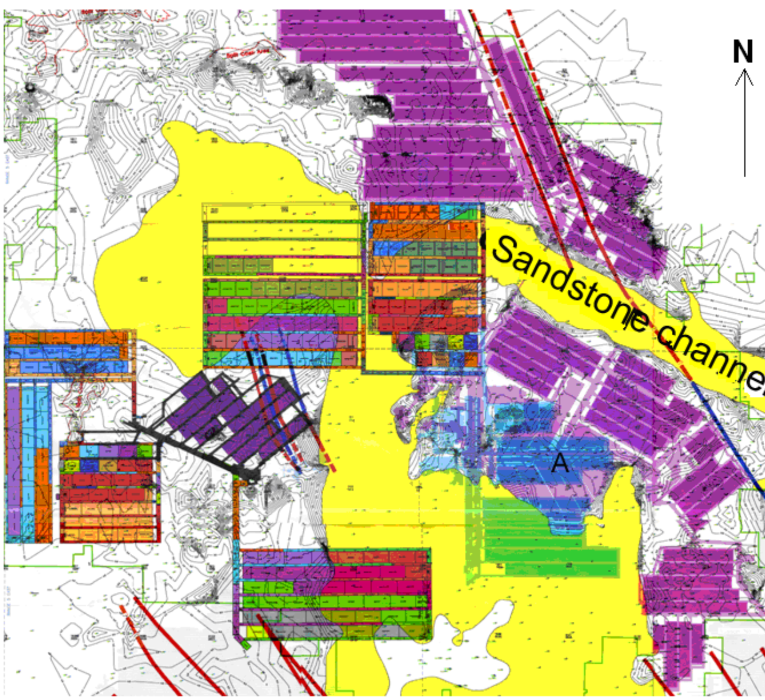


Fig. 6.2.18 Longwall panel layout in Herrin # 6 seam in central coalfield

Theoretically, this mine had mined two districts with the worst panel orientations, i.e., north-south and N23°W. And yet anecdotal evidence showed that there was no ground control problem with the N23°W panels. For the north-south panels, there were roof control problems in the headgate initially, but after the application of cable bolts, the problems disappeared. The N50°E panels were moderately favorable in terms of high horizontal stress, and yet the one that is south of the sandstone channel had no problem, while that in the West Reserve had considerable problems.

Another example for the Pittsburgh seam is shown in Fig. 6.2.19. Just like all other Pittsburgh seam longwalls, when the mine was initially designed, all longwalls were laid out in the east-west direction. This left a small plot of reserve that was shaped such that longwalls must be oriented in the north-west direction to make the panels sufficiently long enough for economical mining. Those panels were successfully mined without any incidents.

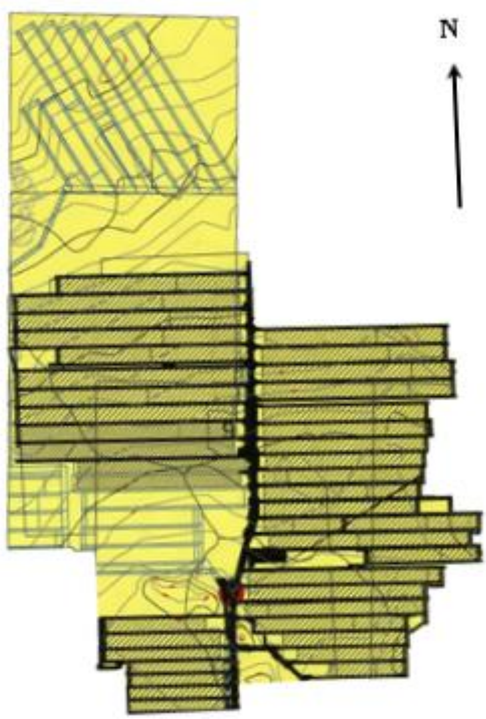


Fig. 6.2.19 Longwall panel layout in the Pittsburgh seam in the eastern coalfield

Therefore, high horizontal stress is not the only factor to be considered in mine design. Other factors, especially site-specific geology and the roof support system, must be evaluated simultaneously for a stable design (Peng, 1999; Van der Merwe, 2000).

6.3 CUTTER ROOF AND HIGH HORIZONTAL STRESSES

Underground observation of cutter roof formation in weak massive roof strata (Zhang et al., 2007b) showed that cutter formation is a progressive process. It begins as cracks on the surface of roof-rib corners and propagates upward until it encounters a competent stratum. The cracks then follow the bedding plane separation in the horizontal direction. Eventually the whole block below the bedding plane separation as a whole falls down, or it falls down gradually as the cracks propagate.

Researchers in general agree that high horizontal stresses are a major factors contributing to cutter formation. Hill and Bauer (1884) found that cutters initiated at the intersection of rib and clastic dikes and that horizontal stress orientation does not affect the formation of cutters that occurred adjacent to clastic dikes, but may influence the propagation direction of cutters depending on the ratio of σ_{h1}/σ_v (Kripakov, 1982). In minor biaxial stress fields, i.e., the difference between σ_{h1} and σ_{h2} is small; Ahola and Kripakov (1987) found that changes in a mine plan would not control cutter formation and that bedding plane sliding was a contributing factor to cutter roof formation. When the immediate roof strata were weak, highly laminated with poor bonding condition, and under extremely high horizontal stresses, Khair (1992) found that yield pillars were ineffective because relaxation of the roof strata due to yielding further deteriorated the laminated strata. Increasing bolt density and proper bolt pattern designed to increase friction resistance, and hence reduce lateral movement between laminations, were an effective way to control the cutters. Cutters can be controlled by cutter roof trusses (Seegmiller, 1990).

