CHAPTER 8 MULTIPLE-SEAM MINING

8.1 INTRODUCTION

Multiple seam mining is practiced in varying degrees in every region of U.S. coalfields except southern Appalachia. Multiple-seam mining is most frequently found in central Appalachia where it is not uncommon to find up to 20 coal seams within 1,500 ft (457.3 m) of elevation, more than half of which are mineable.

Coal mining in the U.S. has entered an era when it is fairly uncommon to mine in virgin reserves without consideration of multiple-seam mining effects. In the past, due to issues with coal seam ownership (i.e., adjacent seams owned by different parties), availability, and economics, coal seams in multiple-seam conditions were mined without proper planning consideration for seam interaction. Research in the last three decades has raised awareness of the existence of and problems associated with multiple-seam mining, planning for multiple-seam mining has become an integrated part of modern mine design. With proper planning ground control issues associated with multiple-seam mining can be avoided, minimized, or on occasion, utilized beneficially.

8.2 SEQUENCE OF MULTIPLE-SEAM MINING

In multiple-seam mining, there are many possible sequences of mining different seams. In practice, however, ground control issues associated with two adjacent seams are the most frequently encountered problems in multiple-seam mining. Therefore, mining sequences refer mainly to two-seam mining in this chapter, unless otherwise stated.

There are five mining sequences of multiple-seam mining (Chekan and Listak, 1993; Haycocks and Zhou, 1990; Hladysz, 1985; Mark, 2007a; Hsiung and Peng, 1987a):

1. The upper seam is mined out before the lower seam – **undermining**.
2. The lower seam is mined out before the upper seam – **overmining**.
3. The upper and lower seams are mined simultaneously.
4. The upper seam is partially developed and mined first. Then the lower seam is mined under it. The opposite is also applicable.
5. A combination of any of the above.

Multiple-seam mining in the U.S. involved only undermining and overmining. Simultaneous mining of two-seam longwalls was attempted once in the 1980s without success (Hackett and Park, 1987; Peng and Chiang, 1984). Furthermore, any combination of the first three mining sequences has never been tried in the U.S. The fourth type was described by Lazer (1965).

As a result of interaction among various factors, each mining sequence produces certain types of ground control problems when two adjacent seams are mined. This is **seam interaction**. The intensity of the interaction decreases with an increase in the distance between the two adjacent seams. **Interactive distance** is the distance between two adjacent seams or interburden thickness beyond which seam interaction disappears.

According to Mark et al., (2007a), the failure rate of overmining development cases was three times as great as undermining development case; for undermining development, the failure rate was 10 % crossing the gob/solid boundaries, and 10-19 % for undermining isolated remnant pillars. The failure rates for overmining was 27 % crossing the gob/solid boundaries, and 41 % overmining the remnant pillars.

8.3 INTERACTION FACTORS

There are many factors that affect and determine the type and intensity of seam interaction in multiple-seam mining (Chekan and Listak, 1993; Ganguli et al., 1995; Haycocks and Zhou, 1990; Peng, 1986; Wu et al., 1987). These factors can be divided into two categories, geological and mining. Geological factors come with coal reserves and cannot be changed. Mining factors are those specified in the mine plan and are therefore controllable (Table 8.3.1).

Table 8.3.1 Seam interaction factors in multiple-seam mining (Chekan and Listak; 1993; Ganguli et al., 1995; Haycocks and Zhou, 1990; Peng, 1986; Wu et al., 1987)

Geological	Mining
Location of mine property	Sequence of mining*
Overburden thickness and rock type*	Mining method*
Upper seam thickness	Methods of support
Lower seam thickness	Mining layout and entry dimensions
Upper seam immediate roof and floor	Extraction percentage (both seams)
Lower seam immediate roof and floor	Relative location and orientation of upper and lower workings*
Interburden thickness and rock type*	
Interburden hardrock percentage*	Mining height
Number of layers in interburden*	Mining direction
Coefficient of friction between layers	Extraction ratio
Surface subsidence problems	Time factor*
Seam inclination	
Rock mechanics properties of coal	
Existence of ground water	
Geological anomalies	

* Critical factors

Obviously some factors are critical, while others are minor. Those critical factors are discussed in the following sections in more details.

8.3.1 Geological Factors

Among the 15 geological factors listed in Table 8.3.1, two are critical: overburden thickness and interburden characteristics.

1. Overburden Thickness

The weight of overburden is the source of ground pressure. The thicker the overburden, the higher the ground pressure, and everything being equal, the more intense the seam interaction will be.

2. Interburden Characteristics

Interburden characteristics include thickness, rock type, number of layers, and percentage of hard rock. Within the interactive distance, interburden thickness determines the intensity and types of seam interaction; the thicker the interburden, the less intense the seam interaction. The minimum distance or the interactive distance required for stability for over- or under-mining varies.

Interburden thickness is the most critical factor in determining the potential for seam interaction. Seam interaction has been found to have occurred when the two adjacent seams were separated by up to 850 ft (259.1 m), depending on mining sequence (Peng, 2007). Studies by several researchers in the past (Chekan et al.,1989; Chekan and Listak, 1993; Matetic et al., 1987a and 1987b), showed that seam interaction will occur particularly when the ratio of overburden-to-interburden thickness (OB/IB) exceeds 8:1 to 10:1 and the interburden is of shale composition and less than 110 ft (33.5 m) thick (Haycocks et al., 1982a). Recent case studies by Ellenberger et al., (2003) suggested that for both undermining and overmining, when the OB/IB ratio is less than 7, there will be little risk of adverse interaction. When the OB/IB ratio is above 16, there will be a possibility of extreme interaction. On the other hand, numerical model analysis by Zipf (2005b) showed that when OB/IB ratio is less than 5, interaction does not occur and that when OB/IB ratio is more than 50, there positively will be extreme interaction. The minimum interburden distance to avoid seam interaction is larger for shale strata than for a sandstone layer (Munsamy et al., 2004).

Strata in the interburden that have a high elastic modulus, such as sandstone and limestone are stiffer and tend to bridge. Consequently they tend to dampen stress transfer. Conversely, softer strata such as shale tend to bend more readily, transferring the load (Chekan, 1990; Chekan and Listak, 1993; Hill, 1995; Haycocks et al., 1982b). Therefore the interactive distance decreases with increasing percentage of hardrock, such as sandstone, in the interburden as shown in Fig. 8.3.1 (Haycocks and Karmis, 1983).

Haycocks and Zhou (1990) developed the following empirical equations for determining the interactive distance. It should be noted however, that those equations are independent of mine geometry (i.e., pillar and entry dimensions and layout patterns) and were derived from a rather limited data set and therefore may not represent all stable and/or unstable mining conditions (Haycocks et al., 1983), as demonstrated by case studies by Chekan et al., (1985, 1986a and 1986b).

A. Overmining

According to Haycocks and Zhou (1990), when the upper seam is mined long after the lower seam is mined, then,

$$H_i = (-224 + 3.5\,E_{lower})\,H_{lower} \tag{8.3.1}$$

where H_i is interactive distance, E_{lower} is percent extraction of lower seam, and H_{lower} is the thickness of the lower seam or mining height.

When the upper seam is mined soon after the lower seam is mined, and in this case, the interburden is still in the process of settling, then,

$$H_i = (-937 + 15\,E_{lower})\,H_{lower}/t \tag{8.3.2}$$

where t is time after mining in years. If H_i calculated for a particular case is greater than the actual interburden thickness, then the case is considered unstable. Note that Equations 8.3.1

and 8.3.2 are only valid when E_{lower} is larger than 62-64%. In other words, no damage is anticipated if extraction in the lower seam is below 60-65 % (Zhou and Haycocks, 1986).

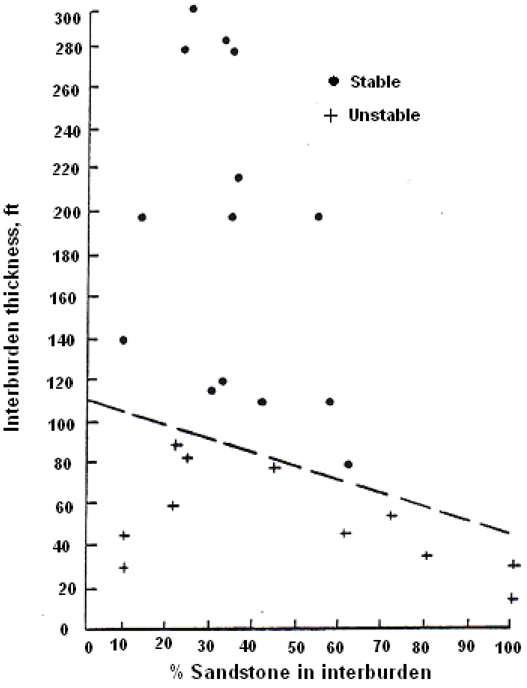

Fig. 8.3.1 Influence of percent hardrock in the interburden on stability in the lower seam (Haycocks and Karmis, 1983)

A multi-seam interaction analysis software program, UGLY (Upperseam Gateroad Longwall Stability), was developed by J Luo et al., (1997) and Kanniganti et al., (1996) to determine the amount of damage in the upper seam when the lower seam had been mined out previously. The program is applicable to both room-and-pillar mining and longwall mining. The damage rating is defined by

$$DR = 1.69\left[\frac{3H_{lower}(HR)h}{H}\right]^{0.05} E_{\ell}T_{lower}^{0.07} \qquad (8.3.3)$$

where DR is damage rating (see Table 8.3.2), H_{lower} is lower seam mining height (ft), h is overburden thickness (ft), H is interburden thickness (ft), HR is percentage of hardrock in interburden (%), E_l is extraction ratio of the lower seam, and T is time delay between mining of the upper and lower seams (year).

Successful overmining was performed in South Africa where the lower seams were mined first using total extraction methods (Hill, 1995). Where the ratio of interburden thickness to lower seam mining height was high (> 9), only minor roof control problems were encountered. When the interburden was all sandstone, 46-55.8 ft (14-17 m) thick, overmining with pillar extraction could be safely performed. Where the ratio of interburden thickness to lower seam mining height was less than 6, roof and floor stability problems occurred.

Table 8.3.2 Damage rating scale for overmining (Westman et al., 1997; J Luo et al., 1997)

Damage rating	Damage
1.12	No damage
1.56	Negligible damage: Fractures present in upper seam, no roof problems, no displacement, and no difficulty of mining due to lower seam mining.
2.00	Moderate damage: Fracture with visible movement, occasional broken roof and/or coal, water entering, mined with minimum or no extra support.
2.44	Considerable damage: Roof problems encountered; seam broken, some bottom heaves and pillar spalling, mined with increased supports.
2.88	Severe Damage: Major roof problems encountered, Entire entries caved, bottom heaved, top broken, coal crushed out, mined with heavy supports.
3.32	Very severe damage: Coal mining abandoned; mining too dangerous or to costly to continue.

B. Undermining

According to Haycocks and Zhou, (1990), when the lower seam is mined long after the upper seam is mined, then

$$H_i = 110 - 0.42\ (HR) \tag{8.3.4}$$

$$H_i = 6.8\ N + 55 \tag{8.3.5}$$

where N is the number of beds in the interburden. If the interburden is completely sandstone, the minimum required interburden thickness is 58 ft (17.7 m) based on Equation 8.3.4. And if the sandstone is a single layer, the minimum interburden thickness is 61.8 ft (18.8 m) based on Equation 8.3.5.

The interactive distance increases as rock layers in the interburden become thinner or the number of layers increases as shown in Fig. 8.3.2 (Ehgartner, 1982).

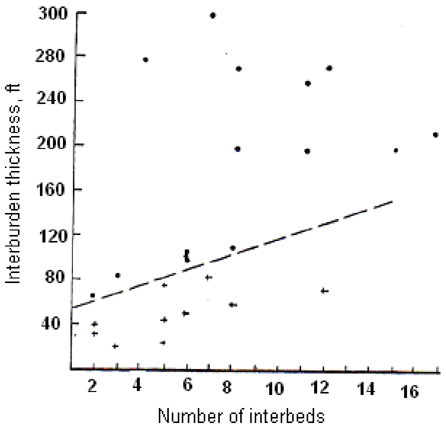

Fig. 8.3.2 Influence of number of beds in the interburden on stability in the lower seam (Ehgartner, 1982)

Layering has a significant influence on the magnitude and distribution of stress below a remnant pillar. Layering will increase stress concentration over that without layering. Thicker layering (greater than 5 ft or 1.5 m thick) will cause higher stress concentration than thinner layering (less that 5 ft or 1.5 m thick) as shown in Fig. 8.3.3.

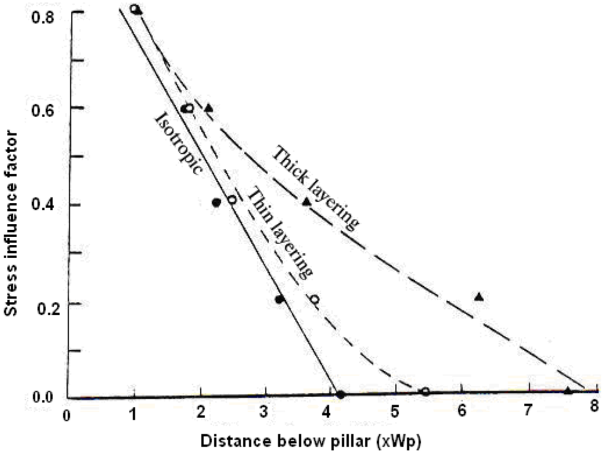

Fig. 8.3.3 Effect of the degree of layering on the magnitude and distribution of stress under a pillar (Ehgartner, 1982)

A study was performed with 22 case histories of multiple-seam interactions in which the upper seam at 1,000 ft (304.8 m) deep was mined first and the lower seam 200 ft below was mined later (Chase et al., 2005). The results showed that the size of the remnant structure in the upper seam can influence the extent of seam interaction. Smaller, critically loaded upper seam pillars are more likely to cause lower seam ground control problems than are wider pillars. The interburden consisted of 50-90 % of hard rock.

In summary, Table 8.3.3 shows the effect of interburden characteristics, such as layer modulus, thickness of layers, the actual number of layers in the interburden, and the coefficient of friction between the layer interfaces, on load transfer.

Table 8.3.3 Effect of interburden characteristics (Ganguli et al., 1995)

Parameter	Effect	Interaction
Young’s modulus	Young’s modulus affects load transfer only for high layer content [1](> 40 %)	Stress above low modulus layers is high, up to 2 times that of high modulus layers
Thickness	Lateral spread increases with thickness	Thin layers increase pressure bulb width to a greater depth than thick layers
Number of layers	Layering increases load transfer	Layering and load transfer have a linear relationship
Coefficient of friction	Low coefficient of friction increases load transfer	The effect is compounded by layering

[1] Layer content is the ratio of layer thickness to interburden thickness.

3. Geologic Discontinuities

Discontinuities refer mainly to joint sets in the roof that tend to cave immediately upon undermining. The severity of joint sets in affecting roof stability depends on several characteristics: spacing, length, and orientation of the joint sets with respect to the upper seam layouts (Chekan et al., 1985; Zhou et al., 1988). The effect of joint sets on roof stability is further enhanced in multiple-seam mining, because when the joint sets are oriented in unfavorable directions, they are prone to the tension and high stress concentration created by the subsidence of strata and load transfer.

8.3.2 Mining Factors

Among the mining engineering factors, the most critical ones are sequence of mining, mining method, and time factors.

1. Sequence of Mining

As stated in Section 8.2 (p. 390), there are five types of mining sequences in multiple-seam mining. For virgin reserves, ground control issues dictate that the mining sequence should be in descending order, because mining operations disturb the strata above the seam much more severely than below the seam. The downside of descending order of mining sequencing is that if the upper seam workings are flooded soon after mining or abandonment, mining of the lower seam may fracture the interburden, resulting in flooding the mine.

In practice, there are more multiple-seam reserves in which one or more seam had been mined previously. In this case, planning for mining a particular seam must take into consideration the location and types of seam interactions generated by the mining of seam(s) immediately above or below the seam of interest.

2. Mining Methods

The mining method used is the key factor in seam interactions. Other things being equal, the severity, magnitude, and extent of disturbance in the overlying strata vary with mining methods in the following order: longwall mining, room-and-pillar mining with pillar extraction, and room-and-pillar mining without pillar extraction. Within room-and-pillar mining with pillar extraction, the severity and magnitude of seam interaction depend on the method of pillar extraction; those with a higher extraction ratio will create disturbance closer to longwall mining, while those with a lower extraction ratio will create the least disturbance, being closer to room-and-pillar mining (without pillar extraction or development mining). Fig. 8.3.4 shows the relationship between the relative extraction ratios in the upper and lower seams and lower seam stability (Ehgartner, 1982).

Longwall mining is well known to have caused subsidence up to 60 times the mining height; to have disturbed workings up to 850 ft above the mined-out seam; and to have created high abutment pressures resulting from chain pillars that could affect workings as far as 800 ft (243.8 m) below (Chekan and Matetic, 1990; Peng, 1986). Subsidence patterns are also different with different mining methods. Subsidence induced by longwall mining follows a predictable pattern, whereas that by room-and-pillar mining depends on the methods of pillar extraction that may vary from mine to mine or area to area, because the remnant or stump pillars left vary with methods of pillar extraction. Remnant pillars are the sources of seam interaction.

The width of the longwall panel also affects seam interaction. Undermining results in subsidence of overlying seam and its effect is most damaging when the panel is subcritical in width (Chekan et al., 1989).

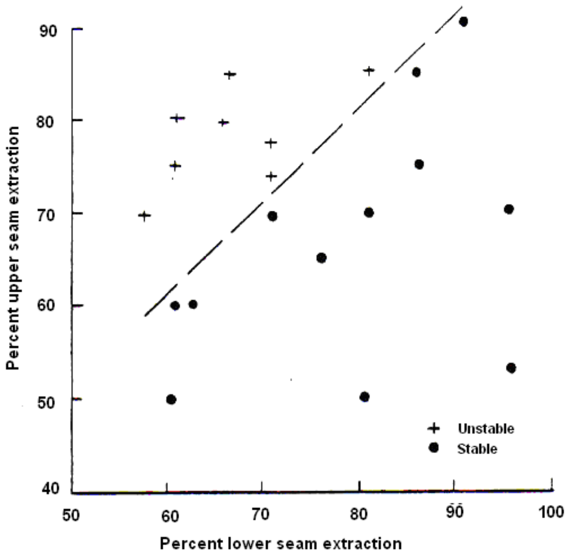

Fig. 8.3.4 Relationship between the relative extraction ratios in the upper and lower seams and lower seam stability (Ehgartner, 1982)

3. Mine Layouts

The relative position of the mine layout between the upper and lower seam determines the extent and distance of seam interaction. If mine layouts of upper and lower seams are exactly the same and superimposed on top of the other, seam interaction would be minor provided the overburden is shallow and the distance between the two seams is large. On the other hand, if the overburden is thick and the seam interburden is thin, seam interaction is likely to occur. The extent and distance of seam interaction can be determined fairly easily based on conventional analytical methods. However, in practice, this type of seam interaction seldom occurs. In a great majority of the cases, mine layouts in both seams are different. Under such conditions, the remnant pillars in the gob and the gob-solid boundaries left in one seam become sources of heavy ground pressure in the other seam. Consequently, knowing how the mine workings are laid out before and after mining in the previous seam is imperative in the mining plan design for the seam of interest in order to reduce seam interaction.

4. Time Factor

Time factor refers to the time lapse between mining of the two adjacent seams. According to Haycocks and Zhou (1990), seam interaction due to time delay in mining can be classified into three categories: active, passive/active, and passive interactions. In active interaction, both seams are mined simultaneously. Strata movement induced by mining of both seams is overlapped and may be enhanced, if not properly designed.