Bugden et al., (2001) found that roof falls in both unsupported and supported areas could be divided into two distinct categories: those associated with slips and those associated with high horizontal stress. The location and orientation of roof falls associated with high horizontal stress are connected with factors that raise stress levels across the entry to higher levels. Failure is by lateral shearing movement and vertical displacement of the roof prior to a roof fall.

Underground observation showed that cutters can occur at different locations with respect to the face and time after mining. Some have a consistent trend while others do not. When the progressive failure behavior is considered in computer modeling to study the effect of horizontal stress orientation, θ, on cutter roof formation, cutting sequence becomes extremely critical in determining the final distribution and severity of cutter failure. The effect of orientation, θ, on cutter formation, except when $\theta = 0^o$ and 90^o, may not follow a unique trend as stated in Section 6.2 above, and is dependent on geometric consideration such as cutting sequence and cutting depth. Fig. 6.3.1 shows the effect of $\theta = 0^o$, 30^o, 60^o and 90^o on cutter location and severity for a three-entry development system created in thirteen cuts of 20 ft (6.1 m) deep each (Gadde and Peng, 2005b). There are no clear trends in cutter location and severity, because cutter formation depends on many factors, including the magnitude and direction of major and minor principal horizontal stresses; strength of the roof strata and cutting sequence, especially the location of the face in a cut with respect to a future intersection near that area; the direction in which crosscuts are turned with respect to the direction of major and minor principal horizontal stresses, pillar size; and the number of entries. Therefore, a case by case study is perhaps the best approach to determine the underlying causes. The strain-softening modeling with a systematic implementation of cutting sequence in computer modeling by Gadde and Peng, (2005a) provides some insights into the reasons for the inconsistent spatial distribution of cutters.

For the three-entry longwall gateroad development system, the results of numerical analysis using the Von Mises failure criteria showed that changing the angle between the major principal horizontal stress direction and/or entry direction can only change the cutter location but cannot eliminate the cutter roof if the roof is weak (Peng and Wang, 1996). In other words, where a cutter roof initiates and how it propagates depend on the combined effects of roof strength and the angle of stress application with respect to the entry. For the same horizontal stress condition, the roof cutter may be initiated and propagated in different ways if the strength of the roof material is different. In addition, stress concentration at the outby intersection corner is always the largest.

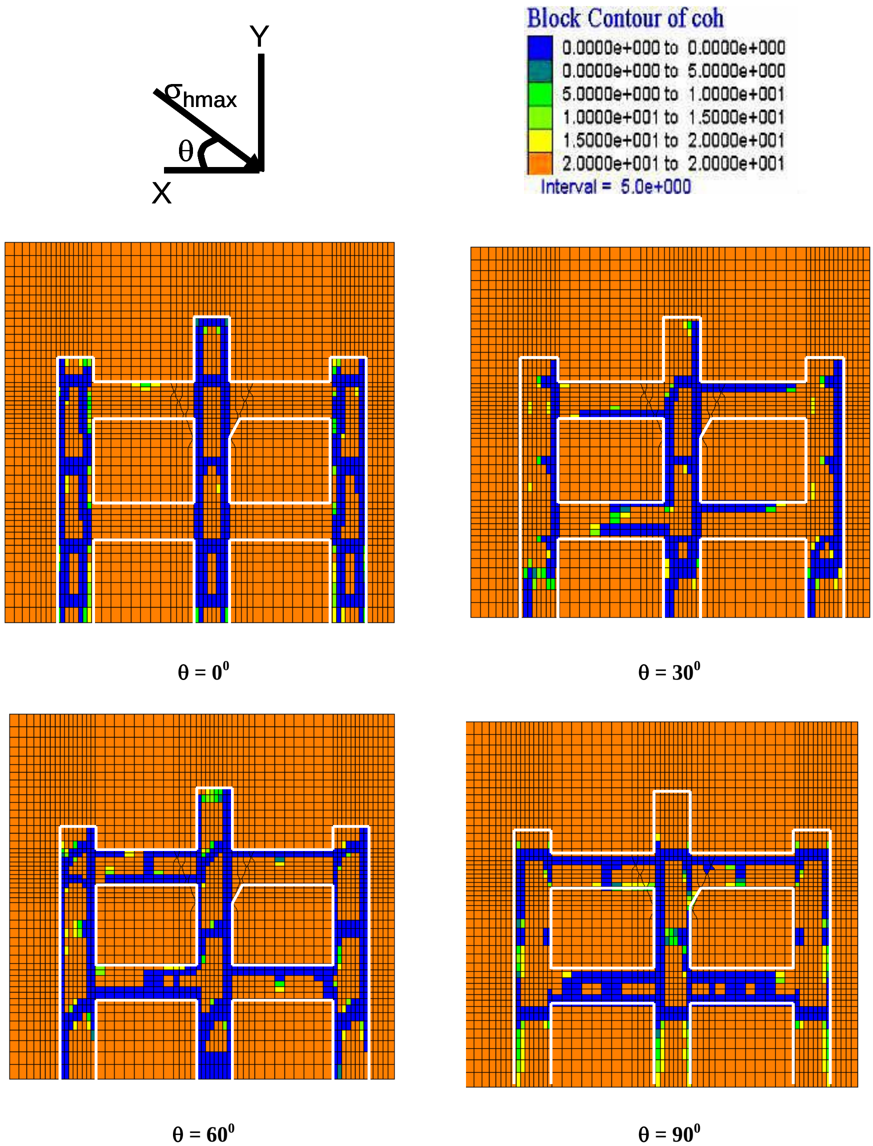


Fig. 6.3.1 The effect of θ = 0°, 30°, 60°, and 90° on cutter location and severity (Gadde and Peng, 2005b)

6.4 EFFECTS OF TOPOGRAPHY UNDER HIGH HORIZONTAL STRESS

It is well known that the roofs under stream valleys are frequently weak and difficult to control. Roof falls occurred more frequently under valley bottoms than mountain ridges (Fig. 6.4.1).

On many abandoned mine maps, it is not difficult to find that a strip of coal under and adjacent to streams was left unmined due to bad roof condition. A study of roof control problems under a stream valley showed that strata under the valleys are of poor quality due to compression failure (Su et al., 2002b). Bedding plane faults and thrust faults are abundant in these strata, and their axes conform to that of the valley bottoms (Molinda et al., 1991).

It is believed that V-notch valleys concentrate stresses at their apices, thereby posing a greater hazard to mining. Flat-bottomed bowl-shaped valleys on the other hand are stress-relieved due to rebound resulting from overburden removal (Fig. 6.4.2) and subsequent decay of the rock mass quality (Hill, 1988). Unloading reduces the vertical stress, but the horizontal stress remains. Thus, the most likely site of unstable roof is under the flat-bottomed bowl-shaped valley floor, and the least likely site for unstable roof is beneath the top of the adjacent valley wall. (Molinda et al., 1991). Frequency of roof falls is much higher under the half-basin-shaped valley end (Stankus and Wang, 1999; Kuhnhein and Ramer, 2004). In V-notched valleys, the sandstone strata on the valley bottom tend to buckle up and heave, whereas those on the flat-bottomed valleys would not.

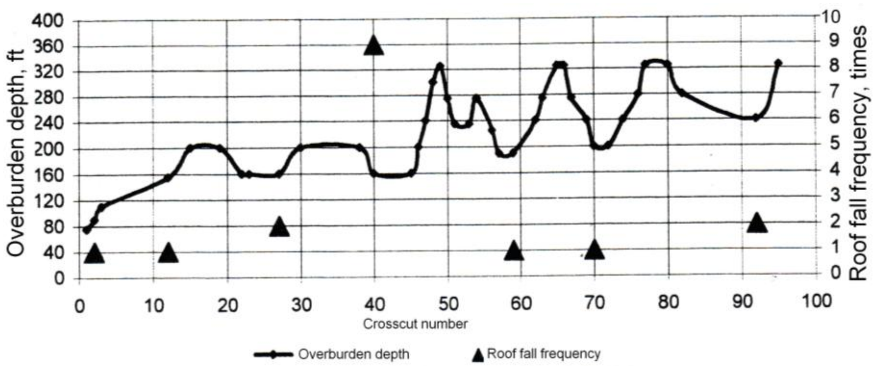


Fig. 6.4.1 Roof fall frequency versus topography change (Stankus and Wang, 1999)

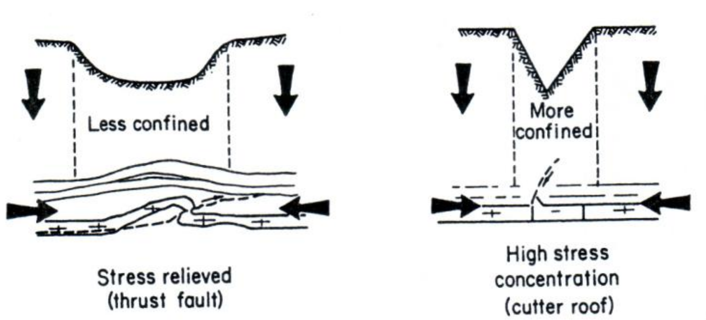


Fig. 6.4.2 Conceptual drawings showing the effect of valley shape (Molinda et al., 1991)

Stress measurements indicated that the ratio of major principal horizontal stress to vertical stress beneath the valley bottom is 2.5-3.6 times that under the valley walls. Therefore, stress relief, up to 40 % of the virgin in-situ horizontal stress, has occurred beneath the valley wall, because the measured local major principal horizontal stress is oriented to be perpendicular to the axis of the stream valley, causing the bedding plane faulting, the axis of which is parallel to the valley trend (Molinda et al., 1991).