In passive/active interaction, mining in one seam is complete, but the ground is still in the process of settling. In this category, mining under existing workings (passive) or being mined over (active) may result in either an increase or decrease in the stress field at the lower seam elevation. Alternatively, two seams are engaged in active mining, but the areas being affected by the other seam are not active. In other words, seam interaction occurs as a result of active strata movement in current workings due to other active workings in a seam below. For instance, an active room-and-pillar mine was undermined by an active longwall mine 850 ft (359.1 m) below. The roof-to-floor convergence of the outby mains in the upper seam room-and-pillar mine, which is far from the influence of current mining activities, was accelerated when the lower seam longwall face retreat mining passed by. Conversely, the opposite may occur.

In passive interaction, the time lapse of the previously mined seam has been sufficiently long such that subsequent mining in other seams will not induce seam interaction. The time lapse required for subsequent mining varies, ranging from one month to 5-10 years (Chekan, 1990; EI, 1981; Haycocks and Zhou, 1990; Hill, 1995; Holland, 1951; Mark, 2007a and 2007b; Peng, 2007; Stemple, 1956). The wide-ranging time lapse required for strata to settle depends mainly on geological conditions and environment. Thick and hard strata will require a longer time to reach a new equilibrium. Thick clayey strata with proper groundwater flow tend to seal off cracks quickly.

8.4 INTERACTION MECHANISMS

There are three major types of interaction mechanisms: load transfer, subsidence, and interburden shearing. **Load transfer** is induced by individual or groups of pillars or solid/gob boundaries in either active or abandoned workings. A **solid/gob boundary** is the line between a solid coal block and a mined-out gob or between a mined-out gob and a row or rows of standing pillars. According to Mark et al., (2007a), when the width of a remnant pillar exceeds W_p in Equation 8.3.6, the remnant pillar edge is a gob/solid boundary. Conversely, it is a **remnant pillar**.

$$W_p = 5\sqrt{H} \tag{8.3.6}$$

where W_p is the maximum allowable pillar width to be considered as a remnant pillar, and H is seam depth.

Load transfer is transmitted both in the upward and downward directions, affecting both over- and under-mining. Subsidence on the other hand, is produced by the mining of the lower seam, affecting mainly overmining.

8.4.1 Load Transfer

Two types of theories have been developed in the past to determine the magnitude and extent of load transfer due to the existence of remnant pillars and gob-solid boundaries. They are based on conventional analytical solutions and as such do not account for the non-homogeneity and anisotropic nature of coal measure strata. However, the theories are simple to follow and, for homogeneous materials, are fairly accurate. On the other hand, it must be emphasized that with the advance of computer technology in recent years, numerical modeling of mine structures has been the preferred method for analyzing multiple-seam mining interactions (Morsy et al., 2006; Zhang et al., 2005b). The advantage with numerical modeling of mine structural analysis is that it can properly simulate, case by case, the detailed 3-dimensional mine layouts in both seams, considering all the factors stated in Section 8.2. The disadvantage is that it is time-consuming and highly sophisticated, requiring in-depth knowledge, experience, and special training.

1. Pressure Bulb Theory

Figure 8.4.1 shows the pressure contour lines under a pillar subject to uniform loading (Peng and Chandra, 1980). The weight of the overburden is presumably shared equally by the pillars, which in turn transmit to the floor. But the pressure in the floor beneath a pillar is nonuniform. Higher pressure occurs near the contact plane between the bottom of the pillar and the floor line, gradually decreasing downward and disappearing at a distance approximately four times the pillar width.

The contour lines of pressure resemble a series of bulbs (Fig. 8.4.1). Similar pressure contour lines are expected in the roof immediately above a pillar. If the interburden is less than eight times the pillar width, the pressure contour line at the bottom of pillar P3 will superimpose on those at the top of pillar P8. The pressure experienced at any point is the sum of the two pressure contour lines generated separately by P3 and P8. The smaller the interburden, the larger the sum. Similar pressure contour lines and interactions occur between P2 and P7 and between P4 and P9. Since the entry width is usually equal to or less than 20 ft (6.1 m), while pillar width is larger than 40 ft (12.2 m), there will be interaction laterally and more pressure added by the pressure contour lines generated by P2, P3, and P4, respectively. The total pressure created by interactions determined whether the strata between the seams would fail or not.

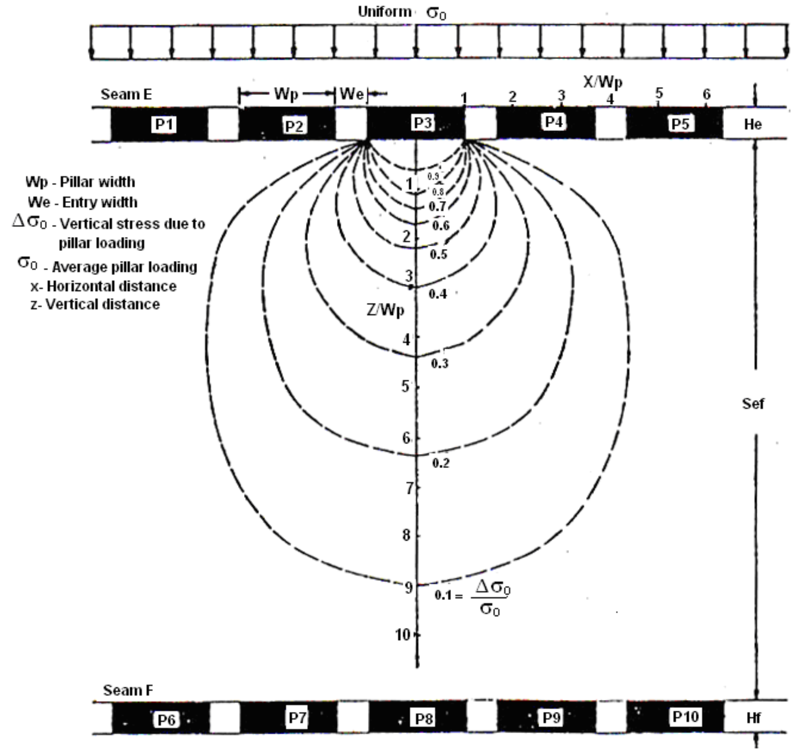

Fig. 8.4.1 Simplified model of pressure bulb interaction between pillars (Peng and Chandra, 1980)

If the areas on both sides of pillars P7-P8-P9 are extracted, the roof strata on both sides will act like a cantilever beam whose supports rest above pillars P7-P8-P9. The additive effect of abutments induced by both cantilever beams can be sufficient to fracture strata in the area. Thus, when the face in the upper seam reaches this area, serious roof control problems may be encountered.

Layered hard rock tends to inhibit pressure bulb formation, while layered soft rock increases the vertical and horizontal distance stress that can be transferred from overlying pillars (Haycocks et al., 1983). A high degree of strata layering transfers load in greater magnitude and distance than thick massive strata (Chekan and Listak, 1993).

A rectangular pillar transfers less load with a smaller interactive distance than would a square pillar (Su et al., 1986). Pillar load will be transferred downward as the dimension of a square pillar increases. The young's modulus of a coal pillar has negligible effect on the pillar load transferring mechanisms (Peng, 1986).

Pressure bulb theory is very useful for analyzing pillar load transfer under "passive" interaction where pillars are columnized and the lower seam pillars are sufficiently large to prevent yielding (Haycocks et al., 1983).

In summary, parameters considered to have an effect on pillar load transfer from pillars in the upper (or lower) seam to the workings in the lower (or upper) seam include pillar size, pillar shape, coal stiffness, extraction ratio, degree of non-homogeneity in the interburden, overburden thickness, mechanical properties of the interburden rocks, strata inclination, and interburden thickness (Peng, 1986).

Figure 8.4.2 shows an example of stress transfer from upper seam remnant structures (a remnant pillar and a gob/solid boundary) through pressure bulbs (Forrest et al., 1987).

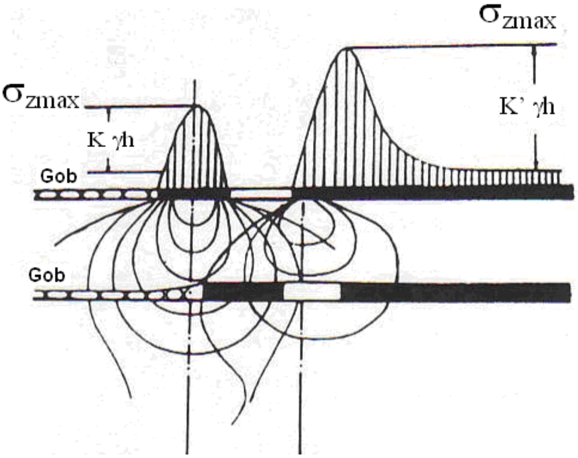

Fig. 8.4.2 Stress transfer from upper seam remnant structures through pressure bulbs (Forrest et al., 1987)

2. Pressure Arch Theory

When an opening is excavated, the vertical pressure above the opening is transferred to both sides of the opening, creating a destressed zone above the opening. The destressed zone assumes a dome shape called a **pressure arch**.

When the width of an opening increases, the width of pressure arch also increases correspondingly. It was believed, however, that a maximum width of pressure arch exits for a particular depth beyond which the arch will collapse (Holland, 1973).

Finite element modeling showed that when openings are narrow and in close proximity, minor pressure arches in adjacent seams can interact, resulting in abnormally high lateral and abutment pressures. For very large openings, such as longwall panels, major pressure arches create high abutment pressures around the edges of the gob, producing points of excessive pressure in seams above or below. Minor pressure arches are more applicable for depicting seam interactions between entries in close proximity, whereas major pressure arches are more suitable for describing the large interactive distance associated with wide, deep openings (Fig. 8.4.3) (Haycocks et al., 1983).