Numerical analysis comparing two different configurations of valley bottoms (Fig. 6.4.3A) shows that the major horizontal stress at the valley bottom is larger than under the valley walls and that its magnitude increases with increasing depth. At the 50 ft (15.2 m) depth level, horizontal stress drops under broader valley. It does not drop under the narrower valley (Fig. 6.4.3B). However, at the 300 ft (91.5 m) depth level, horizontal stress under both types of valley configurations is the same (Fig. 6.4.3C) and increases toward the valley bottom (Molinda et al., 1991). Therefore, at shallower depths, horizontal stress is relieved under the broader valley bottoms. It must be emphasized that the horizontal stress profile under the valley bottom varies with valley configuration, and trends other than those stated above may exist (Stankus and Wang, 1999). Therefore, for more precise estimation of horizontal stress profiles, site specific modeling is recommended.

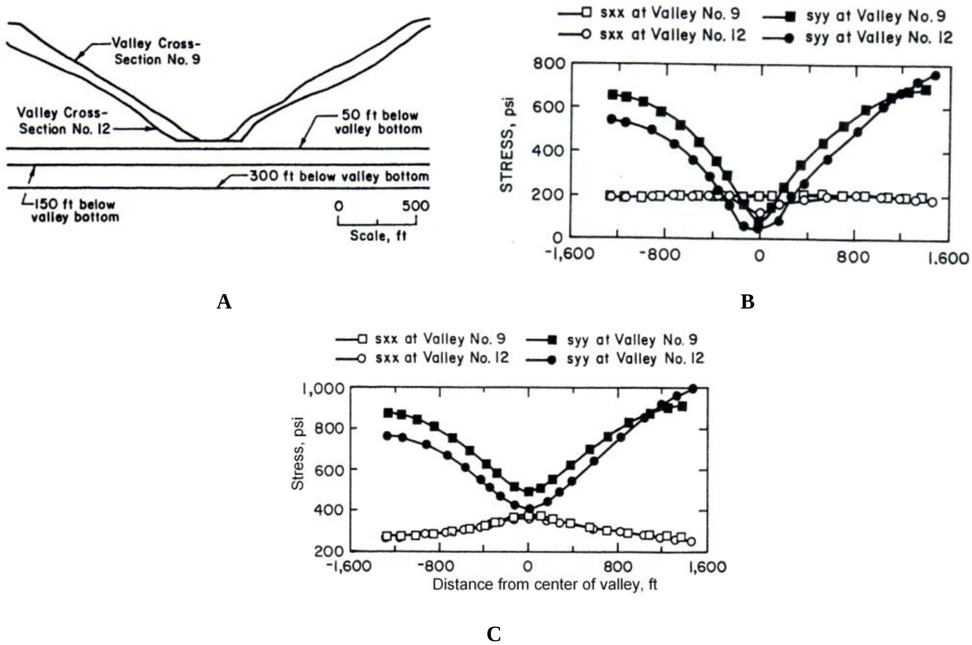


Fig. 6.4.3 Numerical analysis comparing horizontal stress profiles (B, 50 ft and C, 300 ft deep) under two different valley configurations (Molinda et al., 1991)

6.5 INTERSECTIONS OF ENTRIES AND CROSSCUTS UNDER HIGH HORIZONTAL STRESS

Statistics show that for roof falls without injuries, the entry intersection is the single most fall-prone area. On a per linear footage basis, intersections are 8-10 times more susceptible to failure than entries (Molinda et al., 1998). There are two types of intersections: three- and four-way intersections. Obviously, the four-way intersections are more prone to have ground control problems due to their larger spans. Intersection spans are represented by the diagonal distance between the opposite corners or the sum of the entry width plus the adjacent crosscut width at the mouth of the intersection.

According to Gadde and Peng (2004), the effect of the orientation of major principal horizontal stress, θ, on an intersection is different from its effect on an entry (Fig. 6.2.7). If an entry and crosscut are developed at right angles to each other, then for the intersection, the best conditions are seen at $\theta = 0^o$ or 90^o, and the worst is at $\theta = 45^o$. Thus the pie charts presented in Fig. 6.2.7 for an intersection is symmetrical about the axis of $\theta = 45^o$, whereas that for an entry and crosscut, the chart is symmetrical about both the north-south and east-west axes.

High major principal horizontal stress along the east-west direction was responsible for numerous roof falls at intersections outby the faces in a coal mines in southern Illinois (Blevins, 1982; Hanna et al., 1986). The immediate roof of 60 ft (18.3 m) thick was thinly-laminated siltstone and shale. The laminations, 0.5-1.5 ft (0.15-0.46 m) thick, separate easily into individual layers. There were numerous slips, rolls, joints, clay intrusions, and other discontinuities. Joints are oriented at N80^{o}E and face cleats at S25^{o}E.

Typically, the intersection roof falls extended 0.5-1 ft (0.15-0.3 m) above the roof bolting horizon that ranges from 5 to 9 ft (1.5-2.7 m), regardless of bolt length, with one side of the fall cavity highly fractured and the opposite side smooth and blocky.

Instrumentation including measurements of in-situ stresses, bolt loads, and roof displacement was performed to determine the mechanisms of intersection failures (Hanna et al., 1986). The results showed that the failure mechanism followed the behavior of a clamped beam oriented diagonally across the intersection and parallel to the major principal horizontal stress. Failure was initiated by a nearly vertical shear zone due to the high horizontal stress. The shear failure then progressed upward as the intersection was developed. As shearing continued, the outby end of the beam became detached and behaved like a cantilevered beam. This process repeated until it intersected a weak or separated plane above the roof bolt (Fig. 6.5.1) and fell.

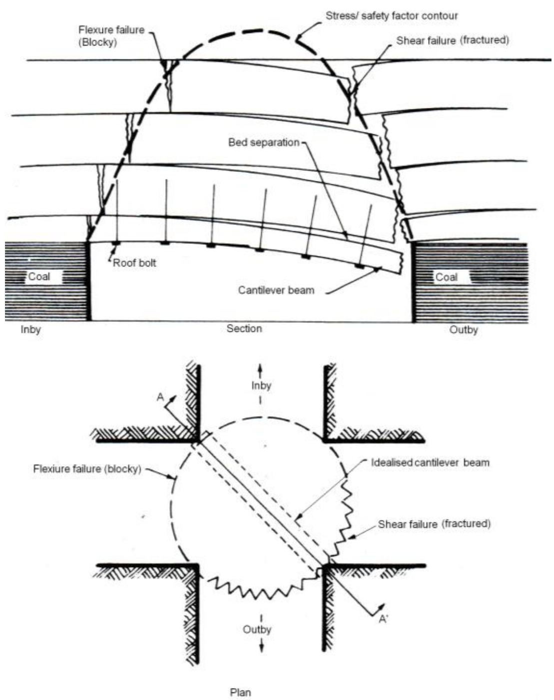


Fig. 6.5.1 Conceptual drawing showing the mechanism of intersection roof fall (Hanna et al., 1986)

6.6 GEOLOGICAL ANOMALIES AND HORIZONTAL STRESS

Geological anomalies are often the source of ground control problems, as described in Section 3.3 (p. 81). The presence of high horizontal stress will intensify the problems (Blevins and Dopp, 1985; Su et al., 2002b).

Several roof falls occurred between crosscuts 16 and 19 of the E3 development (Fig. 6.6.1) (Su et al., 2002b). All roof falls occurred during or soon after the face of the E2 panel immediately to the south had passed the respected fall areas, i.e., after the formation of the E2 panel gob. Extensive roof borehole drilling and borescoping revealed the presence of thick sandstone layers with abundant micaceous and shale streaks in a predominantly shale environment along the E3 and E4 development within the roof fall area. There were more fractured rocks under the valleys near crosscuts 10-12, 18-21, 30-31, and 41. Immediately east of crosscut 23, the strata dip rapidly into a huge syncline (Fig. 6.6.2). Numerical analysis showed that this anomalous geological environment intensified stress concentration on the sandstone unit and explained why there are so many cracks present in the massive sandstone unit upon development. When the E2 gob approached from the south and on the down-dip side, it provided stress-relief in the north-south direction, causing roof falls in the east-west-oriented E3 gateroads. The amount of stress-relief on the sandstone units 1,000 ft (304.5 m) away from the gob was approximately 10 % of their original stress. Prior to the E3 roof falls, all roof falls in this mine occurred at intersections and north-south oriented entries and crosscuts.

When entries were oriented in the north-south direction, roof falls occurred frequently in an Illinois coal mine (Blevins, 1982; Blevins and Dopp, 1985) because the measured maximum principal horizontal stress was oriented in the east-west direction. The entries/crosscuts were re-oriented to intersect the maximum principal horizontal stress at 45^o. Roof falls during mining were completely eliminated. Roof falls continued in the outby areas and were found to be associated with slickensides, clay intrusions, rolls, and rider coals.

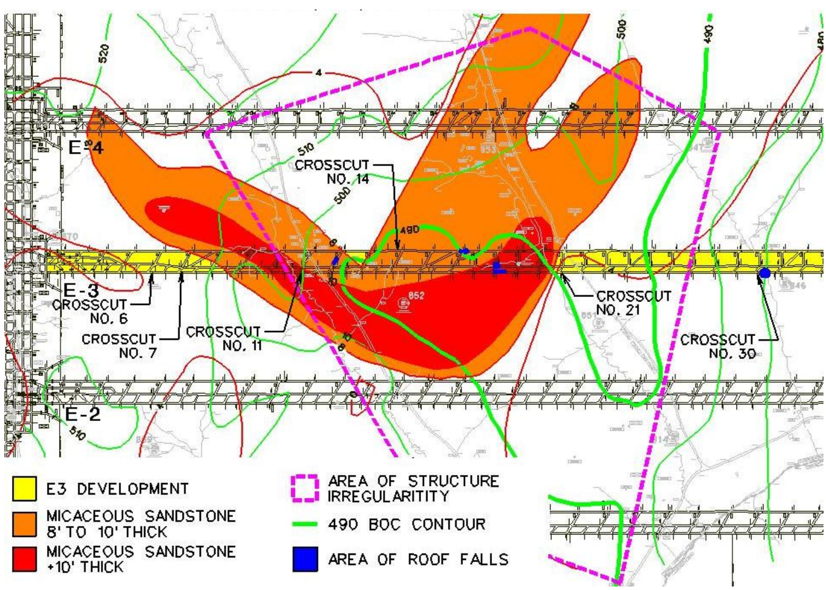


Fig. 6.6.1 Sandstone thickness and structure irregularity within E2, E3, and E4 longwall panels (Su et al., 2002)