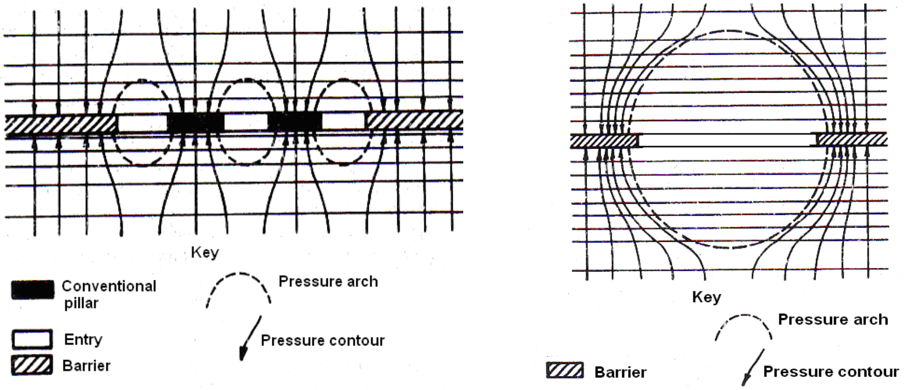

Fig. 8.4.3 Pressure arches: left, minor pressure arches forming from pillar to pillar, right, a large pressure arch resulting from longwall mining

Oram and Ponder (1997) measured the stress field in an underlying longwall where the upper seam was 492-525 ft (150-160 m) above and under an overburden thickness of 3,116-3,313 ft (950-1010 m). The upper seam inter-panel barrier pillars were 311.6-361 ft (95-110 m) wide and left unmined, causing stress concentration in the longwall development below. Fig. 8.4.4 shows the measured stress changes in the lower seam under and beyond the upper seam barrier pillar edge. The measured stress 2,987 psi (20.6 MPa) for roadway 1, which was 197 ft (60 m) beyond the pillar edge and in the gob, represented a vertical stress relief of 20% below the cover load of 3,625 psi (25 MPa); the measured stress of 4,277.5 psi (29.5 MPa) for roadway 4, which was 32.8 ft (10 m) beyond the pillar edge and in the gob, was 20 % above the cover load; and the measured stress of 5,800 psi (40 MPa) for roadway 5, which was under the barrier pillar, 65.6 ft (20 m) from the panel edge, was 60 % above the cover load.

8.4.2 Subsidence

When either a total or high extraction mining method is employed for the lower seam, the overburden above the mined-out gob will subside, creating a subsidence basin and simultaneously producing a caving zone 2-12 times and a fractured zone 30-60 times the mining height (see Fig. 7.3.1 on p. 319 and Fig. 7.3.2 on p. 320 for more detail). All of these features will generate adverse seam interactions in certain areas. The amount of damage subsidence can cause to an overlying seam is mainly dependent on five factors: mining height in the lower seam, angle of draw and caving angle, time lapse of mining between seams, and thickness and geological characteristics of interburden.

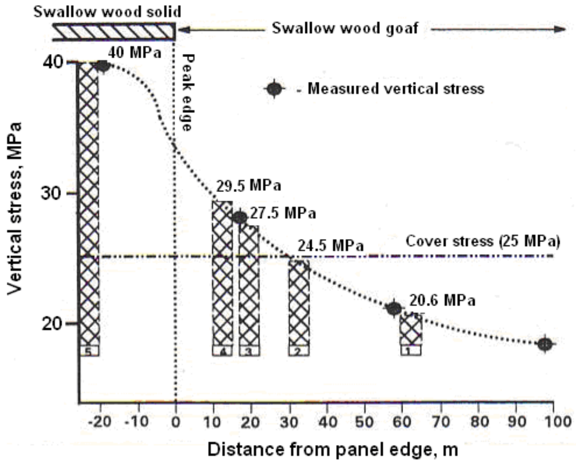

Fig. 8.4.4 Measured stress change around the gob/solid line (Oram and Ponder, 1997)

It must be emphasized that the subsidence effect is not restricted to the caving and fractured zones. Damage to underground openings up to 850 ft (259.1 m) above the underlying longwall panels has been recorded (Peng, 1992). Surface subsidence data showed that surface subsidence occurs even when longwall mining in coal seams is more than 3,000 ft (914.4 m) deep. This means that strata from the top of the fractured zone to the surface are also subject to subsidence-induced movement, which when imposed on openings in the overlying seams, may induce movement of the surrounding strata, causing roof falls or excessive roof-to-floor convergence or rib sloughage or both or a combination of them.

Caving angle is the angle between the vertical line at the panel edge and the surface profile line of the dome-shaped cavity above the mined-out gob. Caving angle varies considerably with researchers and coalfields and ranges from 5^o to 35^o (Choi and McCain, 1980; King and Whittaker, 1971; Mark, 1990; Peng and Chandra, 1980; Wilson, 1983). For practical purpose, a caving angle from 18^o to 25^o may be used.

Within the caving height, strata are completely broken and therefore would not be able to sustain any workings. Caving height is 2-12 times of mining height, depending on researchers and coalfields (Chekan and Listak, 1993; Kendorski, 2006; Peng, 1992). Within the fractured zone, which ranges from 30 to 60 times the mining height, the intensity of vertical fractures and horizontal bedding plane separations decreases upward. Mining within this zone will encounter ground control problems, the severity of which decreases with increasing distance from the lower seam. However, depending on the geological and environmental conditions, the broken rock fragments may be settled, and the fractures in the caving zone may be sealed. This process may take from one month to 10 years. When this occurs, mining in the caving zone is feasible, although may be difficult (Peng, 2007).

The subsurface subsidence basin can be predicted, just like a surface subsidence basin (Luo and Peng, 2000a and 2007). The subsidence basin in the upper seam level extends beyond the vertical projection of the edges of the lower seam mined panel, the limit of which is defined by the angle of draw (see Section 13.2.1, on p. 619).

Based on Peng et al., (1995c), the angle of critical deformation is dependent on seam depth and can be determined by

$$\delta_{all} = 6.87 - 0.0072\,h + 8.872x10^{-6}\,h^2 \tag{8.4.1}$$

$$\delta_{pit} = 3.05 + 0.00023\,h + 4.607x10^{-6}\,h^2 \tag{8.4.2}$$

where δ_{all} and δ_{pit} are angles of critical deformation for all coal seams and Pittsburgh seam, respectively, and h is seam depth.

For critical and supercritical panels, the subsidence basin is flat in the central region where the ground sustains uniform vertical subsidence, but no horizontal displacement or strain. Close to the edges of the mined out panel, the ground is subjected to compressive strain and then turns to tensile strain at the inflection point. Tensile strain extends beyond the panel edges (see Fig. 13.2.3 on p. 620). The location of inflection point is determined by (Peng et al., 1995c),

$$D_{all} = 0.38123\,h\,e^{-0.000688\,h} \tag{8.4.3}$$

$$D_{pit} = 0.45499\,h\,e^{-0.0000914\,h} \tag{8.4.4}$$

where D_{all} and D_{pit} are the offset distances of the inflection point from the panel edge for all coal seams and Pittsburgh seam, respectively.

Within the compression zone, floor heave may occur as humps for soft rock such as shale, or buckle beams for hard rock such as sandstone. In the tension zone, roof cracks or roof failures/falls may occur (Fig. 8.4.5)

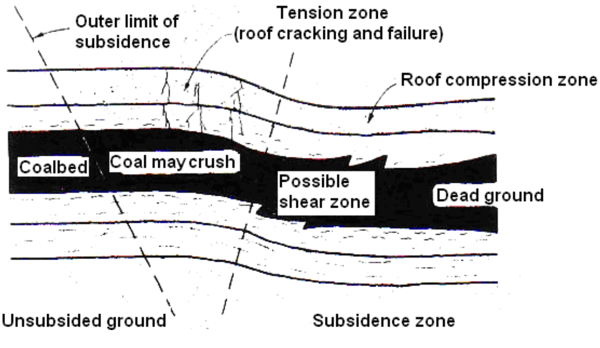

Fig. 8.4.5 Potential ground control problems around the edges of a mined out panel (Haycocks et al., 1982)

In a case study of overmining by Zhang et al., (2005a) the lower seam was mined employing room-and-pillar mining with pillar extraction which preceded the upper seam being mined also by the room-and-pillar method. The interburden was 75 ft (22.9 m) thick of predominately shale. They found that the influence angle of abutment pressure of the gob-solid line in the lower seam was 63.4° beyond the edge of the solid-gob line on the pillar side; the tensile zone was $\alpha = 13.5^o$; and the compression zone was $\beta = 34^o$ inside the solid-gob line (see Fig. 8.4.6 for symbol notation).

Rigsby et al., (2003) investigated another case where the upper seam was 1,100-1,300 ft (335-395 m) deep employing room-and-pillar mining with pillar extraction over the previously longwall-mined lower seam 235 ft (72 m) below. The lower seam mining height was 11 ft (3.4 m). They found that pillar spalling was acute outby and within 12^{o} from the lower seam longwall panel edge. The tensile zone was located from α = 23^{o} to 37.5^{o} inside and from the edge of the lower seam longwall panel edge. Within the tensile zone, joints, bedding marking flow features, and breaks were open. The compression zone extended to a zone of β = 48^{o} (see Fig. 8.4.6 for symbol notation).

In overmining situations where the interburden thickness was 147.6 ft (45m) consisting of sandstone, shale, and shaley coal, Sastry et al., (2007) found that chock-shield leg pressures above the lower seam barriers were 5-17 % higher than above the gob; leg pressure increased about 10 % from solid to gob and then decreased; and that the influence angle of the lower seam solid/gob line was approximately β = 18.5^{o} (see Fig. 8.4.6 for symbol).