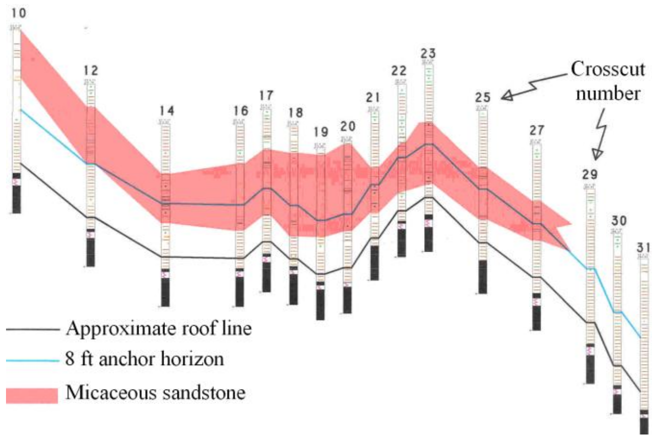


Fig. 6.6.2 E3 roof geology cross section (Su et al., 2002)

6.7 STRESS MAPPING

As stated in Section 2.7.4 (p. 67), in-situ stress measurements were performed using either the overcoring or hydraulic fracturing methods (Section 11.3.1, p. 512). These methods are difficult to perform, time consuming, and expensive. In addition, they require experience to interpret the data. Therefore, in-situ stress measurements are rarely done by coal mining companies at the mine level. Besides, the magnitude and direction of in-situ stresses often change with mine location, and therefore it is impractical to perform frequent in-situ stress measurements to obtain the precise magnitude and orientation. Therefore, other methods that are simple and easy to perform may be desirable. Underground stress mapping is one such method.

Faults and joints are of tectonic origin, except those faults due to sediment slump over ancient river banks. As such they are produced by certain in-situ stress systems following certain modes of failures. Assuming the intermediate principal stress, σ_2, is parallel to the strike of the fault, faults are single or conjugate shear fractures intersecting the major principal stress, σ_1 , at an angle, α

$$\alpha = 45^{o} - \frac{\theta}{2} \tag{6.7.1}$$

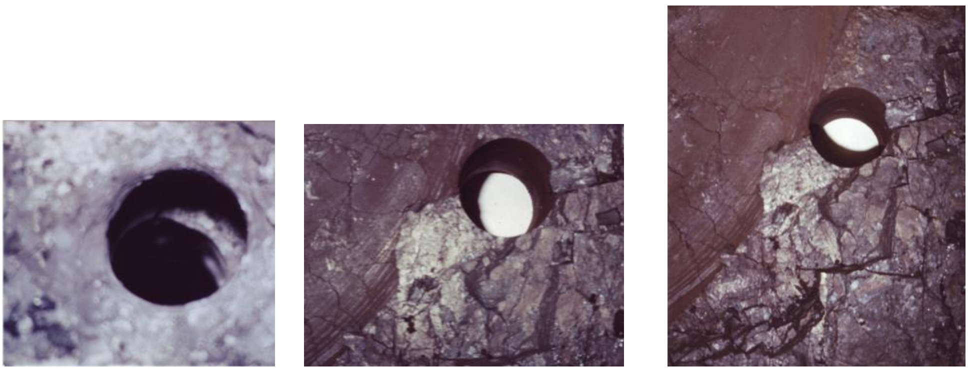
where θ is the angle of internal friction of the material. Therefore, by mapping the orientation of a fault plane, including strike and dip (see Fig. 3.3.8 on p. 87), the directions of all three principal stresses can be estimated. Table 6.7.1 shows the orientations of three principal stresses that generate the four types of faults shown in Fig. 3.3.9 (p. 88). If the strength of the rock mass is known, their magnitudes can also be estimated using certain failure criteria, for instance, the Mohr Coulomb criterion. For joint or joint sets, they are generated mainly by tensile stress perpendicular to it.

It is well-known that boreholes drilled in coal measured strata, especially around underground openings that are often blocked at different horizons at different times after drilling. Blockage occurs when adjacent strata exhibit differential lateral movement, or in most cases, one stratum move laterally against the remainder of the strata. So the original circular-shaped hole becomes elliptical of a progressive degree (Fig. 6.7.1). This is **hole occlusion.** The direction of the maximum offset of the moon-shaped occlusion is considered to be the direction of the major principal stress direction. For accurate measurements, the borehole lateral displacement sensor (BLDS) (Terrill and Lewis, 1996) should be used.

Table 6.7.1 Directions of principal stresses for four types of faults

	σ_1	σ_2	σ_3
Normal fault	Vertical	Horizontal, //	Horizontal, ⊥
Reverse fault	Horizontal, ⊥	Horizontal, //	Vertical
Strike-slip fault	Horizontal, //	Vertical	Horizontal, ⊥
Bedding-plane fault	Horizontal, //	Horizontal, //	Vertical

[1] // and ⊥ are parallel and perpendicular to the fault plane, respectively
[2] σ_1, σ_2 and σ_3 are major, intermediate, and minor principal stresses, respectively



A B C

Fig. 6.7.1 Borehole occlusion. B and C are the same hole at different times showing continuing movement

Hole occlusion may, and indeed often, occurs at various stratigraphic horizons in the same or adjacent holes. Peng (2007) mapped three hole occlusions within a pillar block. Their locations and maximum offsets were not consistent.

Other features employed for stress mapping include cutters, roof potting and roof falls, shear planes, striations, and rock flours (Blevins, 1982; Mucho and Mark, 1994). The major horizontal stress is assumed to be perpendicular to the direction of cutters, rock flours trend, and the long axes of roof potting and roof falls and parallel to shear planes and striations.

Stress-field orientation mapping and analysis (SOMA) has been widely used by structural geologists for stress mapping (Byington, 2004). In this method, open fractures in brittle material are due to simple shear on the σ_1-σ_3 plane, while closed fractures are on the σ_1-σ_2 plane. This occurs regardless of the timing, genesis, intensity, and frequency of the fracture. Therefore, by indentifying and quantifying open fractures in the mine roof, rib, or floor rock, it is possible to calculate the orientation of the stress field that affects the mine workings. Open fractures are mapped underground for features such as the mean fracture's strike, dip, strength type, semi-quantitative amount of carbonaceous filling and clay filling width of the opening, and the general geometric and temporal relationship. The fractures database is processed statistically using the equal-area, lower–hemisphere, and stereonet pole plot. Each pole represents one or more fracture planes with the same orientation, location, and fracture characteristics. The pole plots are contoured for pole clustering. As the open fractures share a common σ_1, they exhibit a common intersection point at σ_1 on the stereonet pole plots. Consequently by calculating the mean orientation for each of the three open fracture groups (1m, 2m, and 3m great circle arcs in Fig. 6.7.2), the common intersection point representing σ_1 is established as N80°E and dip 3°.

Finally, it must be emphasized that for quantitative analysis, stress mapping is no substitute for in-situ stress measurement because the mechanisms causing the selected factors or the principles used very often cannot be clearly defined. Or when mapping seems to show definable trends in one location, it does not necessarily mean it can be transferable to other locations. Therefore, stress mapping can only be considered as a first rough estimate at best.

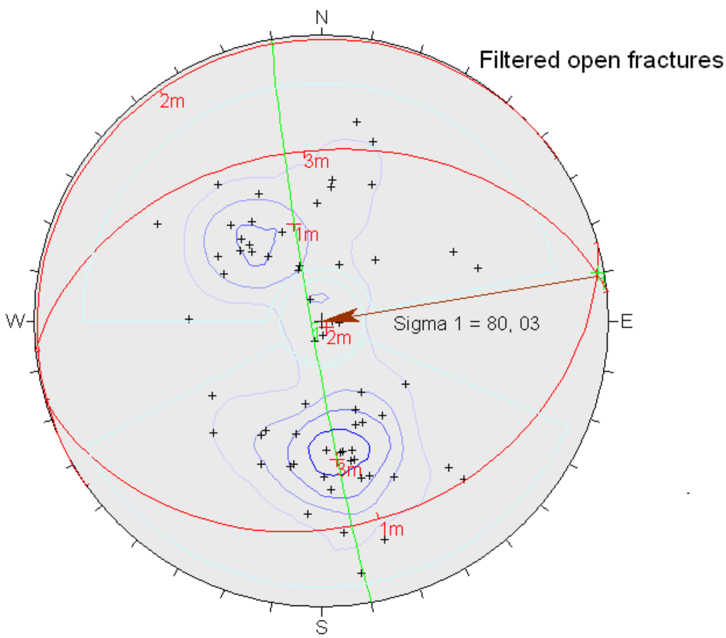


Fig. 6.7.2 Stereonet pole plot showing three mean intersecting fracture-set great circle arcs (1m, 2m, and 3m) (Byington, 2004)

6.8 HORIZONTAL STRESS AND ROOF SUPPORTS

In a high horizontal stress environment, in addition to mining plan described in Section 6.2.1 (p. 288), special roof supports alone, or in conjunction with the mining plan, have been used to deal with the ground control problems associated with high horizontal stresses (Blevins and Dopp, 1985; Dolinar et al., 1996; Guo and Stankus, 1997; Hasenfus and Su, 2006; Thomas and Wagner, 2006; Su et al., 2003).

In the past before the introduction of cable bolts, a roof bolting pattern consisting of 9-5-5-9 ft (2.7-1.5-1.5-2.7 m) long bolts in a row for a 16-ft (4.9 m) wide entry/crosscut and a row spacing of 4 ft (1.2 m) was used to cope with high horizontal stresses that consisted of σ_{h1} = 2,721 psi (18.8MPa) and σ_{h2} = 862 psi (5.9MPa) (Blevins and Dopp, 1985). The 5-ft (1.5 m) bolts were tensioned rebar bolts, ¾ in. (19.1 mm) in diameter and grade 75. The 9-ft (2.7 m) bolts were mechanical bolts, 7/8 in. (22.2 mm) in diameter, grade 75 and installed 2.5 ft (0.76 m) from the ribs. It successfully prevented roof falls during development, but roof falls continued to occur some distance outby the face.