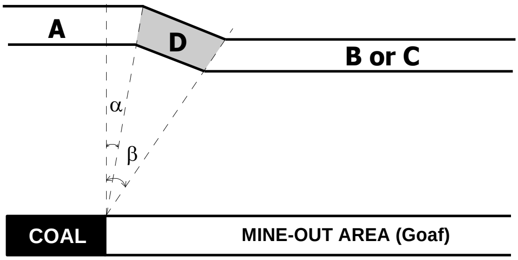

Fig. 8.4.6 Subsidence model revealed by surface drilling (Li and Cairns, 2000 and 2007)

In an Australian multiple-seam mining case study, Li and Cairns (2000 and 2007) investigated an overmining case where the upper seam overburden was 262.4-328 ft (80-100 m) and the interburden, consisting of thinly-bedded mud- and clay-stone, siltstone, and sandstone, was 133-131.2 ft (35-40 m) thick. The lower seam was previously mined by a combination of development, pillar extraction, and longwall, while the upper seam was being mined with longwall. A surface drilling program prior to upper seam mining was performed to define the subsidence profile in the upper seam, resulting from the lower seam mining. Fig. 8.4.6 shows the simplified subsidence profile. From a ground control point of view, the upper seam subsidence profile can be divided into four zones, A, B, C, and D, the characteristics of which are:

1. A Zone

This zone covers the area above the solid coal or development workings of the lower seam. It is not affected by the lower seam mining.

2. B Zone

This zone, being above the center portion of the longwall panels in the lower seam, subsides uniformly and thus flat with occasional reactivated but closed roof joints. This zone presents few difficulties in upper seam mining.

3. C Zone

C zone is similar to B zone except that this zone is above the mined-out room-and-pillar extraction workings below. Due to the nature of pillar extraction and the degree of deformation and location of the remnant pillars, strata conditions vary.

4. D Zone

This zone is over the gob and adjacent to an underlying remnant pillar or the solid/gob line and subject to strata bending, resulting in difficult mining conditions. The two angles defining the D zone were found to be $\alpha = 0^o - 22^o$ and $\beta = 32^o - 45^o$. When rock strength is higher and subsidence differential is larger, α tends to be higher, being close to or more than 15^o.

During development in D zone, ground control problems, varying both in severity and mode from place to place, included strata fracturing, highly uneven roof profiles, and roof falls. Strata deterioration was generally more pronounced in areas above the mined-out longwall panels than those above the pillar extraction panels. Variations in the severity and mode of ground control problems may be attributed to the degree of deformation of remnant pillars and amount of subsidence in the upper seam.

The major failure modes in the D zone were strata delamination and block formation, or a combination of both. Delamination occurred in areas where joints and mining-induced fractures were relatively uncommon, whereas the unstable blocks occurred in areas and were formed by open joints, mining-induced fractures, partings, or undulating erosional surfaces. Many joints were re-activated (Fig. 8.4.7).

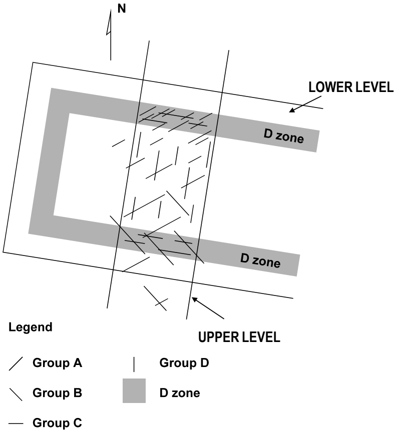

Fig. 8.4.7 Surface subsidence fractures and reactivated joints (Li and Cairns, 2000 and 2007)

8.4.3 Interburden Shearing

When the interactive distance is less than 33 ft (10.1 m), undermining may produce shearing failures in the interburden (Barko, 1982) if the interburden consists of mainly brittle, hard rock. Shearing failures are common when the interburden thickness drops below 30 ft (9.1 m) and where total or partial pillaring has been carried out in the underlying seam.

The greatest potential of shearing occurs in the caving zone. In 38 cases of multiple-seam subsidence problems studied by Holland (1947 and 1951), he observed that 75 % of them had shear-tensile failures (Fig. 8.4.8). Stemple (1956) observed that the shear angle varies with rock type, ranging from near vertical for thick sandstone to 25^o for highly bedded strata.

Load concentrations under upper seam pillars can be a major contributor to shear development at the lower seam rib lines. This is very pronounced when the interburden thickness is 50 ft (15.2 m) or less.

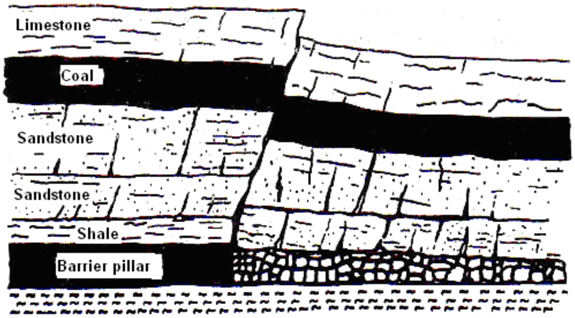

Fig. 8.4.8 Interseam shearing (Holland, 1947)

8.4.4 Summary

Tables 8.4.1 and 8.4.2 summarize seam interaction due to multiple-seam mining. Table 8.4.1 emphasizes interaction mechanisms, while Table 8.4.2 emphasizes mining method and mining sequence.

Table 8.4.1 Summary of seam interaction mechanisms (modified from Haycocks and Zhou, 1990)

Mechanisms	Applicable conditions	Characteristics of interburden problems	Major controlling parameters
Pillar load transfer	Under-mining	Pillar failure, floor heave, roof falls in the area below upper seam remnant structures	Interburden and its characteristics; overburden, old working layout
Pressure Arch	Under -/ over-mining	Serious problems associated with abnormal load on pillars in lower or upper seam, destressed zone	Same as above; caving conditions
Subsidence	Over-mining	Roof falls and associated problems in tensile zone created by lower seam workings	Lower seam height; old working layout
Interburden shearing	Under - / over-mining	Caving or cracking of upper seam floor, large scale roof falls in lower seam workings	Interburden thickness, interburden characteristics

Table 8.4.2 Potential interaction problems in multiseam mining layout (Hill, 1995)

Mining method		Characteristics of interaction problems
Upper seam (U)	Lower seam (L)	
Room & pillar	Room & Pillar	Pillar spalling and interburden collapse if interburden is thin and not columnized
Pillar extraction (1)[1]	Pillar extraction (2)	Roof falls in U seam, interburden collapse if it is thin
Room & Pillar (2)	High extraction[2]	Tensile zones and spalling in U seam when mining over solid/gob boundaries, floor collapse over incomplete gobs, high safety risk if the ratio of interburden to L mining height is low
Remnant pillar (1)	Room & Pillar (2)	Intersection collapse in L seam when mining under remnant pillars
Pillar extraction (1)	Pillar extraction (1)	Simultaneous mining in both seams – roof falls in working areas of L seam
High extraction (1)	High extraction (1)	Preferred method of mining – safety hazard minimal, except where remnant pillars and water exist in the U seam

[1] Numbers in parentheses: 1 – seam mined first; 2-seam mined second

[2] Pillar extraction or longwall

The effects of interburden response on upper seam mining are summarized in Table 8.4.3 (Haycocks and Karmis, 1992).

Table 8.4.3 Effect of the ratio of interburden thickness-to-lower seam thickness on upper seam mining (Haycocks and Karmis, 1992)

Effect	M*	Interburden condition	Upper seam response
Massive shearing	< 6	Massive sandstone	Coal crushed and massive floor displacement
Local shearing	< 20	Sandy shale	Localized floor displacement-crushing
Bending Strata (tension zone)	> 10	Shales, mudstone, laminated sandstone	Roof failure, pillar spalling – excessive floor gradient
Bending stress (compression zone)	> 10	Shales, mudstone, laminated sandstone	Lateral coal shear - excessive floor gradient-bed separation

* Ratio of interburden thickness to lower seam thickness (mining height)

8.5 ULTRA-CLOSE MULTIPLE-SEAM MINING

8.5.1 Introduction

Ultra-Close multiple-seam mining refers to those cases where the interburden thickness is less than 25 ft (7.6 m) (Haycocks and Zhou, 1990; Zhou et al., 1991). The mechanisms of seam interaction for ultra-close seams are different from those described in Section 8.4 (p. 398), except that pillar load transfer mechanisms in ultra-close seam mining does not differ significantly from that in multiple-seam mining with greater interburden thickness (Zhou and Haycocks, 1989). For ultra-close seams, rock mechanics properties of the interburden strata are the control parameter for structural stability, because there were many anecdotal stories in which the interburden broke and fell down completely when the interburden was below 20-25 ft thick (6.1-7.6 m).

Zhang and Zhai (2005) defined ultra-close multiple-seams as: if the depth of damage in the upper seam mine floor due to mining of the upper seam is h_u and the interburden thickness is H_i, the seams are ultra-close when

$$H_i \leq (FS)\, h_u \tag{8.5.1}$$

$$h_u = \frac{1.57\, h^2 W_p\, \gamma^2}{4\, R_{rmc}^2} \tag{8.5.2}$$

where $FS = 1.2$ is a factor of safety, h is seam depth, W_p is panel width, γ is rock density, and R_{rmc} is rock mass strength.

8.5.2 Key Factors Affecting Mining Operations

The key factors affecting mining operations include pillars, interburden characteristics, and weight of the mining machine.

1. Pillars

Case studies by Haycocks et al., (1983) showed that pillar load transfer in ultra-close multiple-seam mining can be divided into three categories: columnized pillars, partially offset pillars, and completely offset pillars.

A great majority of the ultra-close multiple-seam mines involved room-and-pillar mining in both seams in which columnization of pillars in the upper and lower seams workings was commonly employed. At a relatively short distance from the lower seam pillars, the upper seam pillar can transfer highly concentrated stresses to the rib corner of the lower seam pillars. Columinzation in general works well when the seams are shallower, even though it may cause shear failure at the lower seam pillar rib corners when the ratio of entry width to interburden thickness is less than five. At greater depths, however, the overburden weight can create a high stress gradient leading to shear failure at the lower seam pillar rib corner.