In recent years, cable bolts have emerged and proven to be very effective for dealing with high horizontal stress environments for both longwall and room-and-pillar mining. Cable bolts, 0.6 or 0.7 in. (15.2 or 17.8 mm) in diameter, have high capacity 30-40 tons and are highly flexible, capable of sustaining large axial deformation (up to 5 in. or 127 mm) and lateral deformation (up to 2 in. or 50.8 mm) before breakage. Cable bolts are at least 8 ft (2.4 m) long and installed with a minimum of a 5 ft (1.5 m) long resin anchor with or without tension. They can be installed in much longer lengths, up to 24 ft (7.3 m) or more than the conventional steel bar. This feature alone makes it very effective to apply the suspension principle for reinforcing stress-induced soft roof, because under high horizontal stresses, the softened roof strata can reach very high above the roof line where the conventional steel bar bolts cannot be installed effectively. Furthermore, in a high horizontal stress environment, lateral strata movement along bedding planes occurs frequently, often in large magnitude, and often shears off the conventional steel bars, while cable bolts can resist much better. Some examples of successful cable support systems follow.

For the limestone/sandstone transition zone in the Pittsburgh seam, roof falls can reach 8 ft (2.4 m) high. For the 15.5 ft (4.7 m) wide entry, two rows of 12 ft (3.7 m), 0.6 in. (15.2 mm) cable bolts are used for stress zones 20 ft (6.1 m) inby and 12 ft (3.7 m) outby each right-handed headgate intersection, while three rows of 12 ft (3.7 m), 0.6 in. (15.2 mm) cable bolts are used for headgate intersections (Su et al., 2003).

The roof in a western Colorado coal mine consisted of stack rock overlain by another seam with 3-18 ft (0.9-5.5 m) thickness of interburden. The major and minor principal horizontal stresses were 2,175 psi (15 MPa) and 1,450 psi (10 MPa), respectively. Roof falls were influenced by the high horizontal stresses and ultra-close upper seam. For tailgate supplemental support, cable bolts, 16 ft (4.9 m) long and 0.6 in. (15.2 mm) in diameter were used. They were installed 4 bolts per row with 5 ft (1.5 m) row spacing. Each bolt was installed with a high-capacity bearing plate and monster mat. The tailgate was 18 ft (5.5 m) wide. Measurement showed that the cable bolts sustained successfully a maximum horizontal displacement of 1.5 ft (0.46 m) (Dolinar et al., 1996).

For stress pinching on the headgate (see Fig. 6.2.6), Thomas and Wagner (2006) cited a successful case of increasing cable density for the outby end of crosscuts where stress pinching occurred (Fig. 6.8.1). Around the pinch point, 3 x 9.8 ft (3 x 8 m) cable bolts every 3.3 ft (1 m) meter were used, while in the relief zone, 1 x 9.8 ft (1 x 8 m) cable bolts every 6.6 ft (2 m) were used.

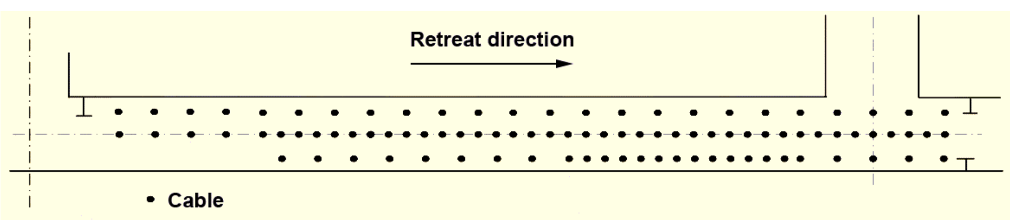


Fig. 6.8.1 Stress pinching and supplementary supports (Thomas and Wagner, 2006)

6.9 COMPLETE STRESS ANALYSIS AND APPLICATION OF HIGH HORIZONTAL STRESSES

As shown in Sections 6.2-6.6, the orientation, θ, of maximum principal horizontal stress, σ_{h1}, with respect to entry/crosscut and longwall retreating direction is very important, because it indicates how much stress will be induced on the strata surrounding the openings, and if these stresses, as compared to the strata strength, will cause failures in these strata. Consequently, it is very important to know the magnitude and orientation of the local in-situ stresses as accurately as possible. In this respect, in order for the principles to work, all of the methods described in this chapter, i.e., reorienting the direction of entry/crosscut development, panel orientation, and retreat direction, stress shadowing of certain openings or panels and change of cutting sequence, require precise determination of local in-situ stresses. Merely citing the trend of regional in-situ horizontal stress, as normally is done by most researchers and practitioners, may not be practical.

The principles discussed in Section 6.2 regarding horizontal stress abutments and stress shadowing are good for design guidelines only. Detailed design for roof supports for the gateroads, especially at the headgate T-junction and tailgate, must rely on detailed stress analysis of the whole mine structure on a case by case basis. Because as demonstrated by HJ.Chen (1999) and Morsy and Peng (2006) that under a fixed orientation of major principal horizontal stress, the state of stress in the roof of head- and tail-gates varies considerably with distance at inby and outby the head- and tail-gate T-junctions and thus may require a different degree of roof reinforcement.

Most papers discussed the horizontal stress abutments and stress shadowing in two-dimension on the coal seam level, which may not necessarily reflect the stress field on the roof and floor strata.