For partially offset pillars, the mine layouts were in most cases designed originally for columnized pillars. But due to surveying errors or based on abandoned mine maps that were either inaccurate or lacked of information, pillars were not exactly columnized. Cutter roofs may originate at the lower seam pillar ribs due to high shear stress generated by partially offsetting the upper and lower seam pillars.

Totally offset pillars when both seams employed the room-and-pillar mining method are undesirable, especially when the overburden thickness is large. The total structure resembles a fixed-end beam subjected to a point-load at the beam center and the interburden, i.e., the roof beam of the lower seam entries/crosscuts, will fail in tension at the center of the openings. Tensile failure may occur when

$$W_o > 5\ H_i \tag{8.5.3}$$

where W_o is the width of the opening and H_i is the interburden thickness (Haycocks and Zhou, 1990). Furthermore, when interburden fails, the effective pillar height increases considerably, thereby greatly decreasing pillar stability.

2. Interburden Characteristics

Strength, rock type, and layering are factors affecting the stability of interburden. The stability of interburden decreases with increasing number of layers in it. Interactive distance will increase with an increasing number of layers in the interburden. Interburden stability will increase with an increasing percentage of hardrock. Fig. 8.5.1 shows the minimum interburden thickness requirement for stability as a function of ratio of opening width-to-pillar width and percent of hardrock in the interburden (Zhou et al., 1991).

Mark (2007b) showed several case studies where interburden consisted of competent sandstone and siltstone. Multiple-seam mining with columnized pillars in both seams was successful even though the interburden was only 20-40 ft (6.1-12.2 m) thick. Proper pillar design in both seams with firm interburden appeared to be the key factor.

3. Weight of Mining Machines

The weight of heavy mining equipment and its cyclic movement on interburden is also a factor to be considered. The stress induced by mining equipment increases rapidly with decreasing interburden thickness (Zhou et al., 1991).

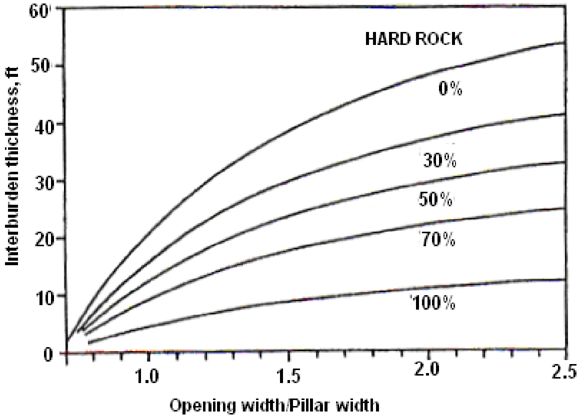

Fig. 8.5.1 Minimum interburden requirement as a function of opening-width-to-pillar-width and percent of hardrock (Zhou et al., 1991)

4. Case Studies

Ultra-close two-seam mining was practiced in northern Appalachia. The lower seam, 7-10 ft (2.1-3 m), was mined previously employing either longwall or room-and-pillar mining with pillar extraction (Peng, 2007). The upper seam, 4-6 ft (1.2-1.8 m) thick with an interburden thickness of 25-30 ft (6.1-9.1 m), was mined 6 months to 2 years after. The coal in the upper seam and its roof were badly broken, but the cracks were sealed with calcite materials. Roof falls occurred frequently and required special supports (Fig. 8.5.2).

For undermining, the roof over the face of the lower seam was broken badly and fell down easily. Support loading at the longwall face was small without periodic weighting. As the face advanced, caving occurred immediately. The front abutment pressure decreased significantly as compared to single-seam mining. The position, extent, and range of the front peak abutment pressure decreased with decreasing interburden thickness (Zhang et al., 2005b).

Seedsman (2003) found that the onset of roof falls were associated with multiple parallel joint sets in ultra-close multiple seam mining where the lower seam being mined was 20-33 ft (6-10 m) below the inactive upper seam workings. The interburden was thick-bedded sandstone. Two types of roof falls occurred: cantilever failures when one joint exposed along the ribline and joint block failures when two joints exposed in the roof.

5. Summary

In summary, interburden stability is the single most important factor in ultra-close multiple-seam mining. Failure of the interburden can then cause instability to pillars and other components of the mine structure with damage to mining operations in both seams. For mine design with columnized pillars, a model of fixed-end beams with self-weight may be used to determine the maximum tensile stress causing beam failure of the interburden. But for more detailed analysis and for situations other than columnized pillars, 3-dimensional numerical computer analysis is recommended.

A rating system quantifying the geological factors for ultra-close, multi-seam mining has been proposed (Zhou et al., 1991), as shown in Table 8.5.1, using the following equation:

$$R = \frac{\sum_{i=1}^{6} W_i R_i}{\sum_{i=1}^{6} W_i} \tag{8.5.4}$$

where W_i is weight assigned to factor i, and R_i is rating number for factor i.

Fig. 8.5.2 Cracks in the upper seam roof that were caused by lower seam mining had been sealed with calcite (white) (left), a typical roof fall in the upper seam (right) (Peng, 2007)

8.6 DESIGN OF MULTIPLE-SEAM MINING PLAN

8.6.1 General Procedures

Multiple-seam mining plan design involves the determination of the stress fields of various mine layouts in both seams and the selection of proper pillar dimensions and their relative positions. In calculating the stress field, all the key factors described in Sections 8.3 and 8.5 must be considered. Depending on the method selected, the guidelines described in those two sections may be used.

Figure 8.6.1 depicts the simplified mining plan design flow charts for room-and-pillar or longwall mining plans (Fraher et al., 1992; Grenoble and Haycocks, 1985). The first step is to identify the location of remnant pillars and gob/solid boundaries. The second step is to calculate the magnitude and extent of stress concentration generated by the remnant pillars and gob/solid boundaries, taking into consideration the interburden characteristics. The third step is to evaluate the induced stress at the seam level to be mined and its effect on roof and floor stability.

Table 8.5.1 Rating system for ultra-close multiple-seam mining (Zhou et al., 1991)

Factor	Rating				
	1	2	3	4	5
Interburden rock type	Massive sandstone, sandy shale, massive hard shale	Massive sandstone, sandy shale, massive hard shale	Interbedded shale and sandstone, crystallized sandstone and conglomerate.	Thinly interbedded shale and sandstone, crystallized sandstone and conglomerate	Slumps deposits, channel scours, fireclay, kettlebottoms, slickensides, pinchouts
M^1	> 6.3	5 – 6.3	4 - 5	3.5 - 4	< 3.5
Geological weak zone	none	Not likely	likely	localized	Large scale
Time lapse between mining, year	>5	2 - 5	1 - 2	0.5 - 1	< 0.5
Ground water	Completely dry in both seams	Mostly dry in lower seam; dry in upper seam	Moist only in both seams	Moderate pressure, Upper seam wet	Very wet, rock, very sensitive to water
Interburden layer	1 – 5	6 - 8	9 - 11	12 - 19	> 20
Hardrock, %	> 70	51 - 70	31 - 50	11 - 30	< 10

[1] Ratio of interburden thickness to lower seam thickness

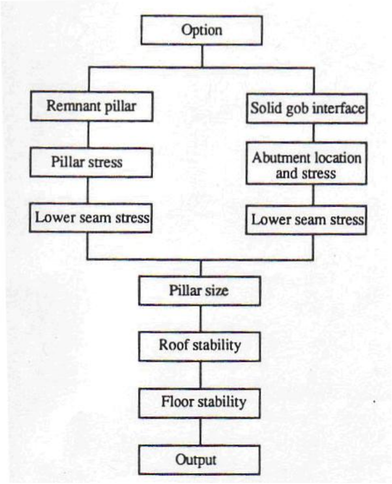

Fig. 8.6.1 Multiple-seam mining plan design flow chart (Grenoble and Haycocks, 1985)

For overmining, if the lower seam employed high extraction methods (i.e., longwall mining or room-and-pillar mining with pillar extraction), the induced caving and fractured zones above the mined-out panels must be considered. In simultaneous mining, the effect of both dynamic and final subsidence profiles on the other seam must be evaluated for the full overburden thickness.

The pressure bulb and arching theories can be used to calculate pillar load transfer (Chekan and Matetic, 1987; Matetic et al., 1987a and 1987b). But, it must be emphasized that if three-dimensional mine structural analysis is employed; all the factors described above can be considered simultaneously (Han et al., 2005, Kripakov et al., 1986; Morsy et al., 2006).

1. Room and Pillar Mining in both Seams

For a room-and-pillar mining plan similar to that shown in Fig. 1.3.1 (p. 4), in which production panels are separated by barrier pillars, the interactive distance, and thus the minimum interburden thickness, depends on the size and layout of panel and barrier pillars. Consequently, pillar design and their layout pattern are related to the interactive distance or the minimum interburden thickness required for safe operations in both seams. Tables 8.6.1 and 8.6.2 and Fig. 8.6.2 show the guidelines established for South African coal mines (Salamon and Oravecz, 1976; Bradbury and Lear, 1984).

Munsamy et al., (2004) demonstrated through numerical modeling that the effect of pillar width on minimum interburden thickness follows a power law; that the minimum required interburden thickness increases with pillar width, more so under the barrier pillar than under the panel pillar, the difference of which ranges from 40 to 75 %; that the presence of sandstone in the interburden decreases the minimum required interburden thickness and the closer the sandstone is to the bottom of the interburden, the smaller is the reduction in the required interburden thickness; and that the required minimum interburden thickness changes very little when sandstone reaches more than 60 %.

Figure 8.6.2 shows that larger pillar centers, C, are required when the limiting distance falls below 0.75 C (Bradbury and Lear, 1995; Hill, 1994).

Table 8.6.1 Multiple-seam mining guidelines for South Africa (Salamon and Oravecz, 1976)

Interburden thickness, H_i	Panel pillars
$H_i > 1.5\ W_{pc}$ [1]	No need to columnize
$H_i < 0.75\ W_{pc}$	Pillars are to be columnized
$H_i > 2\ W_o$[2]	Pillars should be designed with safety factor being 1.6
$H_i < (0.3 – 0.5)\ W_o$	Mining adjacent seams will only be practical if the interburden contains a reasonable percentage of sandstone
$H_i < (1.5 – 2.0)\ W_o$	The possibility of interburden failure should be considered. The safety factor of individual workings should be > 1.8

[1] W_{pc} is pillar center distance.

[2] W_o is entry width.

Table 8.6.2 Maximum influence distance of barriers for different pillar geometry (Hill, 1995)

Panel width to depth ratio	Barrier pillar width W_b,(m)	Panel pillar width W_p,(m)	$\frac{W_b}{W_p}$	H_{imax} (m)	$\frac{H_{imax}}{W_{pp}}$	$\frac{H_{imax}}{W_b}$
0.4	12	12	1	14	0.77	1.16
0.8	12	12	1	15	0.83	1.25
1	12	12	1	16	0.88	1.33
2	12	12	1	13	0.72	1.08
0.5	24	12	2	28	1.55	1.16
0.8	24	12	2	14	1.33	1
1	24	12	2	26	1.44	1.08
1.4	24	12	2	27	1.55	1.12
0.5	48	12	4	38	2.11	0.79
1	48	12	4	39	2.43	0.81
1.4	48	12	4	32	1.77	0.67
2	48	12	4	33	1.83	0.68

H_{imax} is maximum distance (m) below barrier pillar where stress returns to within 5 % of the virgin stress and W_{pp} is panel pillar center distance (m)

2. Room and Pillar Mining over Total Extraction

Using three-dimensional modeling, Morsy et al., (2006) established the following guidelines for room and pillar development mining over a previously mined-out longwall gob, in which pillars were severely sloughed accompanied by floor heave:

A. The average pillar stability factor should be greater than 1.2.

B. The reduction of pillar stability due to earlier mining excavation should be less than 40%.

C. The ratio of overburden depth-to-interburden thickness should be less than 7.5.

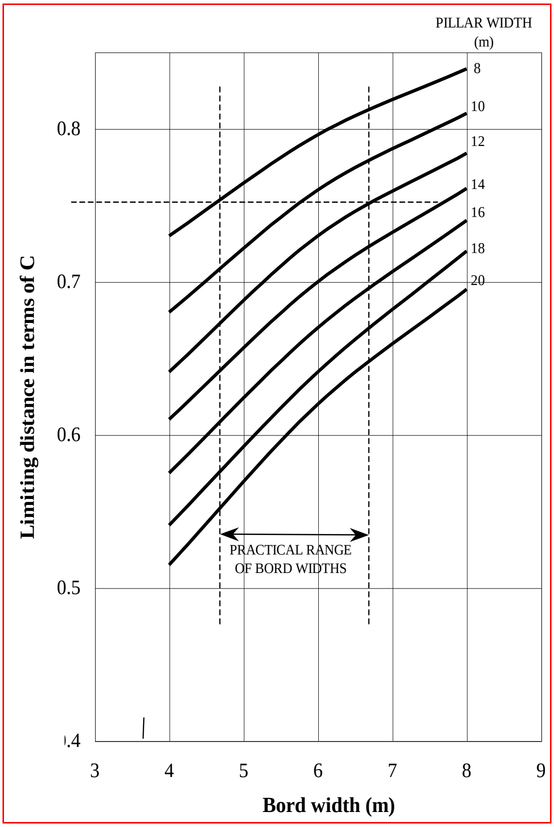

Fig. 8.6.2 Effects of entry width and pillar width on interactive distance (Bradbury and Lear, 1995)

8.6.2 Longwall in one Seam and Room-and-Pillar Mining in another Seam

Zipf (2005b) conducted numerical analyses for three case scenarios: (1) undermining, in which the upper seam is longwall-mined first, followed by lower seam by room-and-pillar mining, (2) overmining, in which the lower seam is longwall-mined first, followed by the upper seam by room-and-pillar mining, and (3) simultaneous mining, in which the lower seam is mined first by longwall, followed with time lapse by room-and-pillar mining in the upper seam. He found four controlling factors that dictate how far above and below the total extraction area the stress field changes in multiple-seam mine design: (1) overburden thickness (OB) to interburden thickness (IB) ratio, (2) gob width to interburden thickness ratio, (3) site specific geology, and (4) horizontal stress to rock strength ratio.

When the ratio of overburden thickness (OB) to interburden thickness (IB) is less than 5, no seam interaction occurs. When OB/IB is greater than 50, seam interaction is very severe, even if strong roof is present. When OB/IB is 15-17, seam interaction is possible.

Vertical stress increases in relatively narrow areas around, and decreases with distance above and below, the total extraction area. Horizontal stress increases above and below the total extraction area for a distance much larger than the vertical stress. The size of this zone of vertical stress relief and horizontal stress increase determines the extent of adverse seam interactions. A major variable in geology is the percentage of strong rock in the interburden and its location. A higher ratio of applied horizontal stress to immediate roof strength increases the chance of adverse seam interaction.

Other numerical modeling studies by Chekan (1990) and Su et al., (1984) showed that:

A. Vertical stress across the longwall face is greatest when overlying workings are crossed at a 90° angle. An acute or obtuse approach angle will decrease vertical stress. Conversely, the approaching angle has minor effect on the gateroads below.

B. Columnization of chain pillars will generally produce the most adverse conditions in the gateroads. Conditions in the gateroads improve greatly when gateroads are placed below the gob of the upper seam.

C. Subcritical panels may influence the interactive distance.

D. Longwall gateroad design needs to consider the loading history of the pillars. A pillar may be stable during development, but problems occur during retreat or during second panel mining, even though interburden is very thick.

8.6.3 Longwall Mining in both Seams

Germany has more than 100 years of experience in multiple-seam mining. In some mines, more than 20 seams have been mined within the last decade (Studeny and Wittenberg, 2007; Witthaus and Opolony, 2007). Longwall mining has been exclusively used, and due to historical development, mining has been conducted in descending order. With this vast experience, a systematic method has been developed for multiple-seam mining planning for roadway design. The planning work consists of the following sequential tasks: (1) determination of geological and geotechnical characteristics, (2) measurement of the stress field and modeling of stress distribution under the proposed panel layout and mining sequence, (3) determination of strata and roadway deformation using both numerical and physical modelings, (4) selection of support elements and systems based on the results of item 3; and (5) monitoring the effectiveness of the designed systems.

For overmining in a single-entry development without pillars in between, the NCB (1972) recommended that gateroads should be located 15 ft (m) inside the lower seam gateroad or placed at least 0.03 times the depth or more to the solid side of an underlying gob solid edge. Numerical modeling and case studies by Bigby et al., (2007) indicated that siting longwall gateroads near the underlying pillar edges may create serious ground control problems, and mixed results were shown by placing the upper seam gateroads between 26.2 and 49.2 ft (8 and 15 m) inside the lower seam pillar edge. The numerical model also showed that potential problems will arise by placing upper seam gateroads in the zone 49.2-131.2 ft (15-40 m) over the lower seam gob edge, and therefore, considering the heavy equipment employed in modern longwall mining, it appears to be more advantageous to place the gateroads above the center of the lower seam gob with the face straddling the gateroad pillars.

In summary, columnization of longwall panels in upper and lower seams tends to increase loadings on the pillar system of the seam mined later. Pillar loading may be too excessive to maintain entry stability if the seam depth is large. Putting the gateroad system of one seam over or under the panel center of the other seam will decrease the pillar loading, but it may cause roof control problems at the longwall face under or above the gateroad system, especially under deep cover. The alternative is to align the gateroad systems in both seams with some offset distance, e.g., 80-150 ft (24.4-45.7 m) and more (Peng et al., 2008). This type of layout has the advantages in that the gateend shields have higher weight-bearing capacity than face shields and can take the heavier loading under or above the load transfer from the gateroad pillar system above or below. Again the amount of load transfer depends on many factors, mainly, the thickness and characteristics of interburden and the layout of longwall panels in the upper and lower seams and their relative position. Consequently, for optimum design of panel layout in multiple-seam mining, numerical modeling is highly recommended since it is the only available technique that can take all of the relevant factors into account.

8.6.4 Analysis of Multiple Seam Stability (AMSS)

NIOSH recently released a software program titled analysis of multiple seam stability (AMSS) (Mark et al., 2007b) based on data of 309 cases of multiple seam mining. For a given case, this program estimates the multiple seam pillar stability factors and a critical interburden thickness or interactive distance. Based on these two parameters, the program predicts the conditions and severity of seam interaction during development or retreating.

AMSS first estimates the ALPS or ARMPS stability factor depending whether the active working is longwall or pillar retreating. Then it automatically uses LaM2D (Akinkugbe and Heasley, 2007; Heasley, 2007; Heasley and Agioutantis, 2007) to estimate the multiseam load transfer due to previous seam workings and also estimates total vertical stress. After this, it estimates ALPS or ARMPS multi-seam stability factor (SF_{ms}) and compares the results with the recommended safety factors for ALPS or ARMPS (Fig. 8.6.2). Note the recommended safety factor in Fig. 8.6.2 is similar to that shown in Fig. 5.8.3 (p. 278) except that it has been adjusted for the multiple seam stress calculated by LaM2D. If the estimated safety factor is less than the recommended value, pillar size needs to be increased.

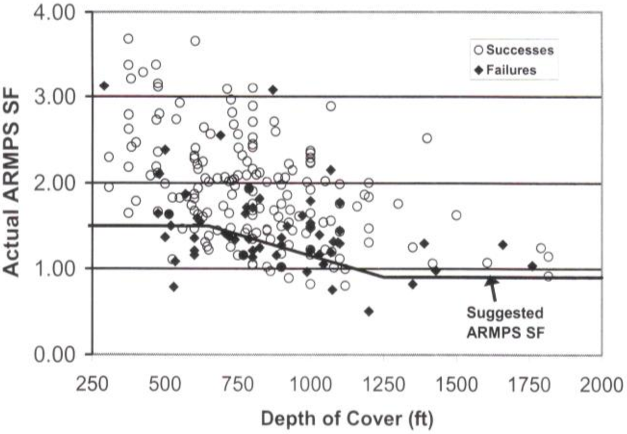

Fig. 8.6.2 ARMPS SF adjusted for the multiple-seam stress (Mark and Chase, 2007)

AMSS also calculates the critical interburden thickness (INT_{citLN}) or interactive distance using Equation 8.6.1 which is the result of applying logic regression to the 309 cases (Mark et al., 2007a and 2007b).

$$INT_{critLN} = Exp\ (35\ TVS - 77\ UO - 87\ EX + 77\ REMPIL - 83\ (LnCMRR20) + 359 \qquad (8.6.1)$$

where TVS is total vertical stress on the critical pillar (10^3 psi), UO is the mining sequence indicator (1 for undermining and 0 for overmining), EX is extra support indicator (1 for extra support and 0 for none), *REMPIL* is load transfer indicator (1 for remnant pillar and 0 for gob/solid boundary), and *Ln(CMRR20*) is natural logarithm of (CMRR20). If the actual interburden thickness exceeds the critical interburden thickness, a serious seam interaction is unlikely. Similarly, if the actual total vertical stress is less than the allowable stress, a serious seam interaction is unlikely.

Note that based on Equation 8.6.1, the critical interburden thickness is statistically independent of interburden characteristics, time lapse, and ratio of interburden-to-lower seam mining height. This is in complete opposition to findings discussed in Sections 8.3 (p. 391) and 8.5.2 (p. 407) and is due in large part to the fact that the stresses determined by LaM2D are generated by a single set of default overburden/interburden properties (E = 3,000,000 psi, υ = 0.25, and laminations thickness = 50 ft.) without due consideration of interburden characteristics, which is a key factor in determining seam interaction.

8.7 THREE-SEAM MINING

Kripakov and Sun (1996) investigated a case with three-seam mining where the upper seam was 1,500 ft (457.2 m) deep; the interburden thickness was 63 ft (19.2 m) between upper and middle seams and 30 ft (9. m) between middle and lower seams. Both the upper and middle seams had been mined previously, employing room-and-pillar mining, the upper seam with pillar extraction and the middle seam without pillar extraction. Numerical modeling analysis showed that stress concentrations in the lower seam increased approximately 100 % when compared to cases in which the upper and middle seams were not mined, and the areas located directly below the solid/gob boundaries experienced the highest stress concentrations.

Peng (2007) described a case of three-seam mining in descending order. The upper seam was 900 ft (274.3 m) deep with interburden thickness 80 (24.4 m) and 29 ft (8.8 ft) between the upper and middle seams and between the middle and the lower seams, respectively. There were no interaction problems during upper and lower seam mining. But during the middle seam mining, roof falls and floor heave occurred outby the pillar line. Finite element modeling showed that the three remnant pillars left accidentally in the upper seam gob caused a zone of stress concentration in the middle seam 100 ft (30.5 m) beyond the remnant pillar edges or a cave angle of 51^{o} from the pillar edge.

Maleki et al., (2007) used a numerical modeling method to calculate the amount of load transfer in three-seam mining, where the interburden between the upper and middle seam was 206 ft (62.8 m) thick and consisting of sandstone, and that between middle and lower seam was 100 ft (30.5 m) thick consisting of sandstone, siltstone, and mudstone. The upper seam was previously longwall-mined. In the modeling they used the measured surface subsidence over the upper seam gateroads for back-calculation. They found that due to the presence of upper-seam longwall remnant gateroad pillars, the maximum pre-mining vertical stress increased 30% in the middle seam and 14% in the lower seam. Therefore, instead of columnization, mine management chose to offset longwall gateroads in the lower seam from that of the upper seam. Preliminary operation experience showed that the lower seam face condition was good but with elevated hydraulic leg pressure for shields located beneath the abutment pillars of the upper seam.

Columnization of gateroad pillars was superior to offset stacking in a case of three seam multiple-seam mining reported by Latilla et al., (2007). Table 8.7.1 shows a summary of the mining and geological conditions. Mining was in descending order with shortwall mining in No. 5 and No. 4 seams preceding No. 2 seam which is being mined.

Table 8.7.1 Mining and geological conditions (Latilla et al., 2007)

Parameter		No. 5 seam	No.4 seam	No. 2 seam
Average cover depth, ft (m)		230 (70)	312 (95)	361 (110)
Average seam thickness, ft (m)		5.6 ft (1.7)	13.1 (4.0)	16.4 (5.0)
Panel Width, ft (m)	Range	466-531 (142-162)	394-462.5 (120-141)	390-531 (119-142)
	Average	485 (148)	420(128)	426 (130)
Overburden and interburden*		Soil 5%, dolerite 28%, interbedded shale & sandstone 62%, laminated sandstone 5%,	Interbedded sandstone and shale 19%, shaley sandstone 20%, laminated sandy shale & shaley sandstone 49%, coal & shale, 12%.	Shaley sandstone 30%, interbedded shale and sand-stone 70%

In the beginning, the shortwall in #2 seam was laid out such that gateroad chain pillars of the overlying #4 seam were roughly located within the central third of the #2 seam panel. Because numerical modeling indicated that the stress under the #4 seam was merely 290 psi (2 MPa) higher than under the #4 seam gob, offsetting the chain pillars would produce more evenly subsided surface. As mining began, roof falls occurred frequently in the unsupported distance between canopy tip and face and mostly under the #4 seam chain pillars. Roof falls ranged from 1.64-3.28 ft (0.5-1 m) to more than 32.8 ft (10 m) high.

Numerical modeling comparing offset and columnized chain pillar design was conducted again, and the results showed that columnized pillars decreased the stress along the face but increased the load on the No. 2 seam chain pillars. A decision was made to columnize the chain pillars in the new panels. The results showed a marked decrease in roof falls at the face. However, surface subsidence is considerably steeper and deeper with columnized pillars than with offset pillars.

Using scale models of simulated materials, Li et al., (2000) investigated three-seam simultaneous longwall mining where the interburden thickness was 295.2 ft (90 m) between the upper and middle seams and 492 ft (150 m) between the middle and lower seams. They found that the vertical abutment pressure influence zone is 213.2 ft (65 m); that when a seam is being extracted, the distance of advance influence is 137.8 ft (42 m) and the angle of advance influence is 65.5^o; and that within a distance of 13.1-164 ft (4-50 m) inby the face, the overburden movement is most active. After the face has passed 164 ft (50 m), overburden subsidence slows down.

8.8 MULTIPLE-SEAM HIGHWALL MINING

8.8.1 General

Since web pillars in highwall mining are very narrow and extremely long, columnization of web pillars between the upper and lower seam are difficult to maintain. In a case study by Newman and Zipf (2005) where the seam split by a parting (interburden) of sandy fireclay and weak shaley coal, 42-45 in. (1,067-1,143 mm) thick, failures of cut openings occurred due to a combination of interburden thickness and the 10.4 ft (3.2 m) wide cut openings. However, opening collapse also occurred where the interburden thickness satisfied long-term stability. In such a case, mine management attributed the opening failure to difficulty in columnization of pillars. Web and barrier pillar widths were determined by Equations 5.9.1 and 5.9.4, respectively.

Conversely, an offset web pillar arrangement was employed by Vandergrift and Garcia (2005) in another case study where the interburden thickness was 12-45 ft (3.7-13.7 m) and UCS 3,674-8,150 psi (25.3-56.2 MPa) (Fig. 8.8.1). The same Equations 5.9.1 and 5.9.4 were used to determine the web and barrier pillar widths. Average penetration depth was 1,051 ft (320 m).

8.8.2 Ultra-Close Multiple-Seam Highwall Mining

Contrary to all other mining methods, the industry practice in ultra-close, multiple-seam highwall mining has been to mine the lower seam first and then the upper seam due to ease of operation.

In the case studies reported by Zipf (2005b), the interburden thickness ranged from 4 to 10 ft (1.2 to 3 m). Due to the length of web and barrier pillars, it is difficult to stack up the web pillars in both seams along the whole pillar length. When deviation becomes severe, the upper seam pillar may be off so much that it is located at the middle of the roof span in the lower seam. Under such pillar loading conditions, tensile cracks and failure will occur at the center of the lower seam roof beam (i.e., interburden thickness). Barrier pillars, due to their greater width are easier and more likely to stay in stacking order.

Also with less interburden thickness (less than one highwall miner hole width), stacked pillars are effectively a tall pillar with its height equivalent to the sum of the height of upper and lower seam pillars plus the interburden thickness.

To avoid web pillar collapse and highwall failure, Zipf (2005b) recommended stacking barrier pillars and decreasing the number of highwall miner holes between barrier pillars to 5. In addition, web pillars should be designed based on the combined height of both seams plus the interburden thickness.

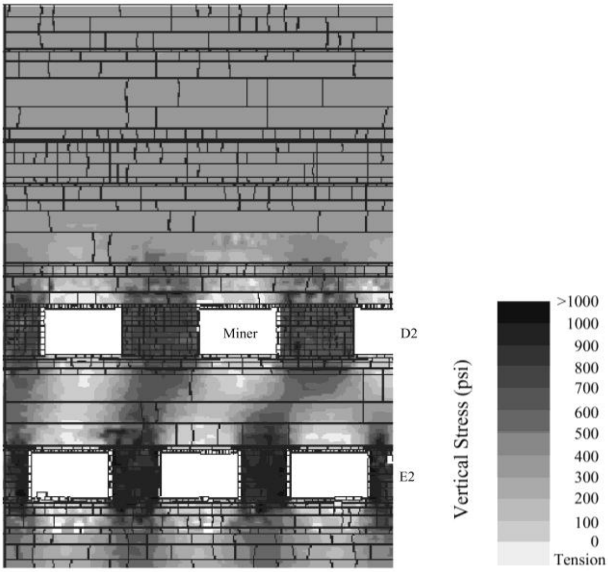

Fig. 8.8.1 Offset pillar arrangement in multiple-seam highwall mining (Vandergrift and Garcia, 2005)